The Influence of macro-roughness elements on the propagation of a bore over an initially dry bottom

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- Smmry, cnclsn, tlk

01.

Introduction

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Introduction

- motivation: tsunami inundation modelling
- depth-averaged models (non-linear shallow water (NLSW) and Boussinesq models):
  - use Manning formula with coefficent for bottom $u = \frac{1}{n} R_b^{2/3} \sqrt{S_0}$
- Macro-roughness elements (buildings and tree vegetation):
  - too small to be represented in numerical grid/mesh
  - may be considered by increased Manning‘s coefficient

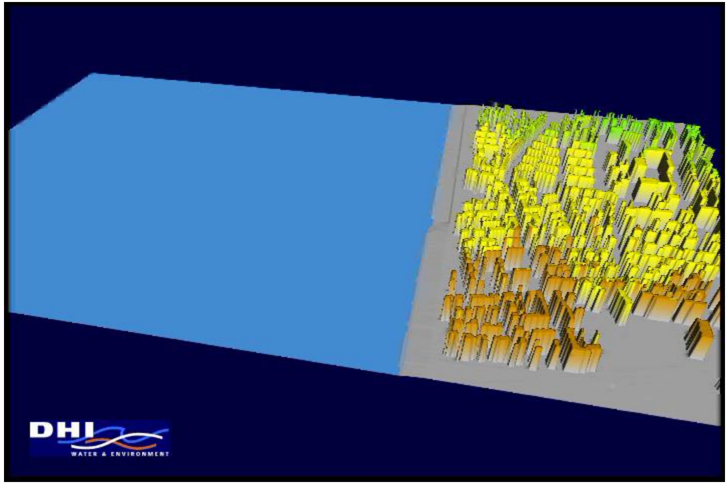
not physically sound → large uncerteinties

02.

Inundation modelling for the Tsunami Early Warning System in Indonesia

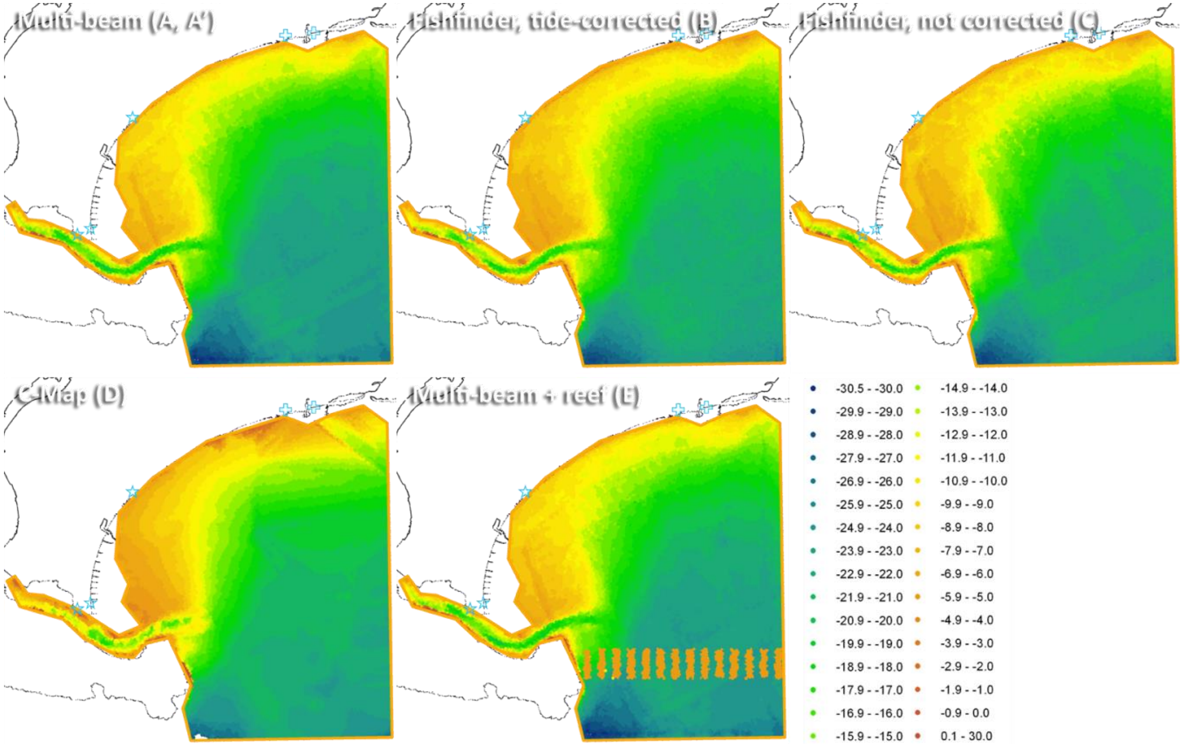
Modeling software

- 2D numerical models (non-linear shallow-water equation model, such as MIKE 21)
- Depth-dependent drag coefficient in quadratic friction law from Gauckler/Manning/Strickler formula
- high resolution required
- model distinguishes between area types (e.g. streets, houses, vegetation)
- Eddy viscosity



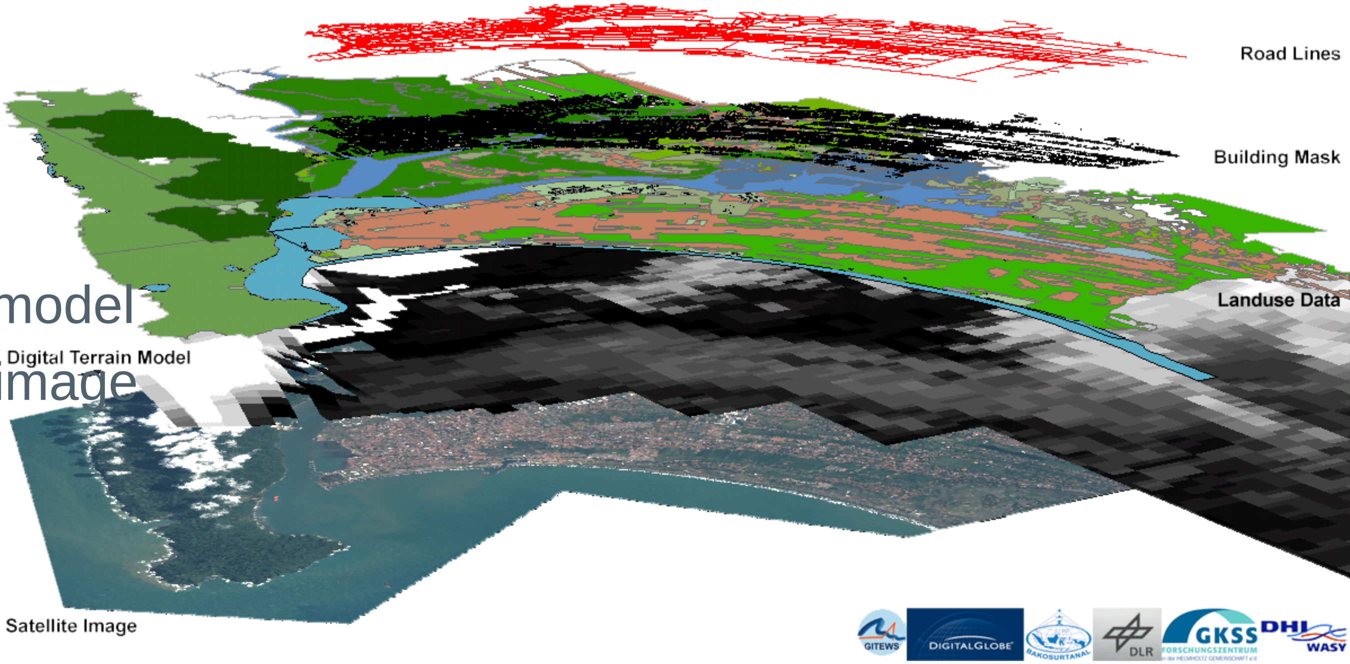
Bathymetry data

- Comparison of different data sets
- Runup does not vary significantly (Leschka, Kongko & Larsen, 2009)



Roughness data

- Onshore:
  - Road lines
  - Building mask
  - Landuse data
  - Digital terrain model
  - Satellite/airial image



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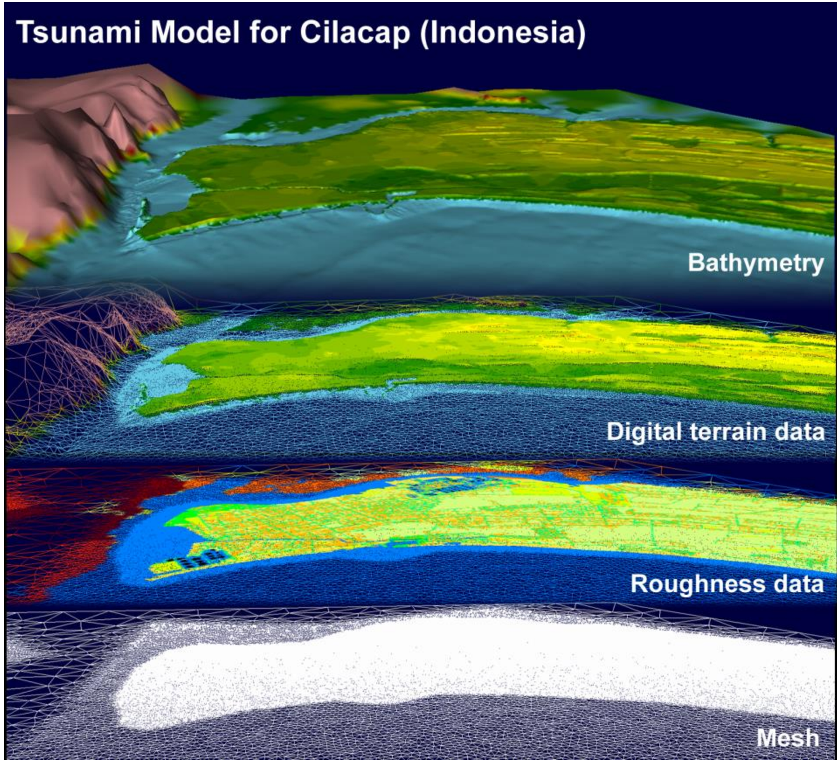
MIKE 21 FM setup

- Discretization: 2nd order time/space
- Timesteps: 0.01 – 10s (CFL_{crit} = 0.8)
- Drying/wetting/flooding: 0.005/0.05/0.1 m
- Eddy viscosity: Smagorinsky
- Bed resistance offshore: 32 $m^{1/3}/s$

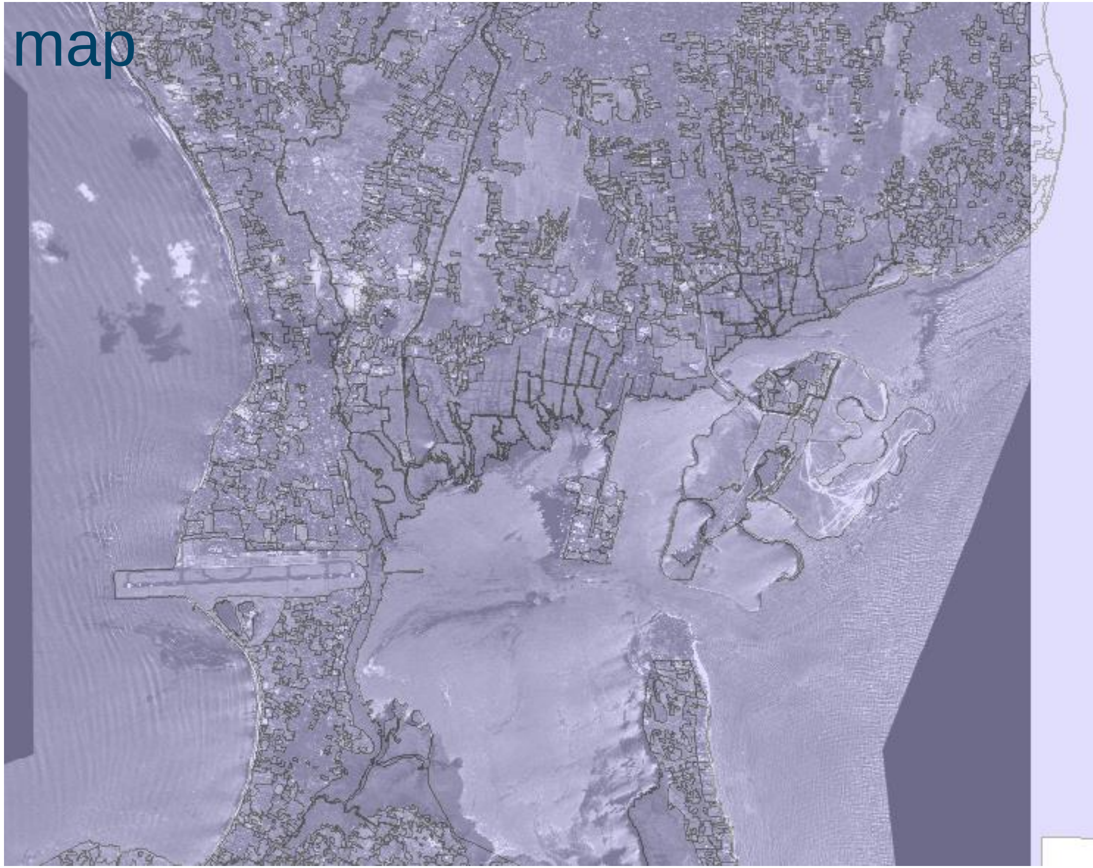


Generation of roughness map

- Digital Globe image (2006): Quickbird Bali South

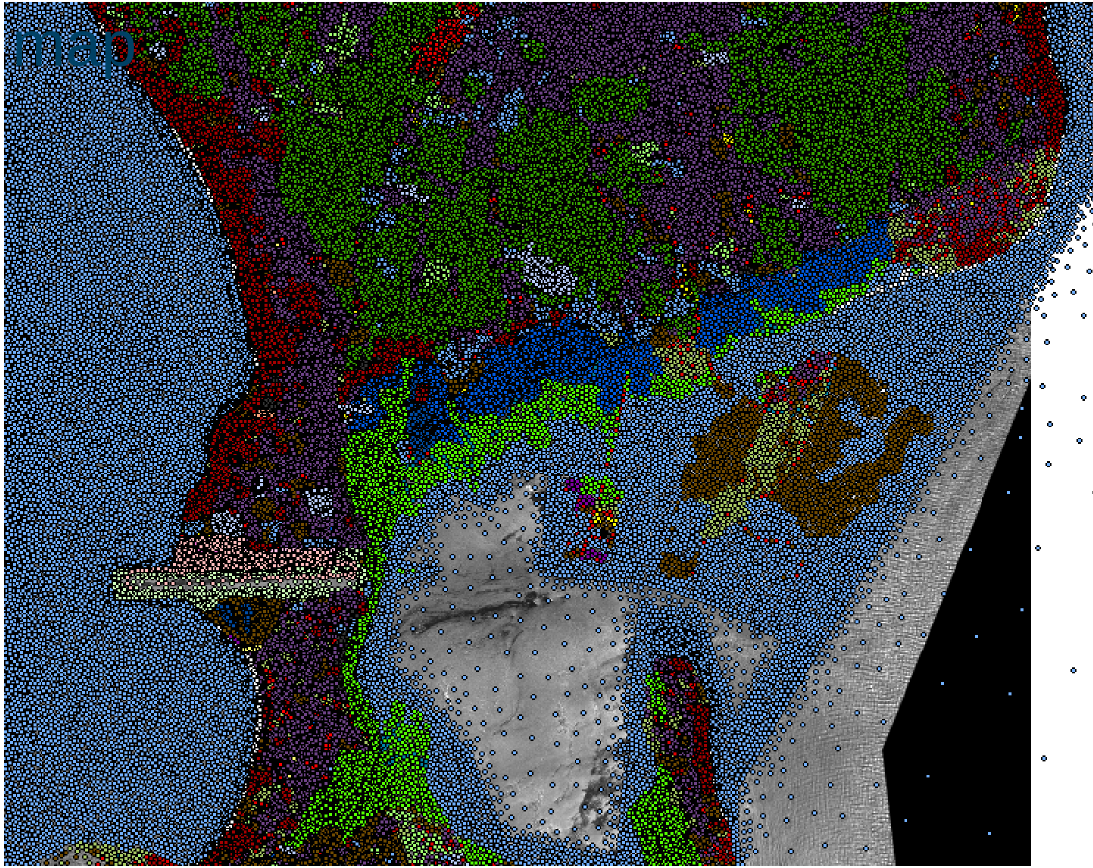
Generation of roughness map

- DLR (2008): Landuse Data
  - Hotel
  - Office area
  - Plantation
  - Industry
  - Settlement
  - Paddy field
  - Savannah



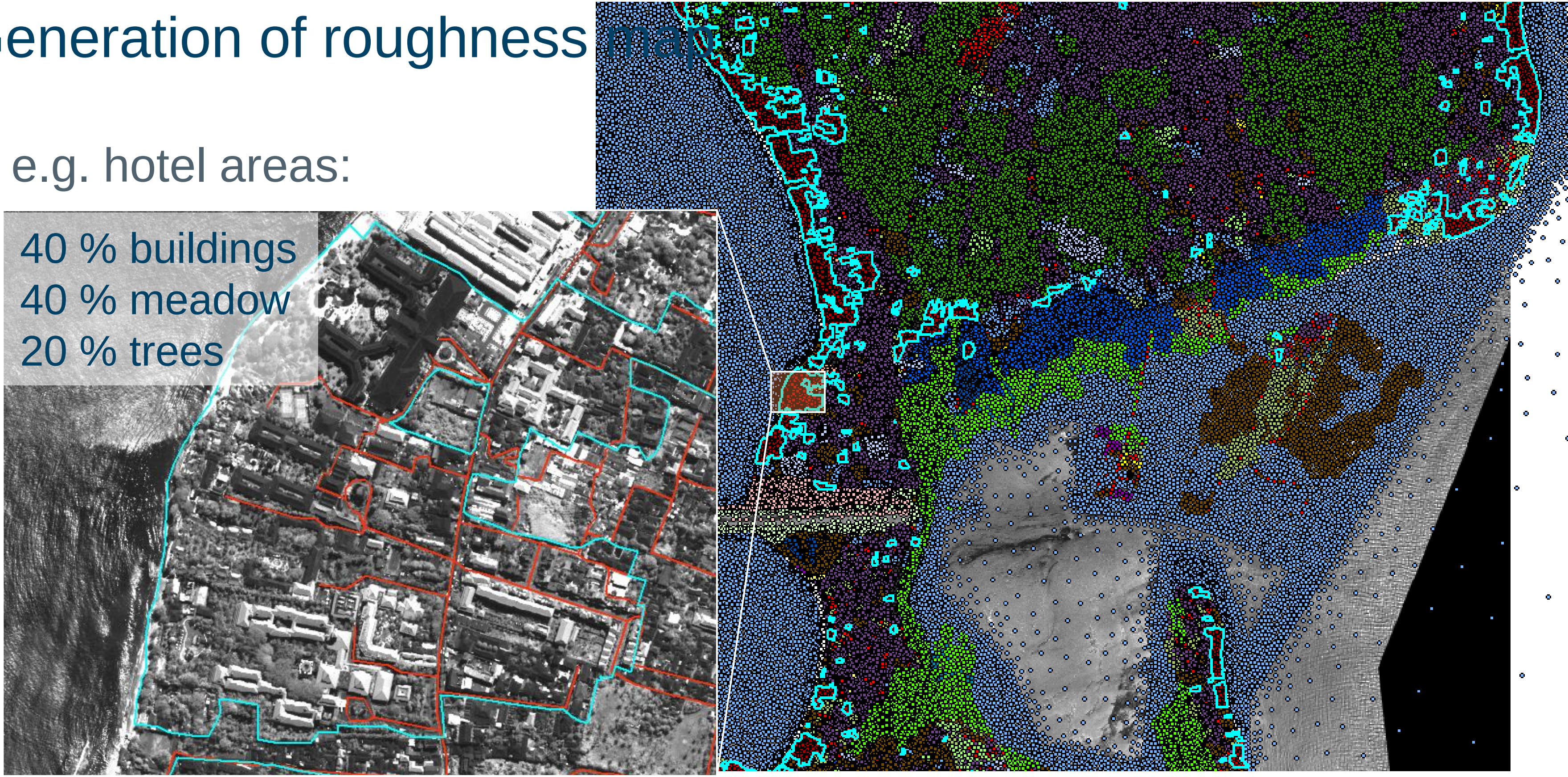
Generation of roughness map

- Splitted into fractions -> Manning no. From literature
  - sand
  - stone
  - soil
  - asphalt
  - meadow
  - Forest types



Generation of roughness map

- e.g. hotel areas:



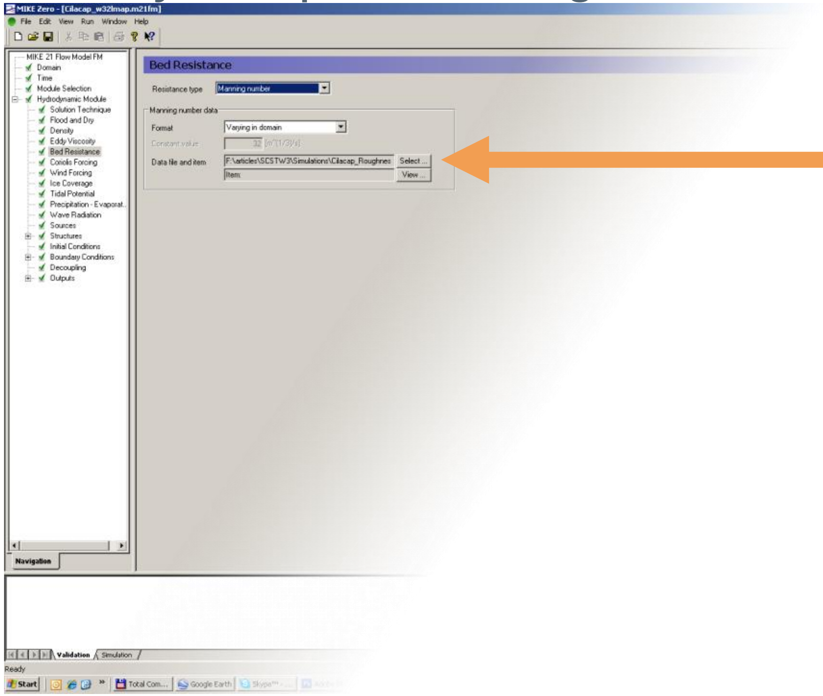
Generation of roughness map

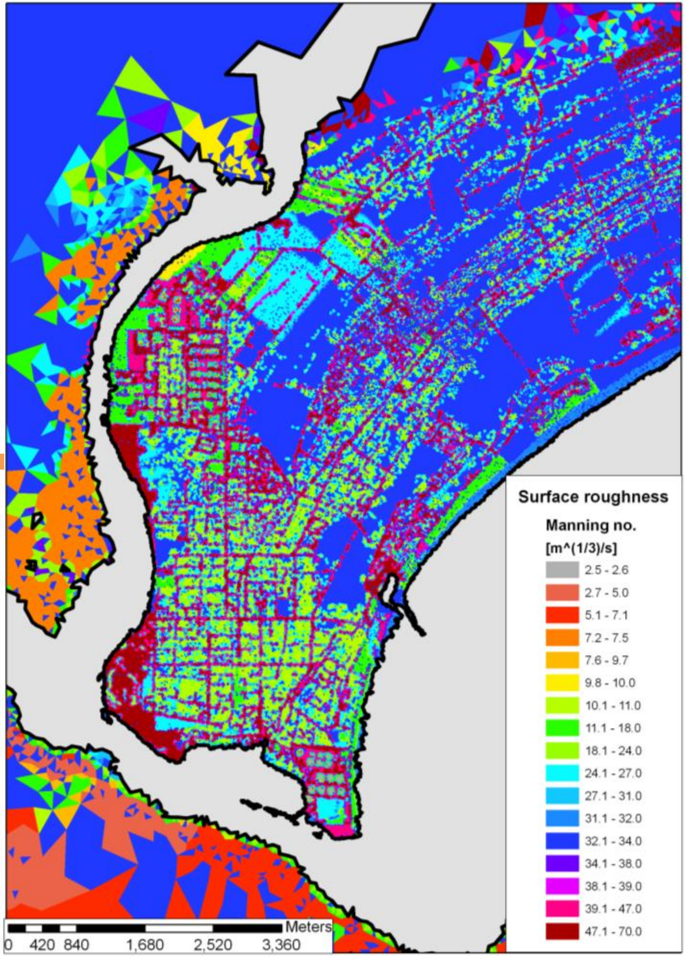
- Buildings
  - resistant: M = 2.5 $m^{1/3}/s$
  - non-resistant: M = 11 $m^{1/3}/s$

  (Gayer, Leschka, Noehren, Larsen & Guenther, 2009. High resolution tsunami inundation modelling. Annual meeting of AOGS, 11-15 August 2009, Singapore.

Generation of roughness map

- Linearly interpolated roughness map Cilacap





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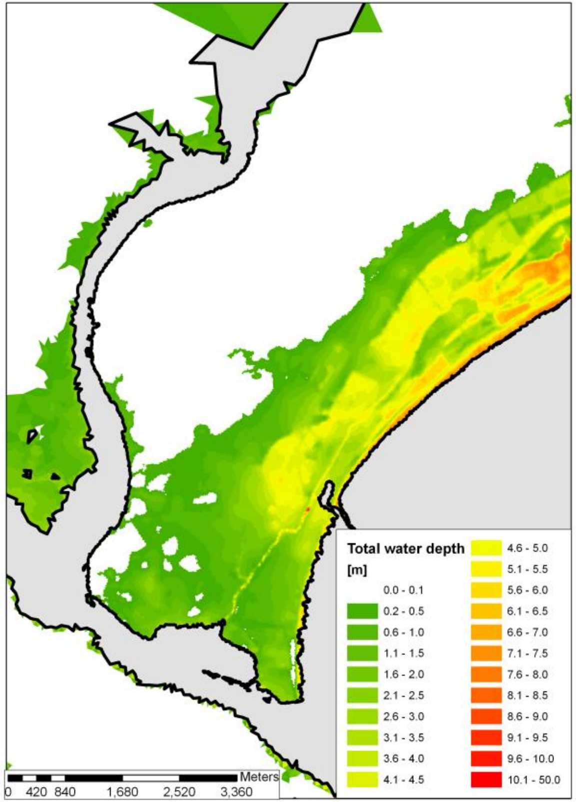
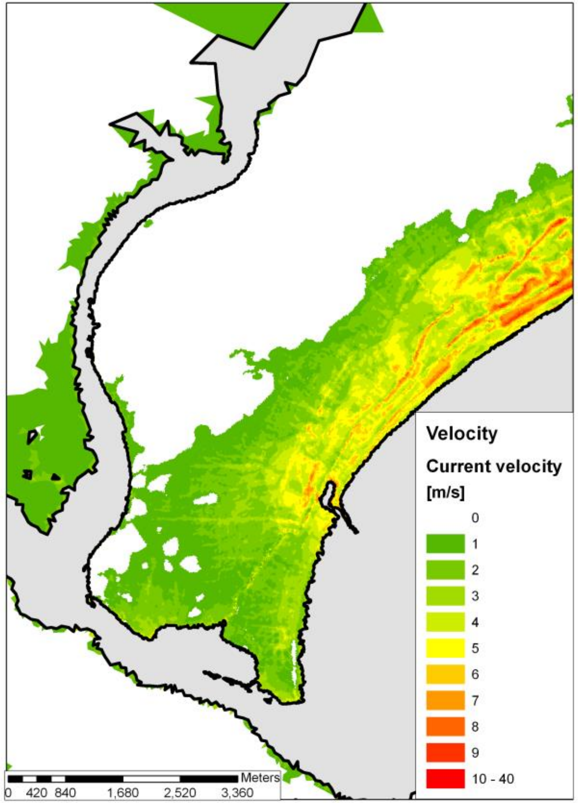
Example results

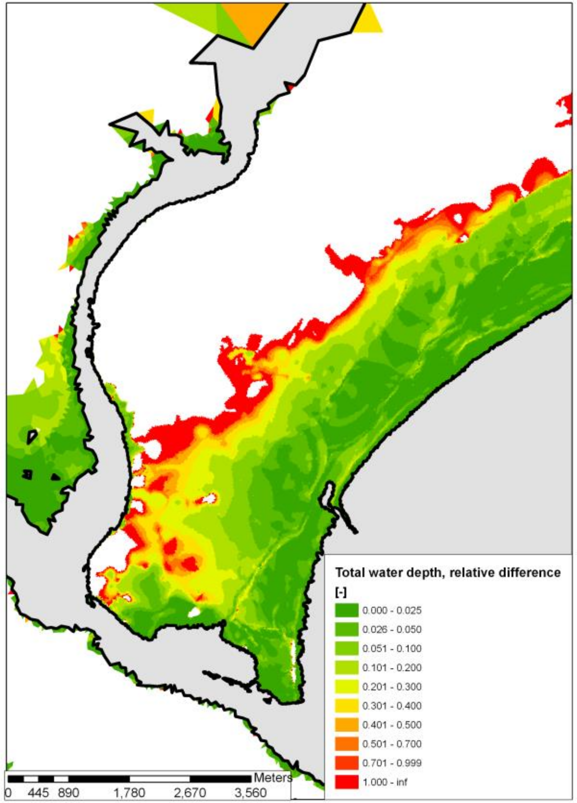
- total water depth
- current velocity

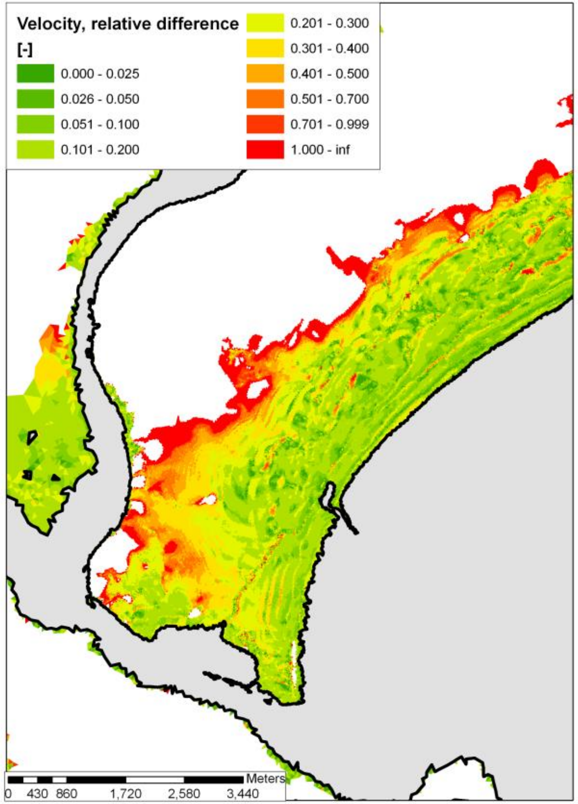




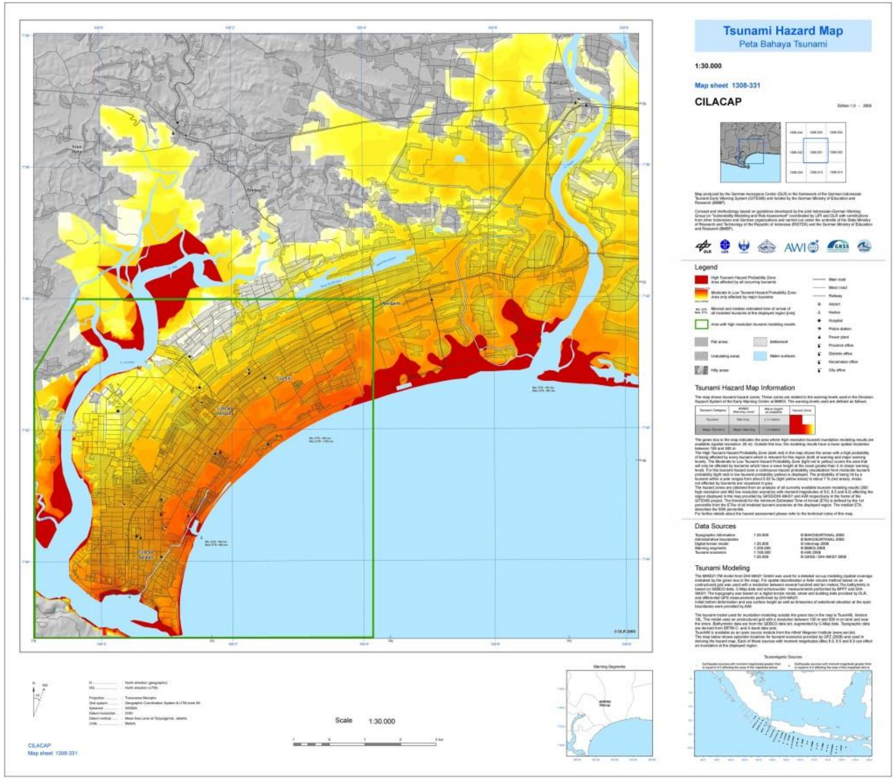
Sensitivity

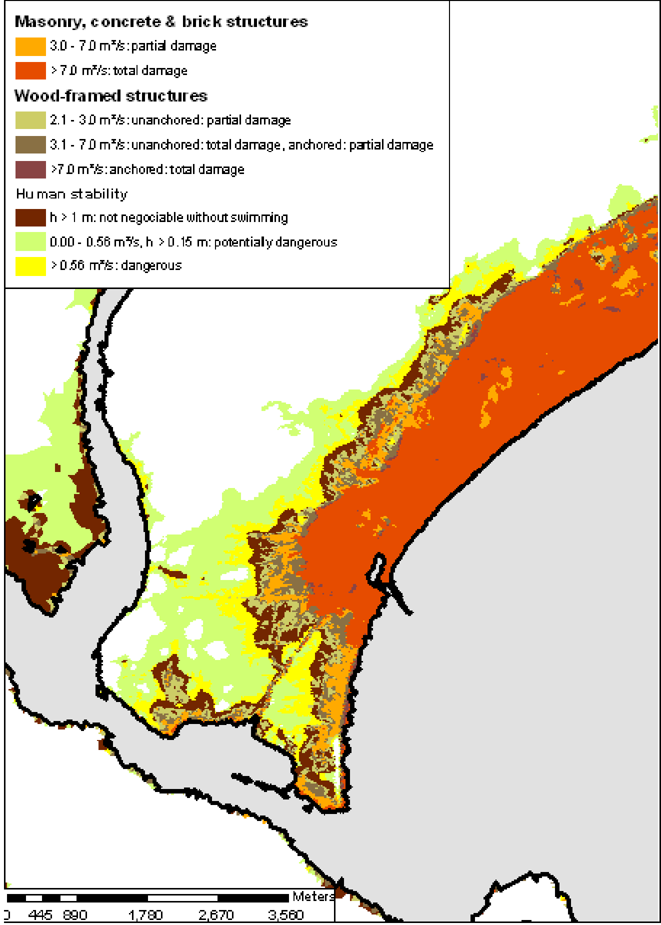
- $M = 35\ m^{1/3}/s$
  vs.
  $M = 5\ m^{1/3}/s$
- total water depth
- current velocity





Hazard


Tsunami Hazard Map
Peta Bahaya Tsunami
1:30.000
Map sheet 1308-331
CILACAP
Legend
Tsunami Hazard Map Information
Data Sources
Tsunami Modeling
Scale 1:30.000
CILACAP
Map sheet 1308-331


Masonry, concrete & brick structures
3.0 - 7.0 m²/s: partial damage
> 7.0 m²/s: total damage
Wood-framed structures
2.1 - 3.0 m²/s: unanchored: partial damage
3.1 - 7.0 m²/s: unanchored: total damage, anchored: partial damage
>7.0 m²/s: anchored: total damage
Human stability
h > 1 m: not negociable without swimming
0.00 - 0.56 m²/s, h > 0.15 m: potentially dangerous
> 0.56 m²/s: dangerous
Meters
0 445 890 1,780 2,670 3,560

03.

Alternative approach

Energy losses

- Energy losses during tsunami inundation
  - Friction
  - Drag
  - Vortex
  - Inertia
- Friction: Chézy (1775), Gauckler/Manning/Strickler
  - no viscosity -> fully rough/fully turbulent conditions
  - R_b hydraulic radius (channel flow)
  - steady state
  - dimensional

$$u = \frac{1}{n} R_b^{2/3} \sqrt{S_0}$$

$$C_F = \frac{gn^2}{h^{1/3}}$$

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Energy losses

- previous work:
  - river engineering
    - Li & Shen (1973)
    - Fisher & Reeve (1994)
  - proposed inertia coefficients
    - Noji et al. (1993)
    - Tsutsumi et al. (2000)
    - Harada & Kawata (2004)
  - extensions to NLSW model
    - Matsutomi et al. (2006)
  - vegetated/urban areas:
    - Augustin et al. (2009)
    - Yuan & Huang (2009)
    - Suzuki & Arikawa (2010)
    - Husrin et al. (2011)
    - Huang et al. (2011)
    - Goseberg (2011)
    - Huthoff (2012)
    - Li et al. (2012)

Energy losses due to friction

- Bradford & Sanders (2002): Manning approach near wet/dry boundary causes unrealistically large predictions of shear stress
- Haaland formula from pipe flow considers Reynolds number

$$C_F = \frac{0.204}{\ln^2\left[\mathrm{Re} + \left(k_S / 14.8h\right)^{1.11}\right]}$$

- still not applicable for vertical structures

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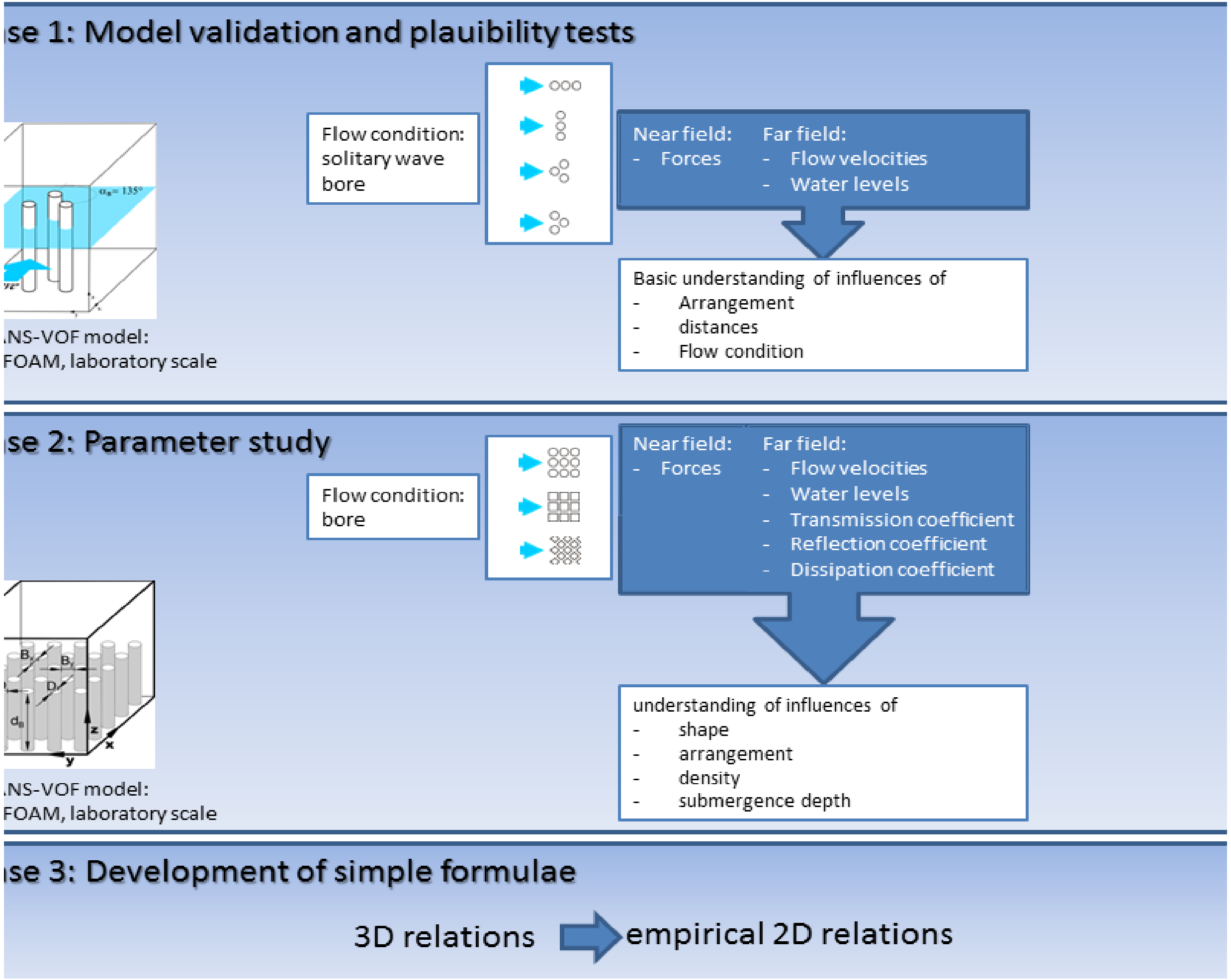
Methodology



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02.

Model validation

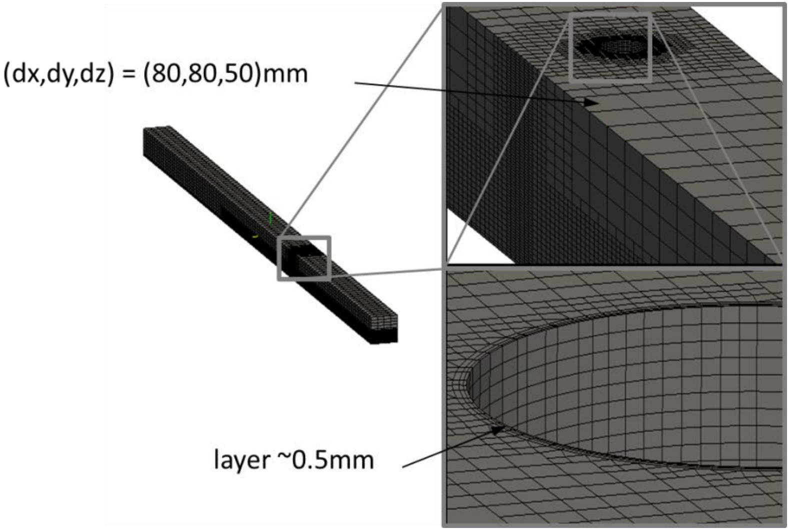
Validation

i. offshore:
   a) forces on single cylinder due to regular waves (data by Bonakdar, 2012)
   wave generation, propagation, force calculation
   b) solitary wave heights (data by Strusinska, 2010)
   numerical dissipation

ii. onshore:
   forces on single cylinder due to bore (Árnason, 2004)

Validation

iii. interaction in a group of cylinders subject to regular waves
a) comparison with laboratory data (Bonakdar & Oumeraci, 2014)
b) plausibility tests with lab data (Bonakdar, 2012) and empirical relations



Mesh scene of the bore validation

Validation: i.b) Bore at a single cylinder

- tank of the Charles W. Harris Hydraulics Laboratory of the University of Washington
  - dimensions:
    L / W / H = 16.62 / 0.61 / 0.45 m
  - column diameter D_B = 0.14 m
  - impoundment height h_0 = 0.25 m

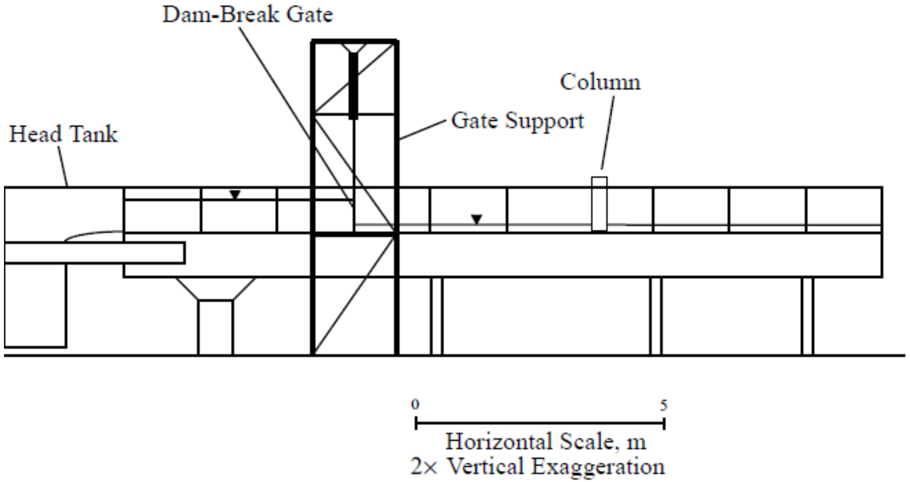
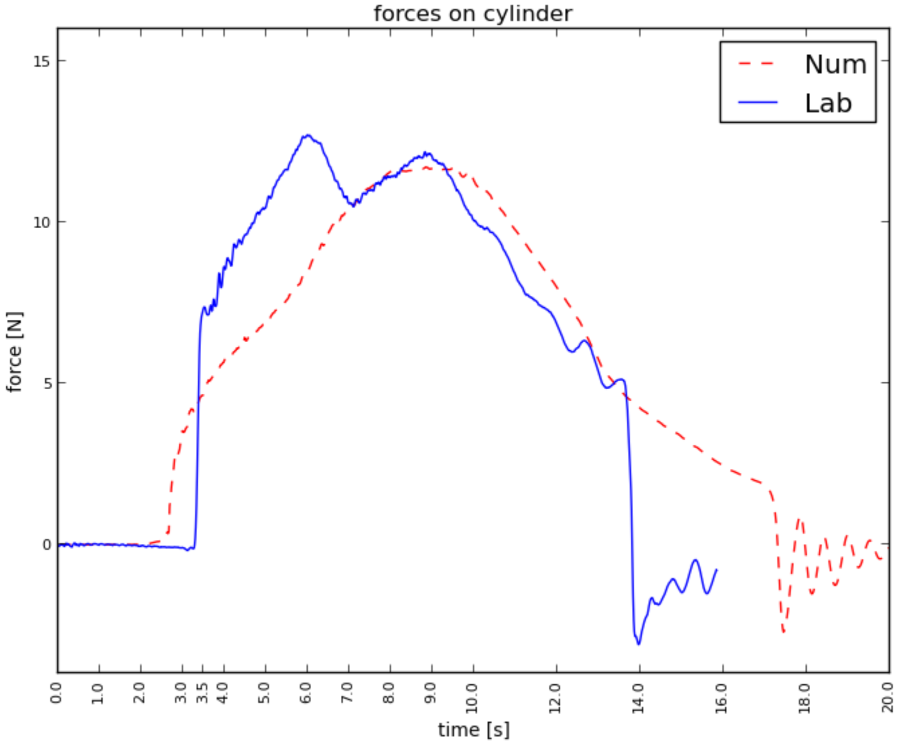


Figure 4.1: A diagram of the tank (adapted from Moore (1999))

source: Árnason (2004)

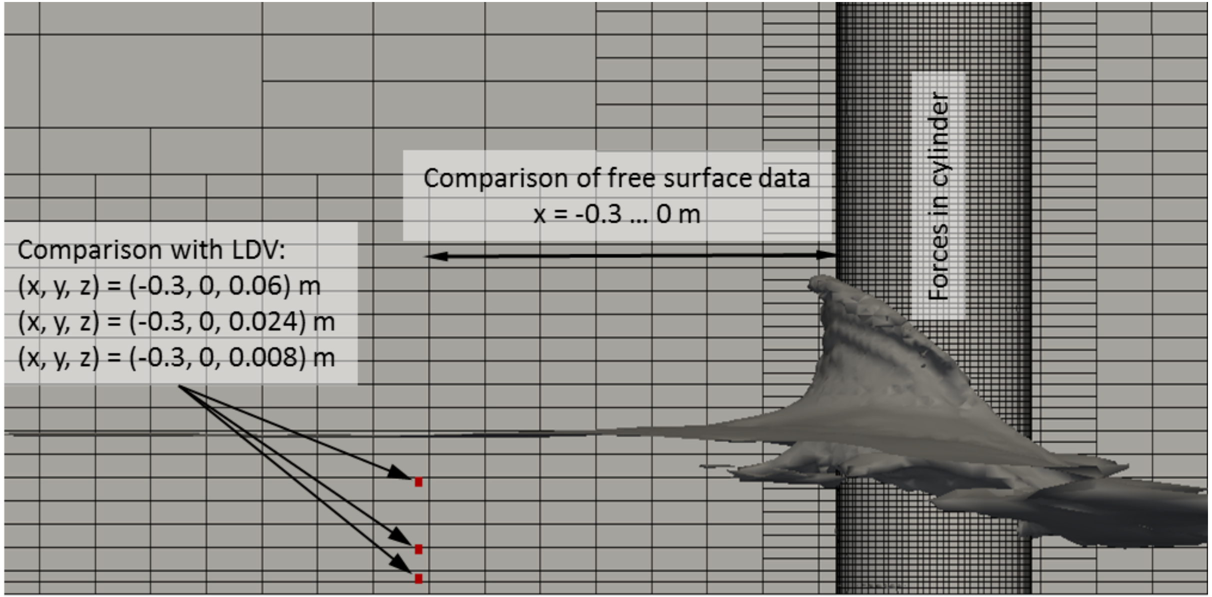
Validation: i.b) Bore at a single cylinder

- first result:

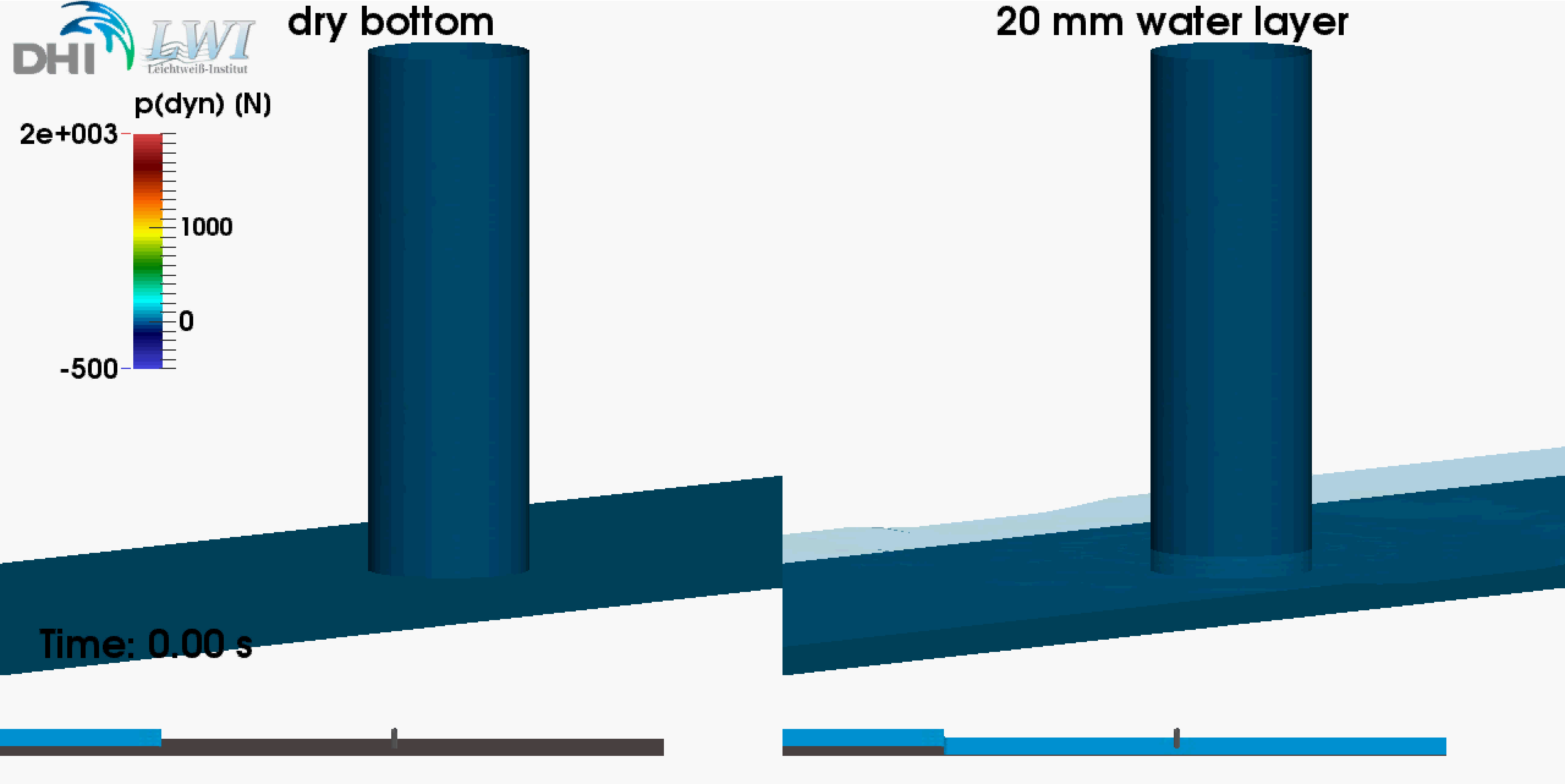


Validation: i.b) Bore at a single cylinder

- bore at a single cylinder (Árnason, 2004)



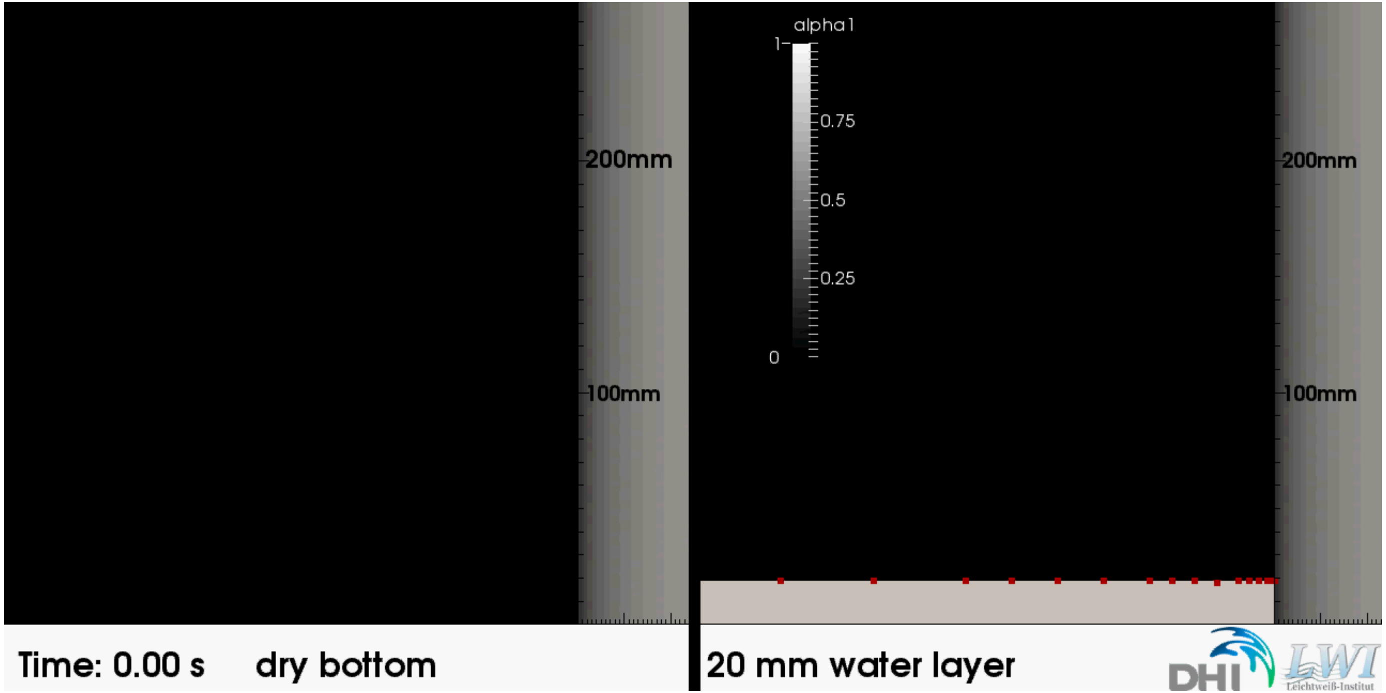
Free surface and velocity comparison


dry bottom
20 mm water layer
p(dyn) (N)
2e+003
1000
0
-500
Time: 0.00 s

Validation: 1.b) Bore at a cylinder

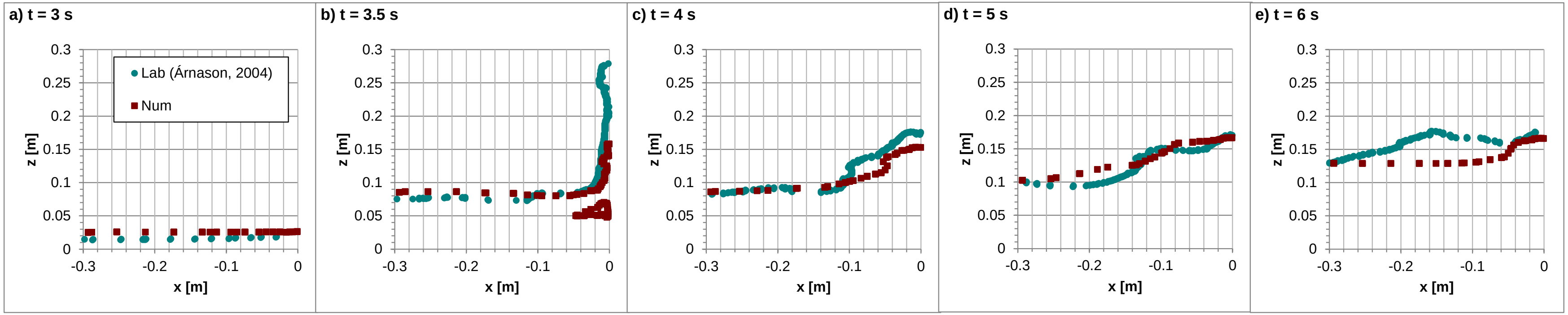
- Free surface in at upstream cylinder face

red dots: interpolated free surface
alpha1: simulated water phase content in cells



Validation: Bore at a single cylinder

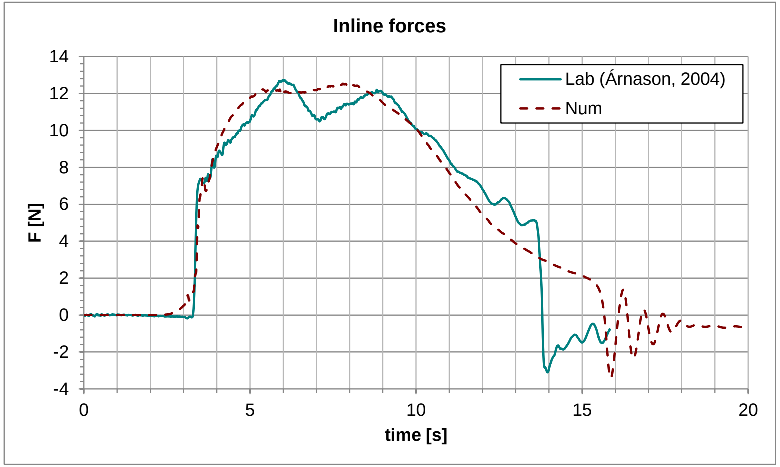
- Free surface data comparison



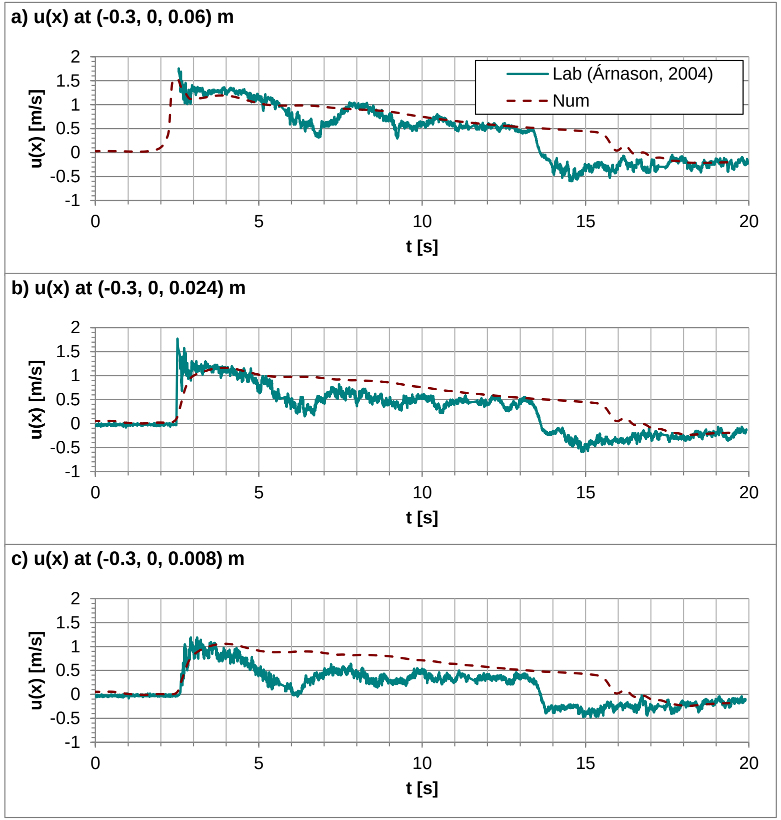
Free surface comparisons at different time steps.

Validation: Bore at a single cylinder

- Bore at a single cylinder
  - Deviation max. F ~ 1.6 %



Force comparisons at different time steps.



Velocity comparisons at different time steps.

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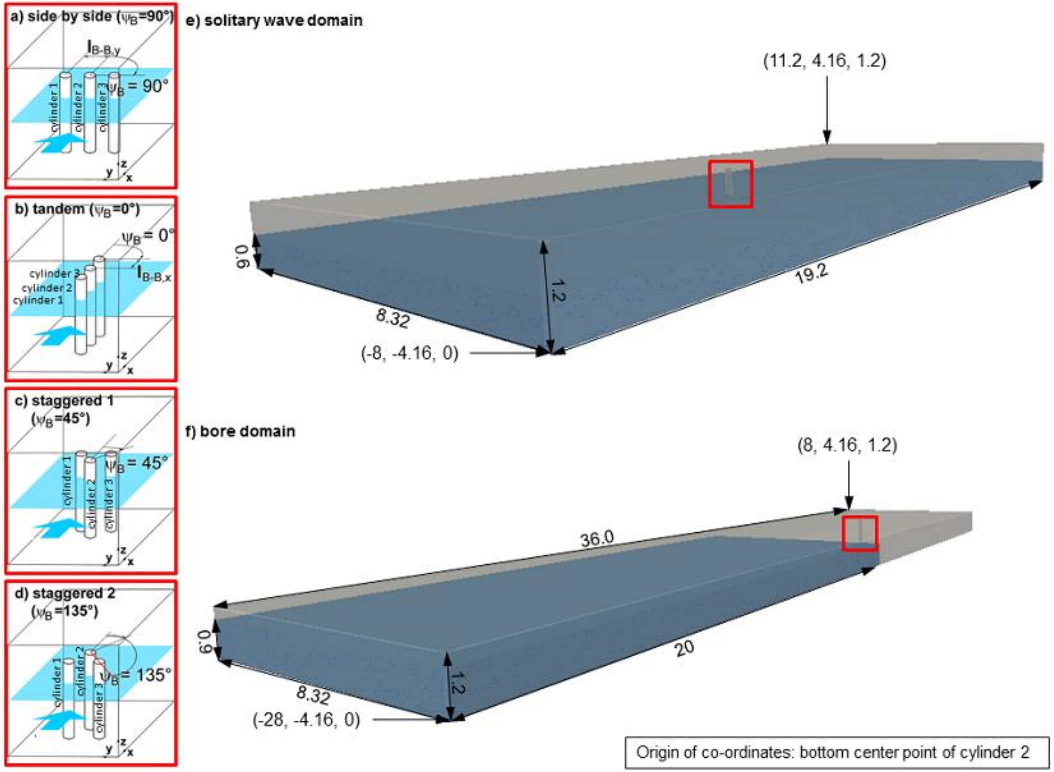
03.

Setup

Setup

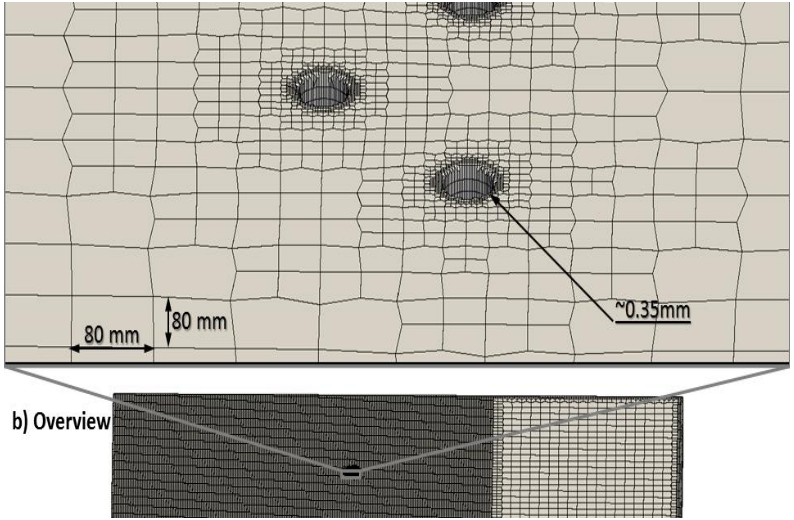
- Distances:
  - $0.5\ D_B$
  - $1.0\ D_B$
  - $2.0\ D_B$
  - $3.0\ D_B$
- arrangement angle Ψ_B:
  - spans clockwise between
    - main flow direction
    - direction of next roughness element



- **Basic arrangements of cylinders**

Setup

- 3D Navier-Stokes model:
  OpenFOAM (OpenFOAM Foundation, 2010)
- wave cases:
  - wavesToFoam toolbox
    (Jacobsen et al., 2012)
- bore cases:
  - interFoam solver



Mesh scene of wave cases

Setup

- numerical parameters:

Domain	**Solitary wave**	**Bore**
X	{-8, …, 11.2} m	{-28, …, 8} m
Y	{-4.16, …, 4.16} m	{-4.16, …, 4.16} m
Z	{0, …, 1.2} m	{0, …, 1.2} m
Mesh		
dx/dy	0.08 m (180 cells/L)	0.08 m
dz	0.01 m (22 cells/H)	0.01 m
initial/BC		
H	0.22 m	-
h_0	0.6 m	0.9 m

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Methodology

- Normalize and analyze
  - flow field

$$u(x)^{*}_{soliton,max} = \frac{u(x)_{soliton,max}}{u(x=0)_{soliton,no\ cylinder,max}}$$

  - forces in cylinders

$$F(x)^{*}_{\max} = \frac{F(x)_{i,max}}{F(x)_{single,max}}$$

04.

Results

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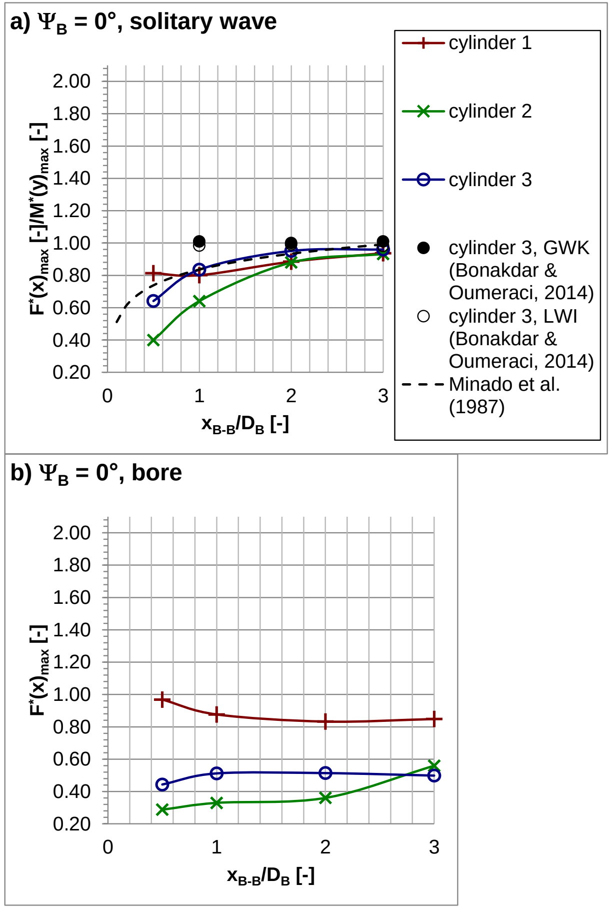
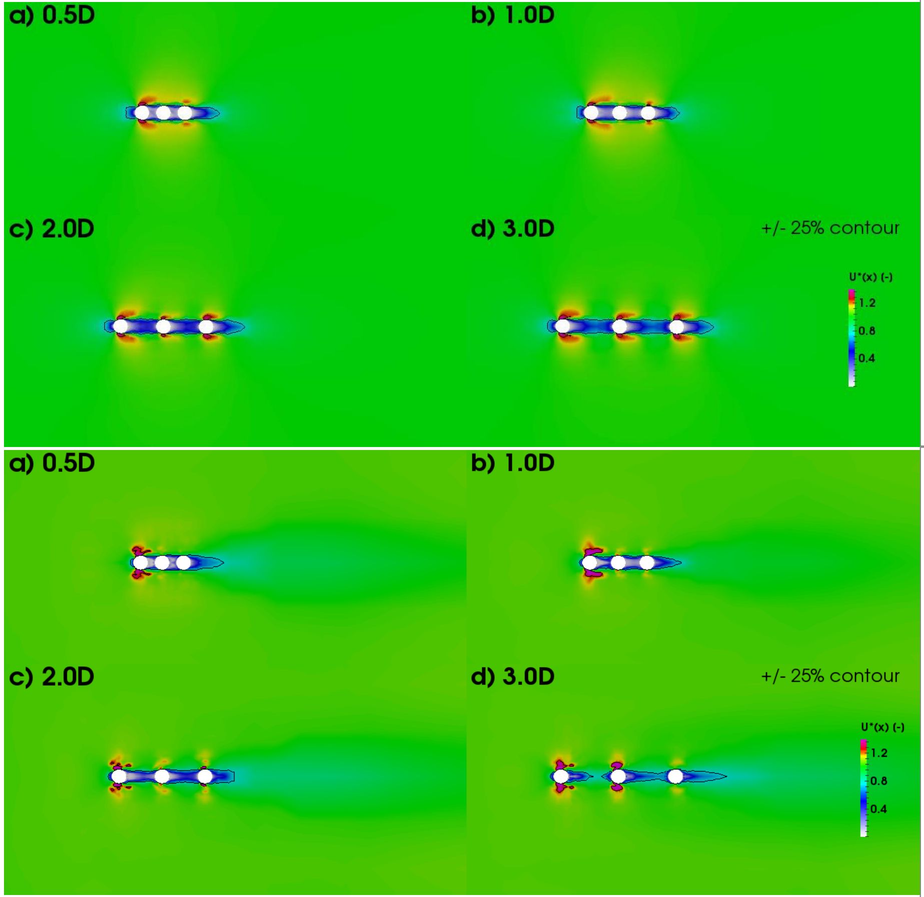
Tandem

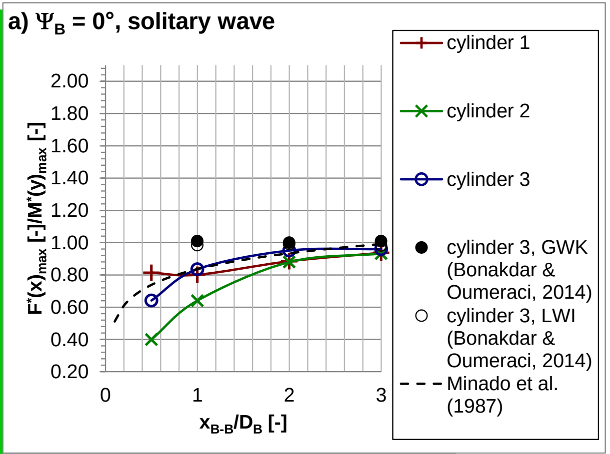
- tandem arrangement (Ψ_B = 0°)
  - differences more pronounced in bore cases
  - distance
    - differences decrease with increasing distance
    - bores: plays minor role
    - solitary wave: at 3 D_B, cylinders independent

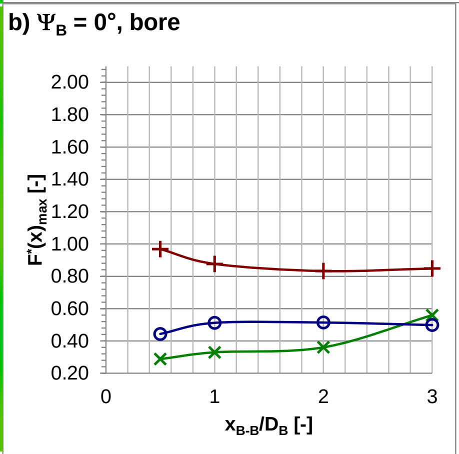
Mindao et al. (1987): $K_z = 0.836 + 0.141 \ln (x_{B-B}/D_B)$



F^*_{max} in three cylinders in tandem arrangement

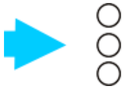




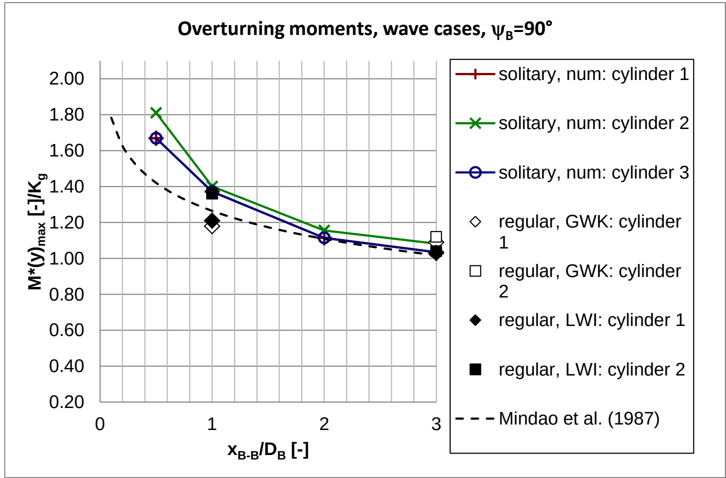


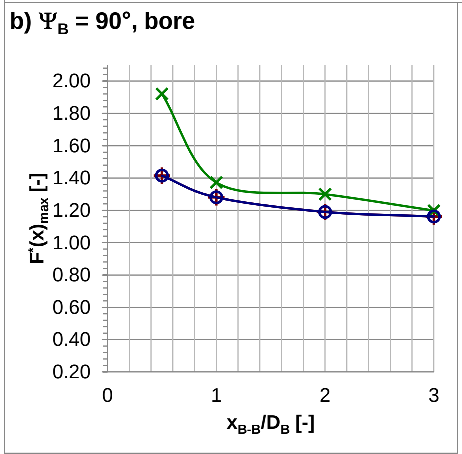
F^*_{max} in three cylinders in tandem arrangement

Side-by-side

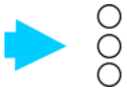


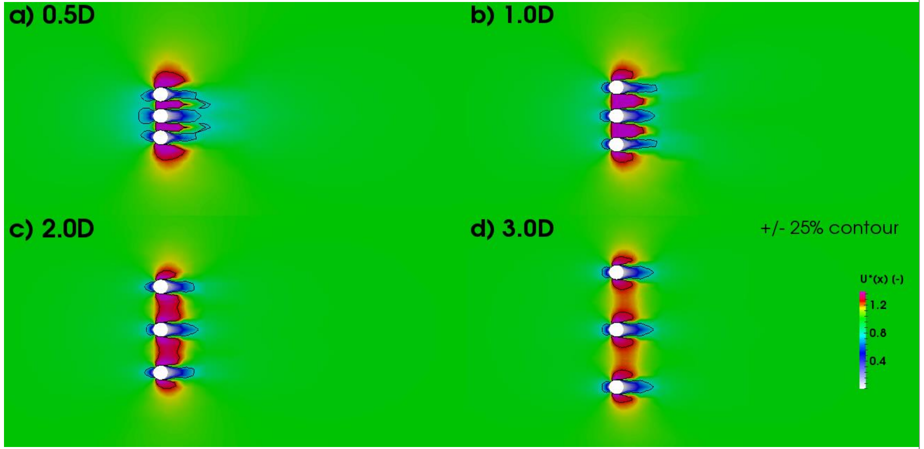
- side-by-side arrangement (Ψ_B = 90°)
  - differences are more pronounced under bore conditions
  - distance:
    - solitary wave: at $3D_B$ cylinders act almost independent
    - bore: differences vanish, but at $3D_B$ cylinders receive higher load than single cylinder

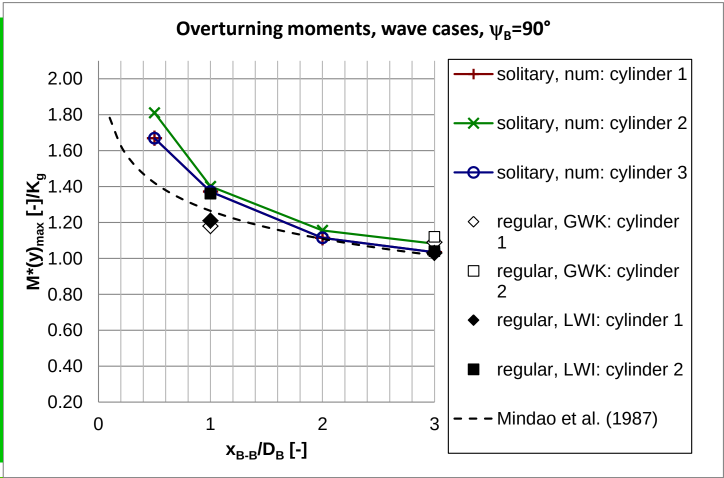


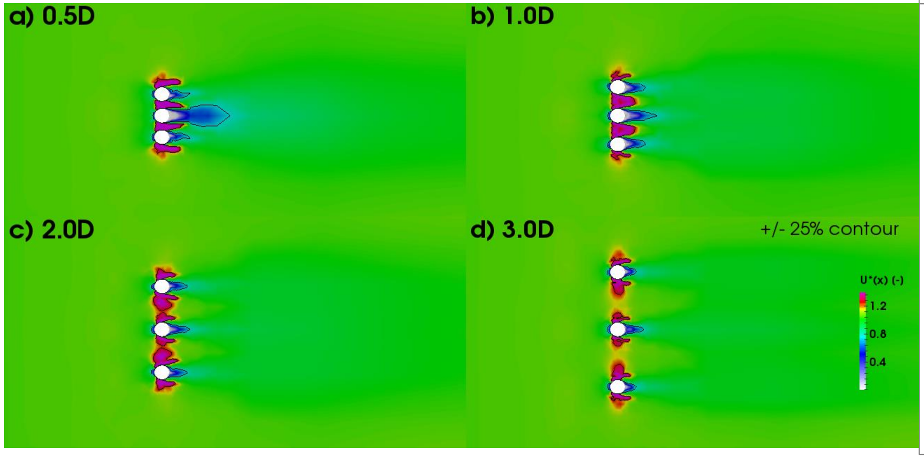


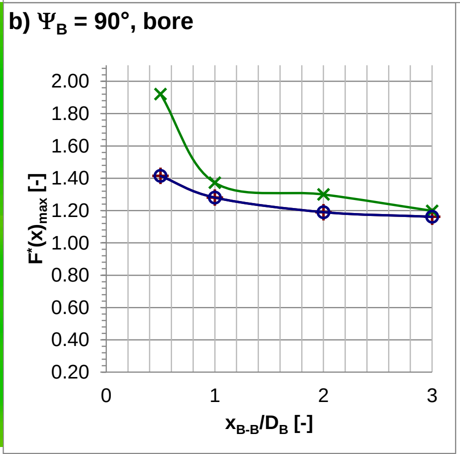
F^*_{max} in three cylinders in side-by-side arrangement; reg. wave case by Bonakdar & Oumeraci (2014)











F^{*}_{max} in three cylinders in side-by-side arrangement; reg. wave case by Bonakdar & Oumeraci (2014)

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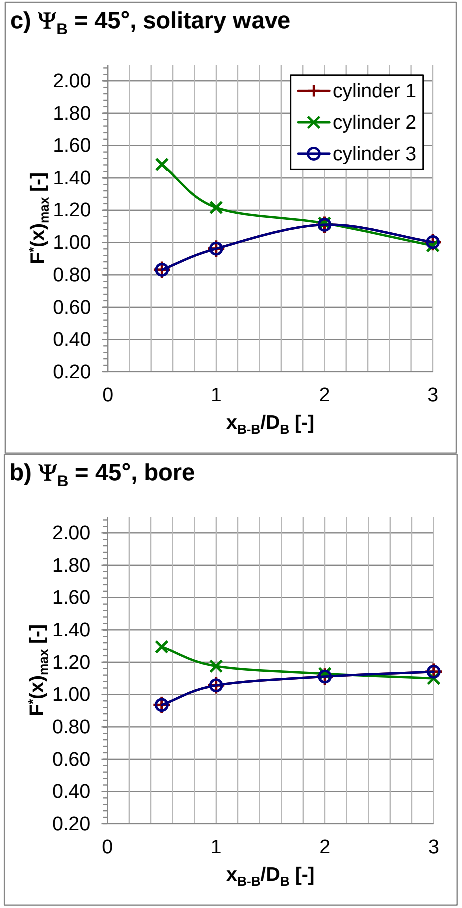
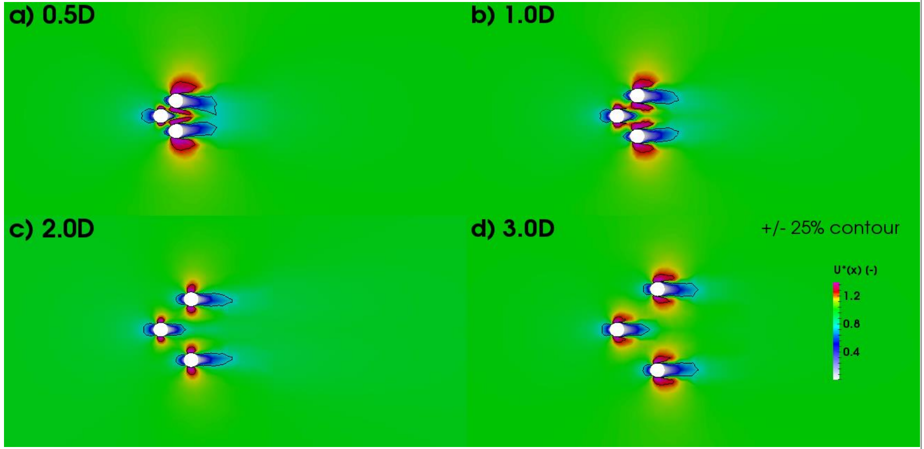
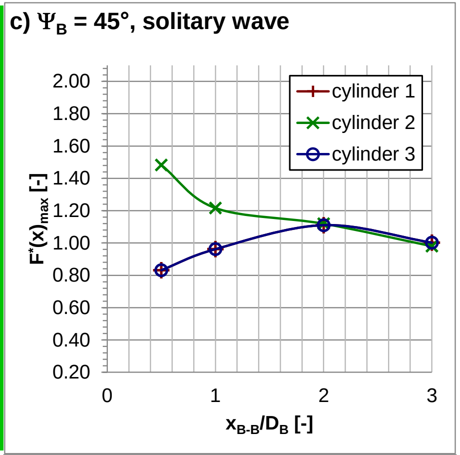
Staggered 1

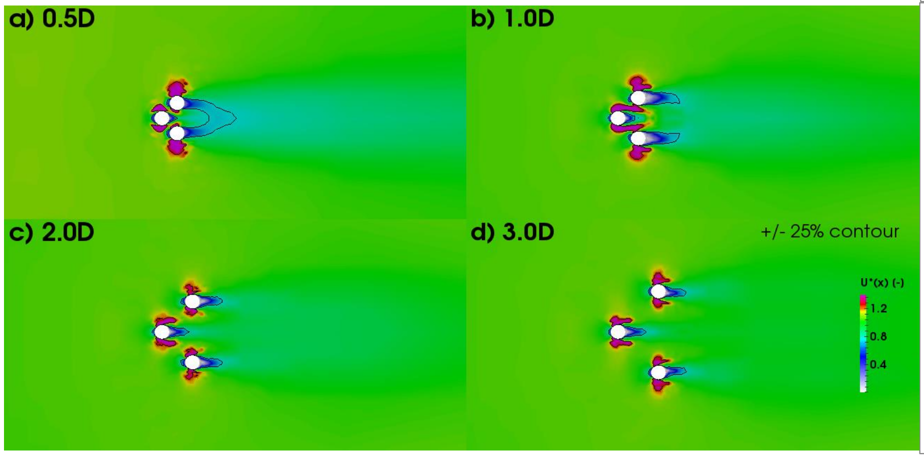
- staggered 1 arrangement (Ψ_B = 45°)
  - differences are more pronounced under wave conditions
  - distance:
    - solitary wave: at $3D_B$, cylinders independent
    - bore: at $3D_B$ still interaction

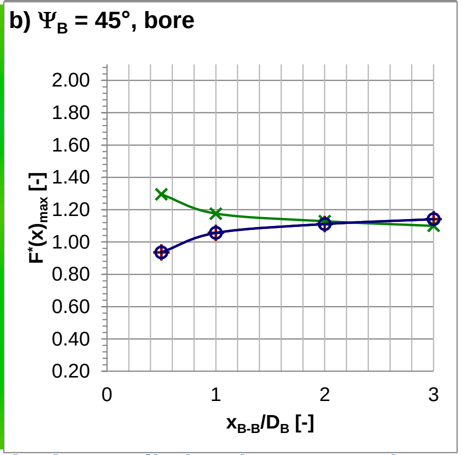


F^*_{max} in three cylinders in staggered 1 arrangement; reg. wave case by Bonakdar & Oumeraci (2014)



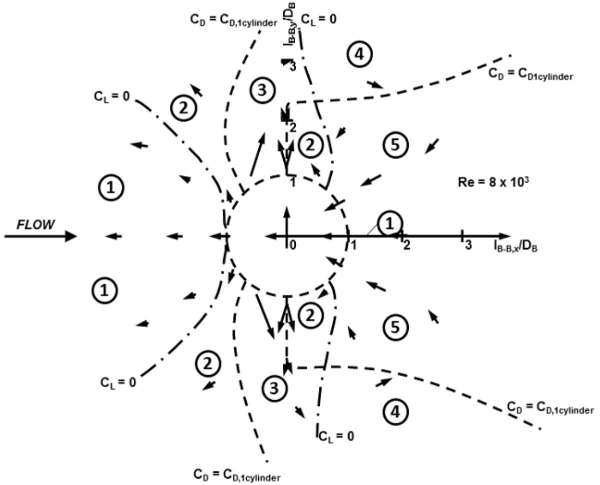


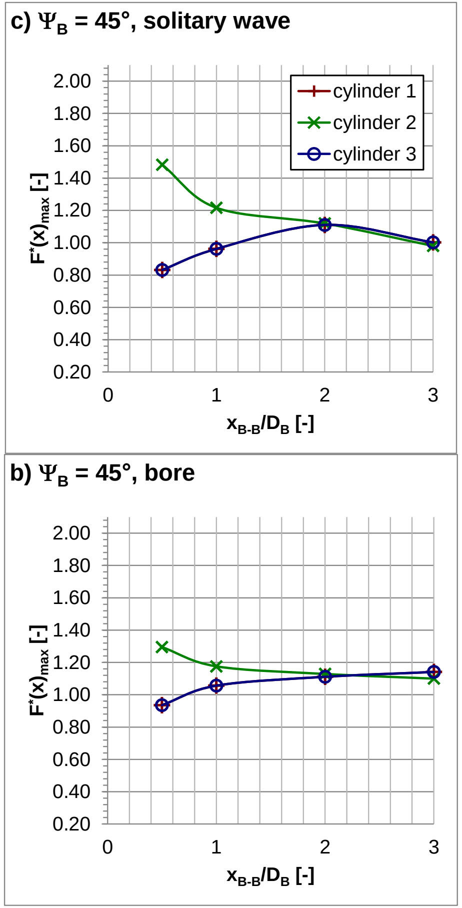




F^*_{max} in three cylinders in staggered 1 arrangement; reg. wave case by Bonakdar & Oumeraci (2014)

- staggered 1 arrangement (Ψ_B = 45°)
  - modified from Hori (1959):

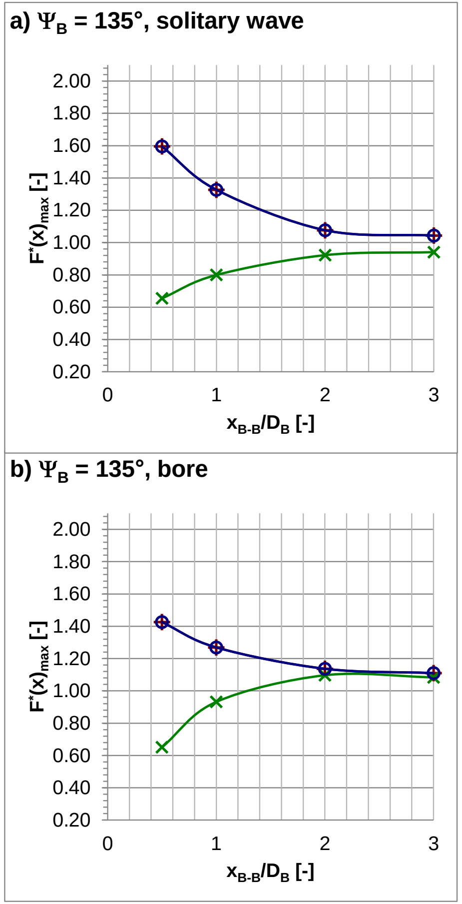




F^*_{max} **in three cylinders in staggered 1 arrangement; reg. wave case by Bonakdar & Oumeraci (2014)**

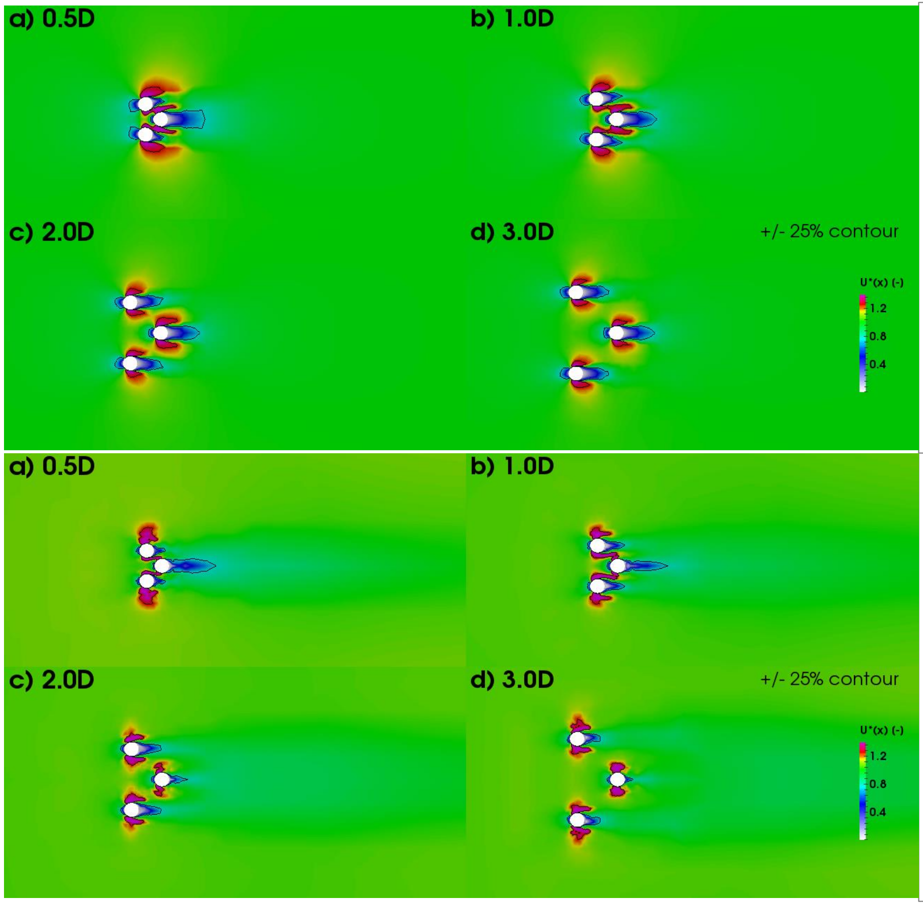
Staggered 2

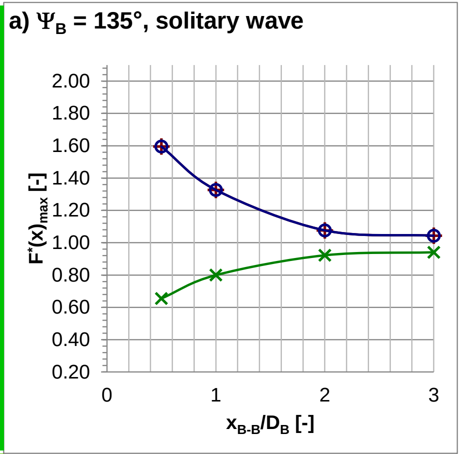
- staggered 2 arrangement (Ψ_B = 135°)
  - differences are more poronounced under solitary wave conditions
  - distance:
    - solitary wave: at $3D_B$, small interaction
    - bore: at $2D_B$, small interaction, differences vanish

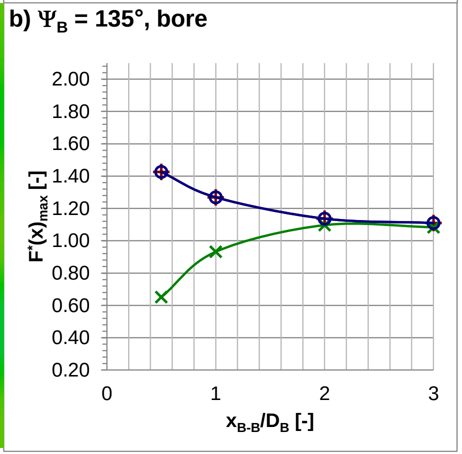


Source: modified from Hori (1959)

F^*_{max} in three cylinders in staggered 2 arrangement



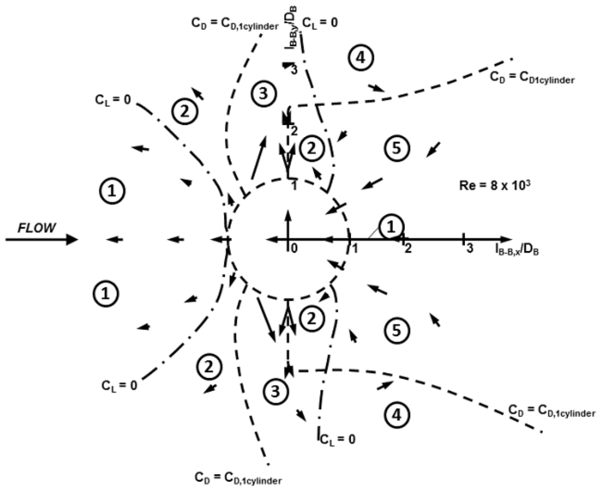




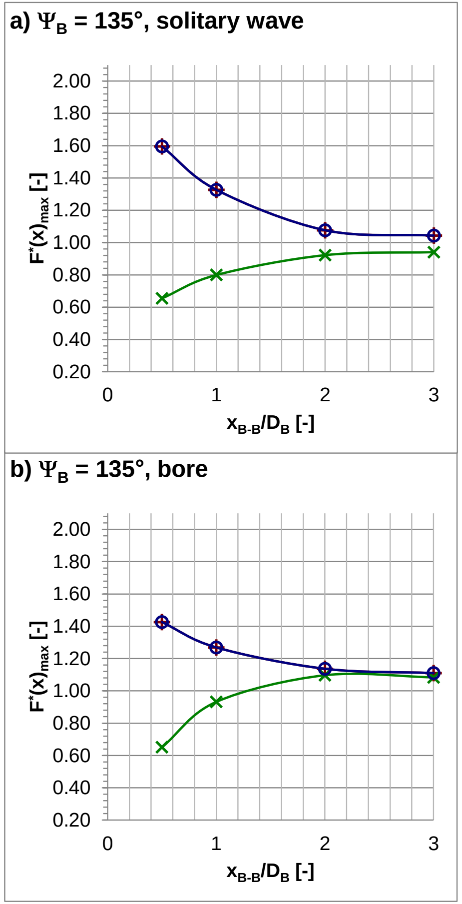
Source: modified from Hori (1959)

F^*_{max} in three cylinders in staggered 2 arrangement

- staggered 2 arrangement (Ψ_B = 135°)
  - modified from Hori (1959):



Source: modified from Hori (1959)



F^*_{max} in three cylinders in staggered 2 arrangement

Results

- cylinder 1:

stdev	solitary wave 0	45	90	135	D_B	bore 0	45	90	135	stdev
0.41	0.81	0.83	1.69	1.59	**0.5**	0.97	0.94	1.41	1.43	0.23
0.24	0.80	0.96	1.36	1.33	**1**	0.88	1.06	1.28	1.27	0.17
0.10	0.88	1.11	1.11	1.08	**2**	0.83	1.11	1.19	1.14	0.14
0.04	0.94	1.00	1.04	1.04	**3**	0.85	1.14	1.16	1.11	0.13
	0.06	0.10	0.25	0.22	**stdev**	0.05	0.08	0.10	0.13	

- cylinder 2:

stdev	solitary wave 0	45	90	135	D_B	bore 0	45	90	135	stdev
0.58	0.4	1.48	1.81	0.65	**0.5**	0.29	1.29	1.92	0.65	0.62
0.31	0.64	1.22	1.4	0.8	**1**	0.33	1.18	1.37	0.93	0.39
0.12	0.88	1.12	1.15	0.92	**2**	0.36	1.13	1.3	1.1	0.36
0.06	0.93	0.98	1.08	0.94	**3**	0.56	1.1	1.2	1.08	0.25
	0.21	0.18	0.29	0.12	**stdev**	0.10	0.07	0.28	0.18	

- cylinder 3:

stdev	solitary wave 0	45	90	135	D_B	bore 0	45	90	135	stdev
0.46	0.64	0.83	1.69	1.59	**0.5**	0.44	0.94	1.41	1.43	0.41
0.23	0.84	0.96	1.36	1.33	**1**	0.51	1.06	1.28	1.27	0.31
0.07	0.95	1.11	1.11	1.08	**2**	0.51	1.11	1.19	1.14	0.28
0.03	0.96	1	1.04	1.04	**3**	0.5	1.14	1.16	1.11	0.28
	0.13	0.10	0.25	0.22	**stdev**	0.03	0.08	0.10	0.13	

Results

- averaged standard deviations of solitary waves and bores for arrangement angle and distance

	solitary wave	bore
Ψ_B	0.22	0.30
x_{B-B}	0.18	0.11

- offshore conditions (solitary wave): both parameters have comparable influence
- onshore conditions (bore): arrangement dominates

05.

Summary, conclusion, outlook

Summary, conclusions

- 36 numerical experiments to quantify the importance of distance and arrangement between roughness elements
- model has been well validated (deviations to experimental data: < 2 %)
- numerical results agree well with laboratory data (Bonakdar & Oumeraci, 2014) and literature
- offshore conditions (solitary wave): distance and arrangement are of comparable importance
- onshore conditions (bore): arrangement dominates

Summary, conclusions

- loads on roughness elements result are related to energy losses in flow regimes offshore and onshore
- for empirical formulae in depth-averaged models
  - both parameters largely influence the results and need to be considered
  - especially for inundation modelling, the arrangement is of high importance

Outlook

- Almost finished systematic simulations of large groups of roughness elements investigating
  - size
  - height
  - arrangement
  - distance
- development of empirical formulae and implementation into NLSW model

Acknowledgements

- The authors like to thank
  - DHI Singapore for constant support
  - Lisham Bonakdar and Agnieszka Strusinska (TU Braunschweig) for data provision, open and fruitful discussions
  - Prof. Harry Yeh (Oregon State University) for data provision and very kind support
  - Dr. Ole Larsen (DHI) for very kind and constant support
  - Hisham El-Safti (TU Braunschweig) for open and fruitful discussions

Thank you for your kind attention!

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