IMPERIAL

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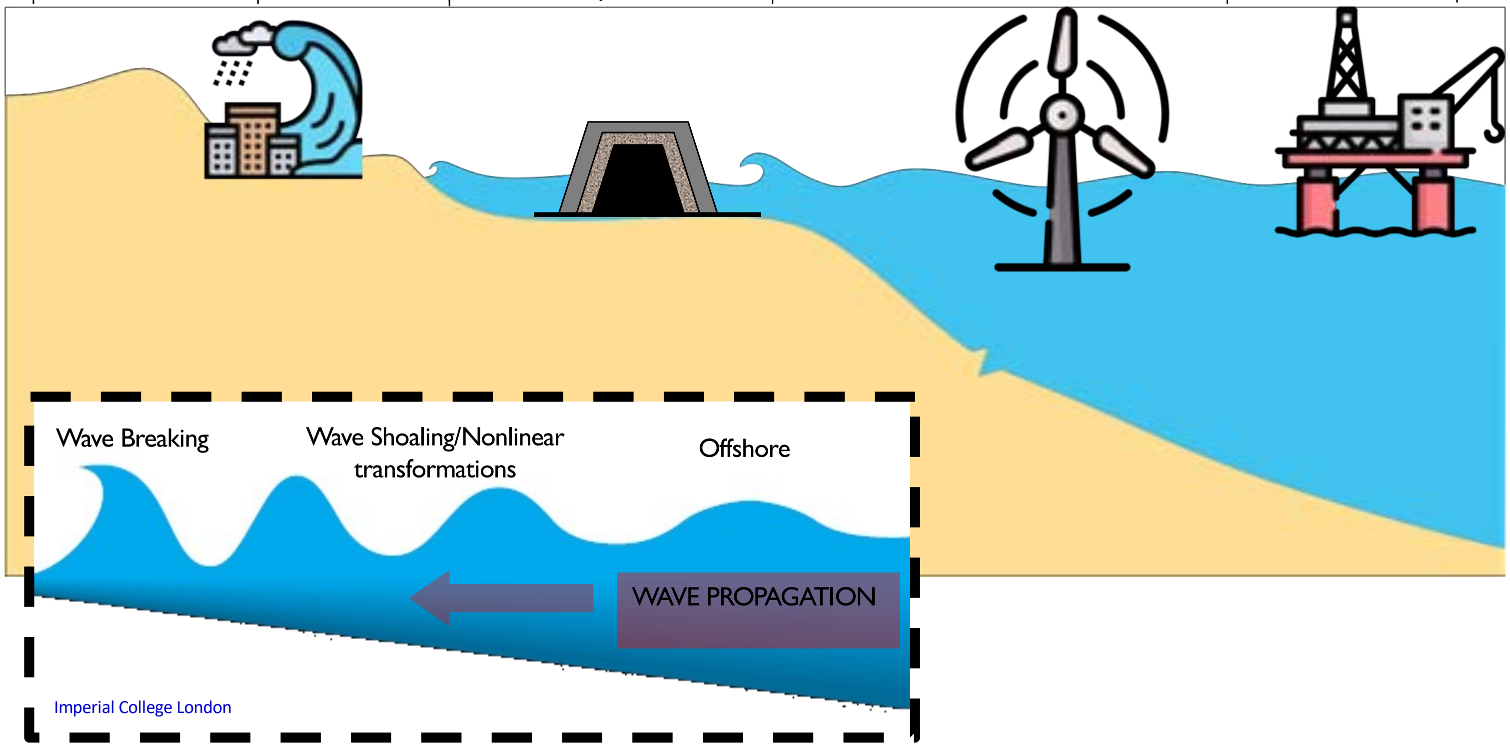
Motivation

Modelling coastal and ocean processes for the reliability of structures/vessels and the health of the environment.

ZONE	BEACH	SURF ZONE	SHOALING ZONE	OFFSHORE
Structure	Flood/Harbour	Coastal protection	Wind Energy	Oil & Gas



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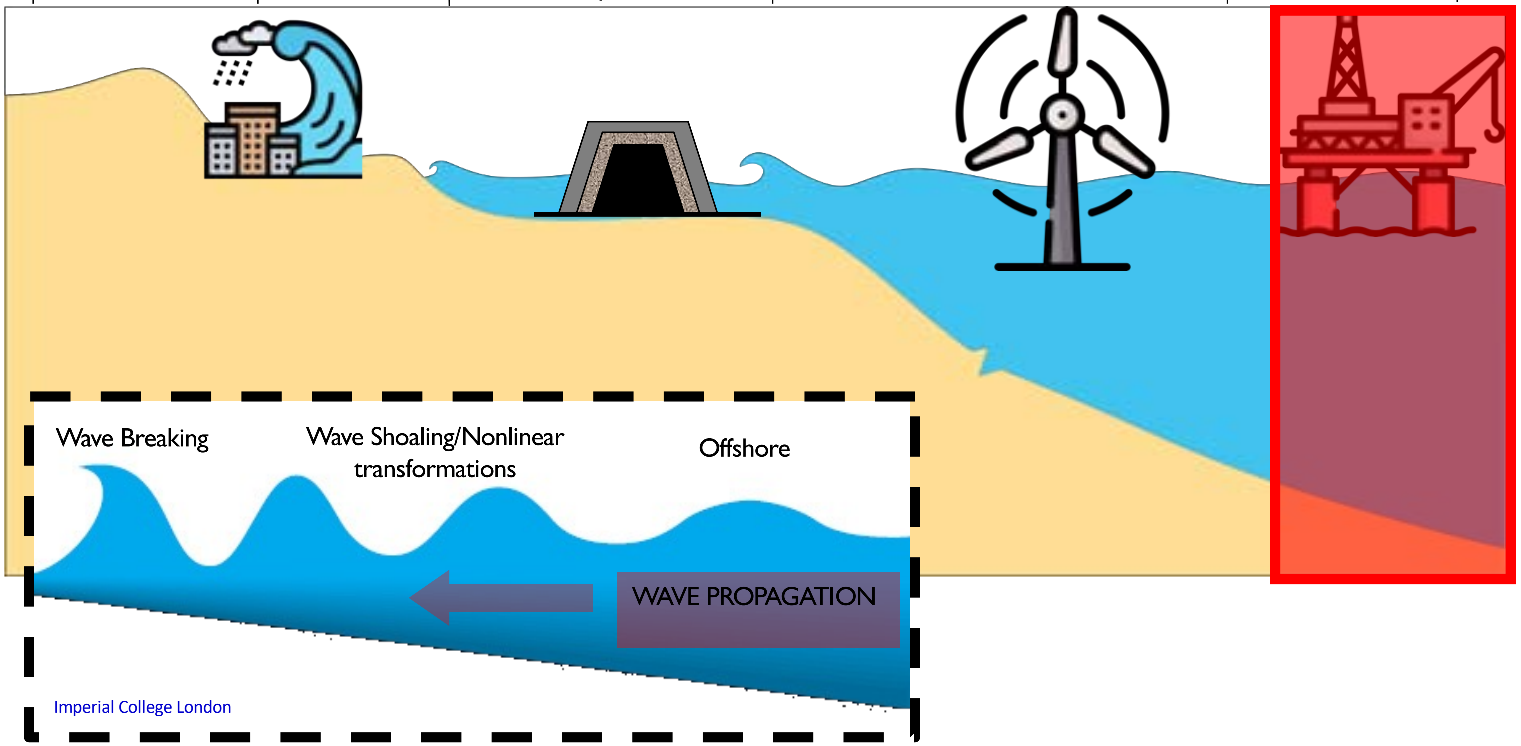
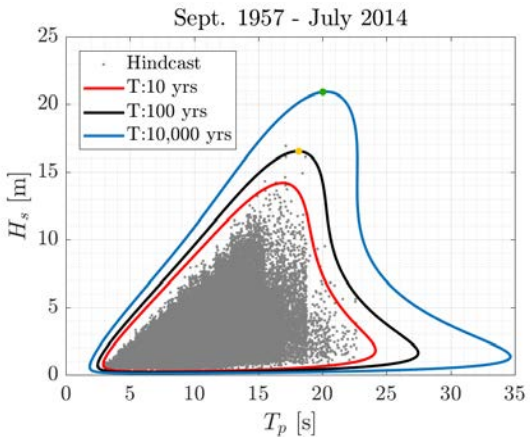


Engineering Design Process

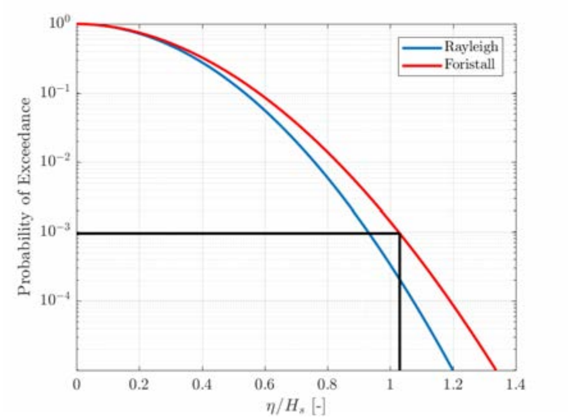
Step 1:
Long-term analysis

Step 2:
Short-term analysis

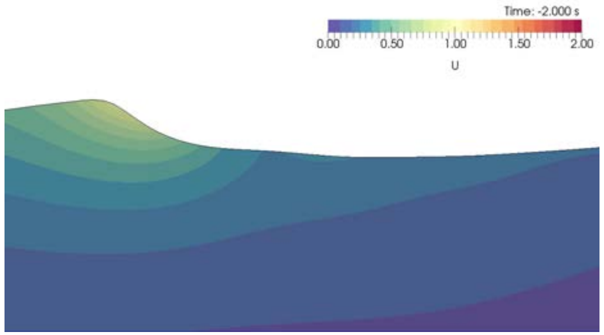
Step 3:
Design wave



Long-term analysis at an offshore location in the North Sea (NORA 10 hindcast)



Short-term crest height distributions; commonly applied models



Design wave:
experimental or numerical generation

Select sea-state $(H_s, T_p, \sigma_\theta)$ given return period

Given the sea-state, select η_c (or H).
e.g. $T_z = 10\text{s}, T = 3\text{hr}$
$N_{waves} \approx 1{,}000 \Longrightarrow Q = 10^{-3}$

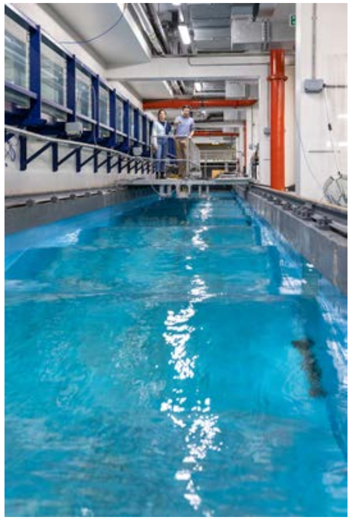
Calculate kinematics, forces, etc.

Hydrodynamics Laboratory

	Facility	Unidirectional waves	Directional waves	Current	Additional capabilities
1	Deep-water Basin	✓	✓		Adjustable bed
2	Shallow-water Basin	✓	✓	✓	Towing facility
3	Coastal Flume	✓			Adjustable bed
4	Long Flume	✓			Towing facility
5	Very Long Flume	✓			Variable bathymetry
6	Double Ended	✓		✓	Wind generation
7	Current Flume			✓	Drop test rig
8	Recirculation Flume			✓	Flow vis
9	3 x visualisation tanks				Density driven flows

Hydrodynamics Laboratory

ICL wave basin



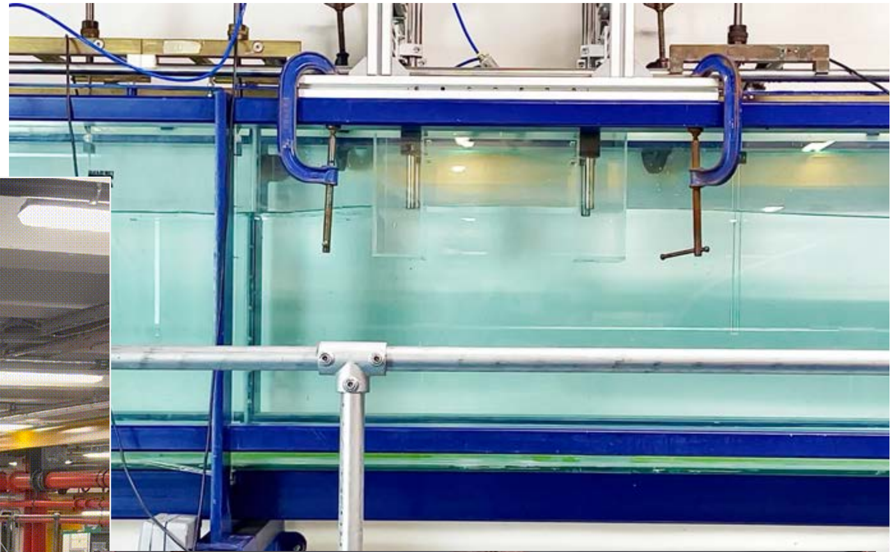
Long wave flume

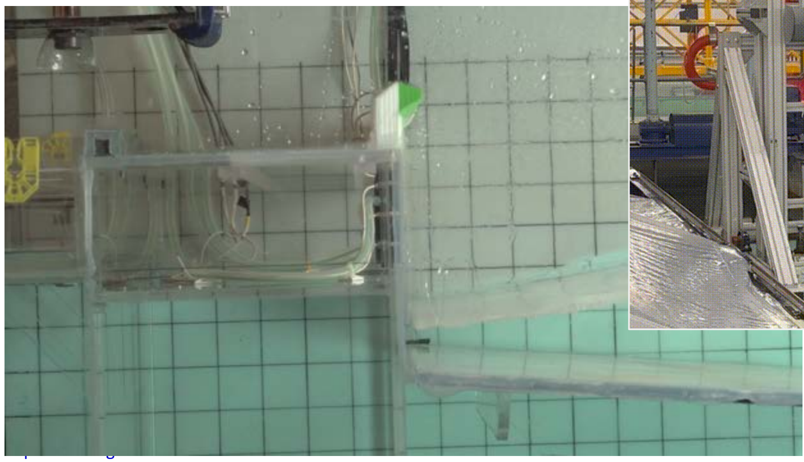
Shallow water basin

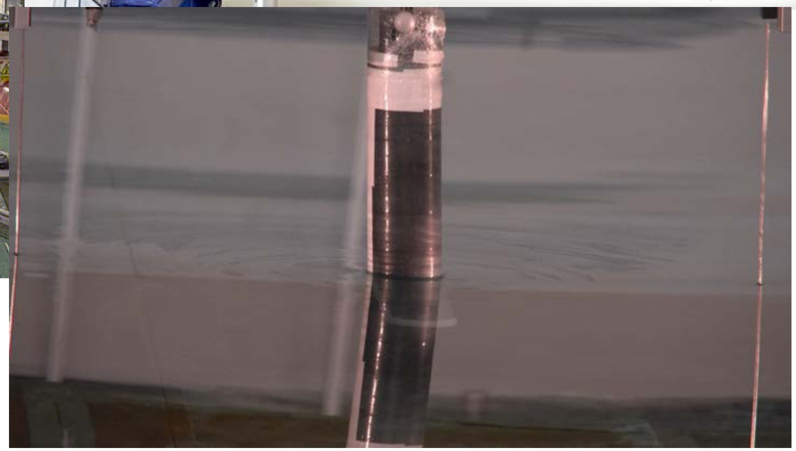
Double-ended flume

Coastal flume

Hydrodynamics Laboratory







Methods
Laboratory experiments

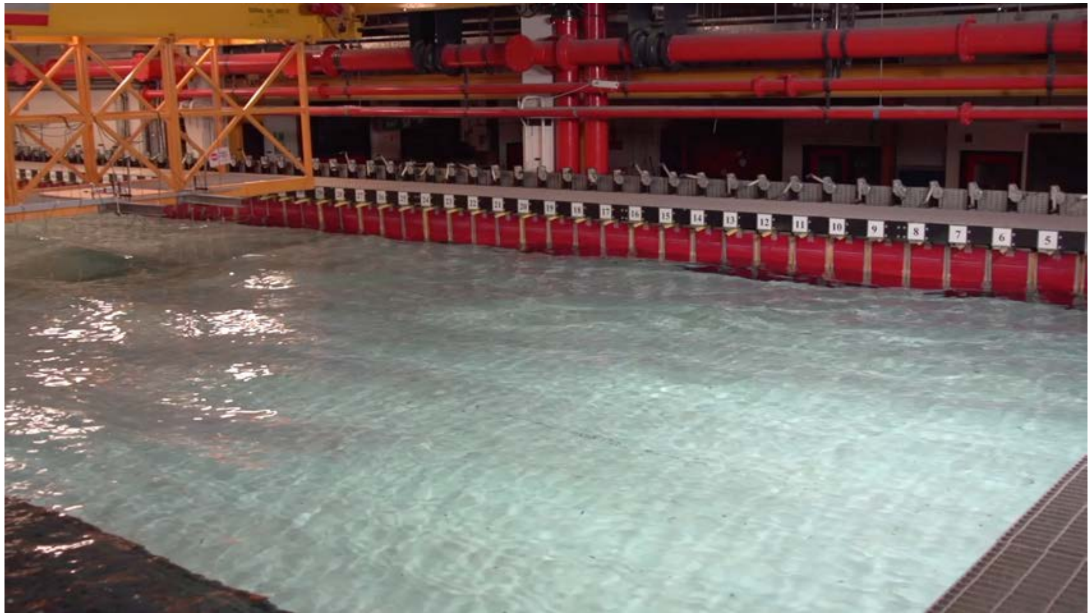
Laboratory investigation

Long random wave simulations – different facilities

- Imperial College London (ICL) [$d = 125, 90, 50\ \mathrm{m}$]
- Queens University Belfast (QUB) [$d = 60, 50, 40\ \mathrm{m}$]
- Danish Hydraulics Institute (DHI) [$d = 45\ \mathrm{m}$] (independent measurements)

Total number of simulations : 1,800 x 3hr storms $k_p d \in (0.85, 3.5)$

Imperial College London wave basin



Methods

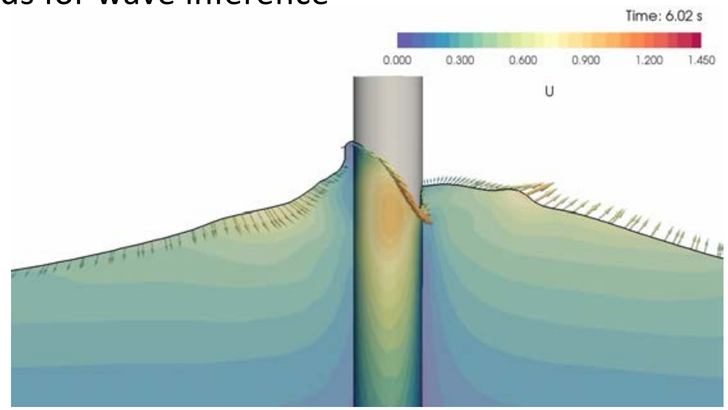
Numerical and remote sensing

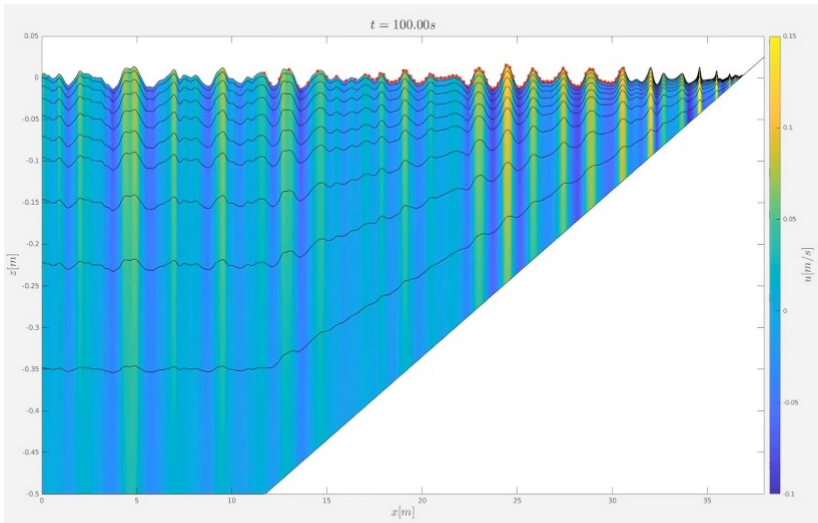
Numerical simulations

- Spectral models (e.g. WW3, SWAN) for regional scale modelling
- Ocean Hydrodynamic models for phase-resolved modelling (HOS-Ocean, BEM, OW3D)
- High fidelity modelling for extreme waves, wave-structure interaction (OpenFOAM, Flow3D)
- Coastal models (SWASH, Whispers3D, Reef3D) for wave evolution in the coastal zone.

Remote sensing

- Satellite methods for shoreline extraction (Sentinel 2, PlanetScope)
- LiDAR methods for wave inference

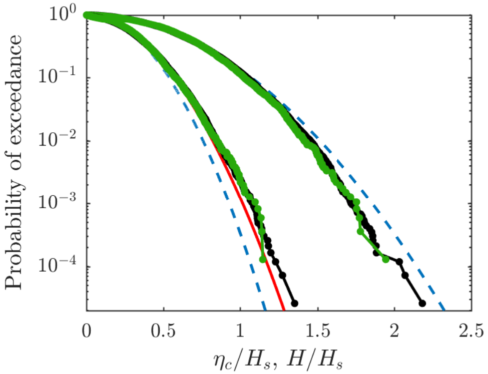




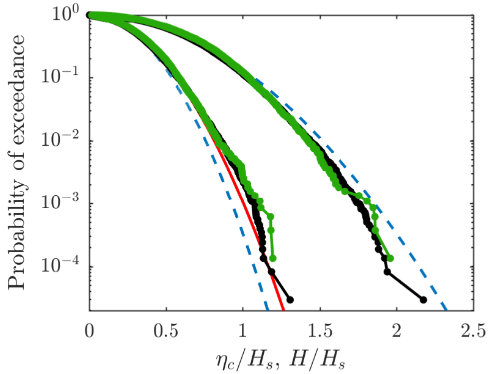
Wave statistics

Flat bed bathymetry

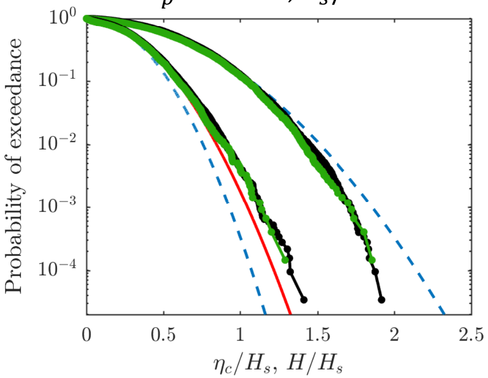
Lab describes the sea!



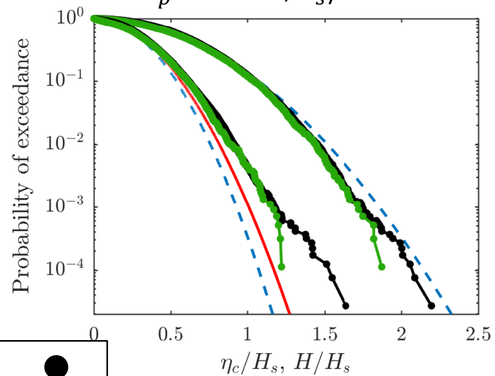
$k_p d = 1.55, H_s/d = 0.15$



$k_p d = 1.19, H_s/d = 0.14$



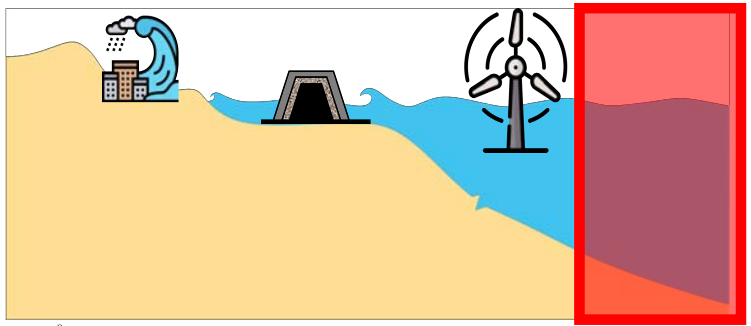
$k_p d = 1.03, H_s/d = 0.22$

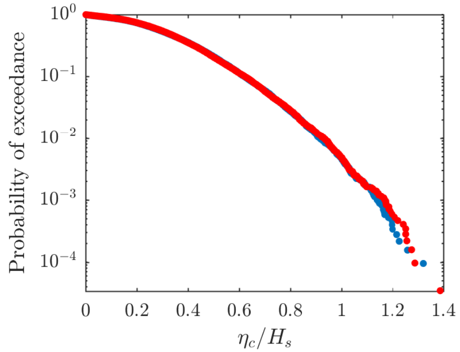


$k_p d = 0.9, H_s/d = 0.24$

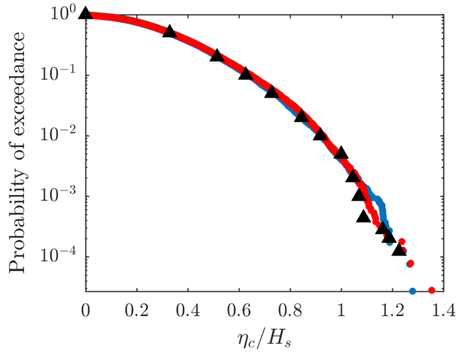
Lab ●
Field ●
Rayleigh - -
Forristall —

Karmpadakis et al., Proc Roy Soc A (2019)





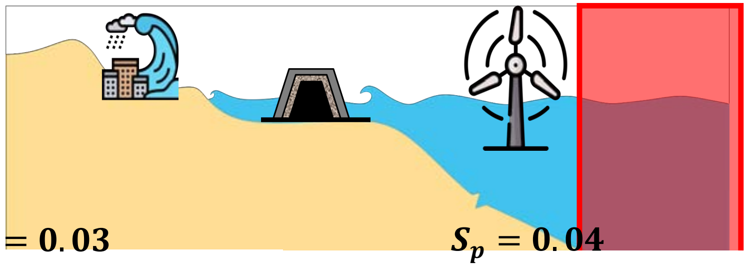
$k_p d = 1, S_p = 0.03, \sigma_\theta = 10^o$

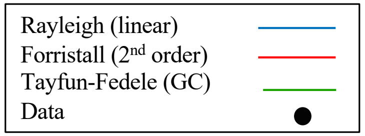


$k_p d = 1.5, S_p = 0.05, \sigma_\theta = 20^o$

ICL ●
QUB ●
DHI ▲

Wave statistics
Flat bed bathymetry

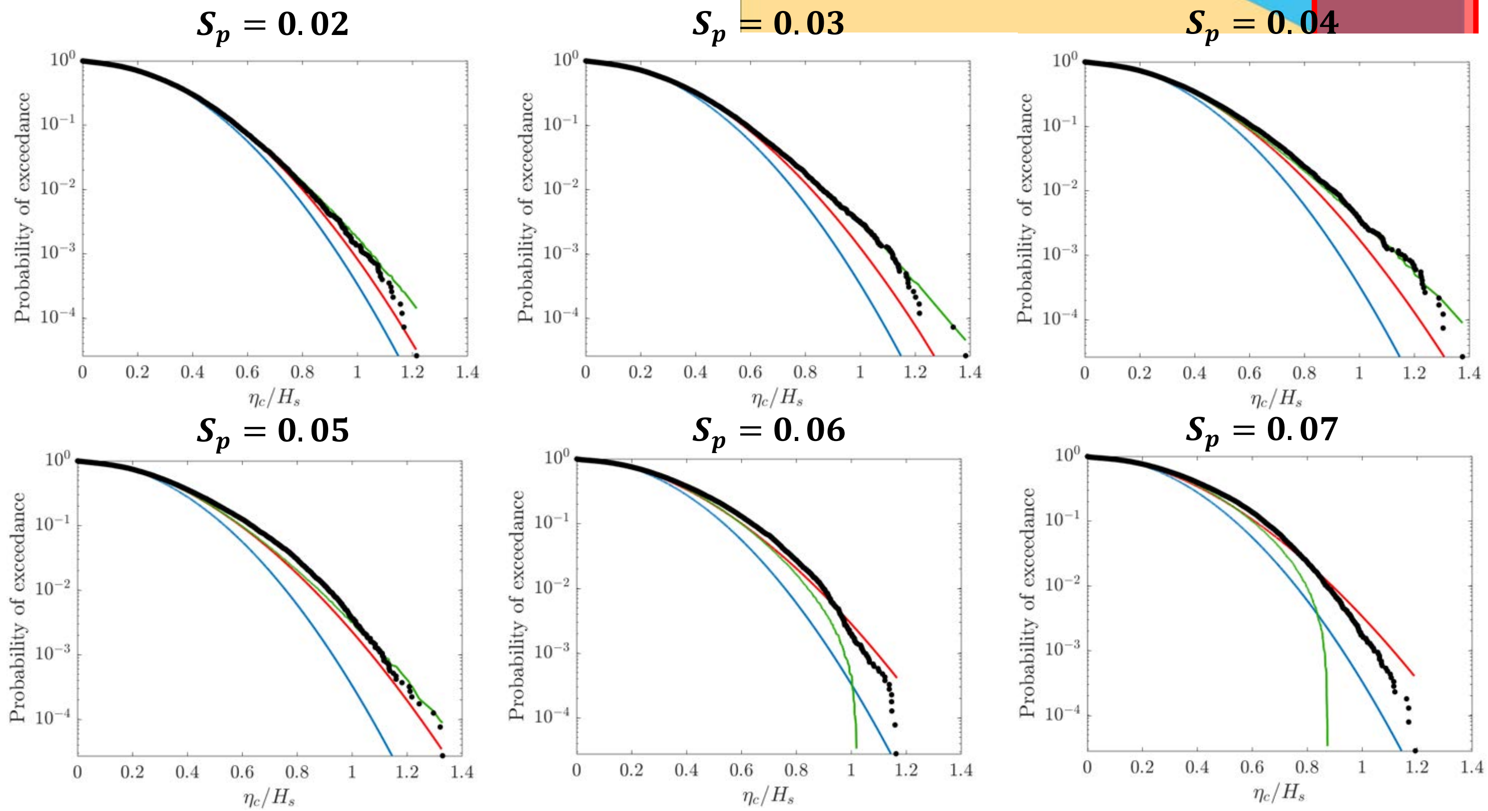




Laboratory results

Amplification beyond 2nd order
- Underprediction of design waves

Wave breaking
- Overprediction of design waves



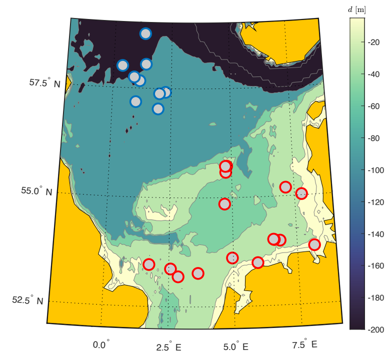
Experimental results: $k_p\, d = 1.5, \sigma_\theta = 10^o$

Karmpadakis et al., Proc Roy Soc A (2019)

Karmpadakis and Swan., JPO (2020)

Wave statistics

Effects of nonlinear amplification and wave breaking



Field results

Consider the ratio:

$$r = \eta_c / \eta_F$$

for $Q = 10^{-3}$.

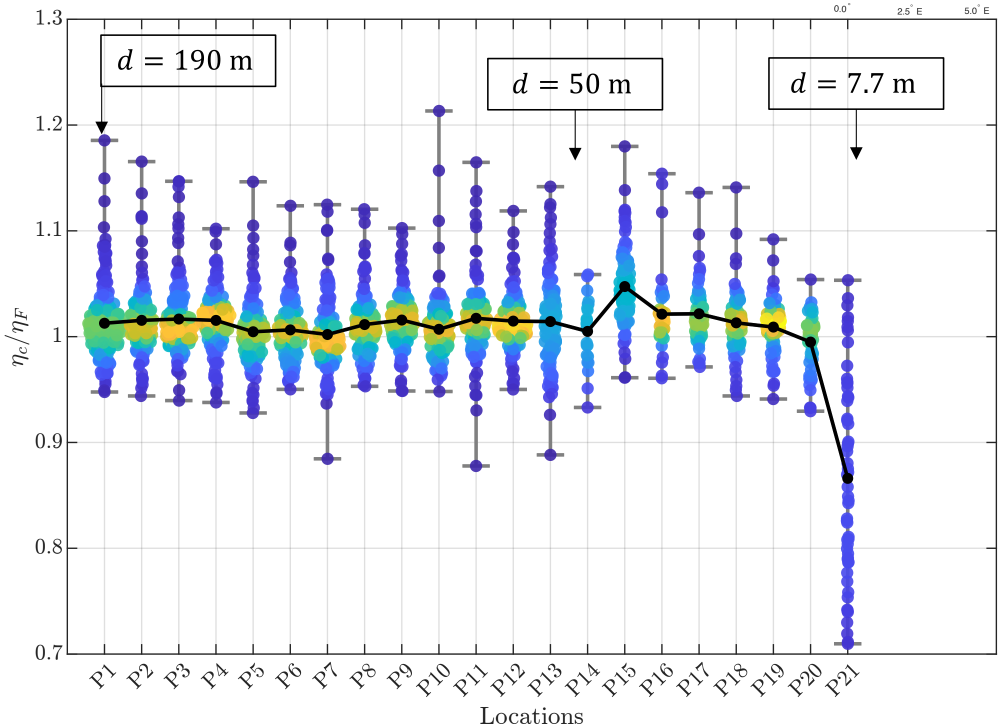
Field data from 21 locations in the North Sea, where

$$d \in (7.7, 190)\ \mathrm{m}$$

And the measurement duration is generally 4-10 yrs.

Each bin a different partition of (H_s, T_p) domain.

- Results from 2 million sea-states/0.5billion waves
- Mode of results 4%>second order
- Extremes show variations up to +20% and -30%.



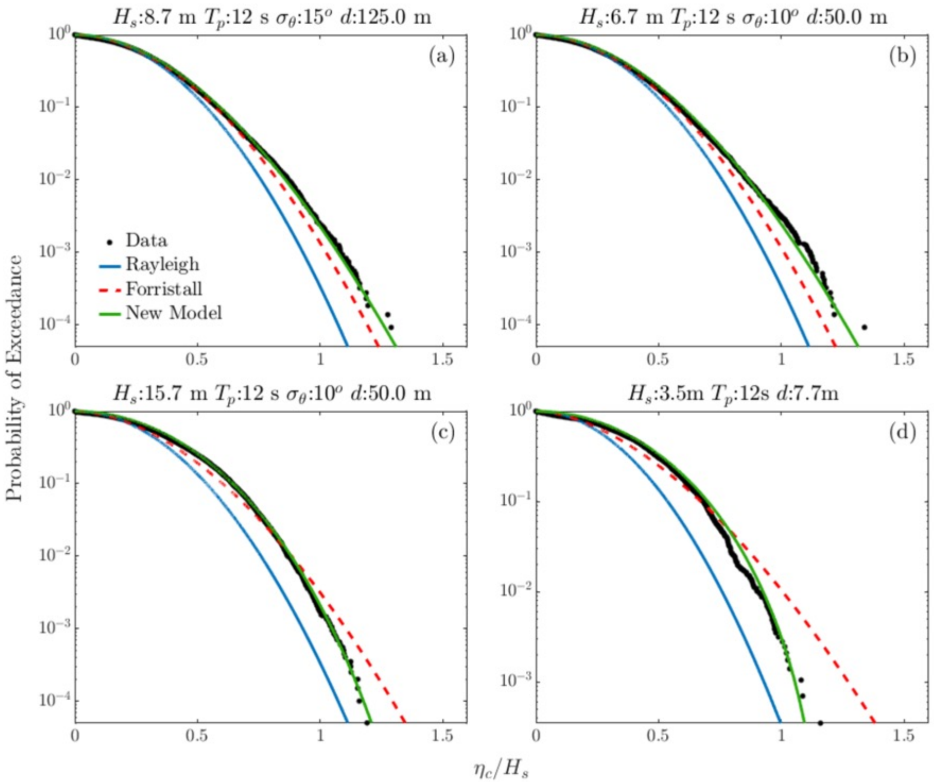
Swarm plot of r considering all available field data.

Karmpadakis et al., Coastal Eng (2020)

New models

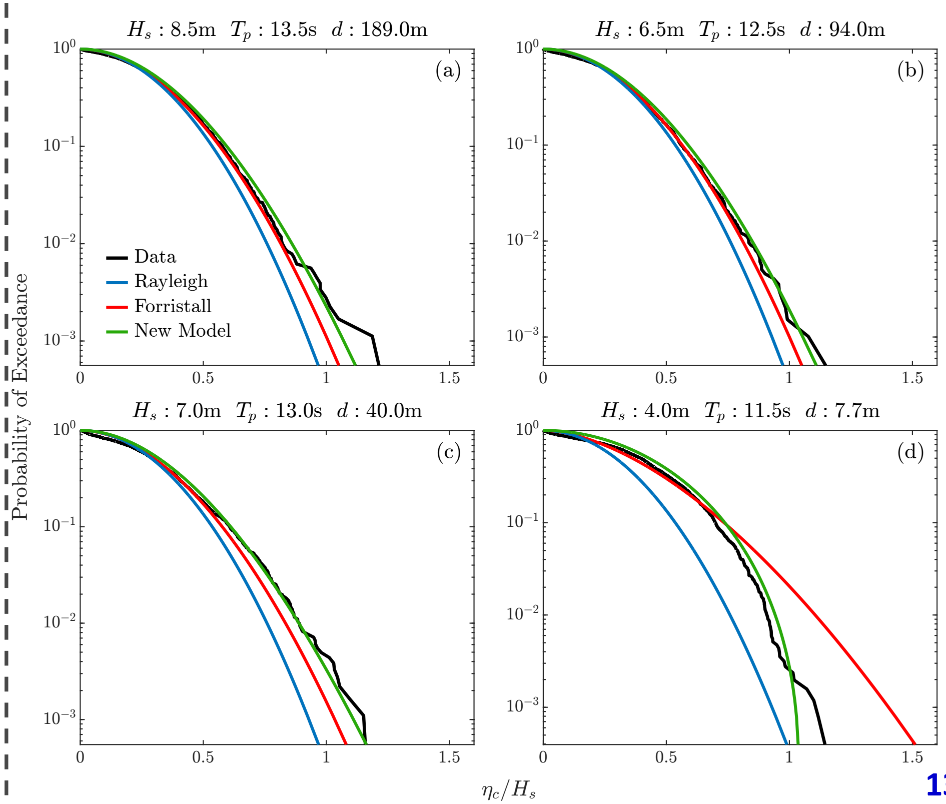
Effects of nonlinear amplification and wave breaking

Performance - experimental data



Karmpadakis and Swan., Ocean Eng (2022)

Performance - field data



Wave statistics
Flat bed bathymetry

Evidence of effects beyond current state-of-the-art modelling procedures.

Effects of **spectral bandwidth** and **wave breaking** captured by new **wave height** model on flat beds.

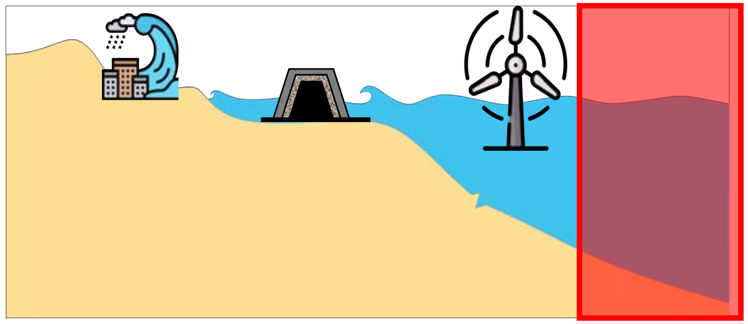
Competing effects of **nonlinearity** and **wave breaking** captured by new **crest height** model on flat beds.

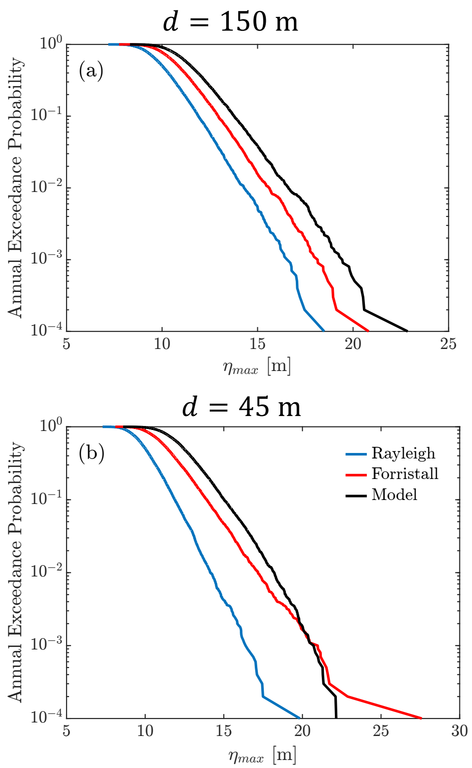
Sloping bed adds complexity in the interplay between nonlinearity and breaking.

Wave breaking effects **critical**.

Profound influence on **long-term predictions**.

- New recommendation by Design Standards (DNV, ISO 19901)



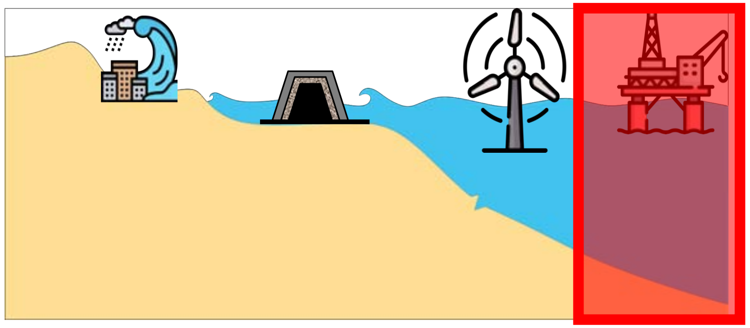


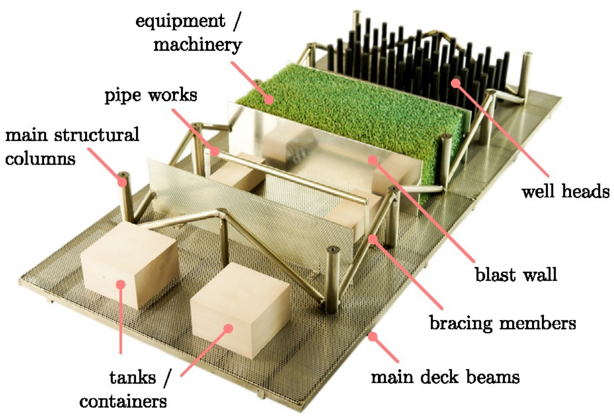
Long-term distribution of maximum crest height.

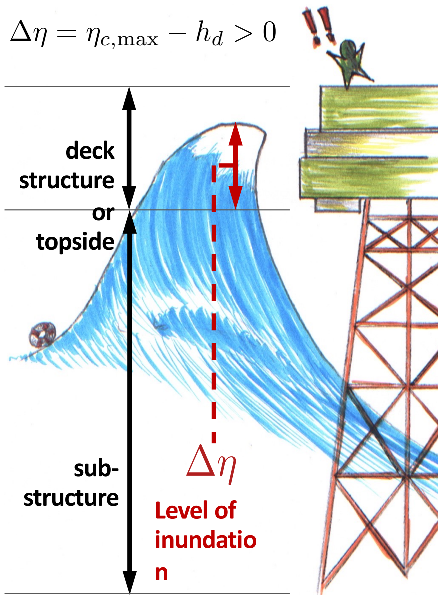
Karmpadakis et al., Coastal Engineering (2022)
Karmpadakis & Swan, Ocean Engineering (2022)

Coastal and offshore structures
Implementing new knowledge into design

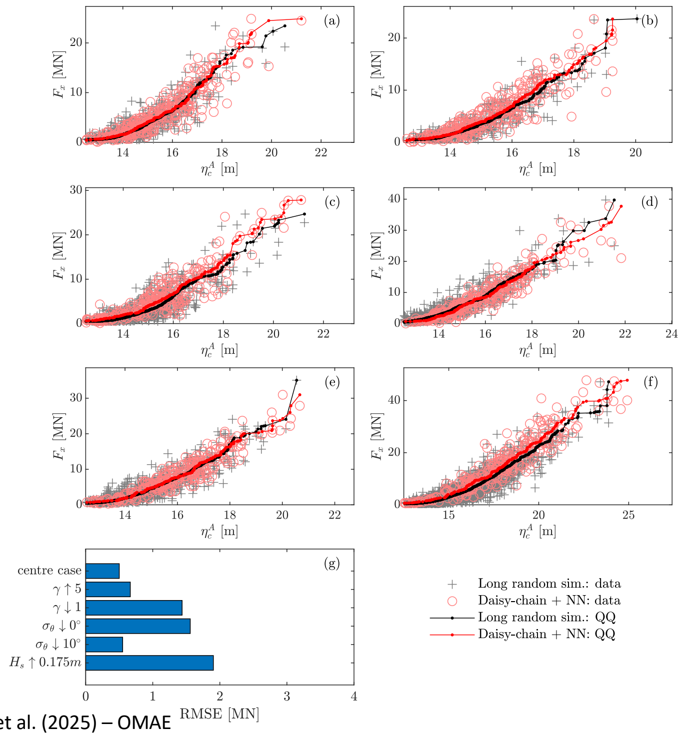
- New method to preselect wave that will yield extreme loading on jacket structures (Huo at al. 2023)
- New experiments to estimate wave-in-deck loading
- ML methods to predict.







Sketch by Dr. Li Ma



Huo et al. (2025) – OMAE
Huo, Ma, & Karmpadakis, Applied Ocean Research (2025)

Coastal and offshore structures

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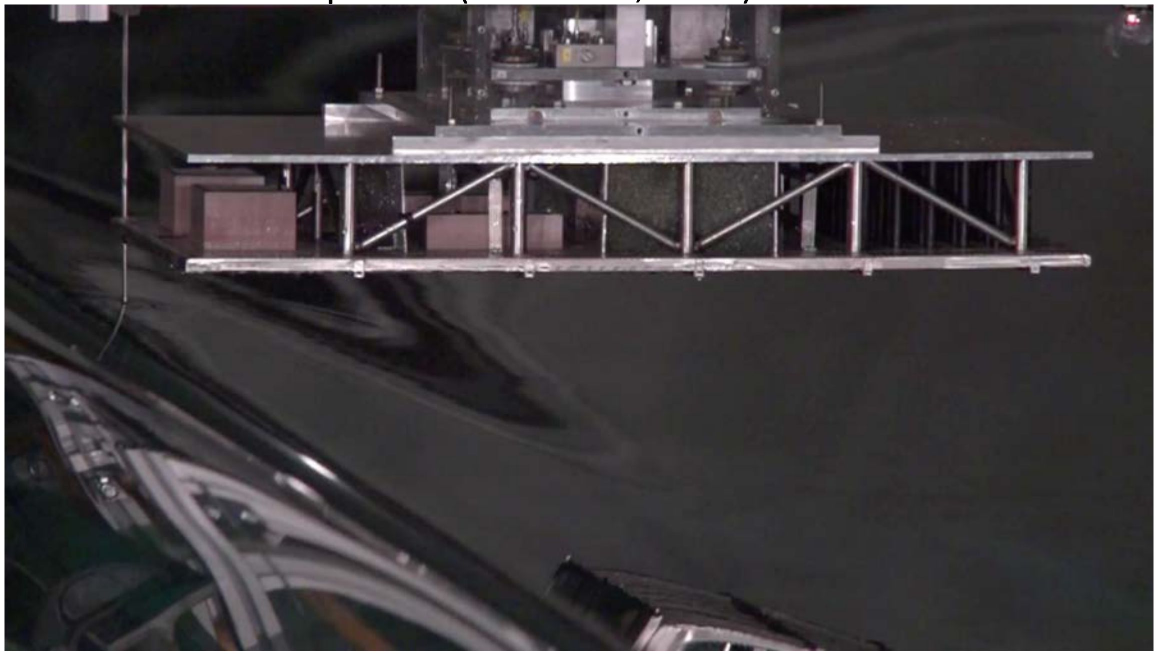
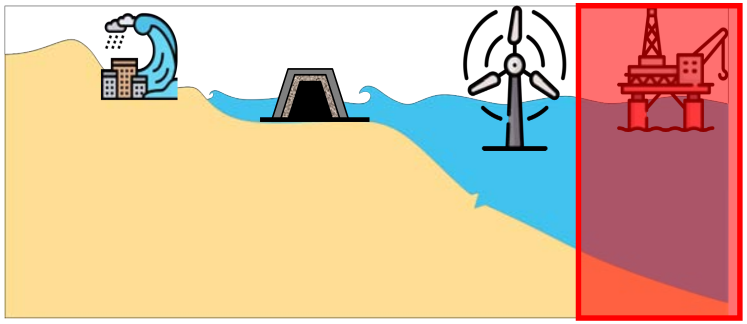
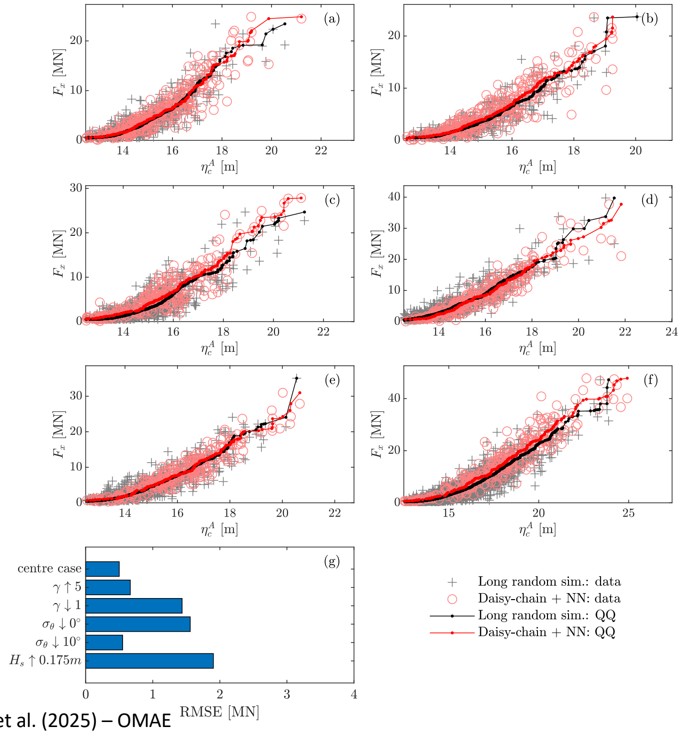






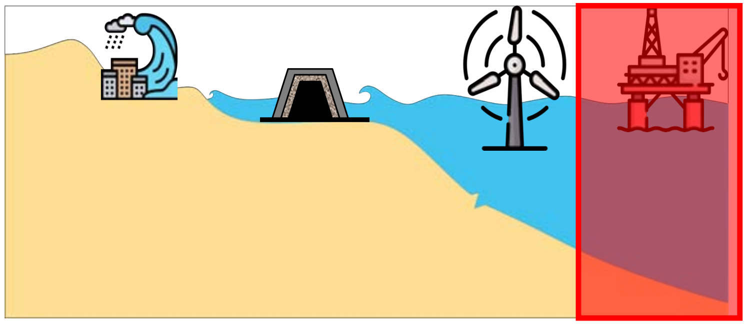
Huo et al. (2025) – OMAE
Huo, Ma, & Karmpadakis, Applied Ocean Research (2025)

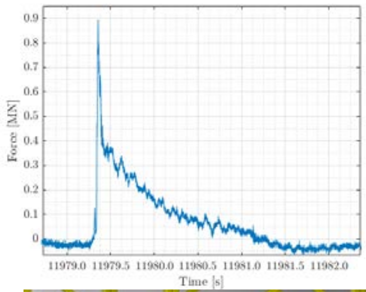
Coastal and offshore structures

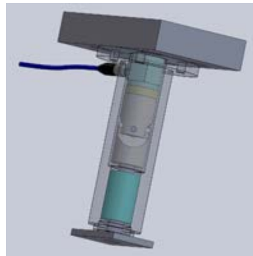
Loading and runup on Gravity Based Structures

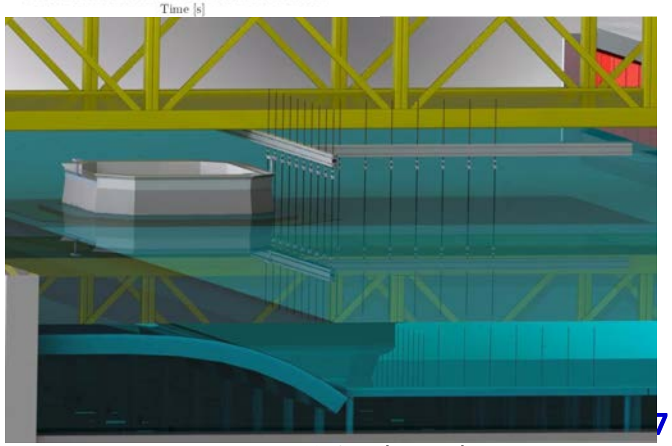
SAKHALIN ENERGY

TO BE THE PREMIER ENERGY SOURCE
FOR ASIA-PACIFIC





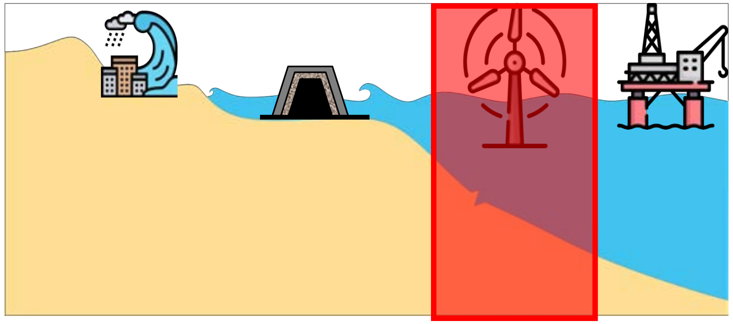


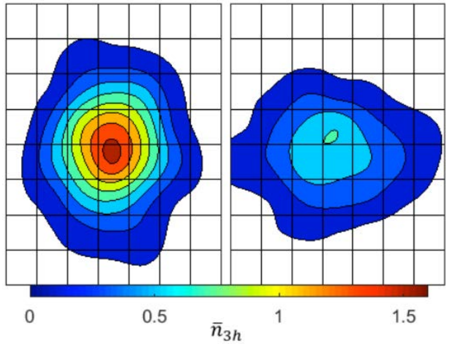


Swan & Karmpadakis (2018)

Coastal and offshore structures
Loading on Monopiles

- Long random simulations of severe sea-states in deep water in the laboratory
- Force measurements on large array of sensors
- Differences arising due to directional effects, nonlinear interactions and wave breaking

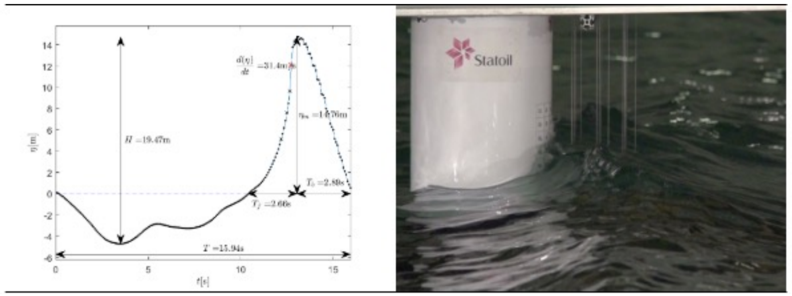




Unidirectional and directional slamming rates

Cylinder in the wave basin

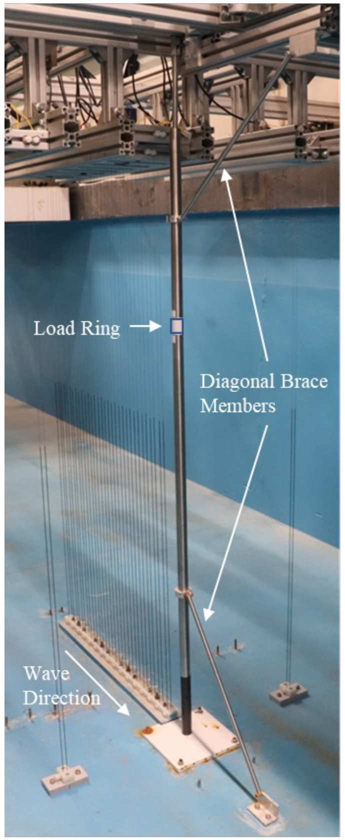
Sensor configuration

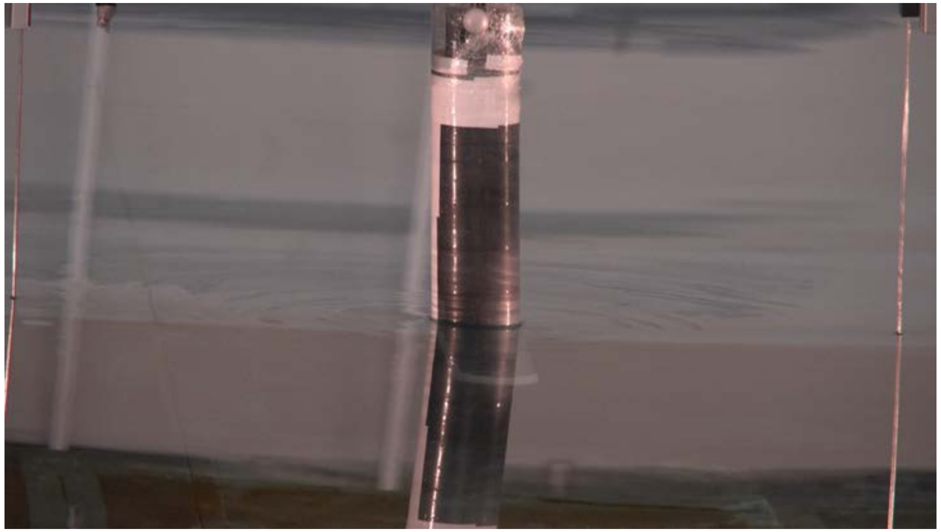


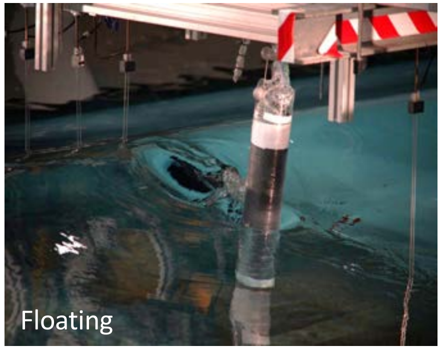
Slamming event

Lian et al. (2018)

Coastal and offshore structures
Loading on Slender Monopiles







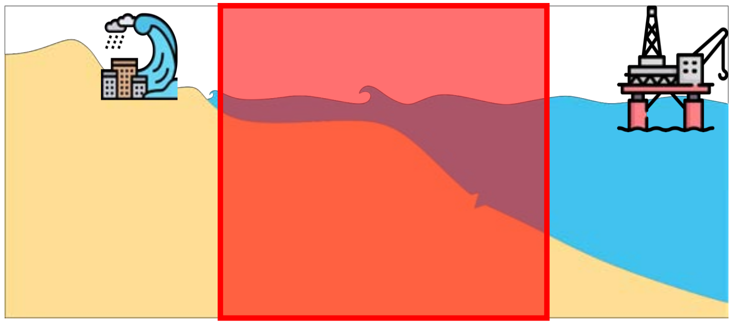
Measurements:
- Surface Elevation
- Local Forces
- Global Loading
- Motion Tracking

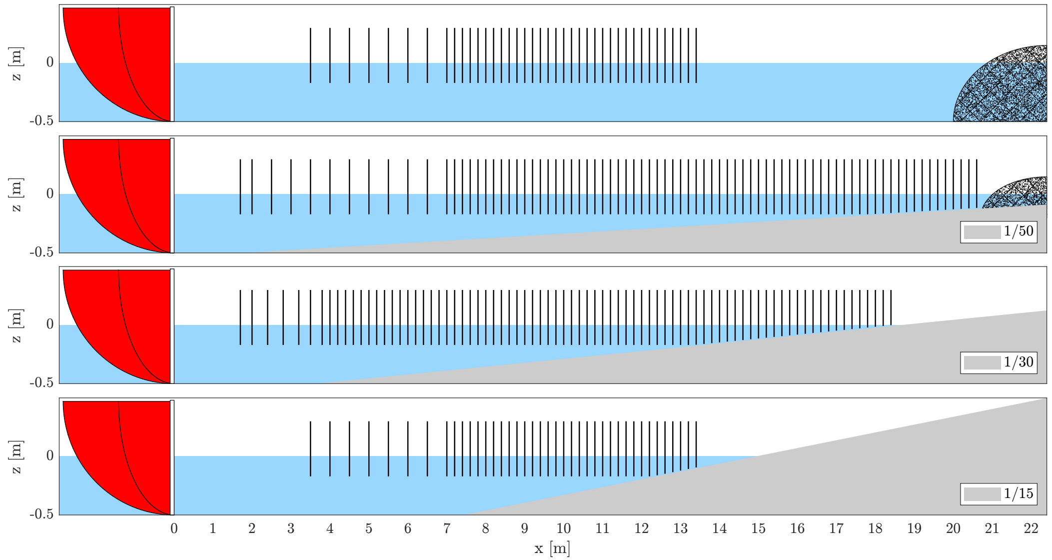
Understand the relationship between hydrodynamic loading and response for the design of floating structures

Mao et al. (2026a
Mao et al. (2026b) - in review

Coastal evolution
Extreme waves at the coast

- New and extensive experimental investigation of coastal evolution
- Coupled numerical simulations using SWASH
- Statistics, new physical insights, new parametric models!





4 different bed slopes

- Flat, 1/50, 1/30, 1/15

40-80 wave gauges in each experiment

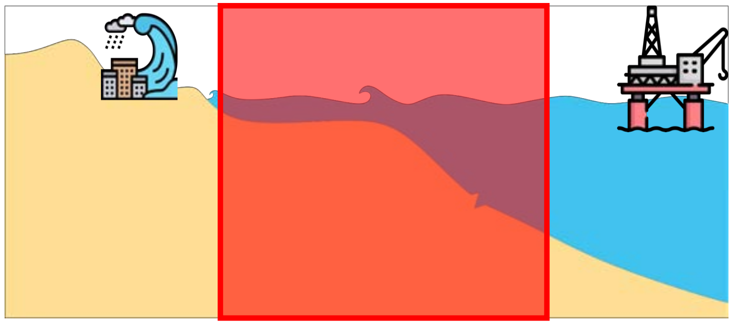
- 20m resolution in field scale

Total of

- 115 sea-states
- approx. 2m waves per location

Bellos, Swan & Karmpadakis, ICCE 2024
Bellos, Swan & Karmpadakis (JFM – under review)

Coastal evolution
Extreme waves at the coast



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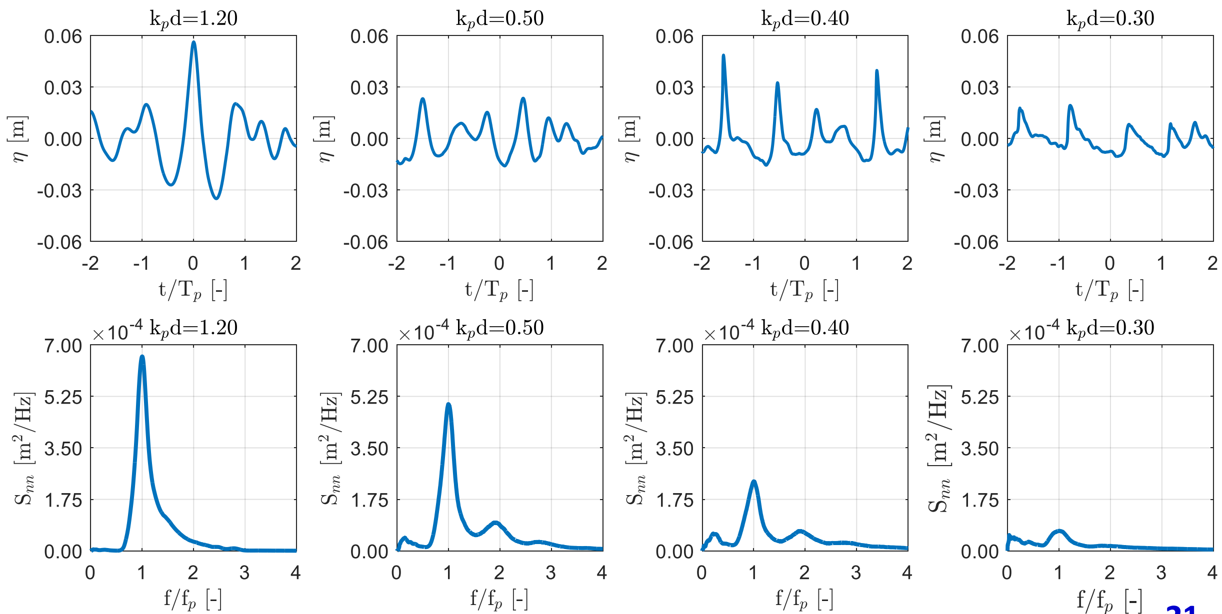
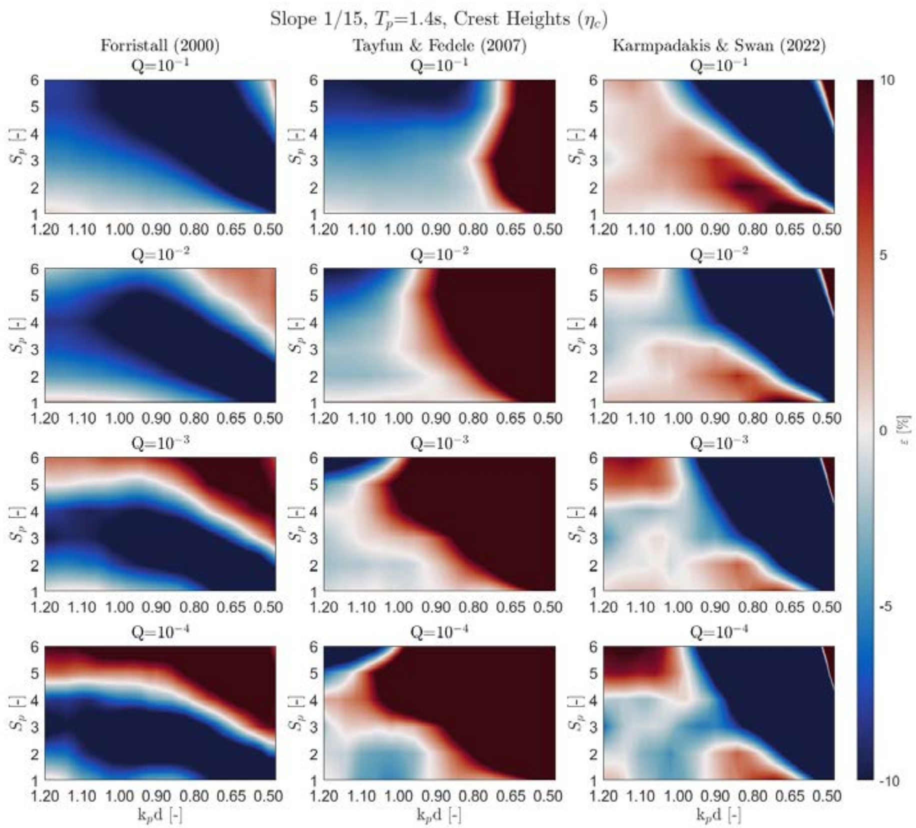


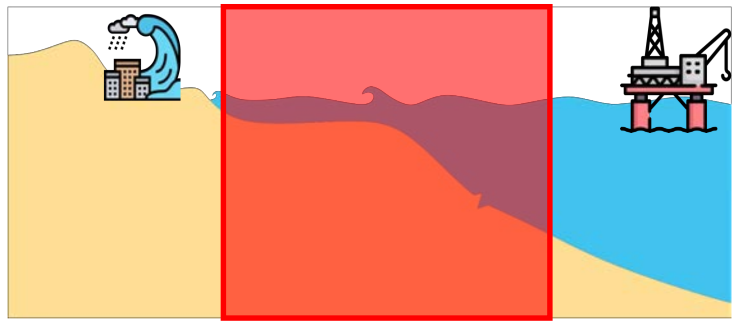
Interplay:
- Nonlinear wave-wave interactions
- Dispersion
- Wave breaking

Bellos, Swan & Karmpadakis, ICCE 2024
Bellos, Swan & Karmpadakis (JFM – under review)

Coastal evolution

Extreme waves at the coast





Error at $Q = [10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}]$

$$\varepsilon = \frac{\eta_{c_{model}} - \eta_{c_{measured}}}{\eta_{c_{measured}}} \cdot 100\ [\%]$$

→Effect of slope needs to be incorporated into models.

Bellos, Swan & Karmpadakis, ICCE 2024
Bellos, Swan & Karmpadakis (JFM – under review)

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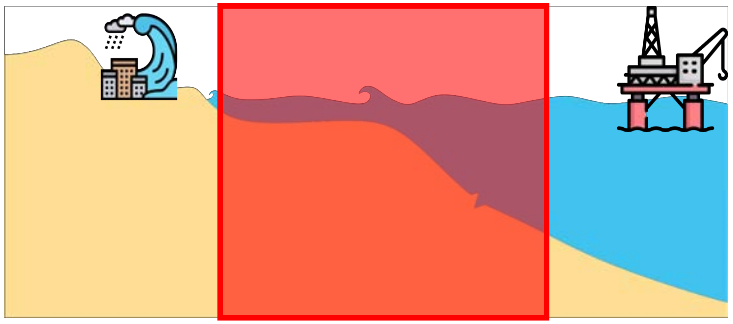
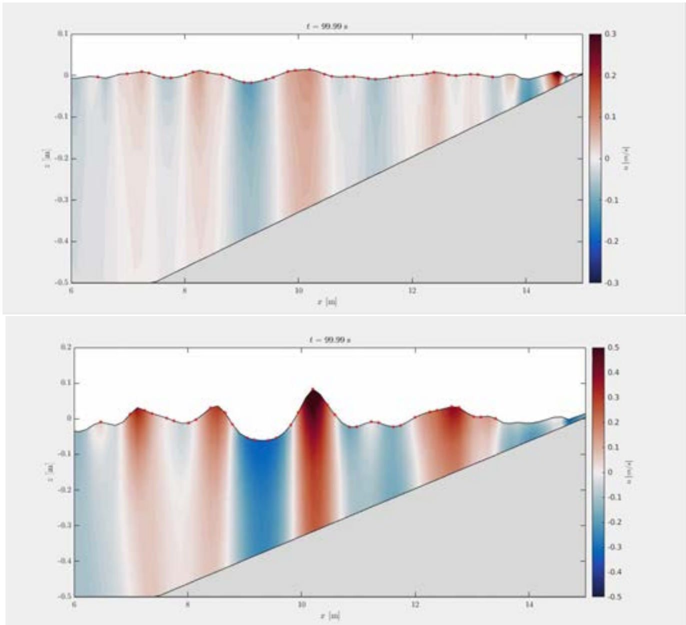
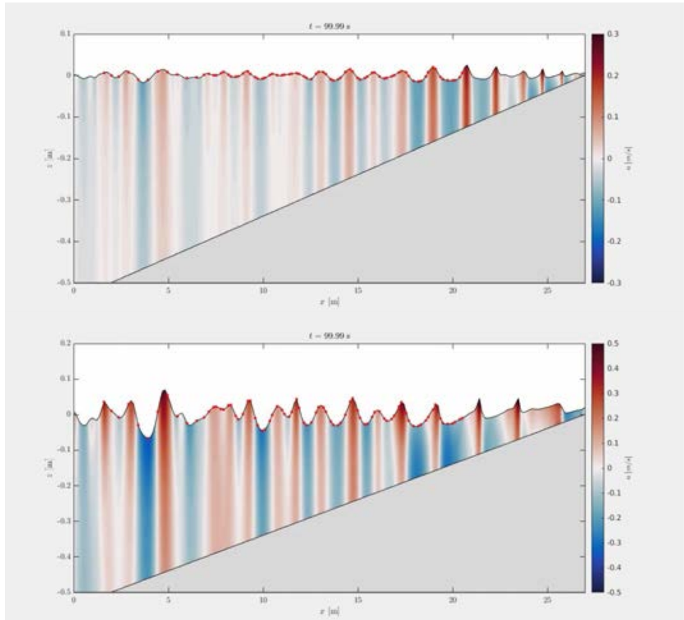


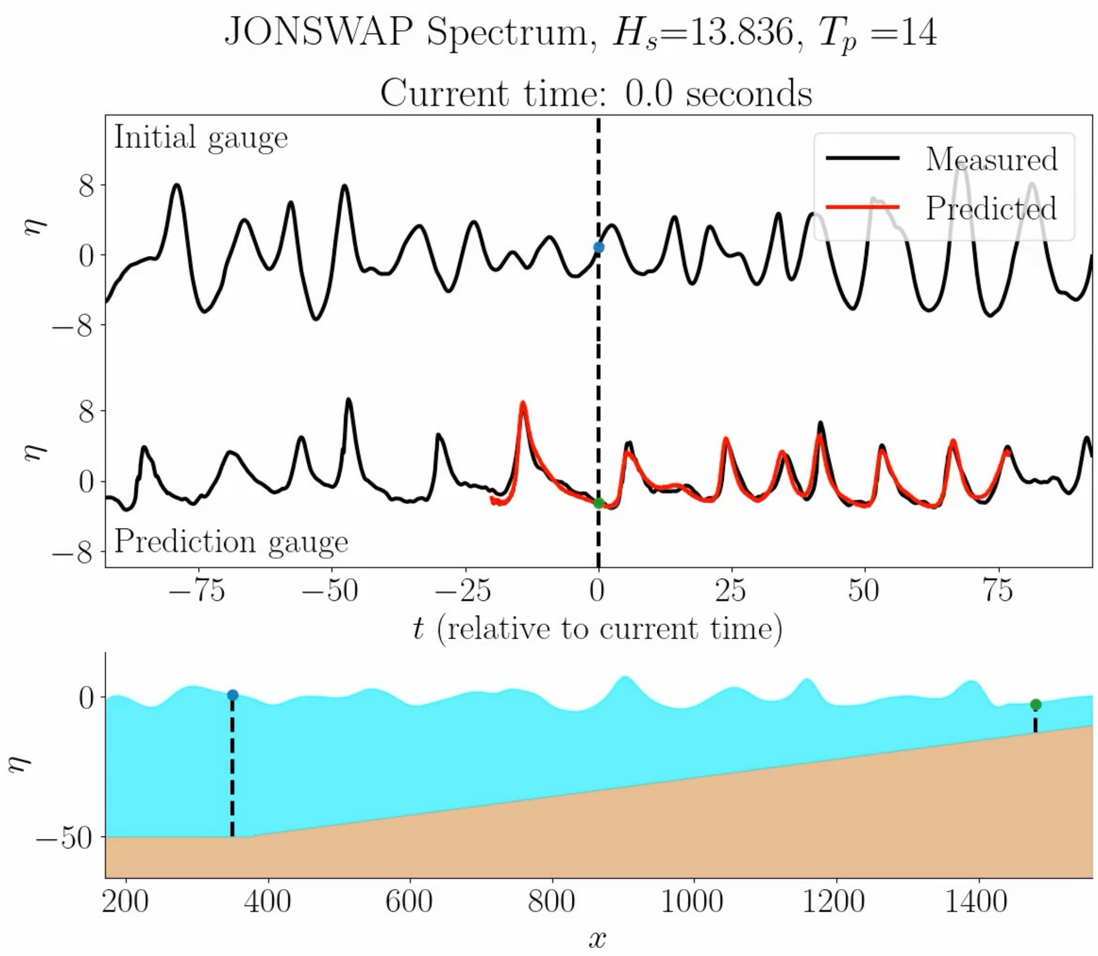




Alkhalili et al., Coastal Engineering (2025)
Alkhalili et al., APOR (2026)
Alkhalili et al., ICE Maritime Eng (2026)
Alkhalili et al., JFM (2026) – in review

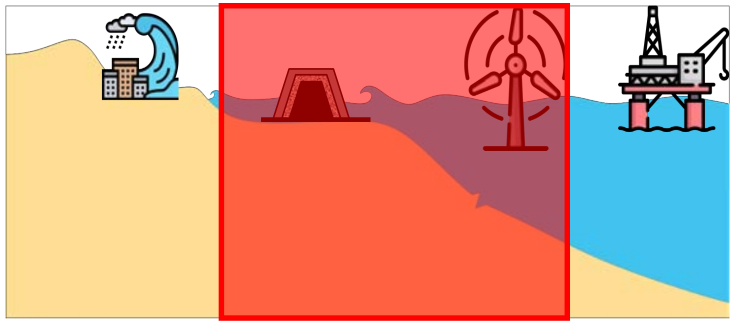
Coastal evolution
Extreme waves at the coast

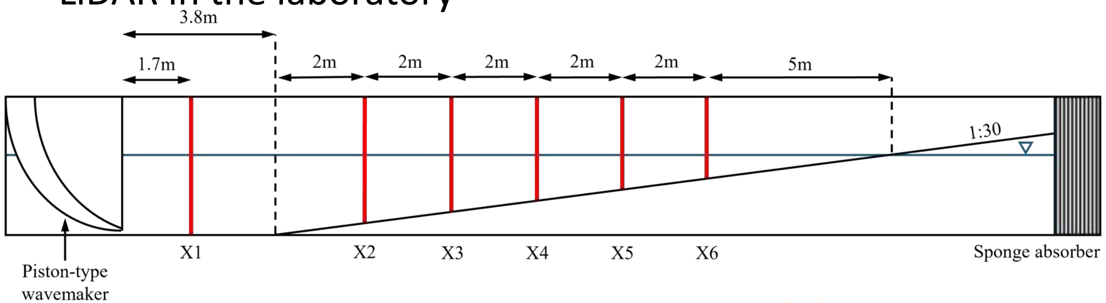
- Real-time prediction
- Wave transpformation from offshore to nearshore
- AI model

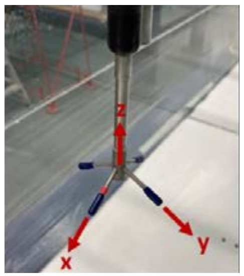


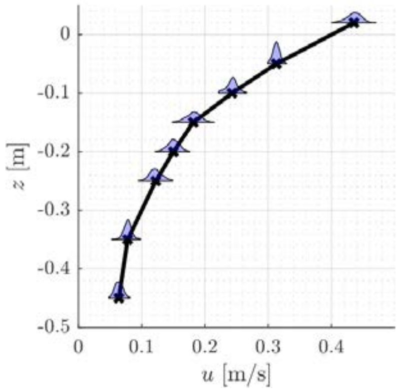
Coastal evolution
Extreme waves at the coast

- Kinematics measurements.
- New experimental methods (4D PTV)
- LiDAR in the laboratory

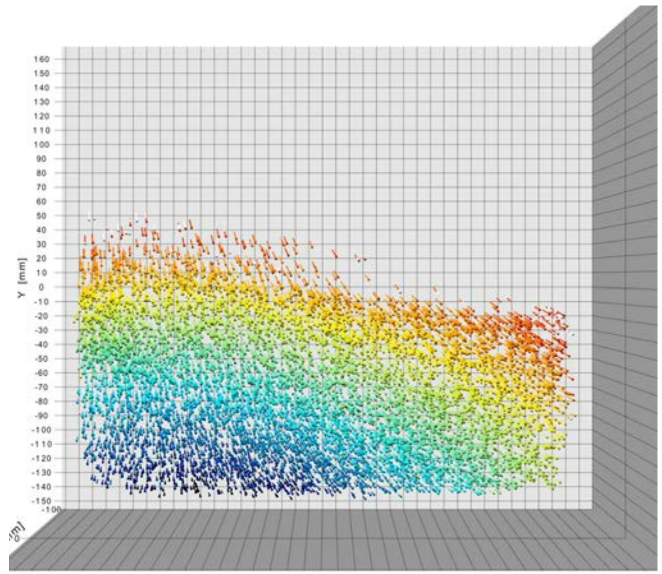






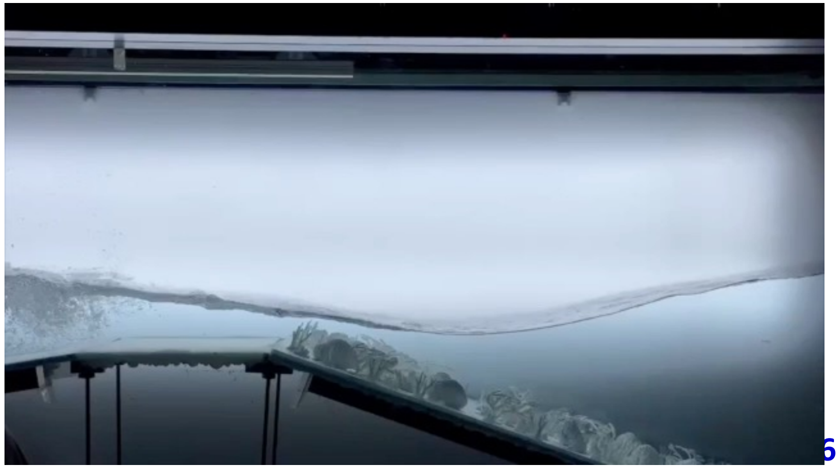


Millar et al., Ocean Engineering (2025)
Kristoffersen et al., Coastal Engineering (2026)



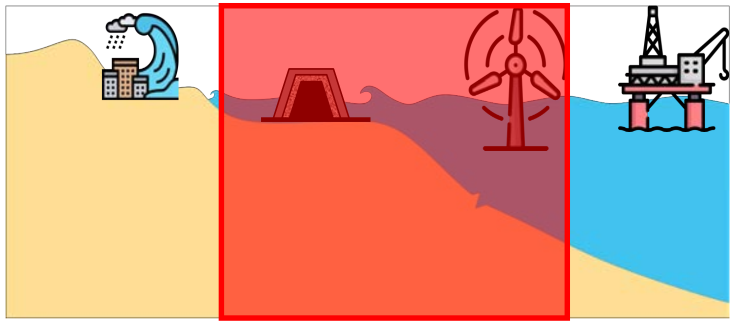
Coastal evolution
Extreme waves at the coast

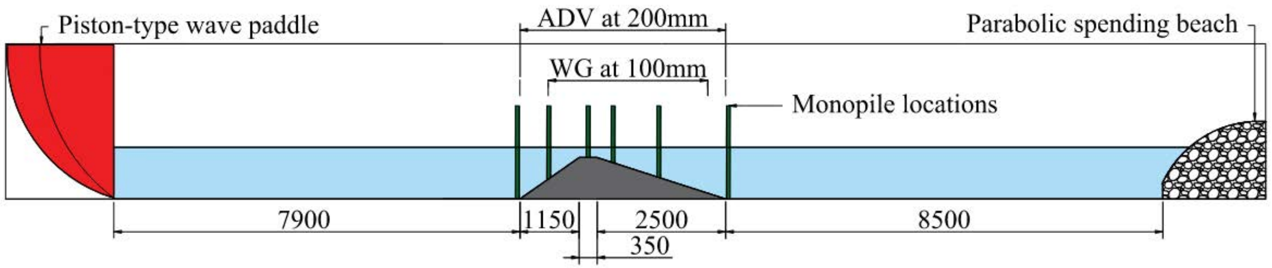
- Natural protection
- Effects of climate change
- Sea-level rise



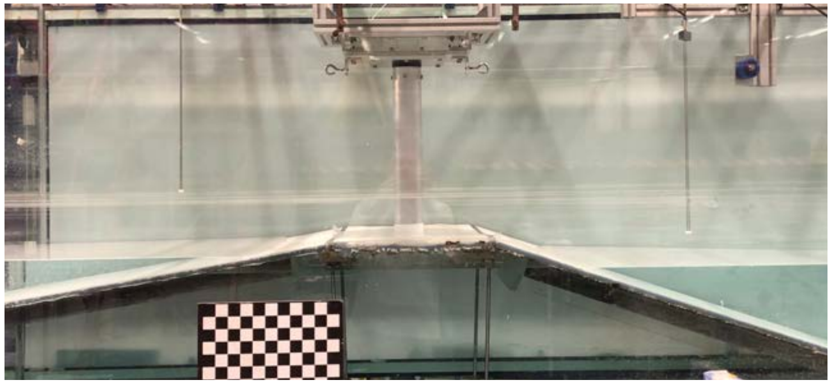
Coastal evolution
Design of coastal structures

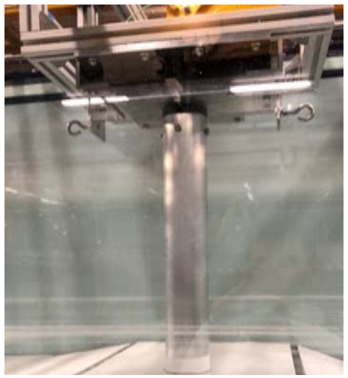
- Kinematics measurements.
- New experimental methods (4D PTV)
- LiDAR in the laboratory





Millar et al., Coastal Engineering (2026)





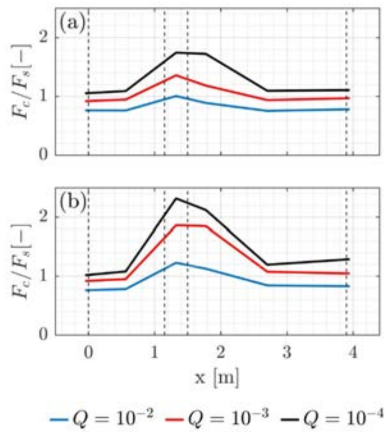
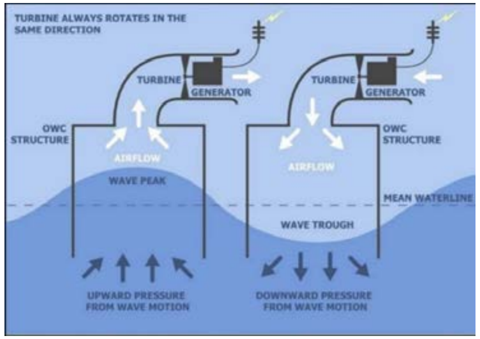


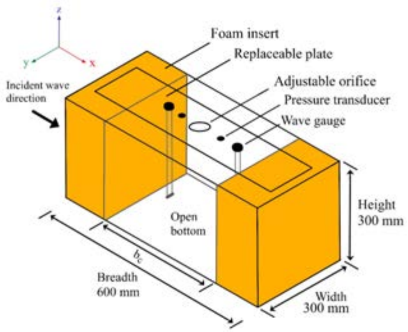
Figure 18: Exceedance thresholds of F_c/F_s around shoal. Key shoal boundaries demarcated by dashed black lines.

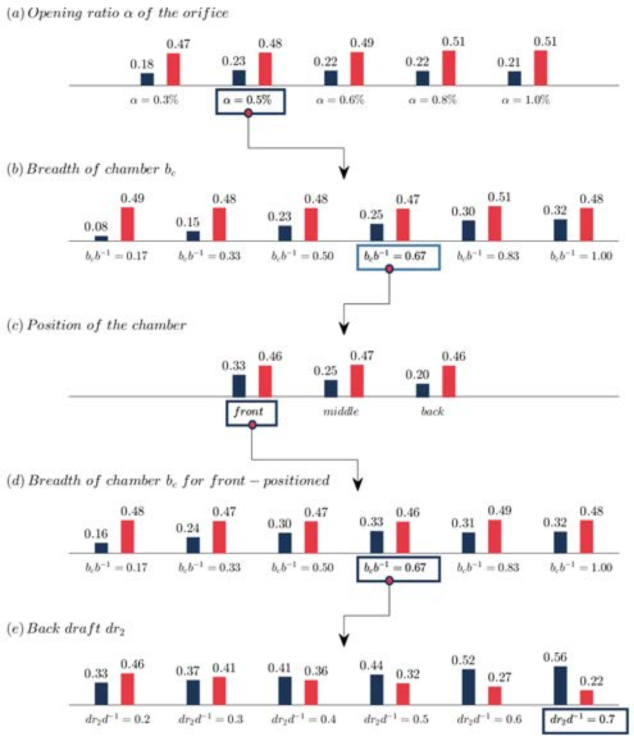
Wave energy converters

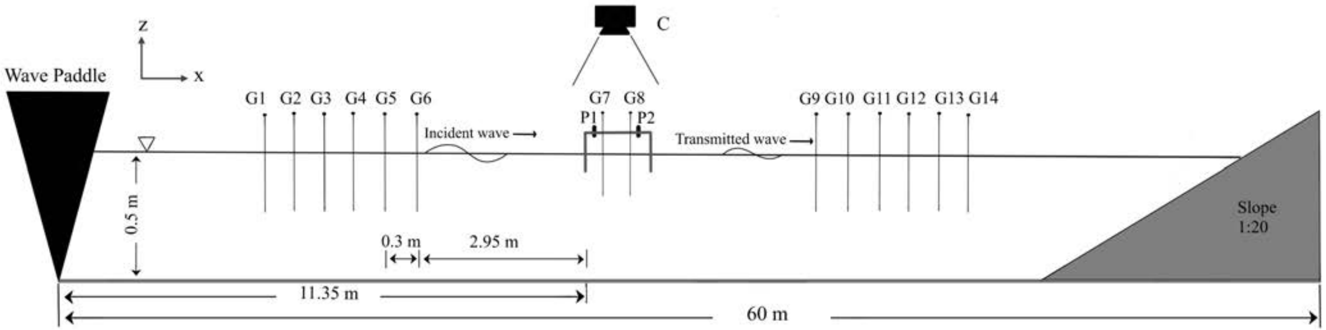
Optimization of design

- Oscillating water columns



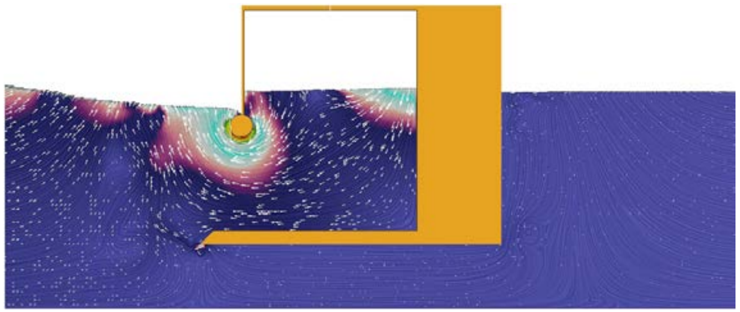


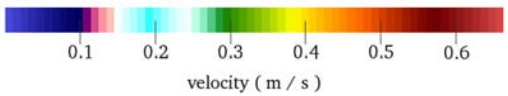


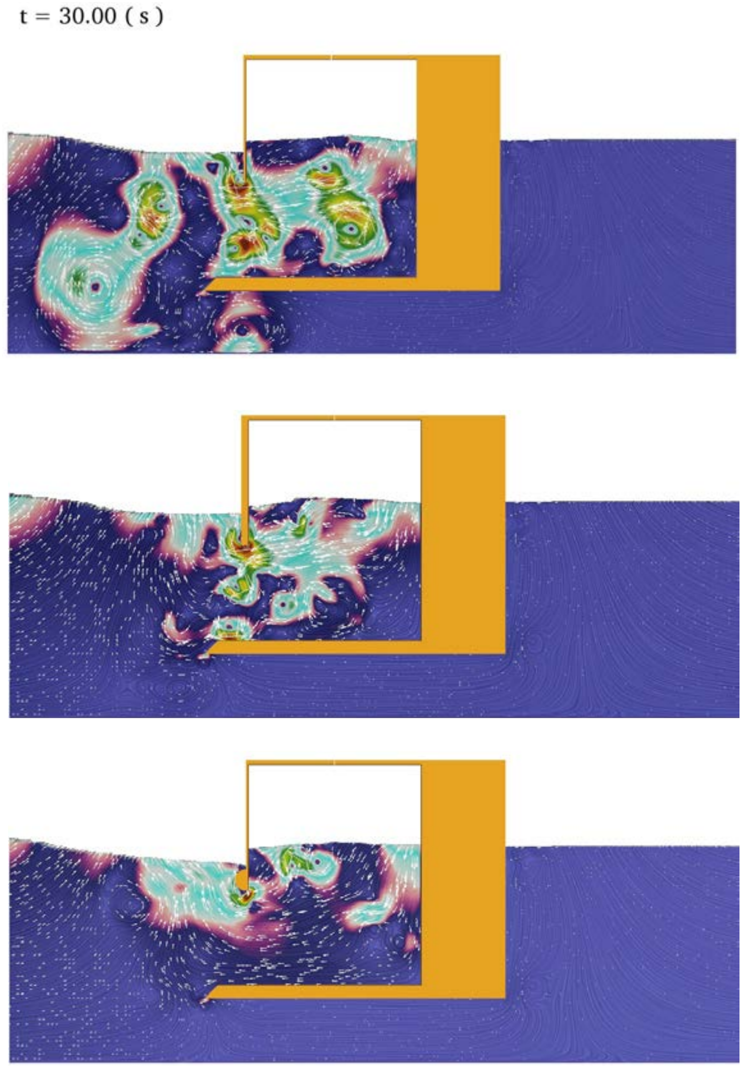


Almalki & Karmpadakis, Renewable Energy (2025)
Almalki et al., APOR (2025)
Almalki & Karmpadakis, APOR (2026)
Almalki & Karmpadakis, Renewable Energy (2026)

Wave energy converters
Increasing efficiency and control

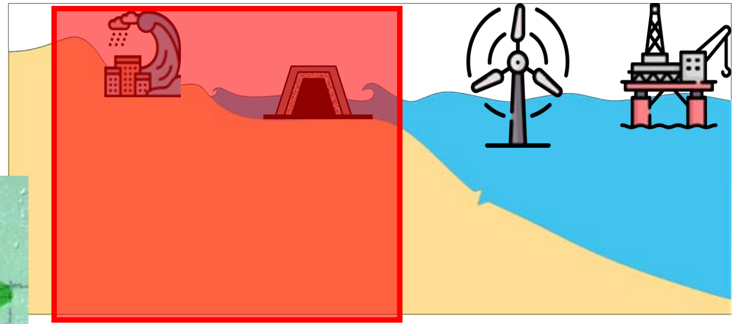


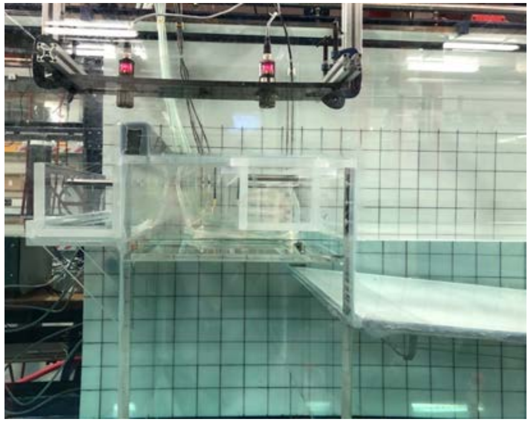




Almalki & Karmpadakis (2026) – Applied Ocean Research

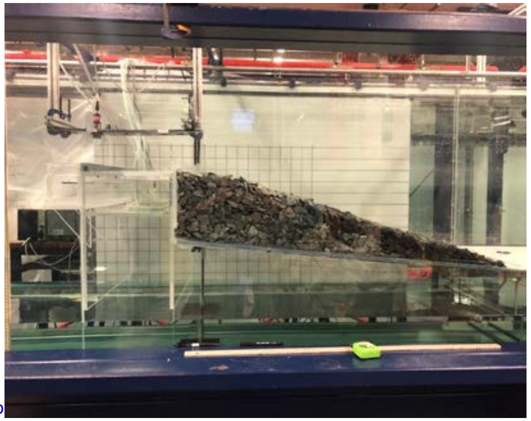
Coastal infrastructure
Design for a changing climate





Configuration 1

Configuration 2



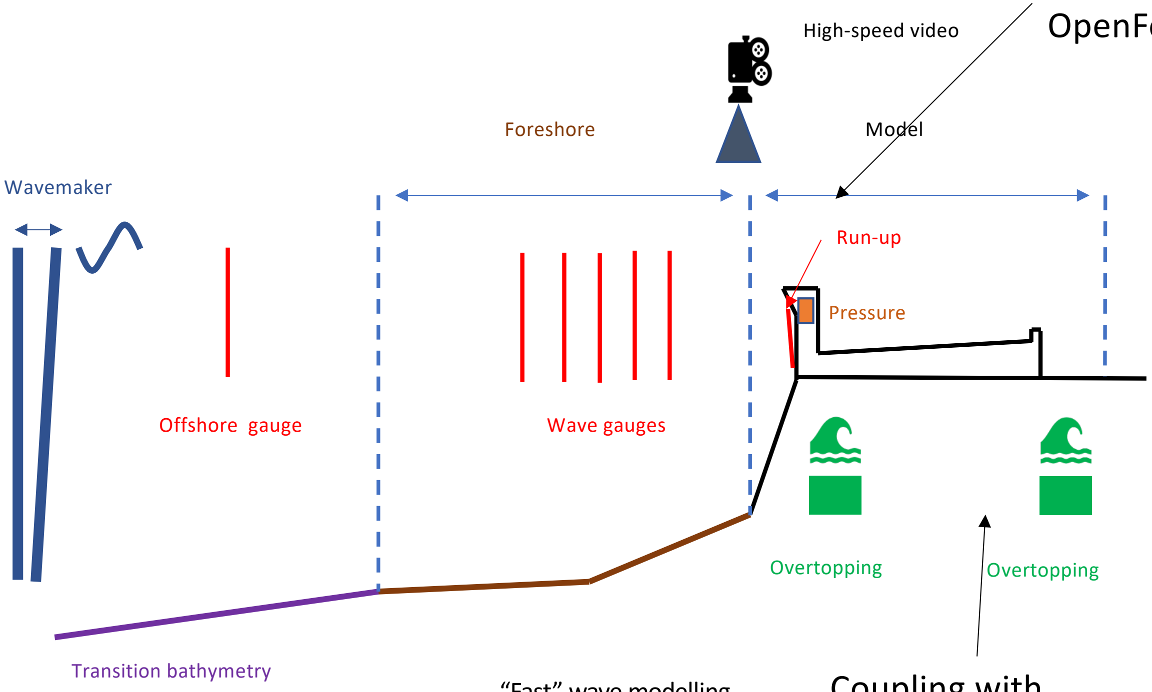
Configuration 3

Sensor array

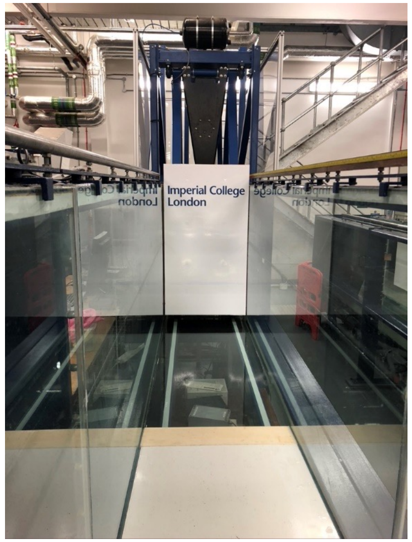
Coastal Structures and Flooding

Redesign of UK coastal defences

Coupling with OpenFoam → "Accurate" wave modelling (CFD)



"Fast" wave modelling (NLSWE) ← Coupling with SWASH



Coastal Flume at ICL

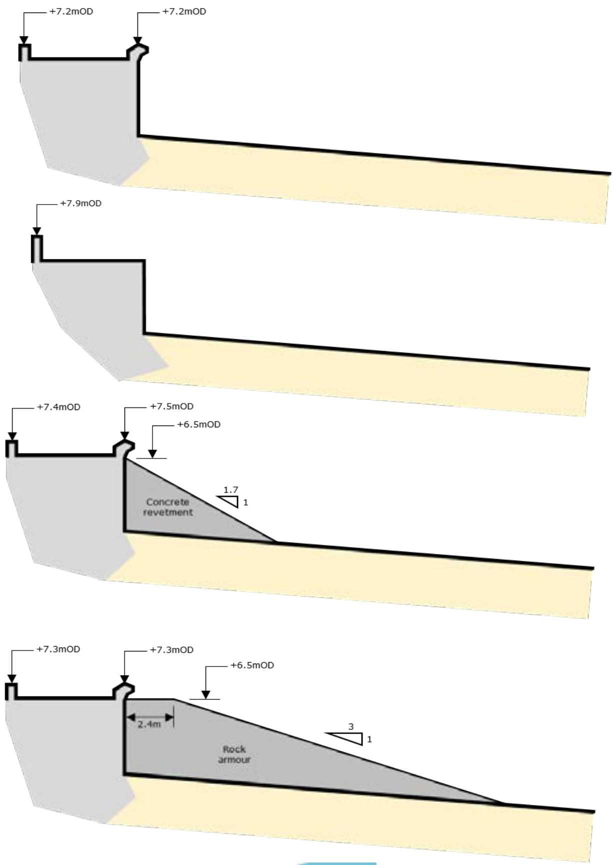
Imperial College London

ARUP

Results in: ICE Breakwaters
Karmpadakis, Dukker, Triantafylou, Button, Campbell (2024)

Coastal Structures and Flooding

Redesign of UK coastal defences



Front recurved wall

Raised back wall

Imperial College London

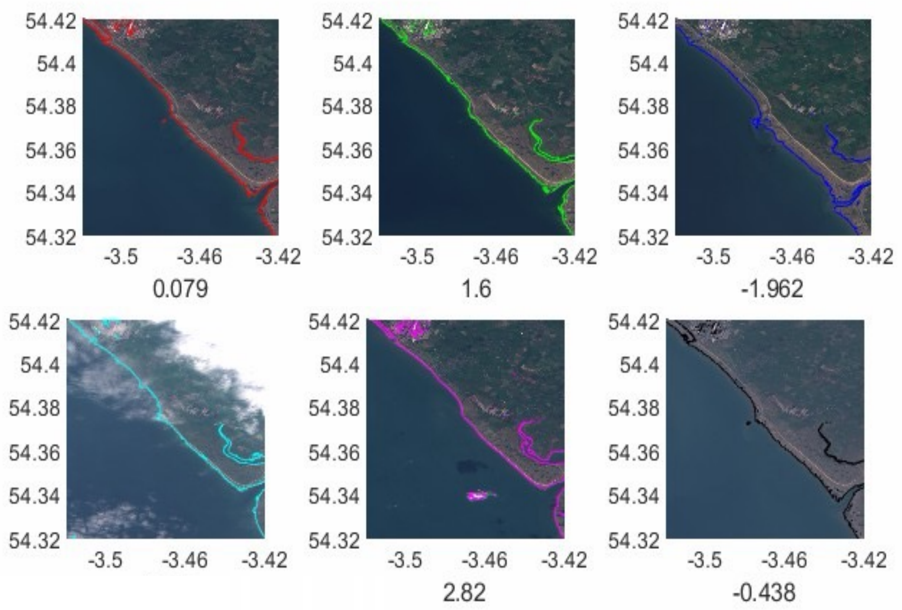
ARUP

JBA consulting

Shoreline evolution

Climate change effects

- **Modelling shoreline evolution in the next 100s 1000s years**
- **Statistical-dynamical approach for morphodynamic modelling**
- **Shoreline extraction: satellite measurements and machine learning**

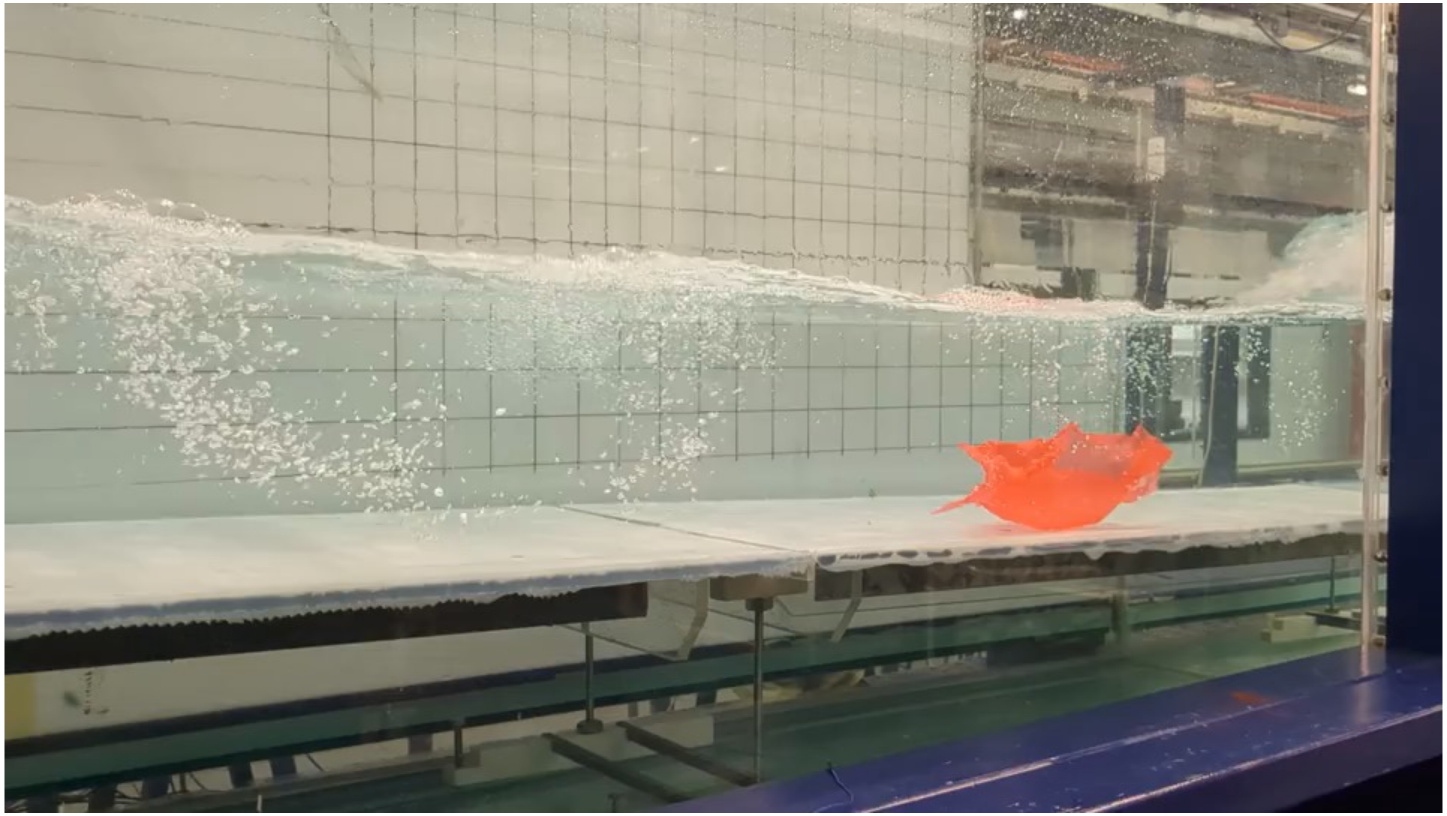


Open access satellite method:
CoastOMatic

Hewetson et al. (2026) – Frontiers in Marine Environment

Coastal and ocean processes
Pollutant transport

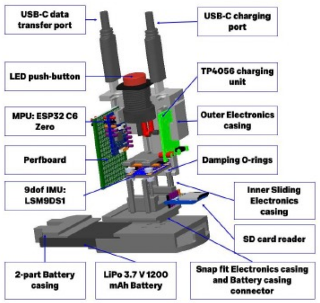
Coastal and ocean processes
Pollutant transport

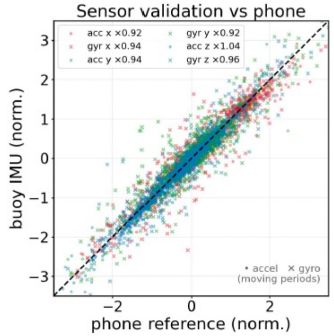


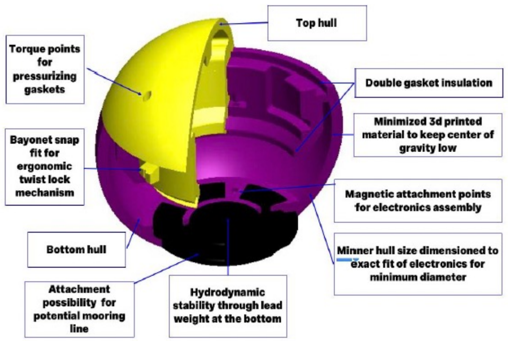
Thank you

Ocean sensing
New wave buoy

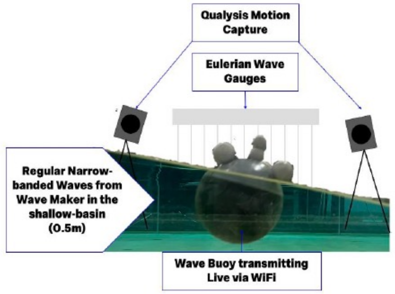
Electronics and Design

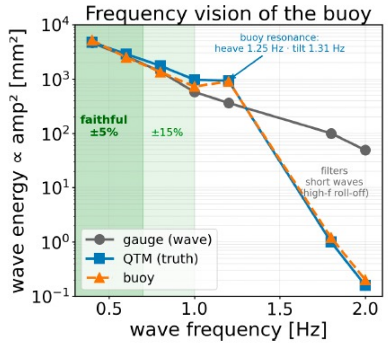


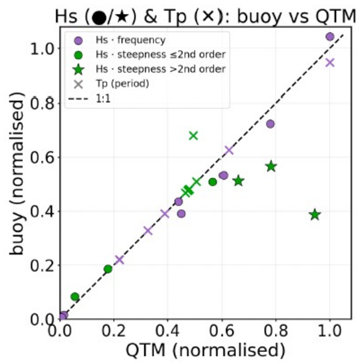




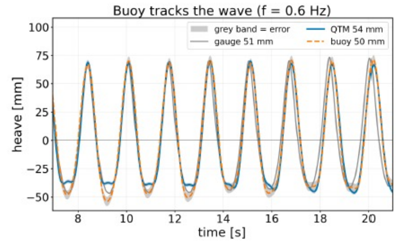
Testing and Validation

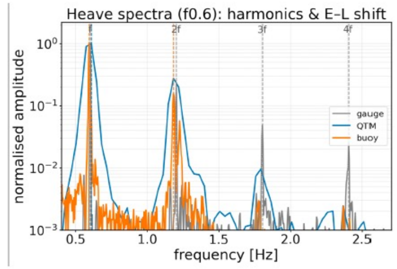






Comparison against Gauges





Conclusion

- **Sensor accuracy:** cheap IMU validated to **≤9% (accel) / ≤3% (gyro)**, $R^2 \geq 0.91$.
- **Buoy accuracy:** reproduces Qualisys **wave height 1:1** (R^2 0.99) and **period** (R^2 0.99)
- **Limitation:** under-reads in steep waves, **resonance at 1.32Hz**
- **Field of vision:** faithful **0.4 -1.0 Hz**, above ~1.4 Hz band set by buoy size.
- **★ Eulerian ↔ Lagrangian:** agree to **~2% in amplitude** at low steepness, but diverge measurably a **1.3% frequency shift**

Imperial College London

My team

Coastal bathymetry

1. Bellos V.(PhD) Statistical distributions of surface elevations. [Experimental]
2. Al Khalili U. (PhD) Numerical investigation of extreme waves using SWASH. [Numerical]
3. Millar O. (PhD) Extreme wave kinematics over coastal bathymetry. [Experimental]
4. McAdam P. (PhD) Effects of shortcrestedness on wave statistics over sloping beds. [Experimental]
5. Wright W (PhD) SDEs and ML predictions of extreme waves across the coastal zone. [ML]

Hydrodynamics

6. Shen S. (PhD) Lagrangian transport of inertial particles in realistic storms. [Experimental, Analytical]
7. Anestidi M. (PhD) Long-term modelling of coastal storms (Uth) [Numerical, Analytical]
8. Irvine L. (Post PhD) Rogue wave occurrence in stratified flows. [Experimental]

Wave-structure

9. Huo S. (Post PhD) Efficient modelling of wave-in-deck loading [Experimental, ML]
10. Mao L. (PhD) Wave loading on truncated cylinders for offshore wind. [Experimental]
11. Lun WL (PhD) Extreme shortcrested wave loading on offshore monopiles and dynamic response. [Experimental]

Wave-wind-structure

12. Kumar N. (PhD) Effects of wind of wave overtopping. [Experimental]

Renewables

13. Almalki. (Post PhD) Efficient modelling of OWC and energy resources [Experimental, Numerical]

Sediment

14. Hewetson (PhD) Long-term modelling of shoreline evolution. [Numerical, Analytical]
15. Jang U (PhD) Fate of radio-active particles in the coastal zone (Oxford) [Numerical]

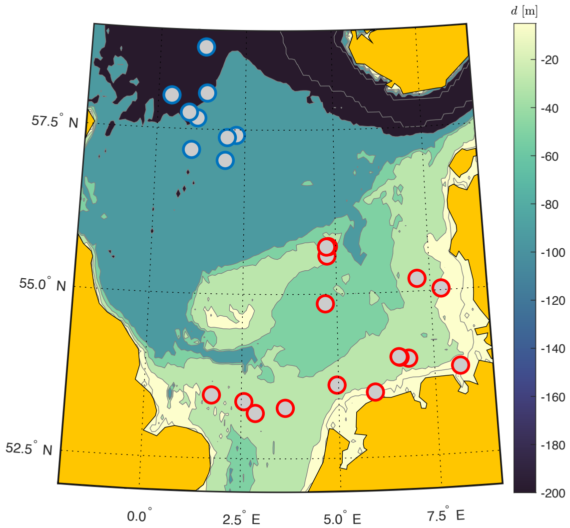
Methods
Field data analysis

High quality surface elevation records (7.7 m < d < 190 m)

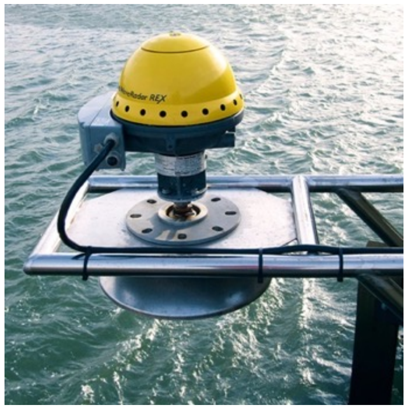
- wave-radar measurements
- 30 individual platforms
- 500,000,000 individual waves
- 2,000,000 (20-minute) sea-states

Largest database in literature

bp MAERSK ExxonMobil equinor TOTAL Woodside



Map of offshore locations



Karmpadakis et al., Coastal Engineering (2020)
Karmpadakis & Swan, Ocean Engineering (2022)