Fabio Pierella and Henrik Bredmose

# Effect of the shape of extreme waves on the loads on a 15MW wind turbine

# The shape of waves matters…

# …especially when computing extreme wave loads

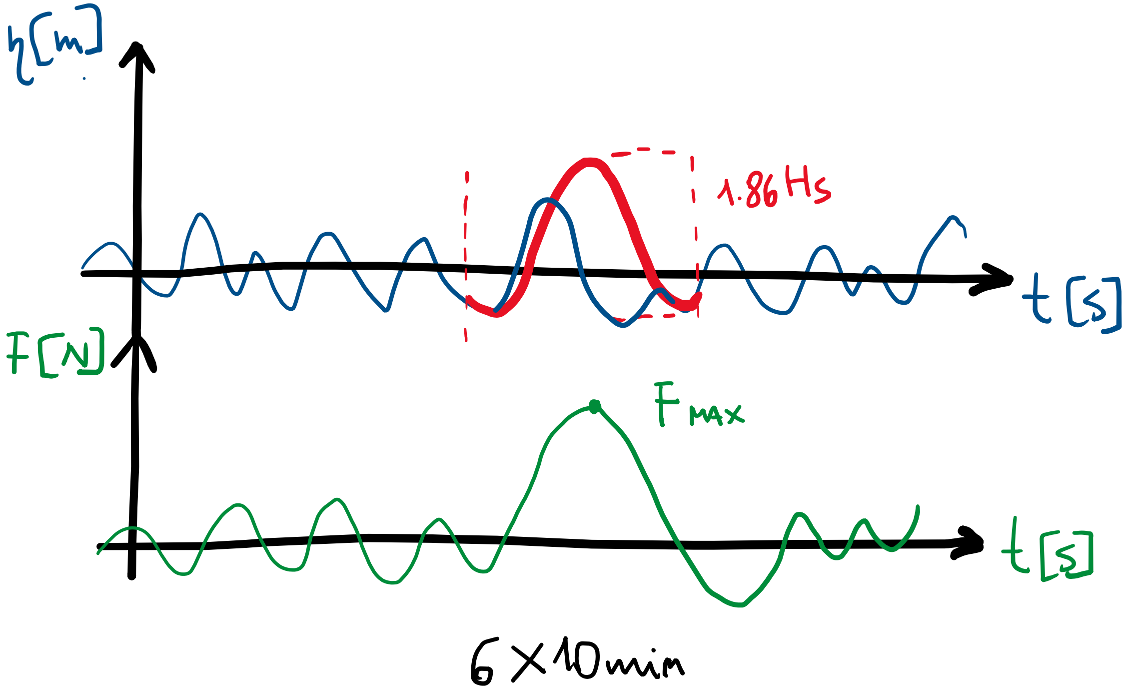
Damsgaard et al. (2007)
Horns Rev I

- Stochastic behavior of waves
- Complex physics
  - Wave nonlinearity
  - Wave slamming
- How to model loads accurately?

# Approach 1: A single large nonlinear wave with prescribed height (IEC Standard)

IEC61400-3:2019

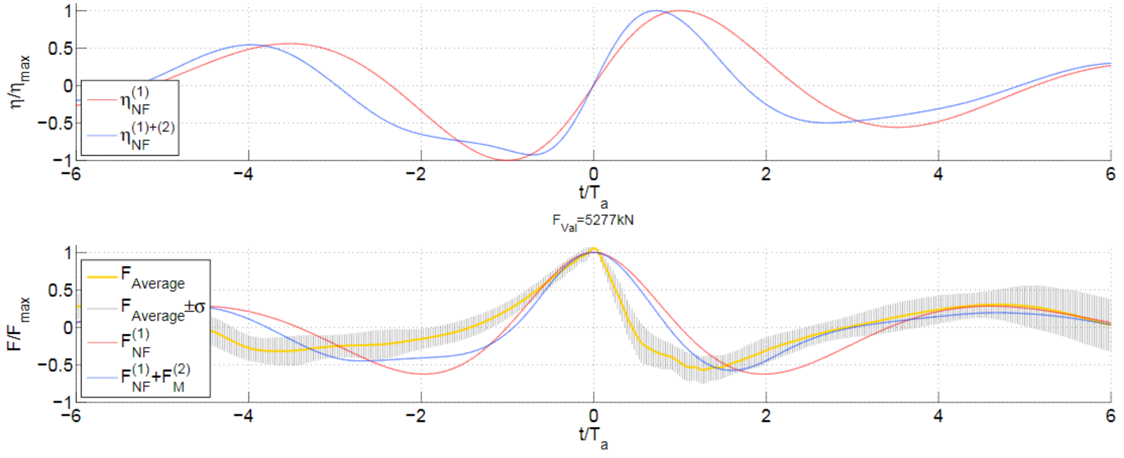
*"Design requirements for fixed offshore wind turbines"*



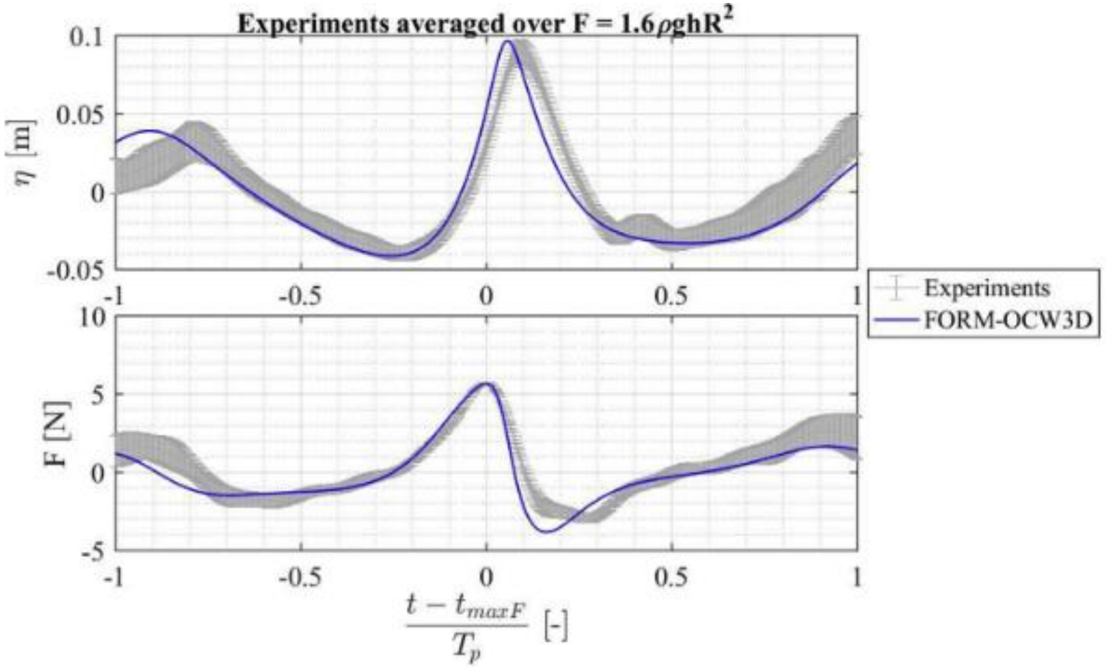

Stream Function Wave

(Dean 1965, Rienecker and Fenton 1981)

# Approach 2: calculate the wave which is most likely to generate a force peak



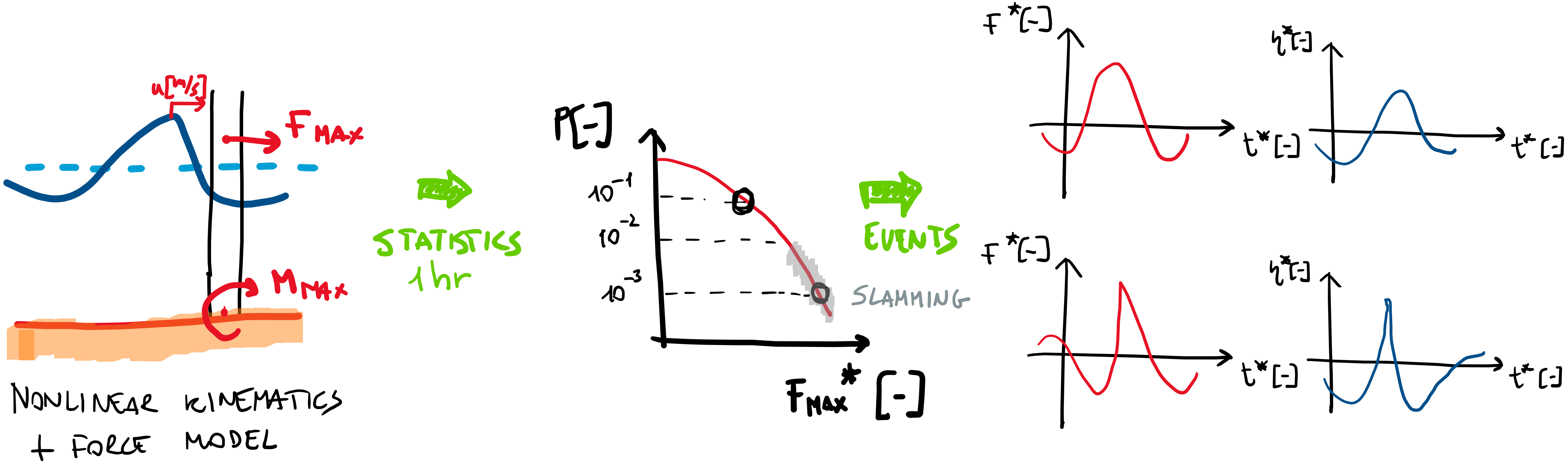

(b) $F/(\rho g h R^2) = 1.3$.




New Force model
(Schløer et al. 2017)

FORM + OceanWave3D
(Ghadirian and Bredmose 2019)

# Current Work: compute the whole distribution of waves and associated loads



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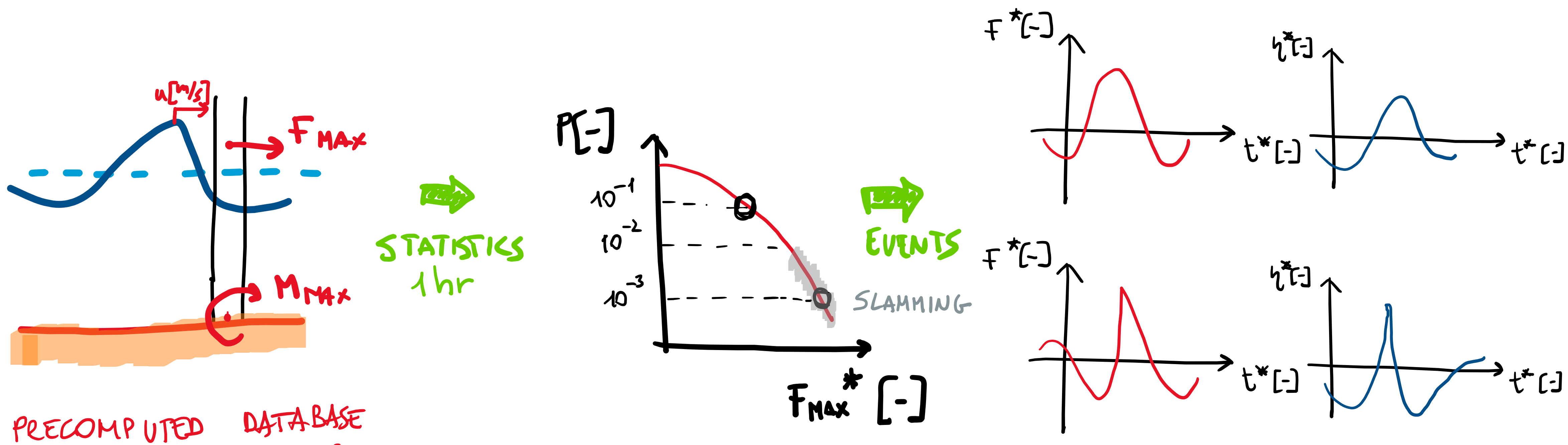
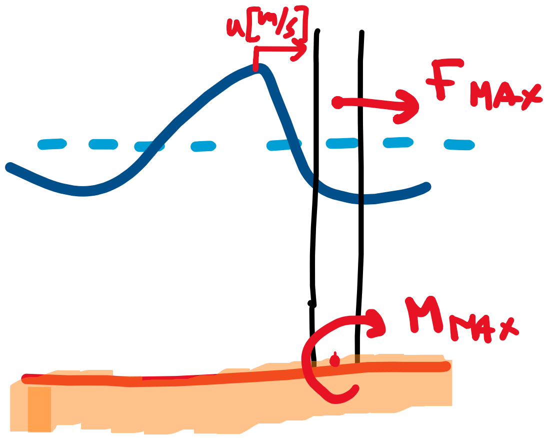


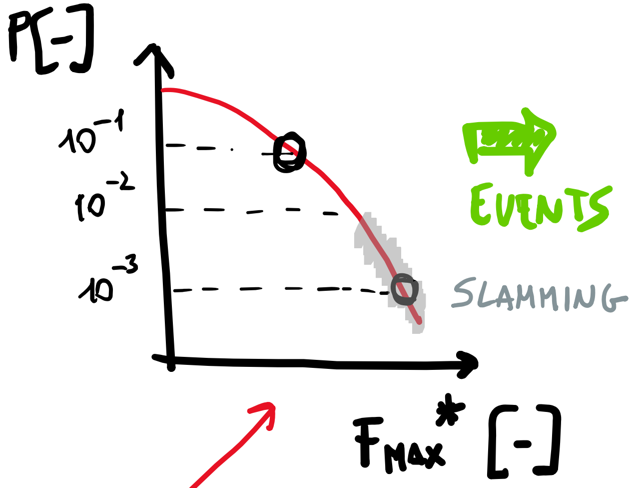

A PRECOMPUTED DATABASE OF FULLY-NONLINEAR WAVE KINEMATICS

B ACCURATE LOAD MODEL WITH WAVE SLAMMING

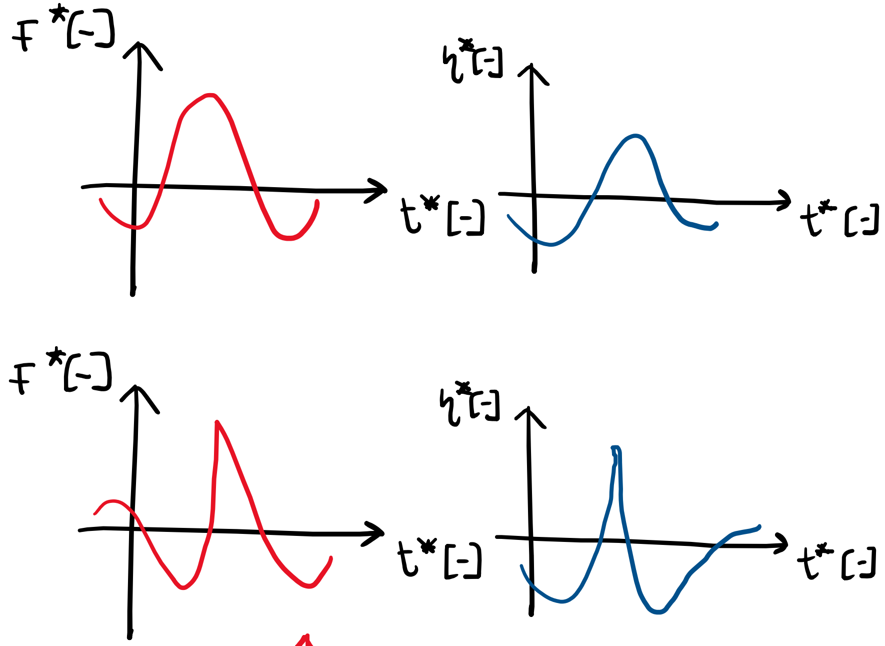
# Current Work: compute the whole distribution of waves and associated loads




STATISTICS
1hr




EVENTS




(A) PRECOMPUTED DATABASE OF FULLY-NONLINEAR WAVE KINEMATICS

(B) ACCURATE LOAD MODEL WITH WAVE SLAMMING

Q1: How well can we reproduce measured loads that include slamming?

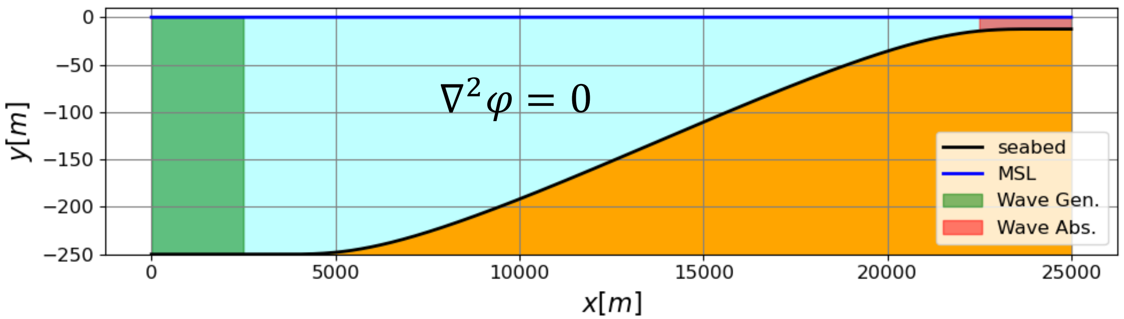
Q2: How do the extreme load waves look, when you also include slamming loads?

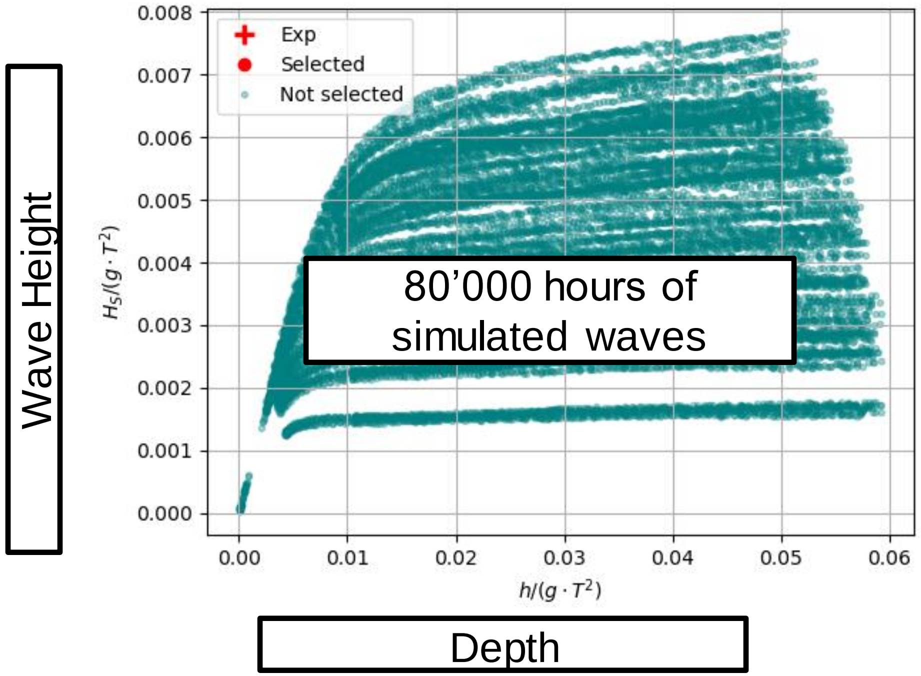
Q3: How can we utilize this in a design context?

# The wave kinematics model: DeRisk Database

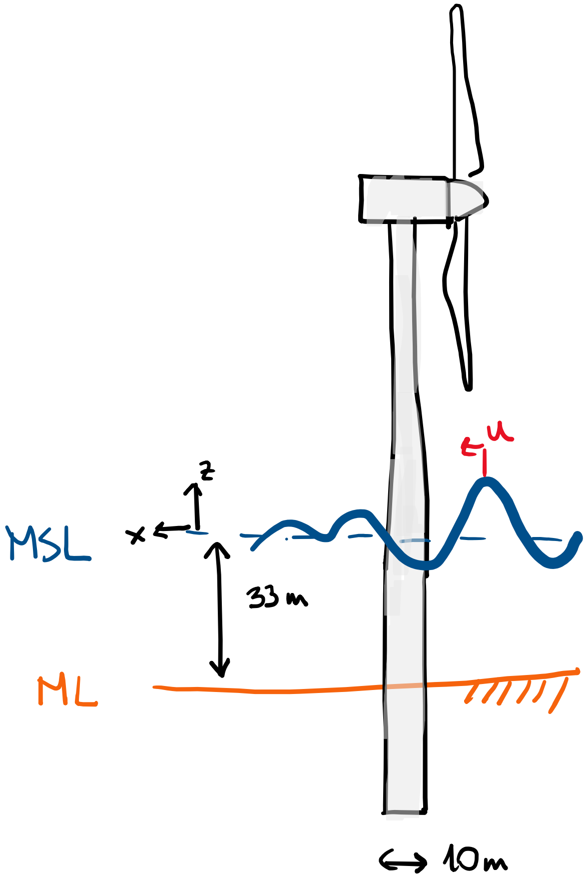
SCAN ME

- Online database of nonlinear wave kinematics hosted on https://data.dtu.dk/
- Fully-nonlinear potential flow solver OceanWave3D
(Engsig-Karup et al. 2009)
- Validated against DeRisk Experiments
(Pierella et al. 2021, *Marine Structures*)



# The non-slamming wave load model: Rainey (1995)



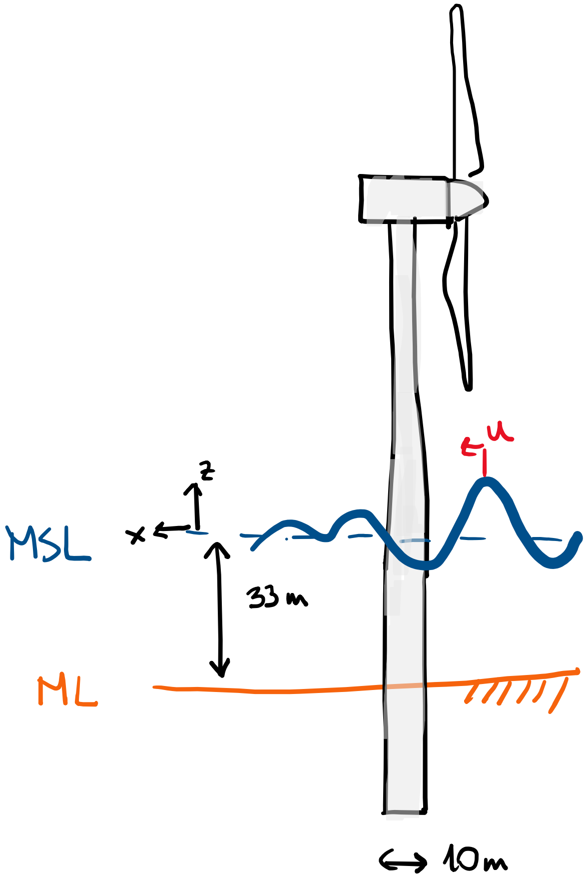

MORISON (1950)

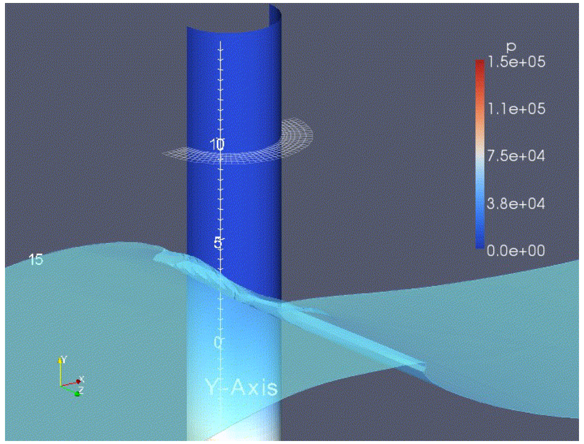
RAINEY (1995)

$$f_x = \frac{1}{2}\rho C_D D u|u| + \rho(1+C_m)\pi R^2 \frac{du}{dt} + \rho C_m w_z u \pi R^2$$

$$F = \int_{-h}^{\eta} f_x \, dz + \frac{1}{2}\rho \pi R^2 C_m \eta_x u^2$$

# The slamming load model:
# Pressure Impulse (Ghadirian and Bredmose 2019)

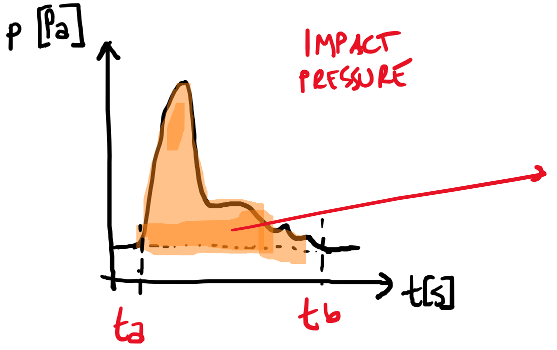



CFD Impact

Bredmose and Jacobsen (2011)

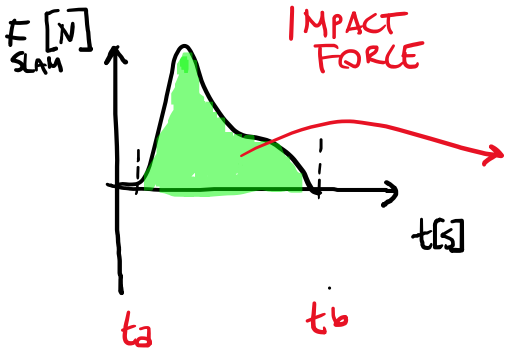
# The slamming load model: Pressure Impulse (Ghadirian and Bredmose 2019)




PRESSURE IMPULSE

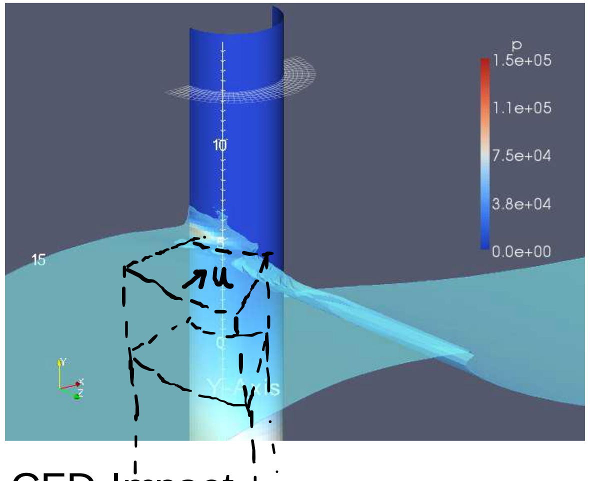
$$P = \int_{t_a}^{t_b} p(t)dt$$

$\int_A \downarrow$ $\int_A \downarrow$




FORCE IMPULSE

$$F_I = \int_{t_a}^{t_b} F_{slam}(t)dt$$

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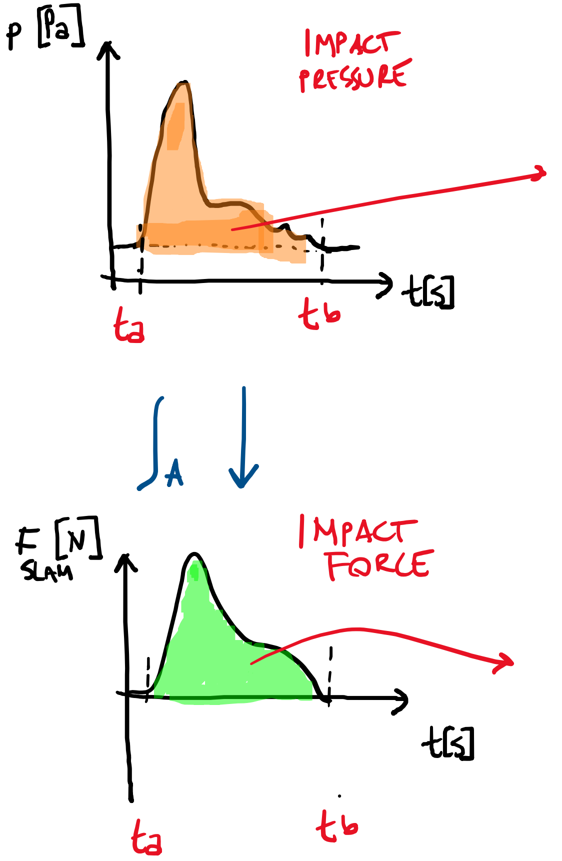


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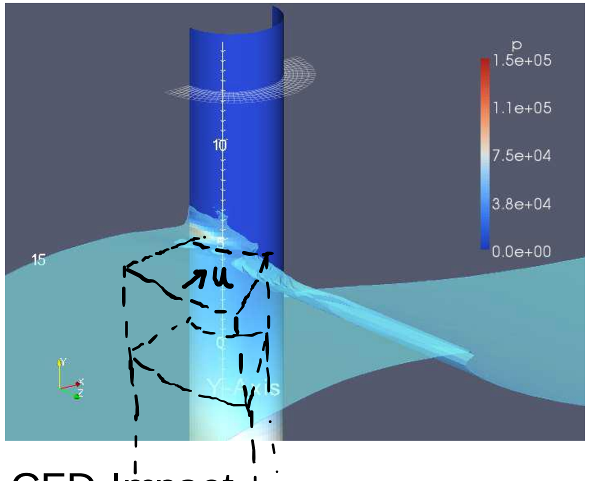


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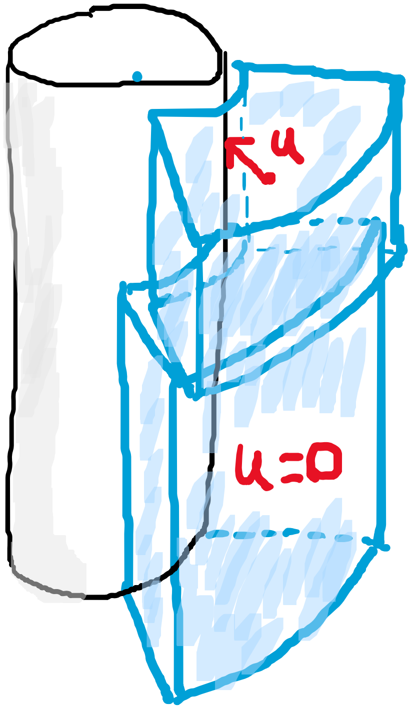


The pressure impulse model

# The slamming load model:
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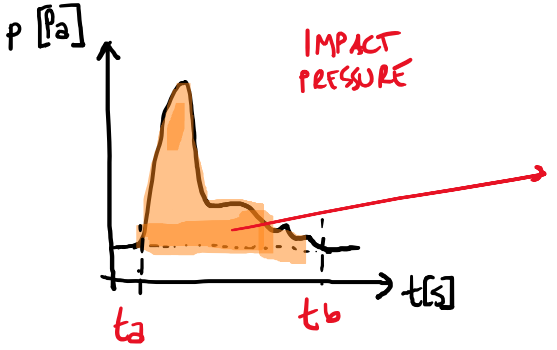


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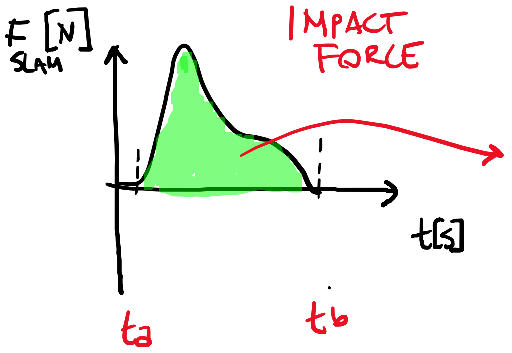


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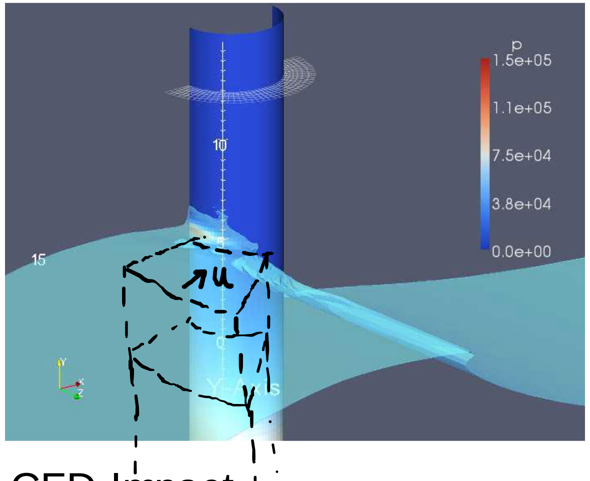


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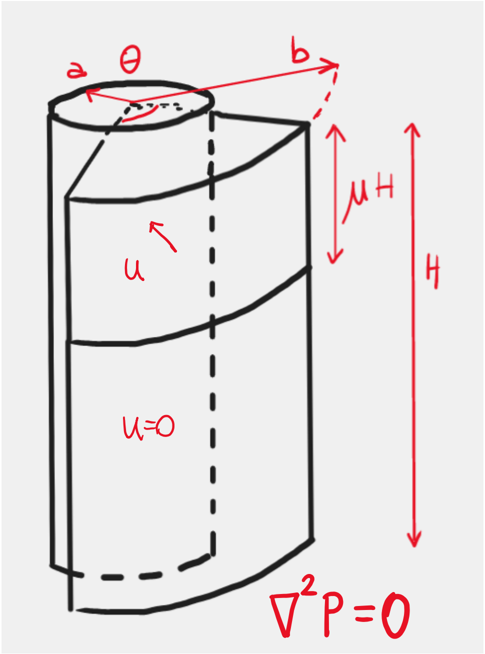
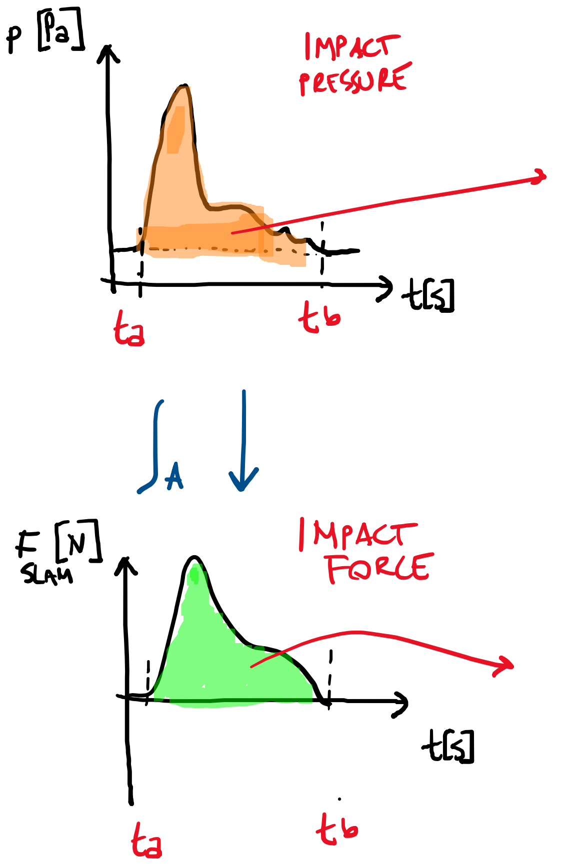



The pressure impulse model

$$P(r,z,\theta) = \int_{t_a}^{t_b} p(r,z,\theta,t)dt$$

# The slamming load model: Pressure Impulse (Ghadirian and Bredmose 2019)

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$$P = \int_{t_a}^{t_b} p(t)dt$$

∫A

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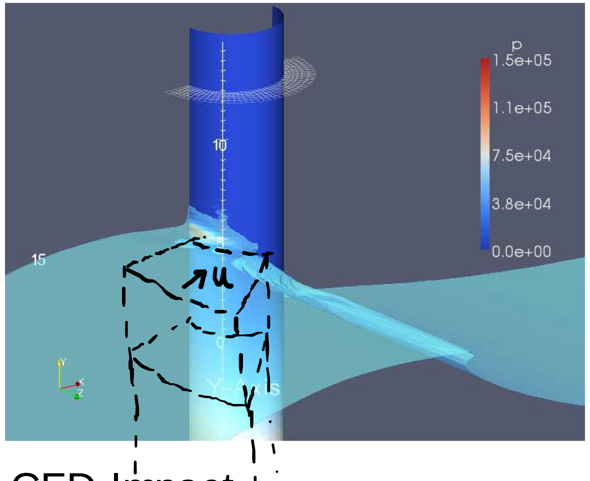


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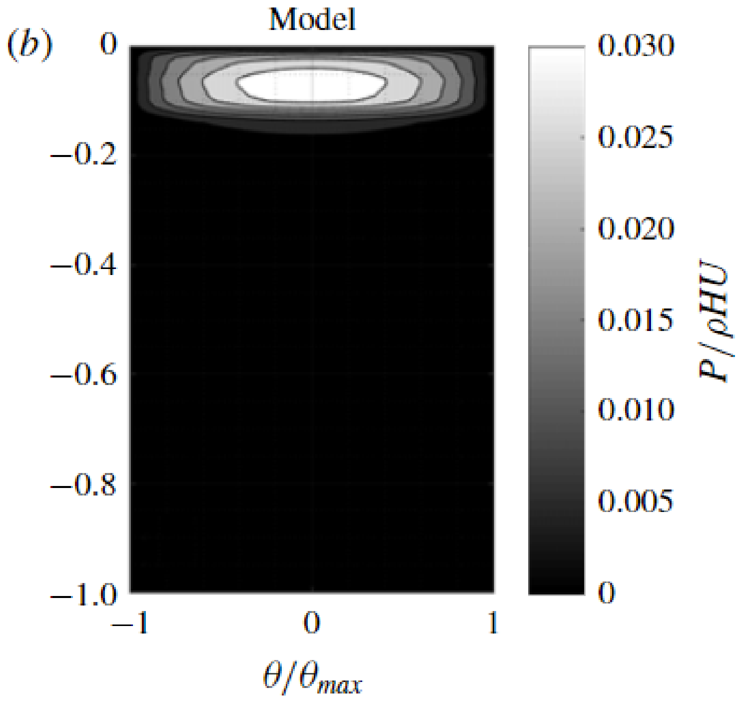
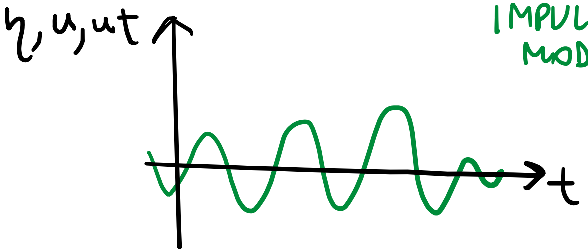



The pressure impulse model

$$P(r,z,\theta) = \int_{t_a}^{t_b} p(r,z,\theta,t)\,dt$$

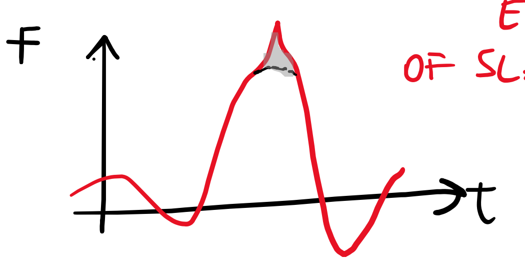
# The slamming load model: Validation (Ghadirian, Pierella and Bredmose 2023)




PRESSURE IMPULSE MODEL (μ, H, b, u)

SIMULATED
FORCE IMPULSE

OCEANWAVE3D RECOMPUTATIONS

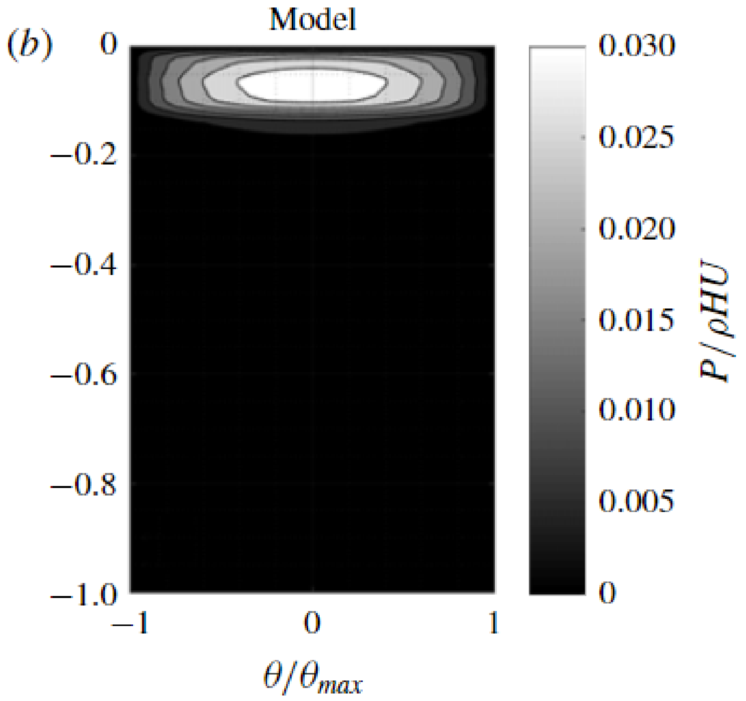



EXTRACTION OF SLAMMING LOAD

EXPERIMENTAL
FORCE IMPULSE

~600 EVENTS

EXPERIMENTS (DERISK, 2016)

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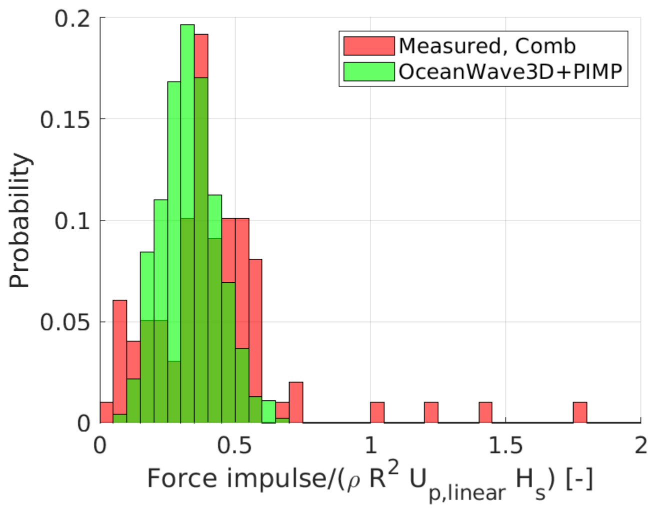
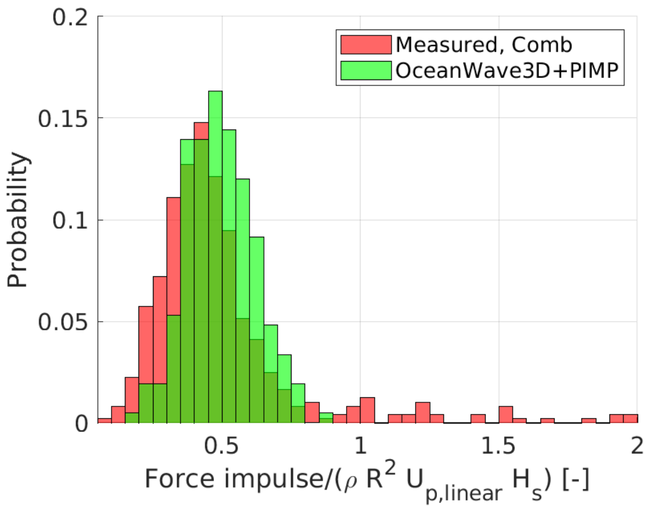
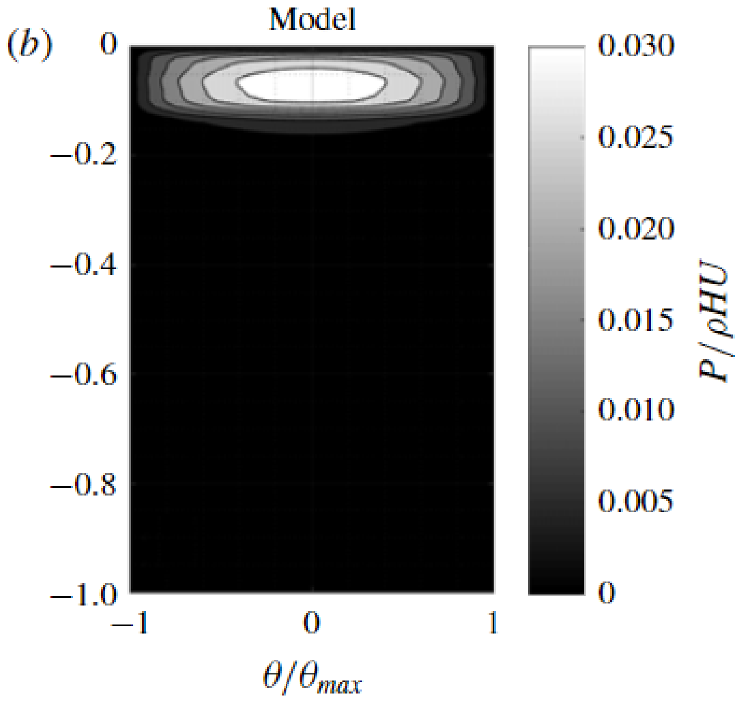
2D




3D

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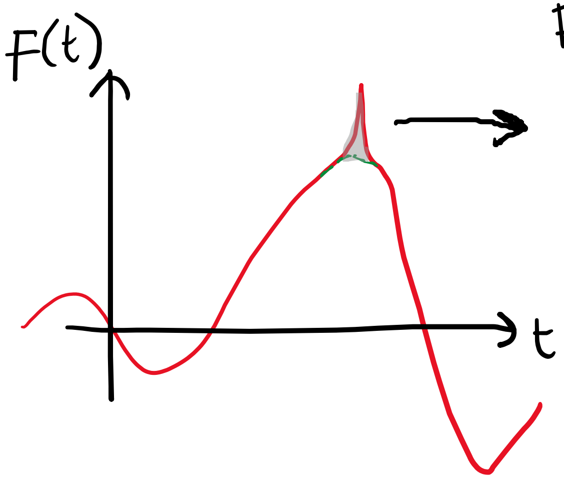
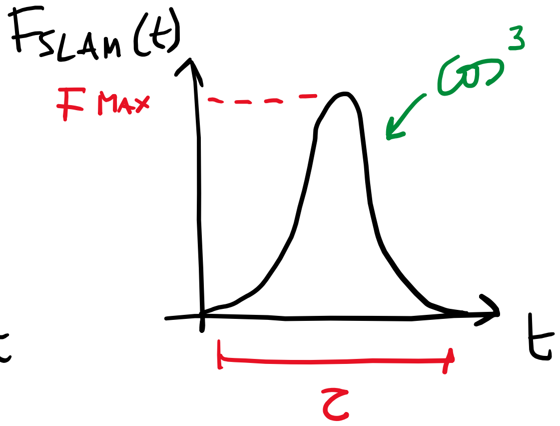
# The slamming load model: Validation (Ghadirian, Pierella and Bredmose 2023)

$F_I = \int_t F_{slam}(t)dt$

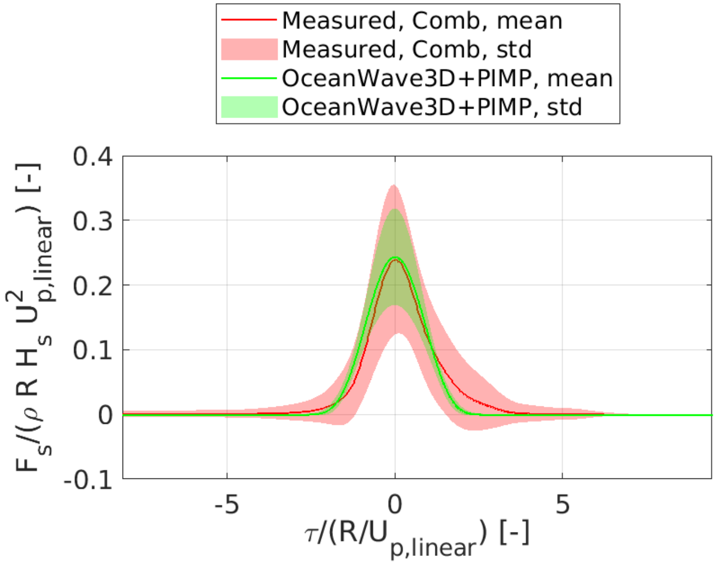
$F_{slam}(t) = h(t)F_I$



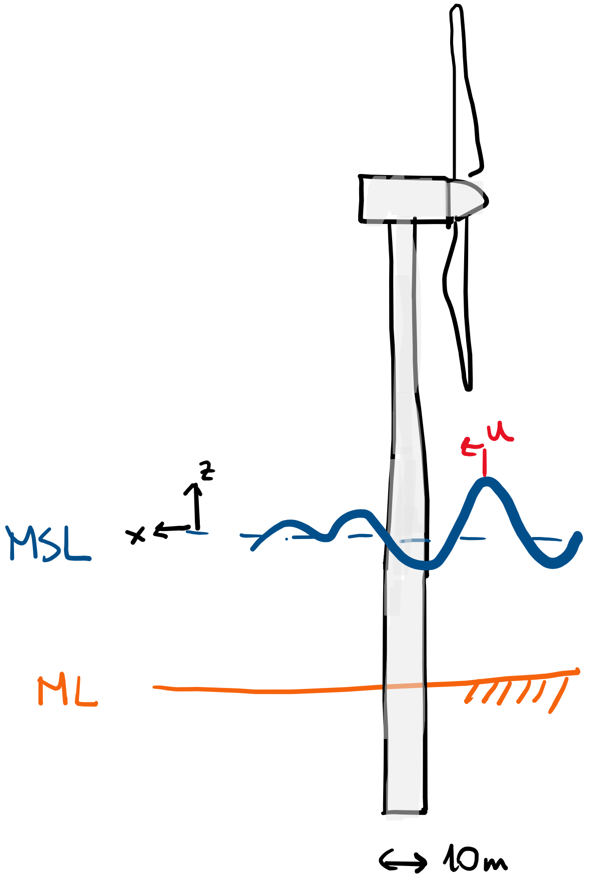




ASSUME

CALIBRATE ON EXPERIMENTS



# The combined wave load model: Rainey (1995) + P.Imp. (Ghadirian&Bredmose 2019)




MORISON (1950)
RAINEY (1995)
GHADIRIAN AND BREDMOSE (2019)

$$f_x = \frac{1}{2}\rho C_D D\, u|u| + \rho(1+C_m)\pi R^2 \frac{du}{dt} + \rho C_m w_z u \pi R^2$$

$$F = \int_{-h}^{\eta} f_x \, dz + \frac{1}{2}\rho \pi R^2 C_m \eta_x u^2 + 2\pi\rho u^2 R \eta_B \lambda_B$$

↑ APPLIED @ $\left.\frac{\partial \eta}{\partial t}\right|_{MAX}$

# Q1: How well can we reproduce measured loads that include slamming?

# Validation:
# The DeRisk Experiments

2D and 3D sea states 10, 100, 1000 year return period

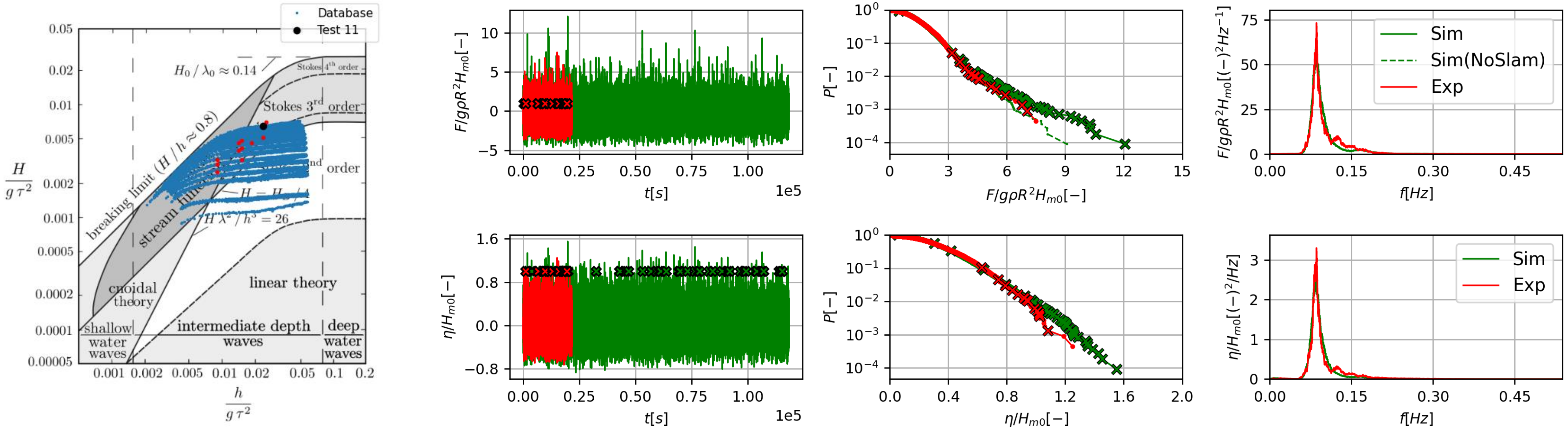
Duration (3D) > 70 hours

33 m depth

20 m depth

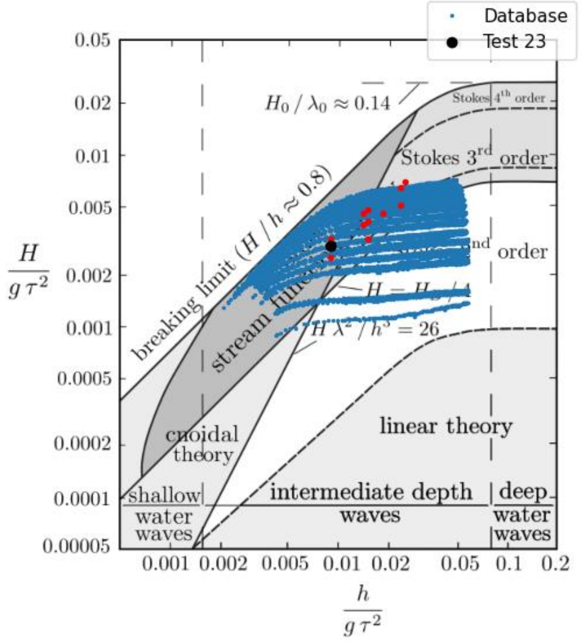
| Test No. | Water depth [m] | $H_s$ [m] | $T_p$ [s] | Directional Spread, $\sigma_p$ [deg] | Approx. return period [year] | Duration [hrs] |
|---|---|---|---|---|---|---|
| 1 | 33 | 8.5 | 13.5 | 0 | 10 | >24 |
| 2 | 33 | 8.5 | 13.5 | 22 | 10 | >70 |
| 3 | 33 | 8.5 | 13.5 | 33 | 10 | >24 |
| 4 | 33 | 7.5 | 12 | 22 | 10 | >70 |
| 5 | 33 | 7.5 | 15 | 22 | 10 | >70 |
| 6 | 33 | 9.5 | 12 | 22 | 100 | >70 |
| 7 | 33 | 9.5 | 15 | 22 | 100 | >70 |
| 8 | 33 | 11 | 15 | 22 | 1000 | >70 |
| 9 | 33 | 7.5 | 12 | 0 | 10 | 6 |
| 10 | 33 | 7.5 | 15 | 0 | 10 | 6 |
| 11 | 33 | 9.5 | 12 | 0 | 100 | 6 |
| 12 | 33 | 9.5 | 15 | 0 | 100 | 6 |
| 13 | 33 | 11 | 15 | 0 | 1000 | 6 |
| 14 | 20 | 5.8 | 12 | 22 | 10 | >70 |
| 15 | 20 | 5.8 | 15 | 22 | 10 | >70 |
| 16 | 20 | 6.8 | 12 | 22 | 100 | >70 |
| 17 | 20 | 6.8 | 15 | 22 | 100 | >70 |
| 18 | 20 | 7.5 | 15 | 22 | 1000 | >70 |
| 19 | 20 | 5.8 | 9 | 22 | 1000 | >70 |
| 20 | 20 | 5.8 | 12 | 0 | 10 | 6 |
| 21 | 20 | 5.8 | 15 | 0 | 10 | 6 |
| 22 | 20 | 6.8 | 12 | 0 | 100 | 6 |
| 23 | 20 | 6.8 | 15 | 0 | 100 | 6 |
| 24 | 20 | 7.5 | 15 | 0 | 1000 | 6 |
| 25 | 20 | 5.8 | 9 | 0 | 1000 | 6 |

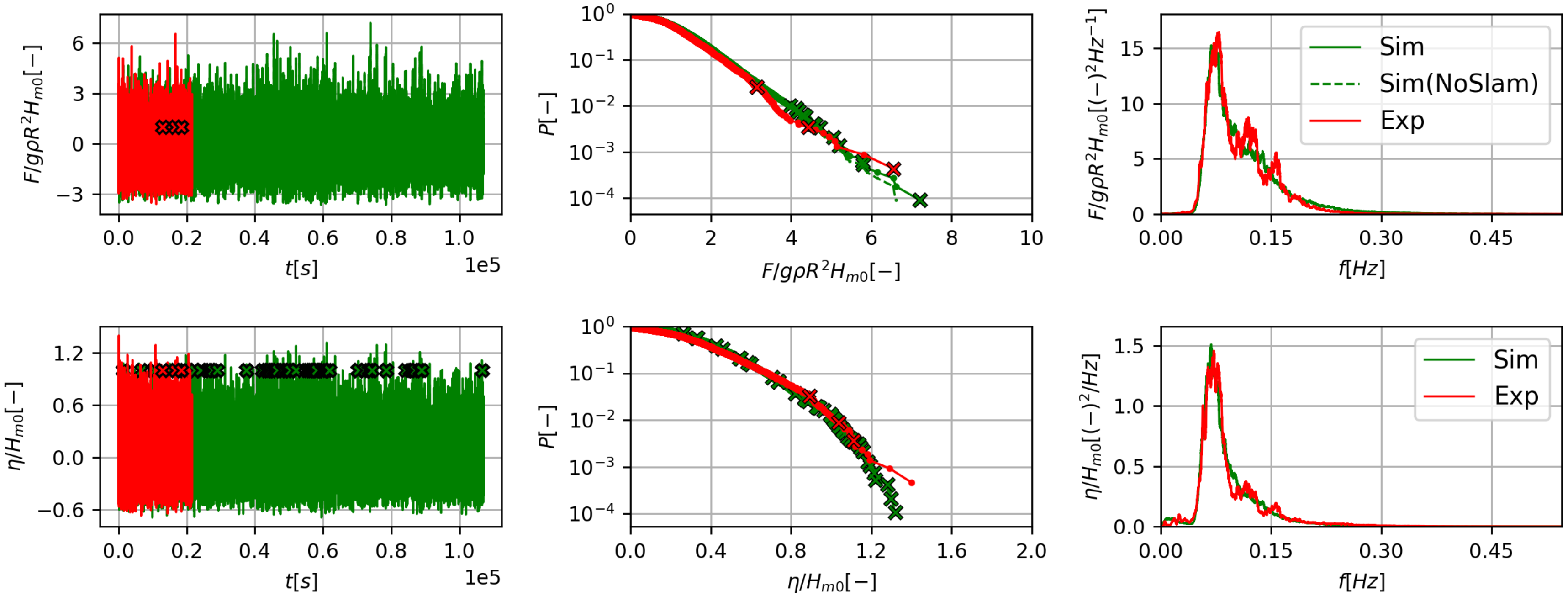
# Test 11 (Hs=9.5m, Tp=15.0 s, h=33.0m)




CD=1.0, CM=1.80

# Test 23 (Hs=6.8m, Tp=12.0 s, h=20.0m)

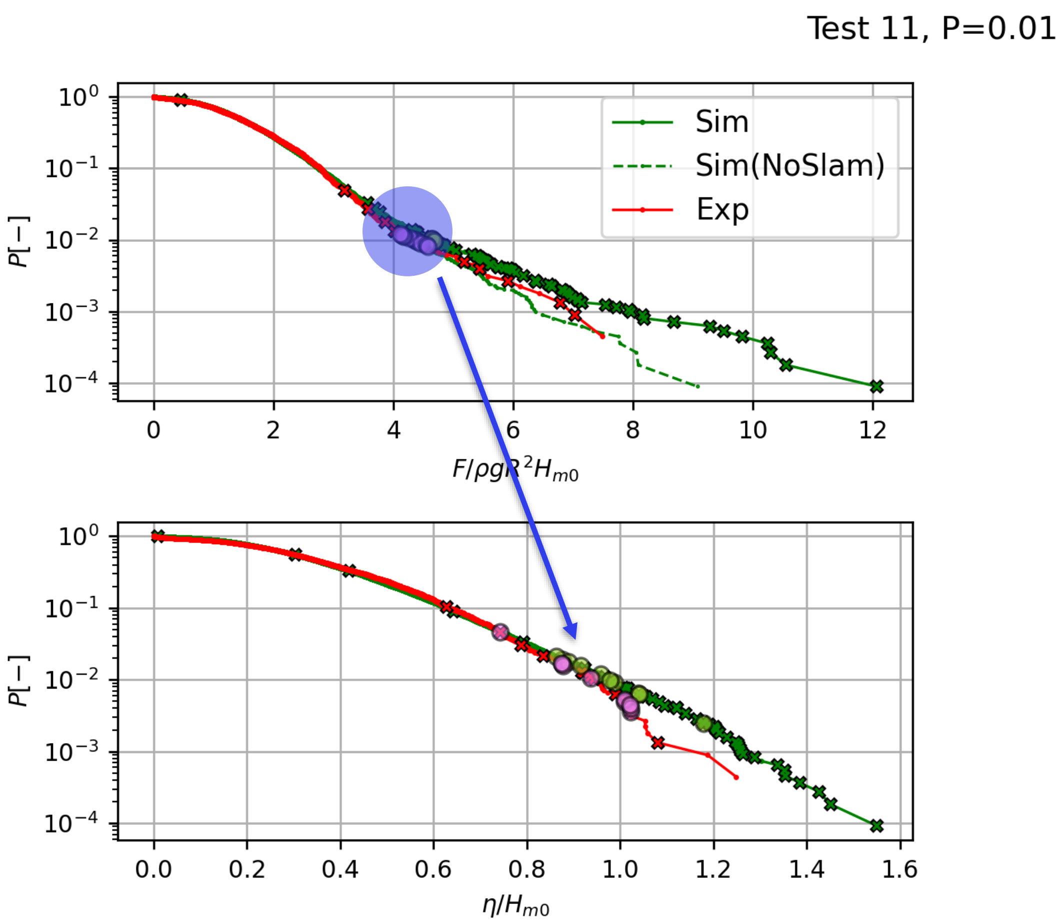


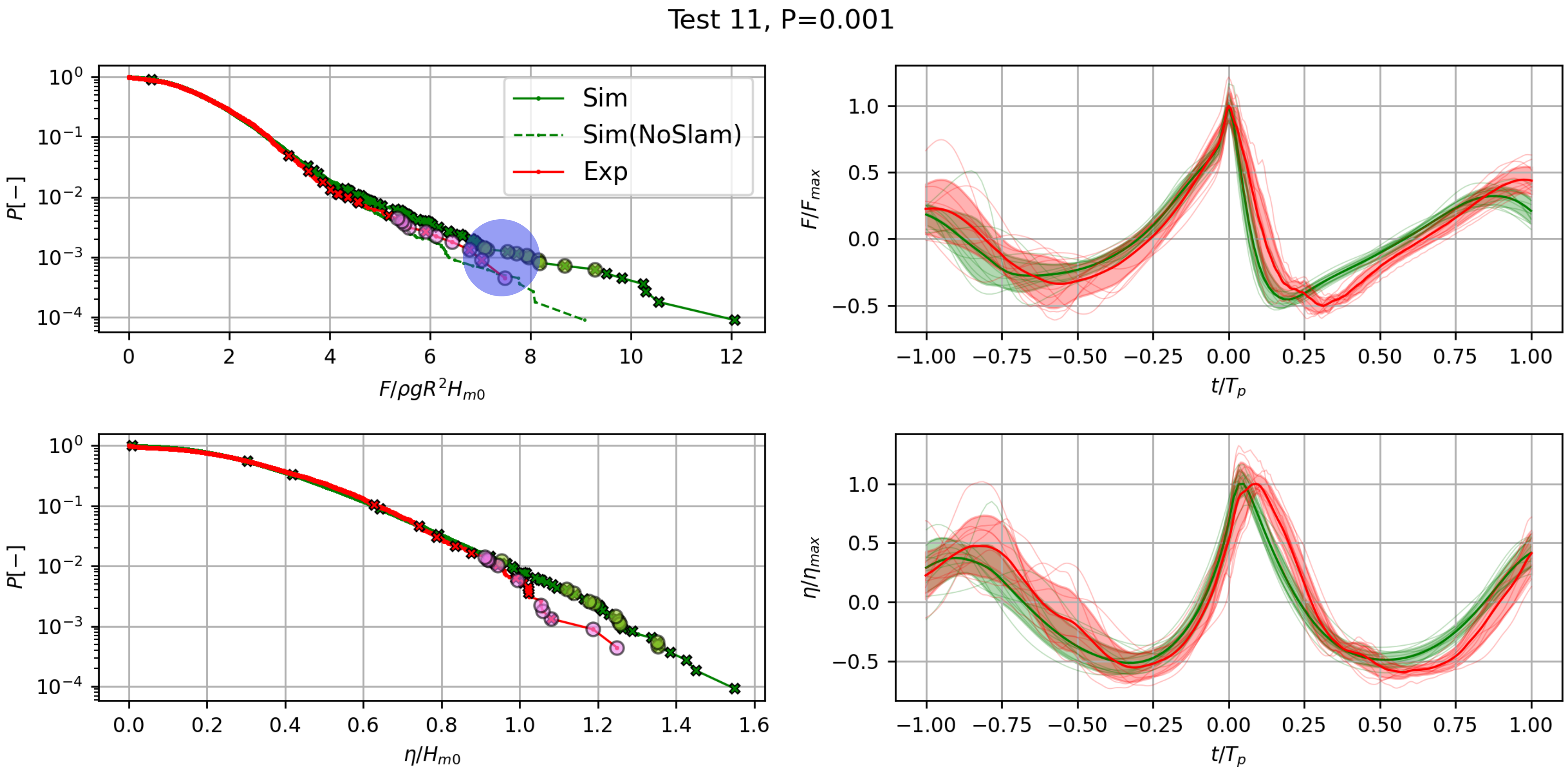

CD=1.0, CM=1.73

# Q2: How do the extreme load waves look, when you also include slamming loads?

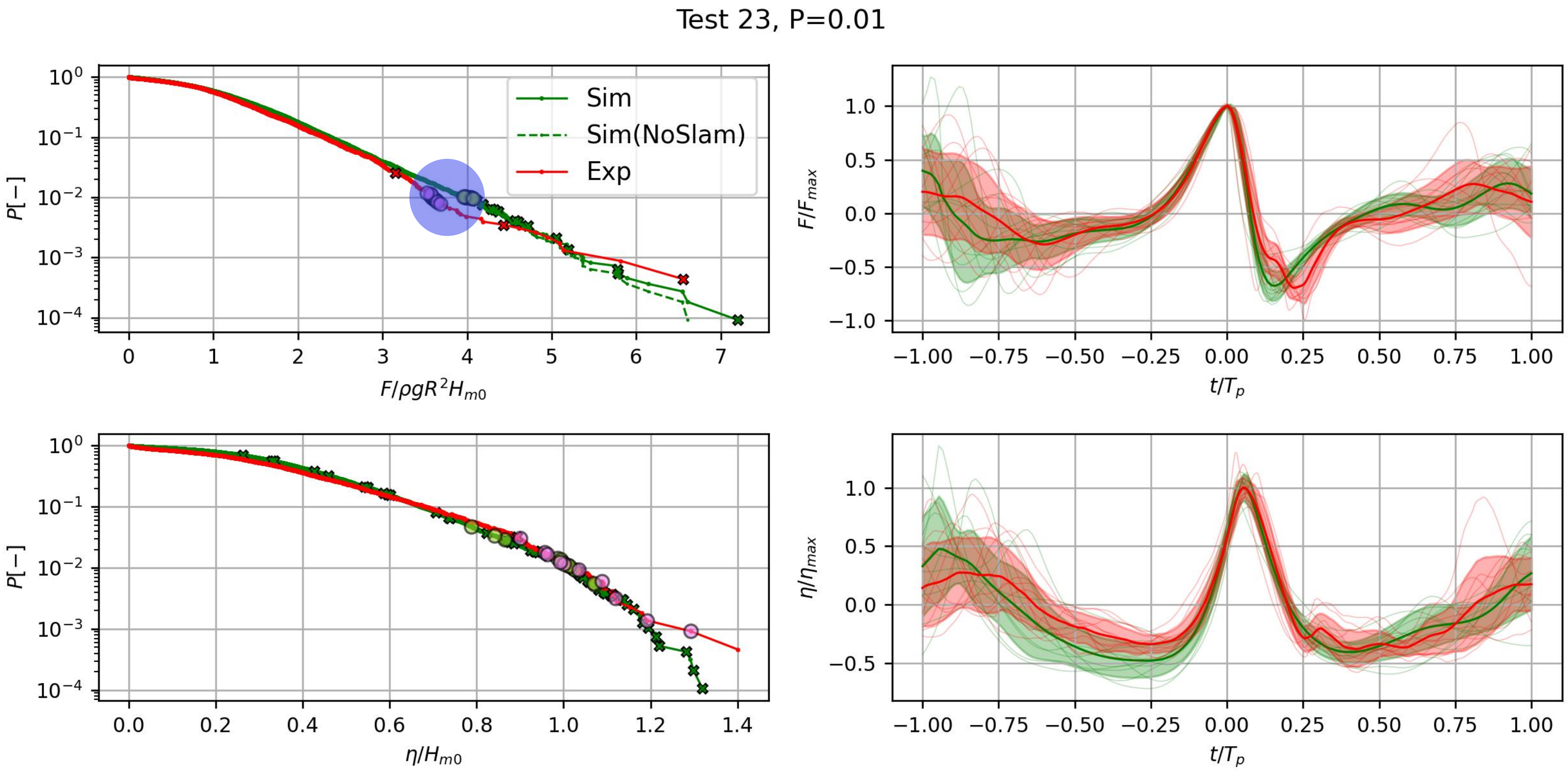
# Shapes of the waves for $P_{exc} = 0.01$ Test 11(Hs=9.5m, Tp=15.0 s, h=33.0m)



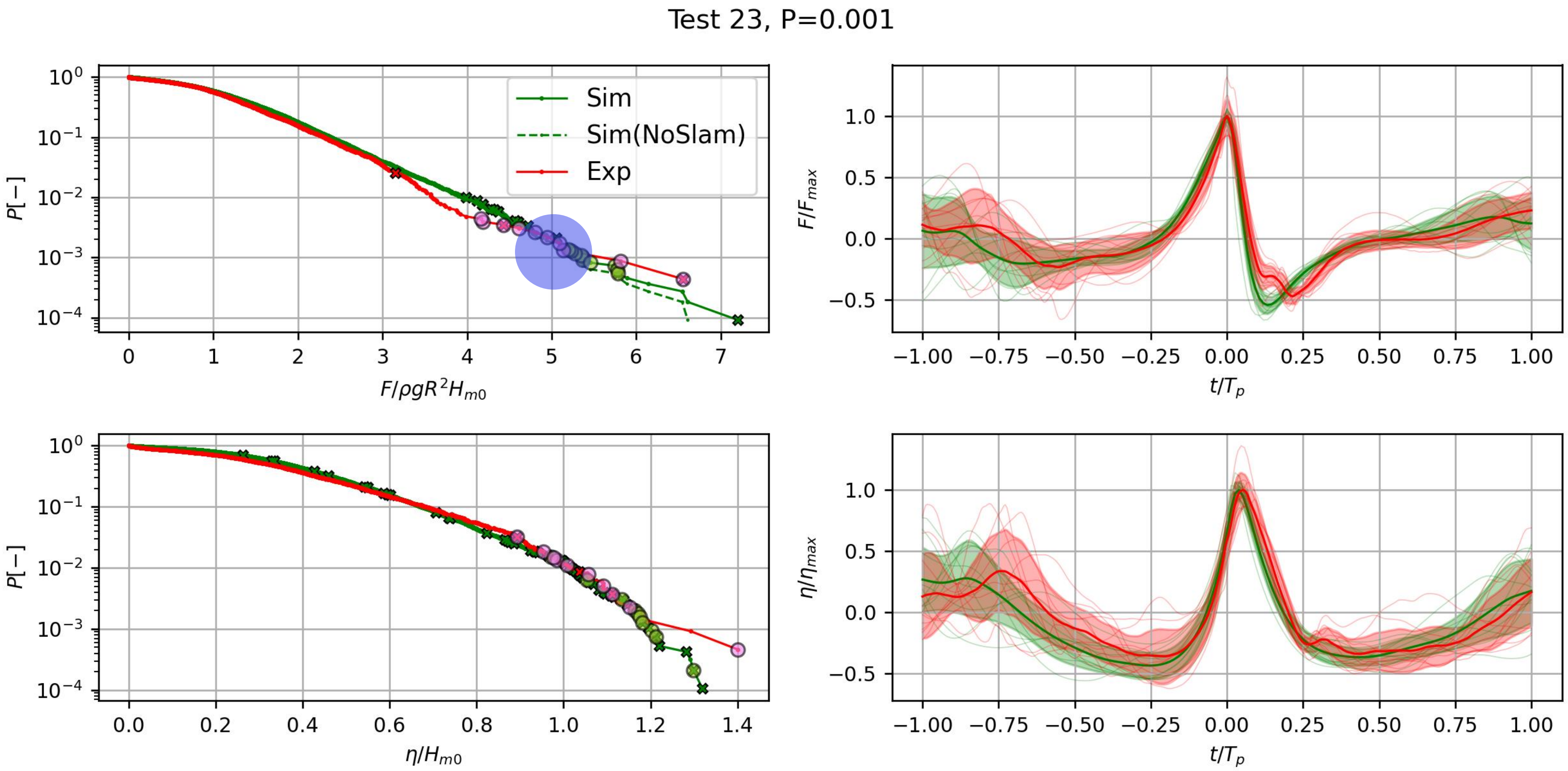
# Shapes of the waves for $P_{exc} = 0.001$ Test 11(Hs=9.5m, Tp=15.0 s, h=33.0m)



# Shapes of the waves for $P_{exc} = 0.01$ Test 23 (Hs=6.8m, Tp=12.0 s, h=20.0m)

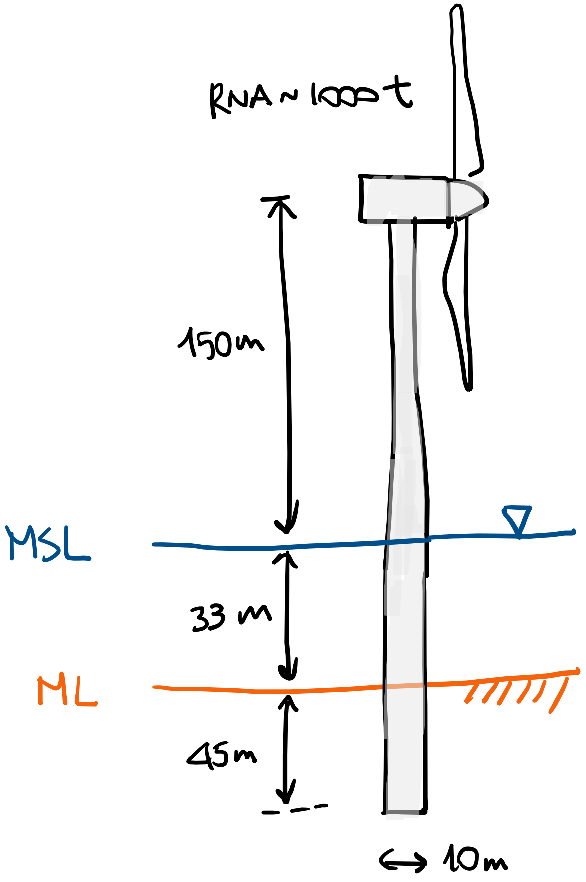


# Shapes of the waves for $P_{exc} = 0.001$ Test 23 (Hs=6.8m, Tp=12.0 s, h=20.0m)

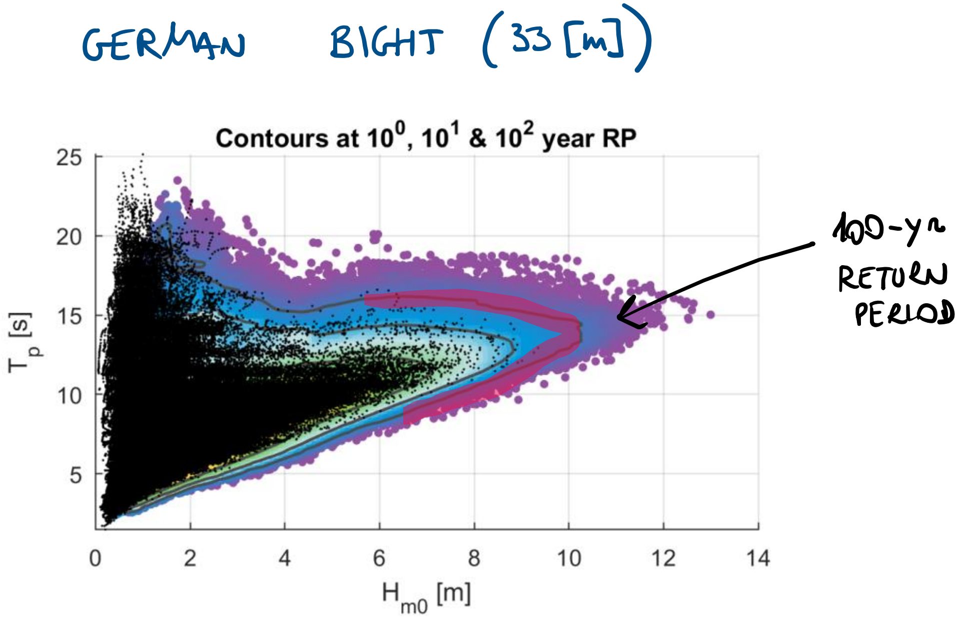


# Q3: How can we use this in a design context?

# Shape of extreme loads and associated waves on the IEA 15MW wind turbine



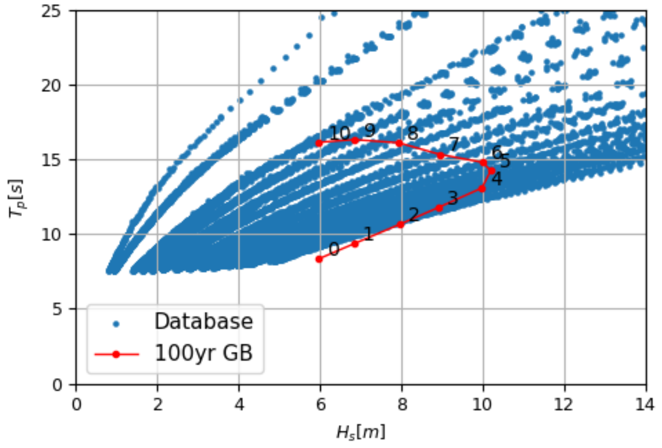

Gaertner et al. (2020)




Sørensen et al. (2021)

Hindcast data (black) + statistical extrapolation (colored)

# Shape of extreme loads and associated waves on the IEA 15MW wind turbine

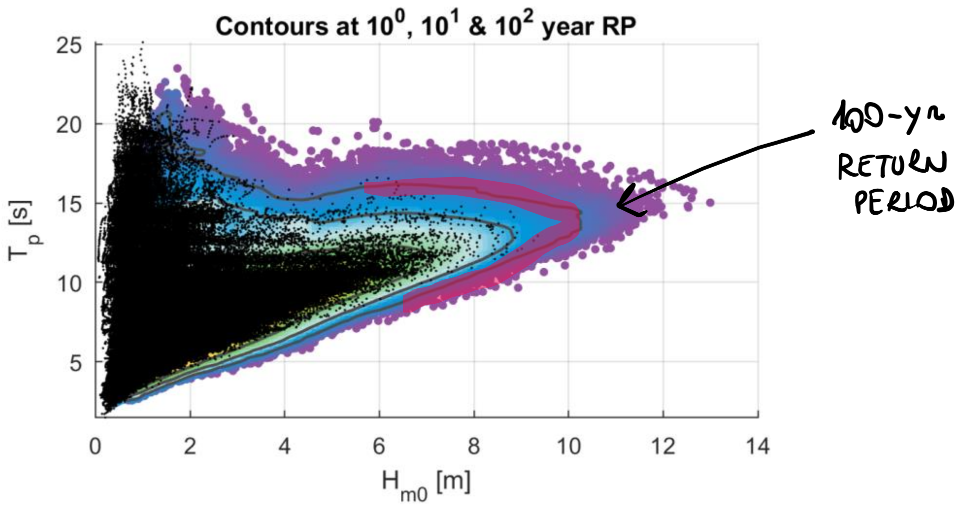



Chosen 10 sea states

Applied force model

$$C_D = 0.6, C_M = 2.0$$

GERMAN BIGHT (33 [m])

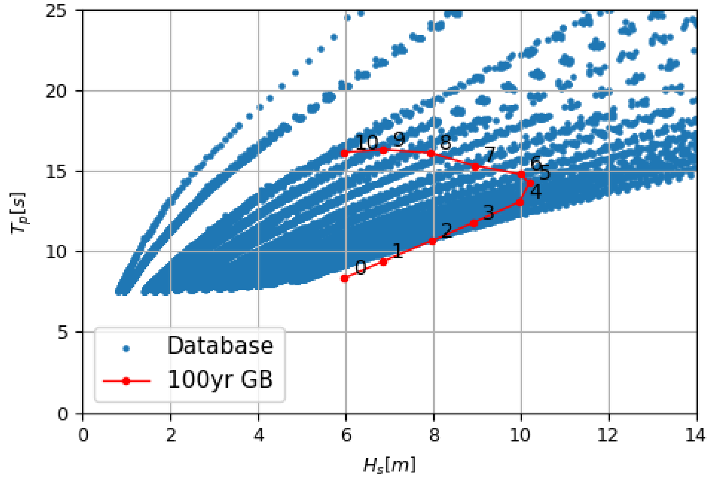


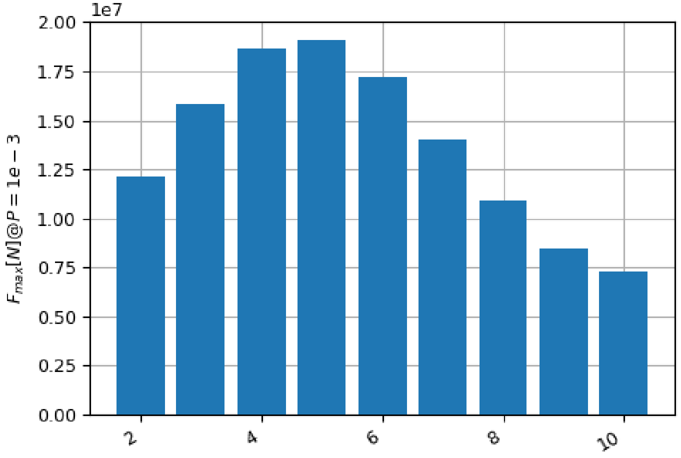

Sørensen et al. (2021)

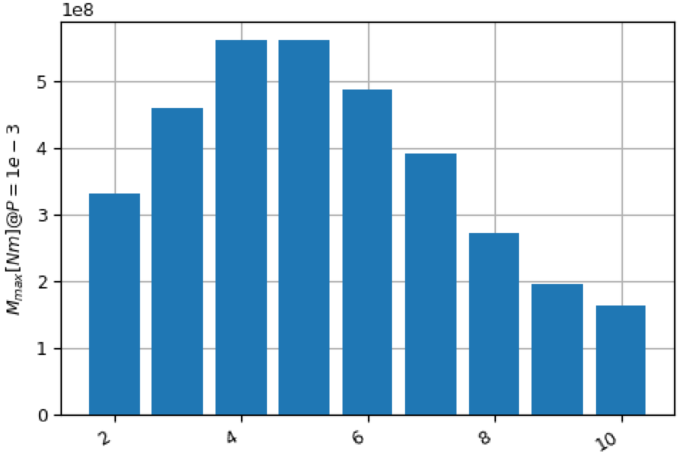
Hindcast data (black) + statistical extrapolation (colored)

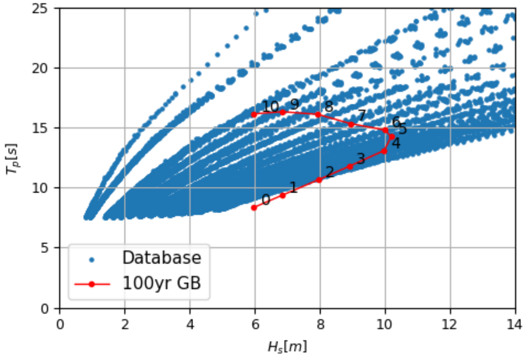
# We obtain time series of loads

- Where is the force / moment largest?
  - Histogram of max loads P=1e-3



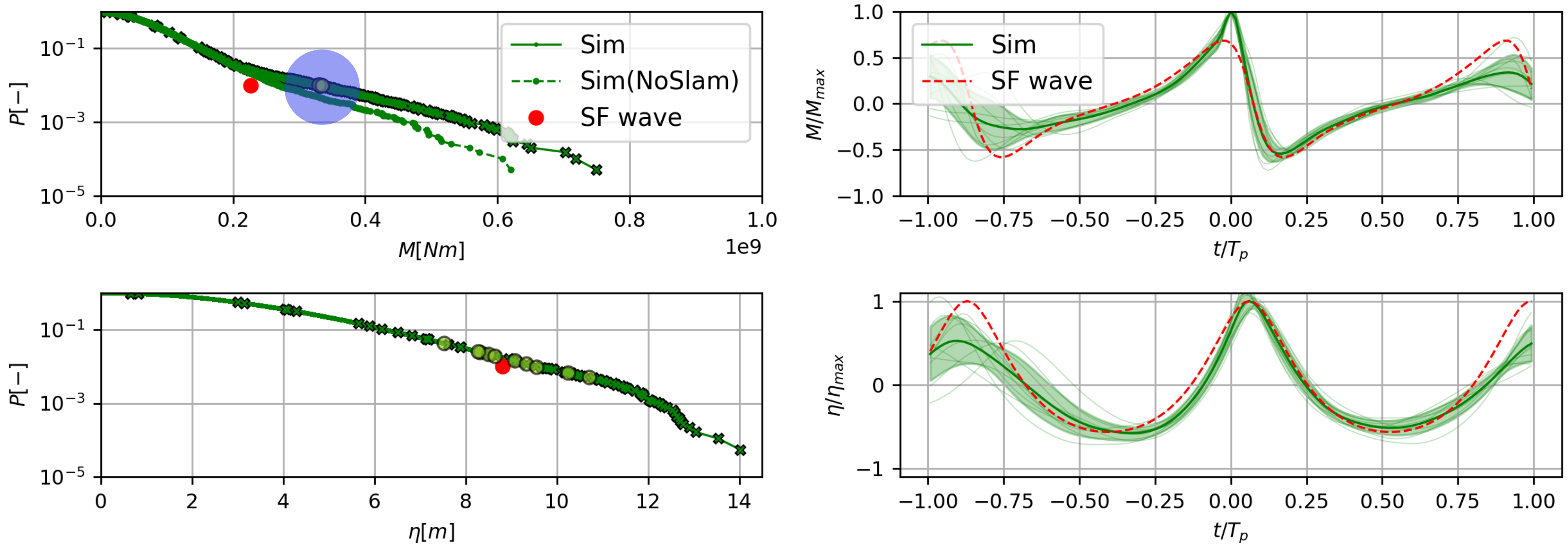



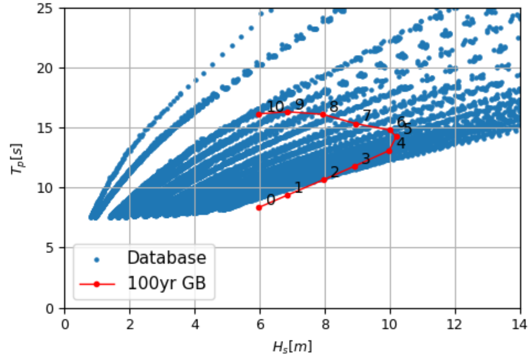



# Sea State 4 (Hs=9.97m,Tp=13.1s)

Test 4, P=0.01



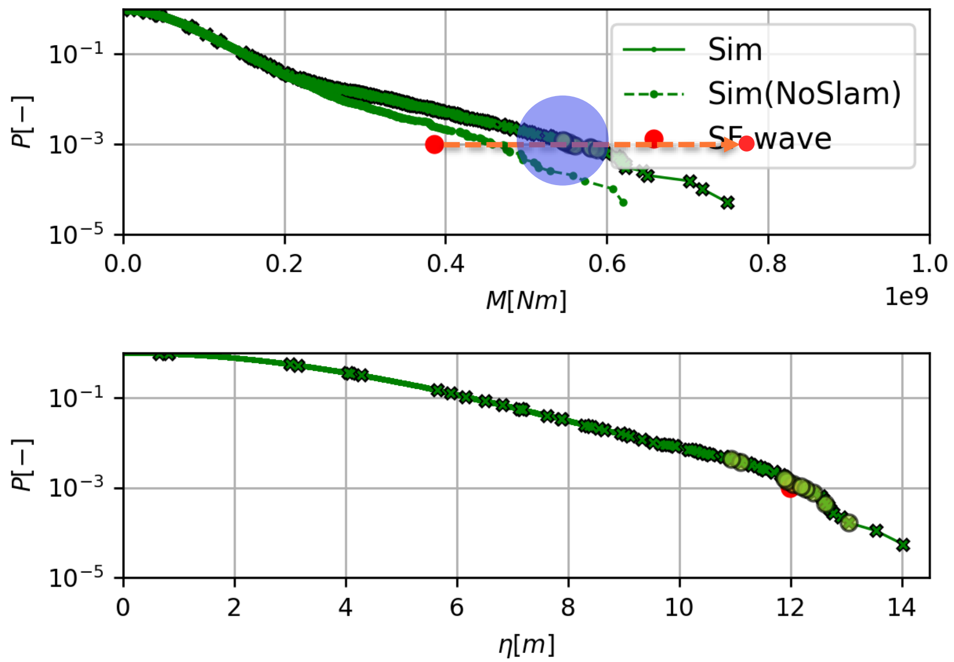
# Sea State 4 (Hs=9.97m,Tp=13.1s)

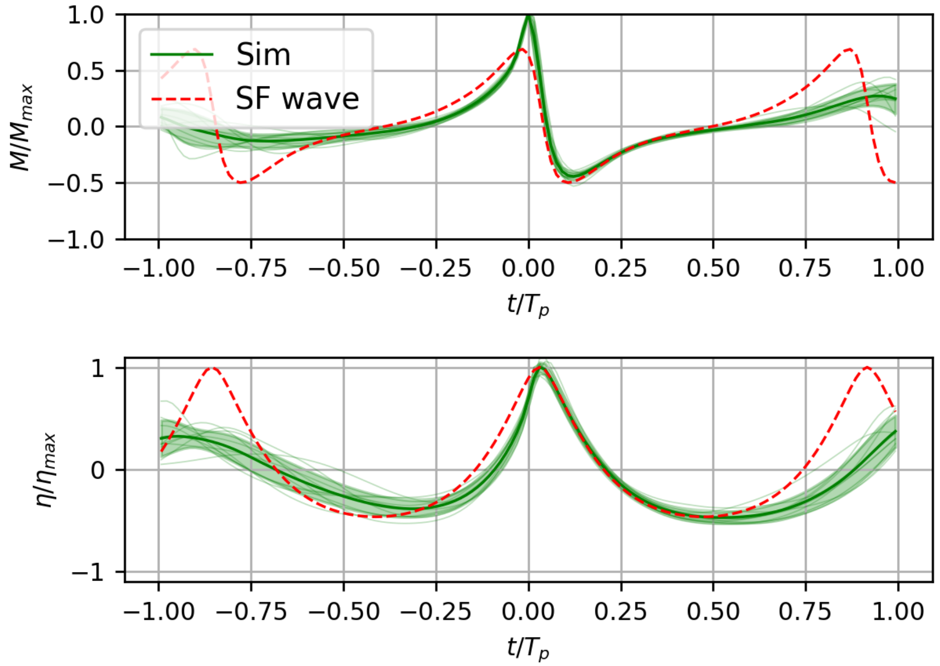



DeRidder et al. (2017)

$$M_{slam} = 4.0e8\ MNm$$

Test 4, P=0.001



# Conclusions

1. *How well can we reproduce measured loads that include slamming?*
   a. Overall agreement of simulated and experimental exceedance probability $\eta$ and $F$
   b. Wave shapes well captured, more challenging in tail of distribution

2. *How do the extreme load waves look, when you also include slamming loads?*
   a. Average force shape shows typical ”hat” due to slamming
   b. Increased front steepness for extreme load waves with lower exceedance probabilities

3. *How can we utilize this in a design context?*
   a. Tested method on a rigid monopile ($D = 10m$)
   b. Along a contour: largest $H_s \Rightarrow$ largest load
   c. For lower exc.prob. the average wave shape deviates more from SF wave