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

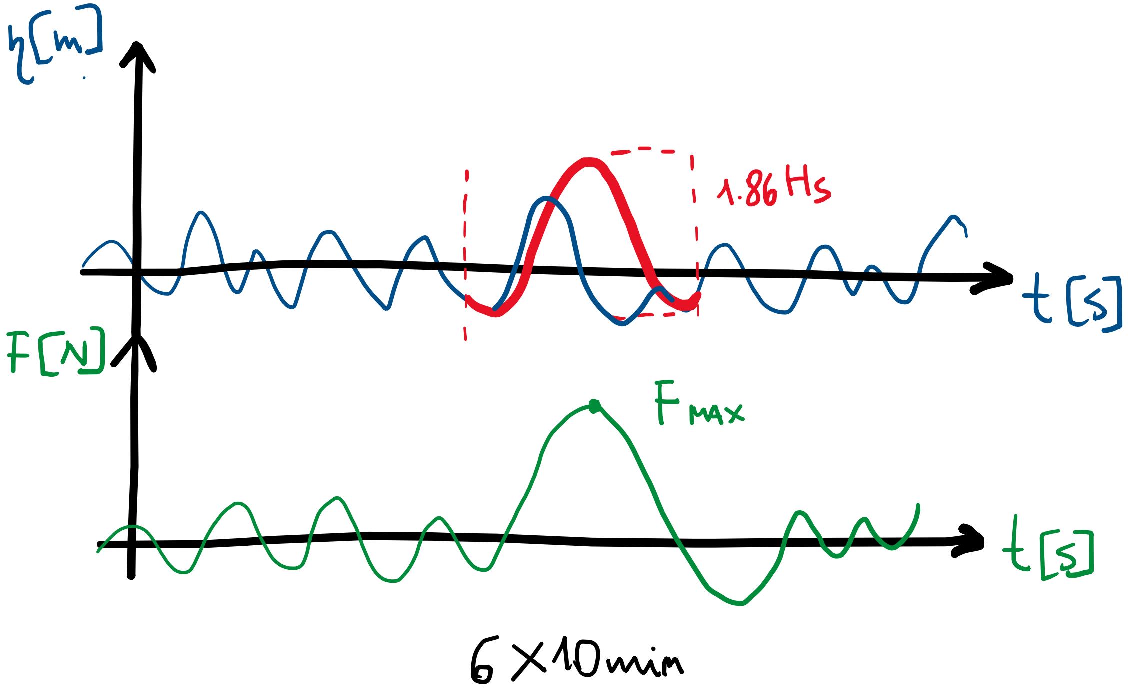
Damsgaard et al. (2007)
Horns Rev I

- 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

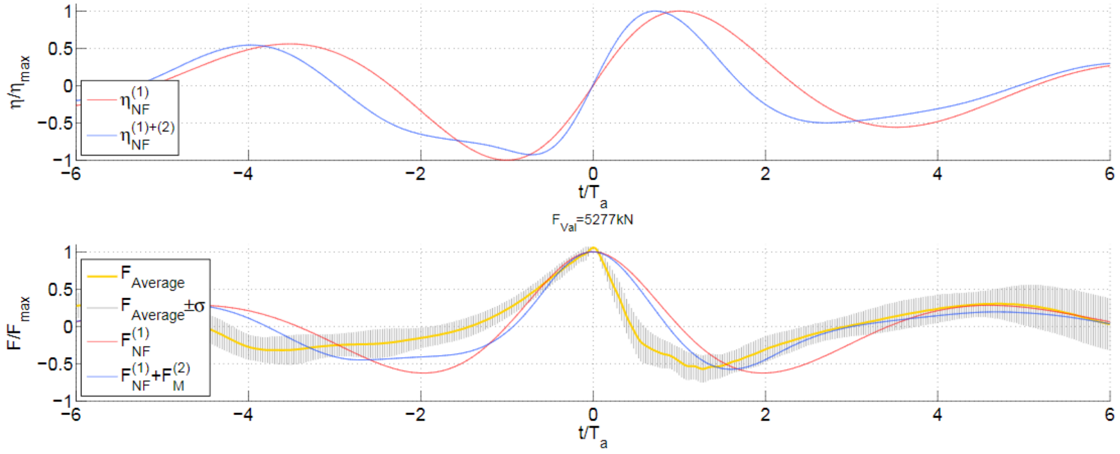
"Design requirements for fixed offshore wind turbines"



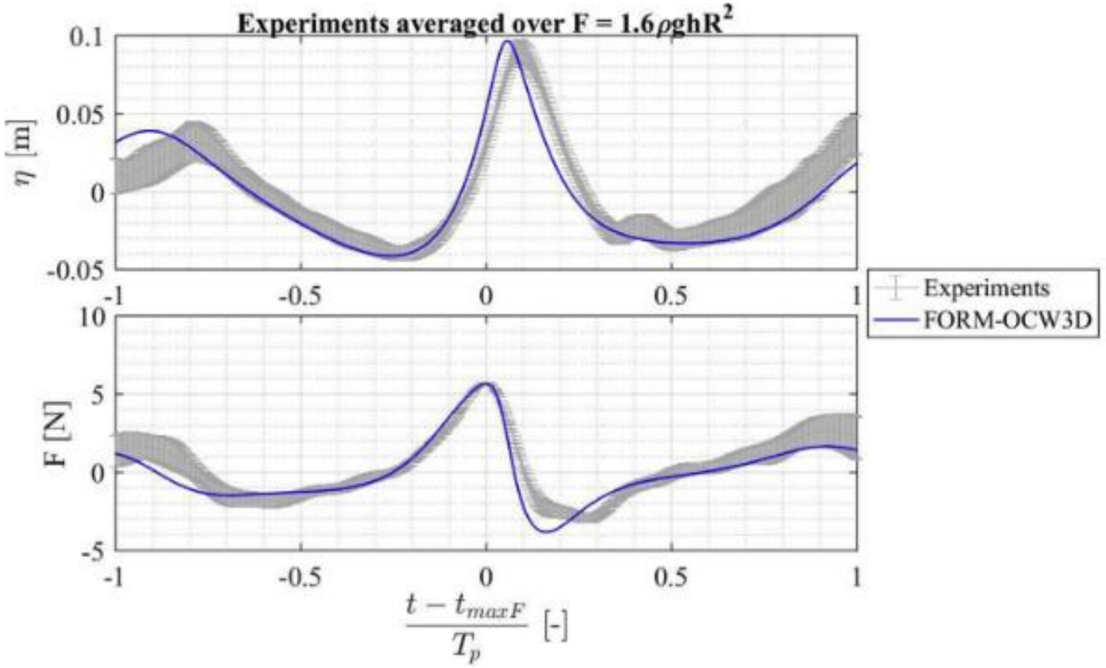
Stream Function Wave

(Dean 1965, Rienecker and Fenton 1981)

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



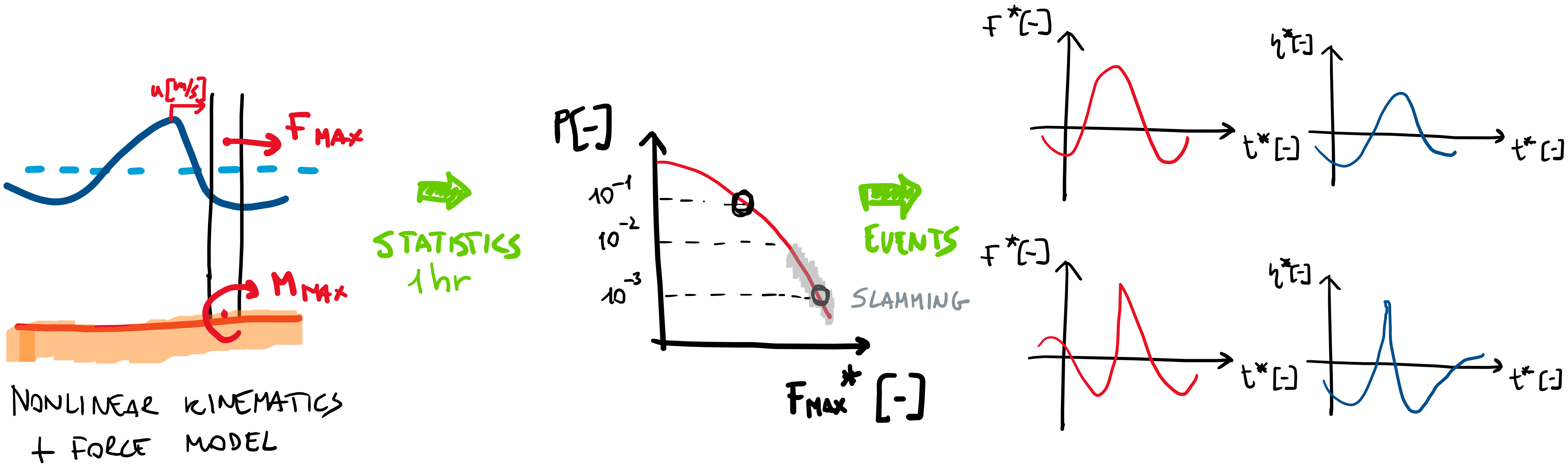
(b) $F/(\rho g h R^2) = 1.3$.



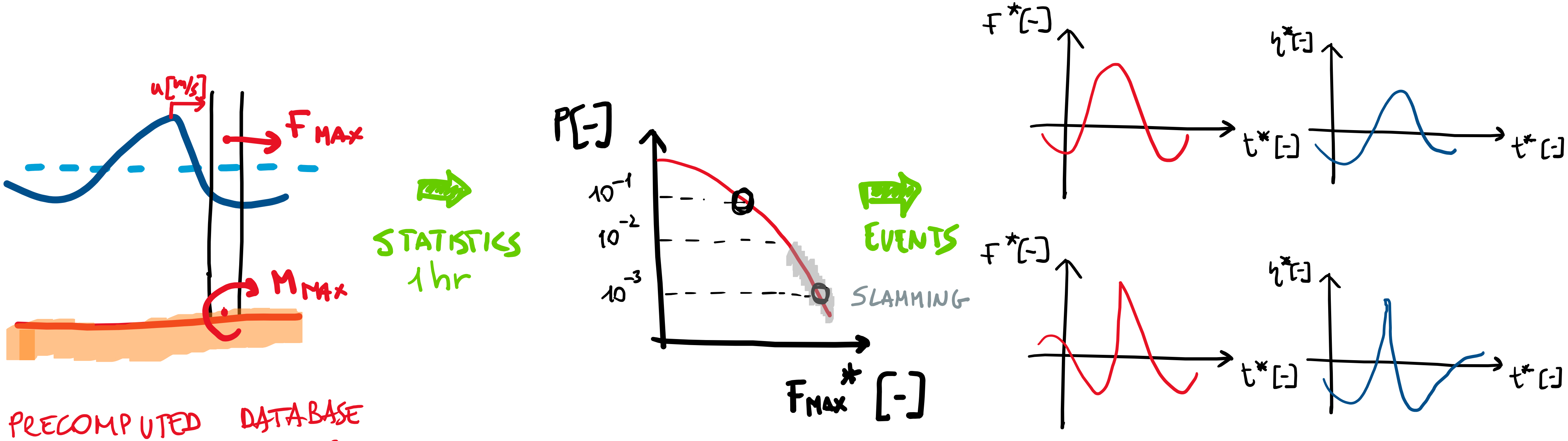
New Force model
(Schløer et al. 2017)

FORM + OceanWave3D
(Ghadirian and Bredmose 2019)

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



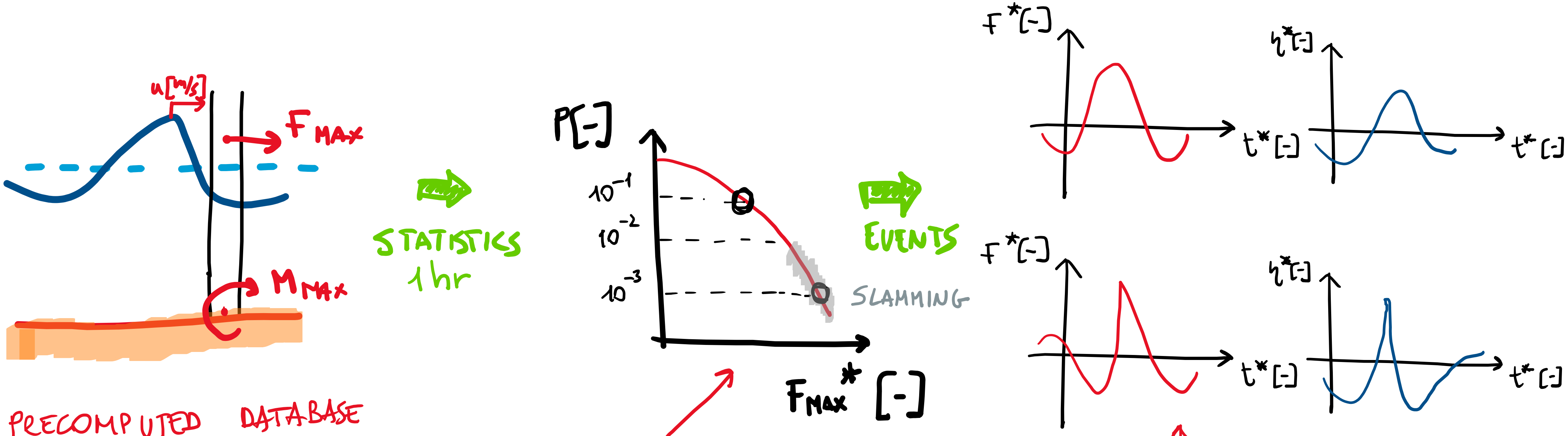
Current Work: compute the whole distribution of waves and associated loads



(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



Ⓐ PRECOMPUTED DATABASE OF FULLY-NONLINEAR WAVE KINEMATICS

Ⓑ ACCURATE LOAD MODEL WITH WAVE SLAMMING

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

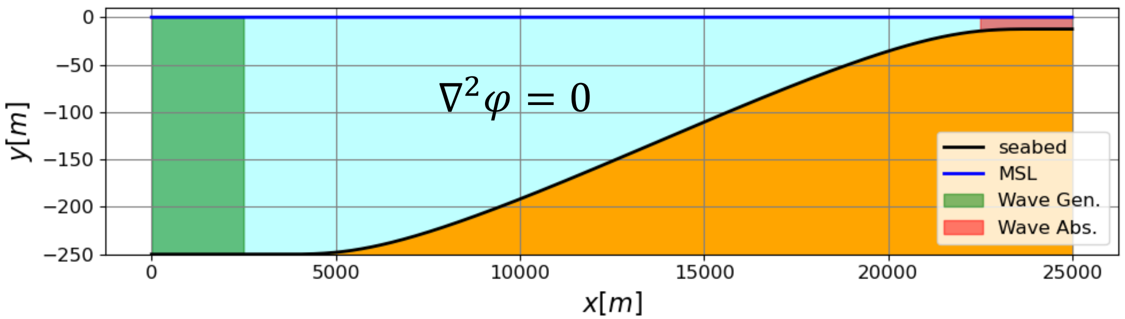
Q2: How do the extreme load waves look, when you also include slamming loads?

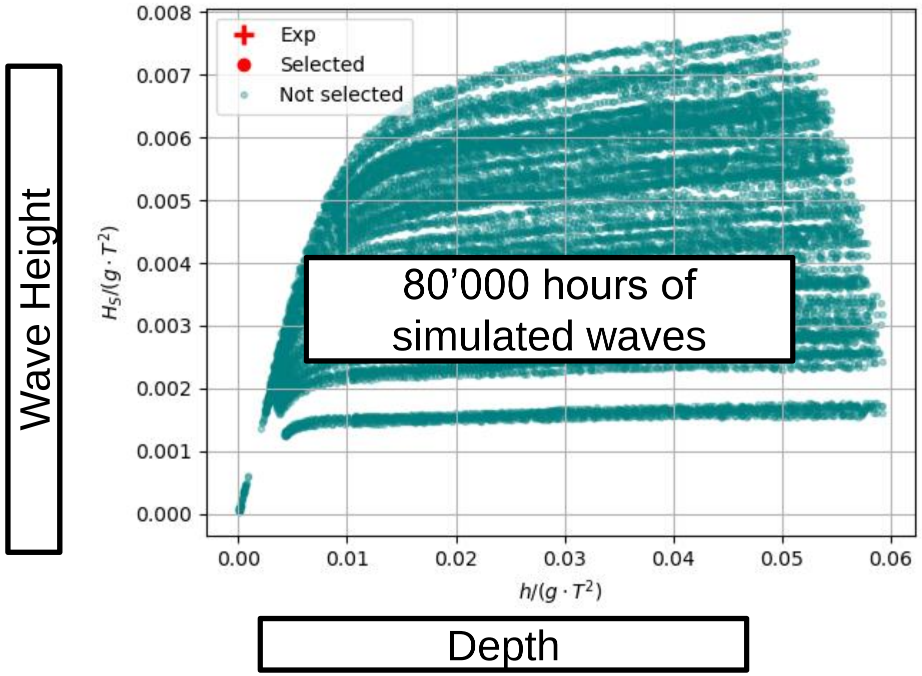
Q3: How can we utilize this in a design context?

The wave kinematics model: DeRisk Database

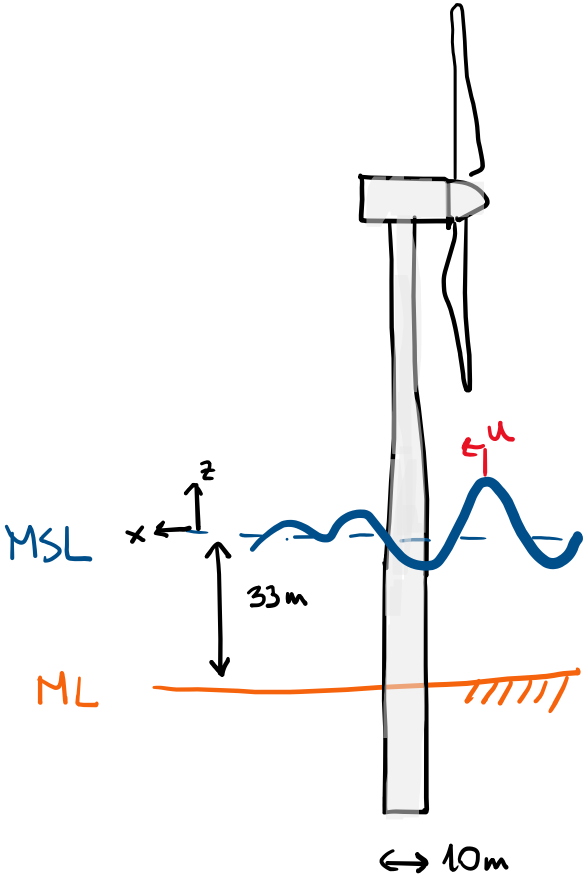
SCAN ME

- 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)



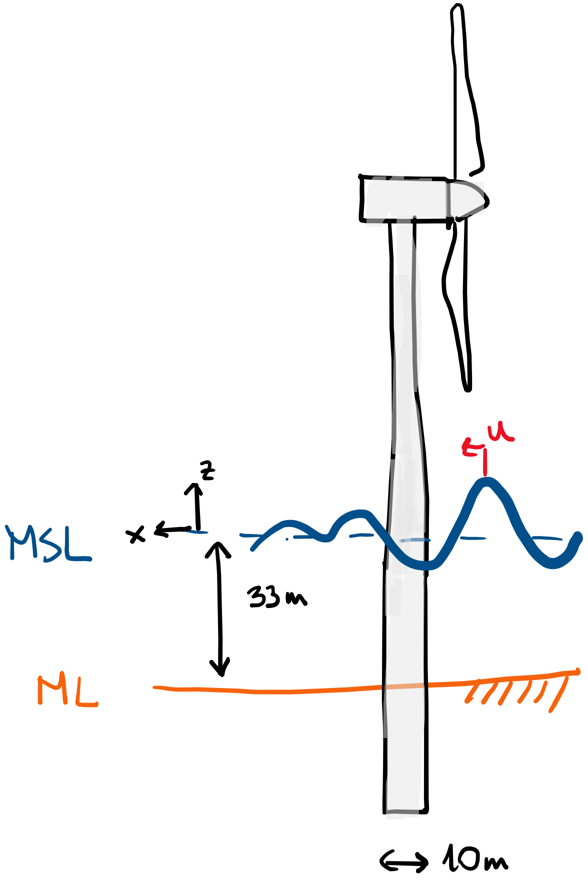
MORISON (1950)

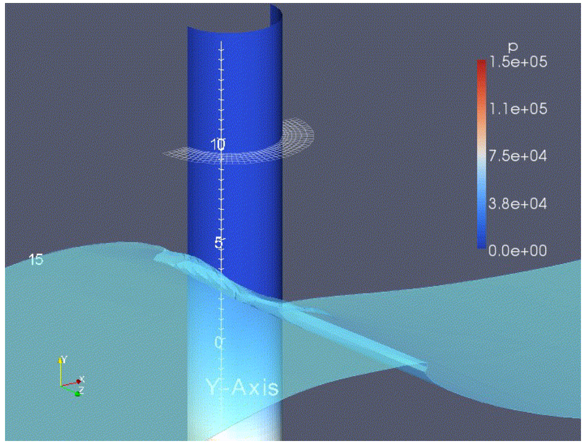
RAINEY (1995)

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

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

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

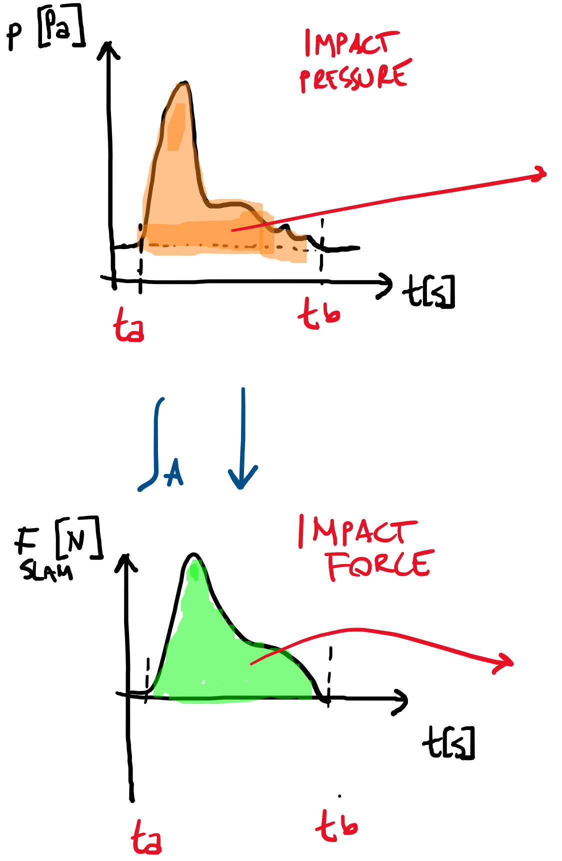




CFD Impact

Bredmose and Jacobsen (2011)

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



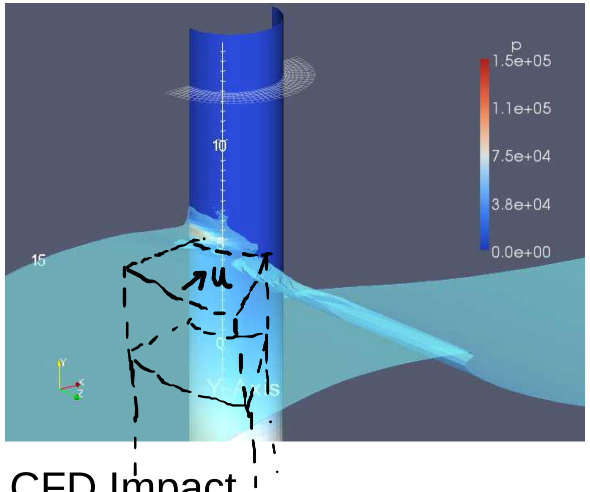
PRESSURE IMPULSE

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

∫A

FORCE IMPULSE

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



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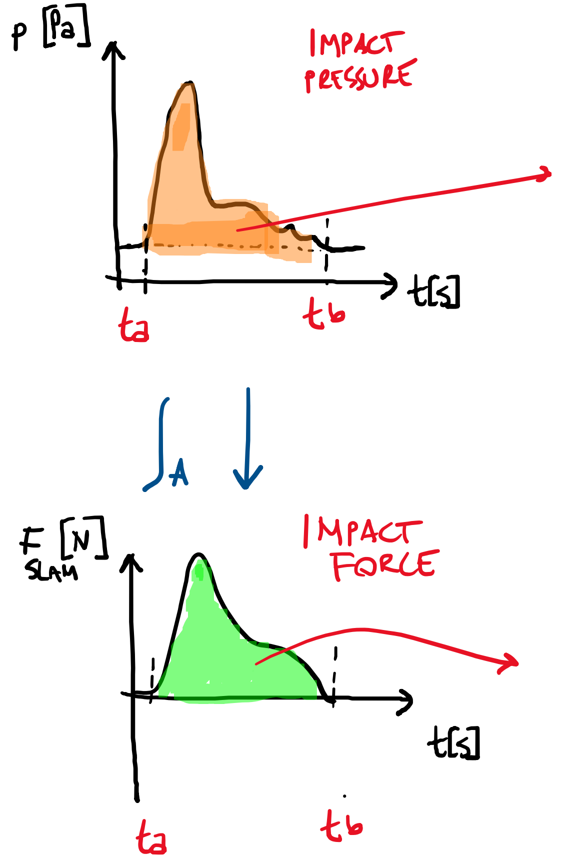

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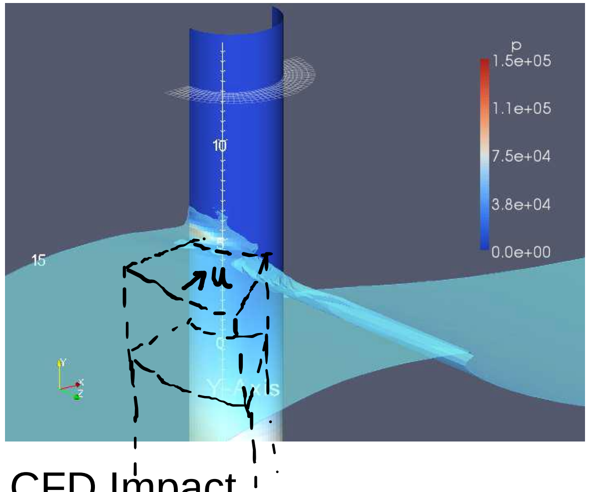

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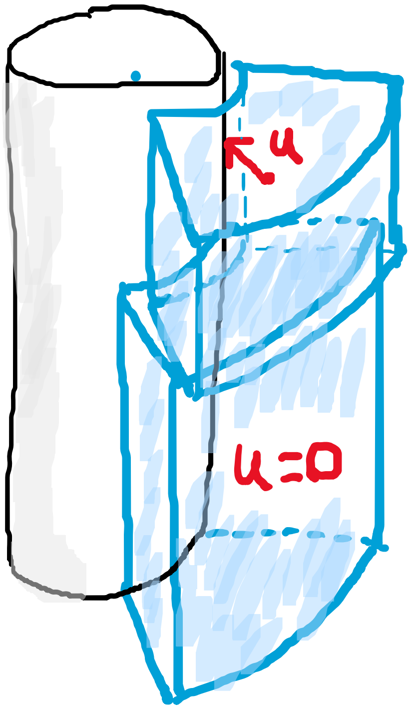
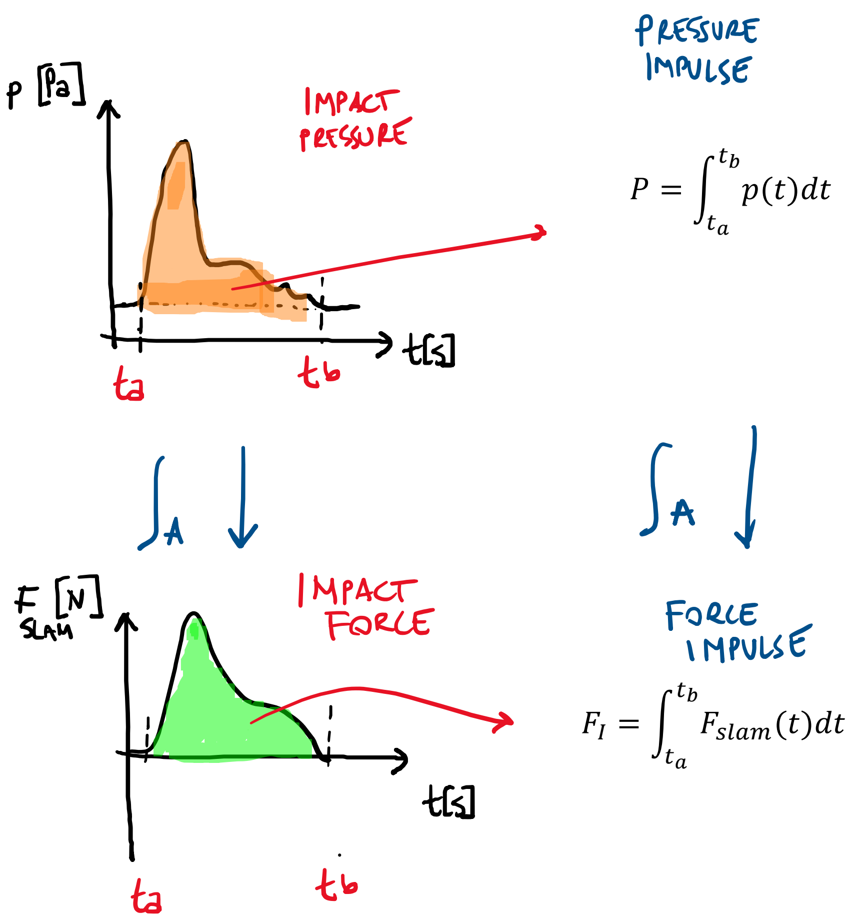


The pressure impulse model

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



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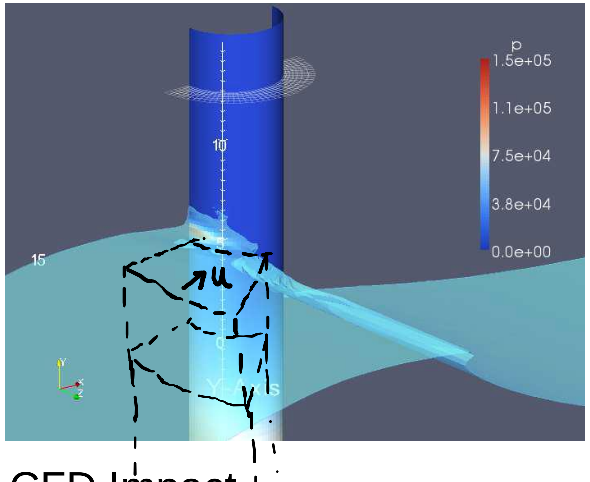

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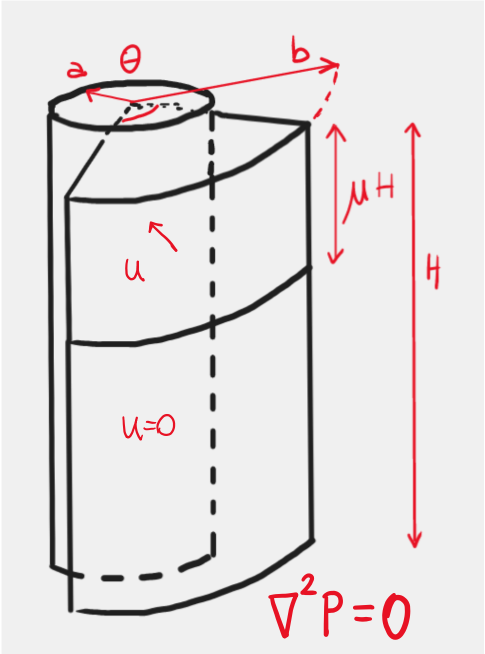
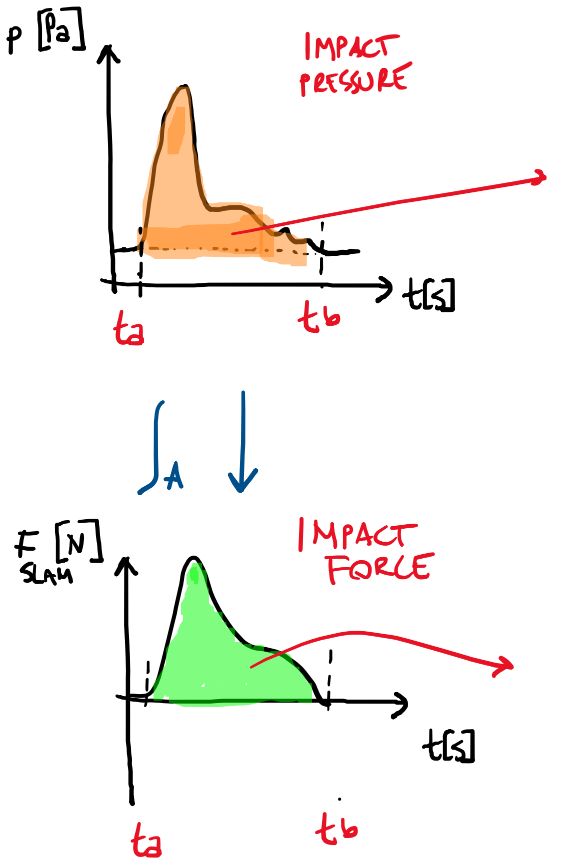


The pressure impulse model

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

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



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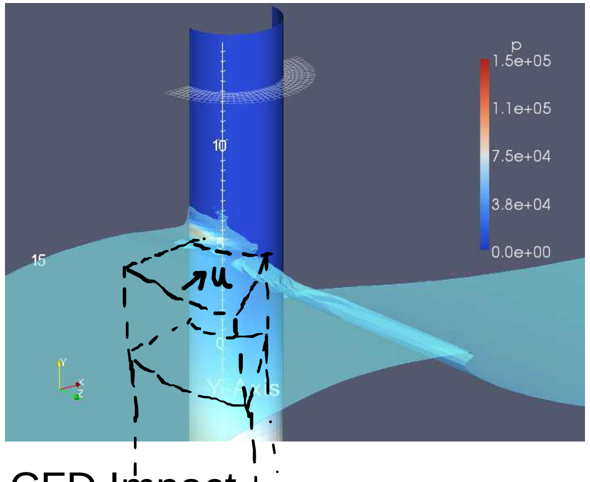

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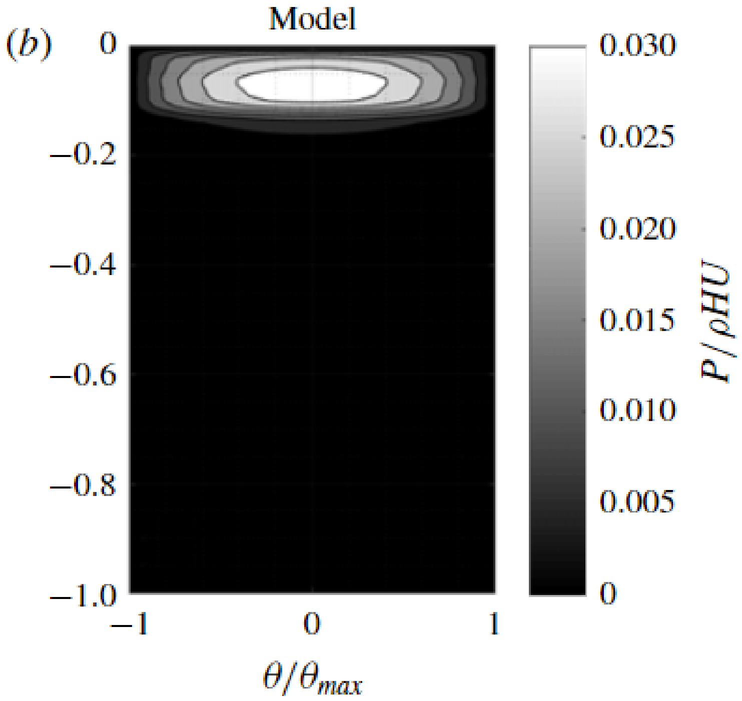

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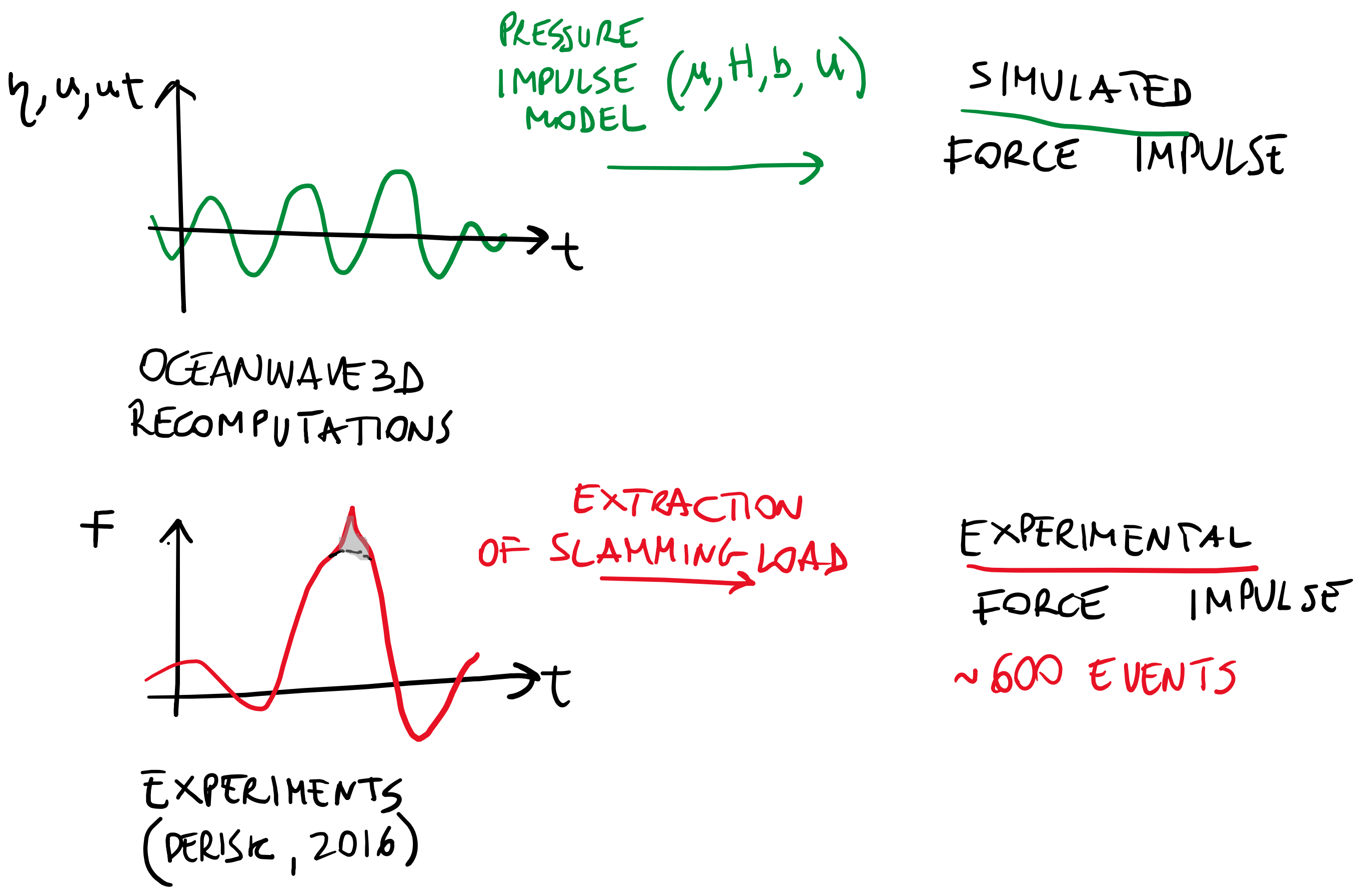
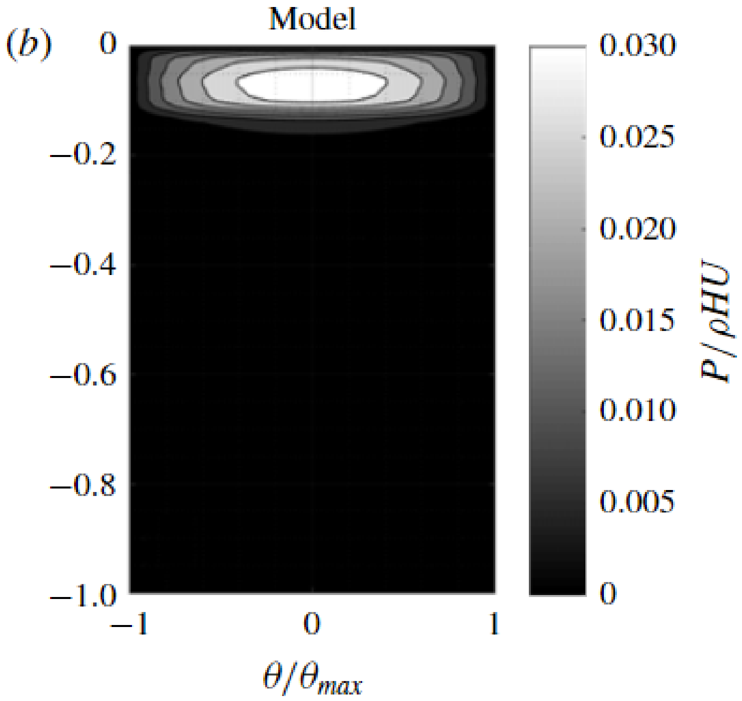
The slamming load model: Validation (Ghadirian, Pierella and Bredmose 2023)





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

The slamming load model:
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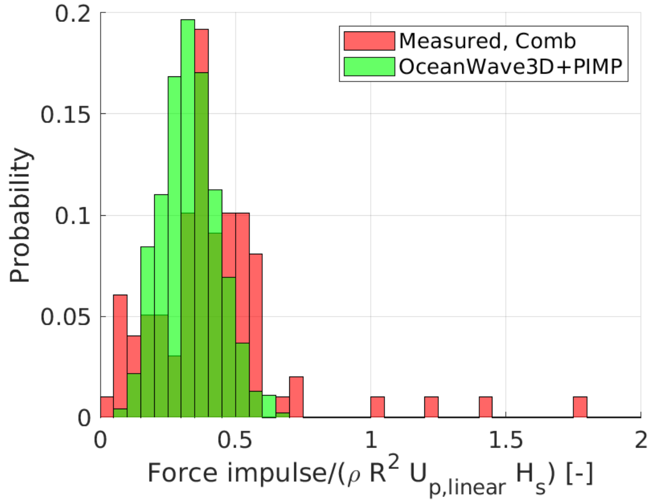
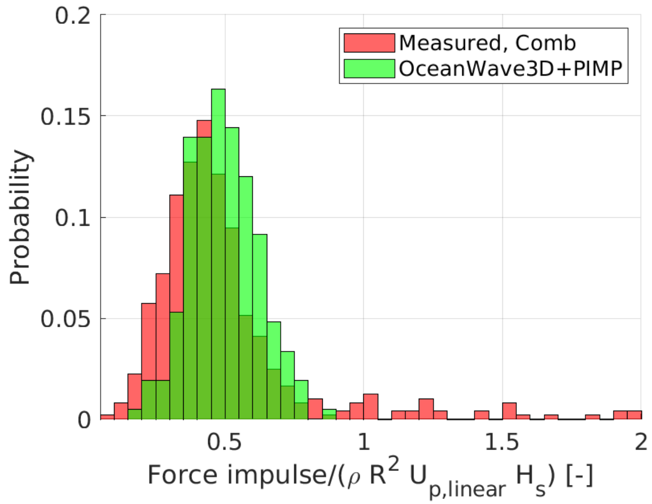
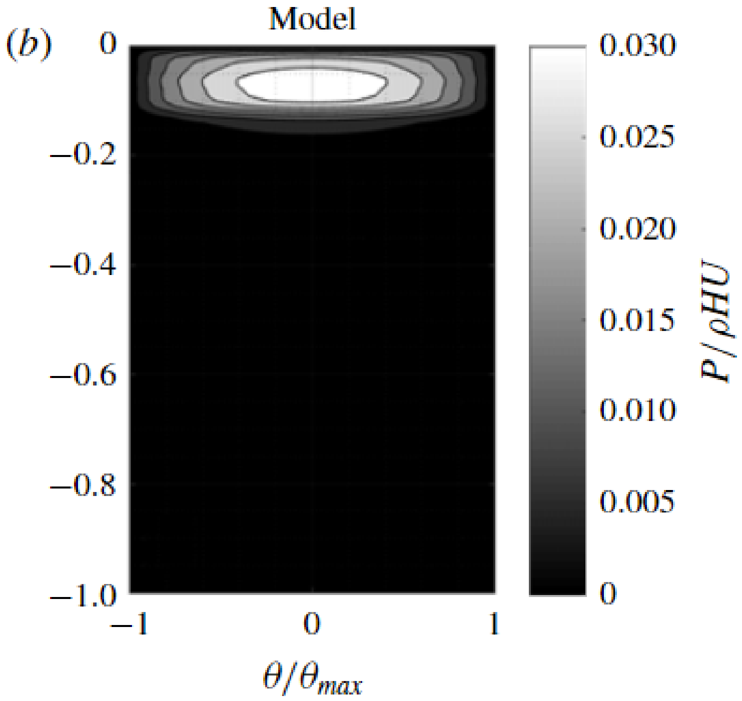
2D



3D





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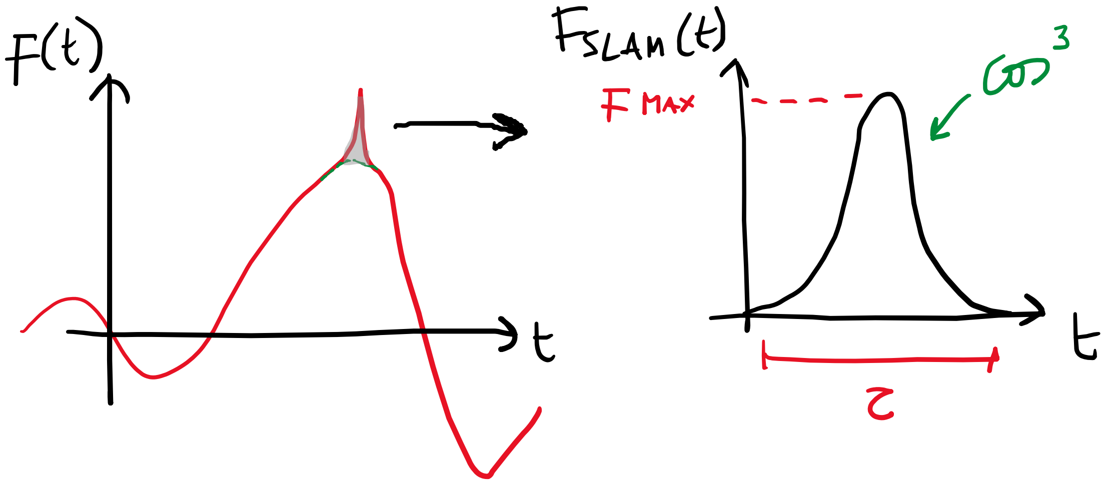
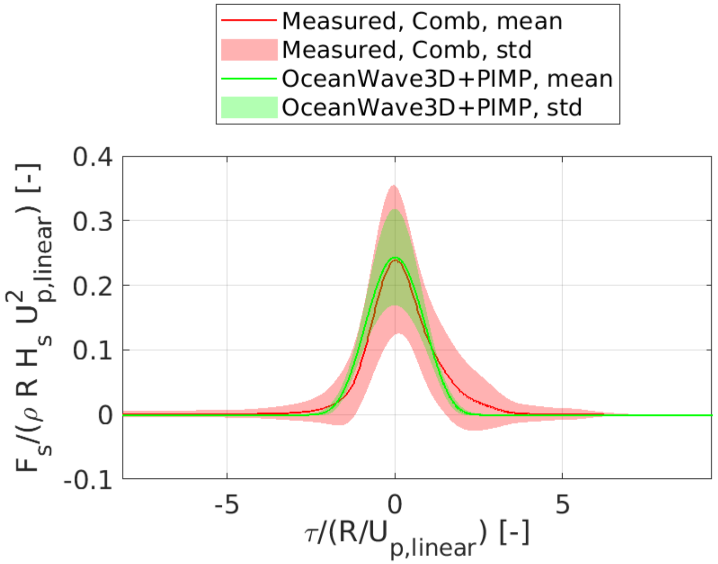
The slamming load model: Validation (Ghadirian, Pierella and Bredmose 2023)

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

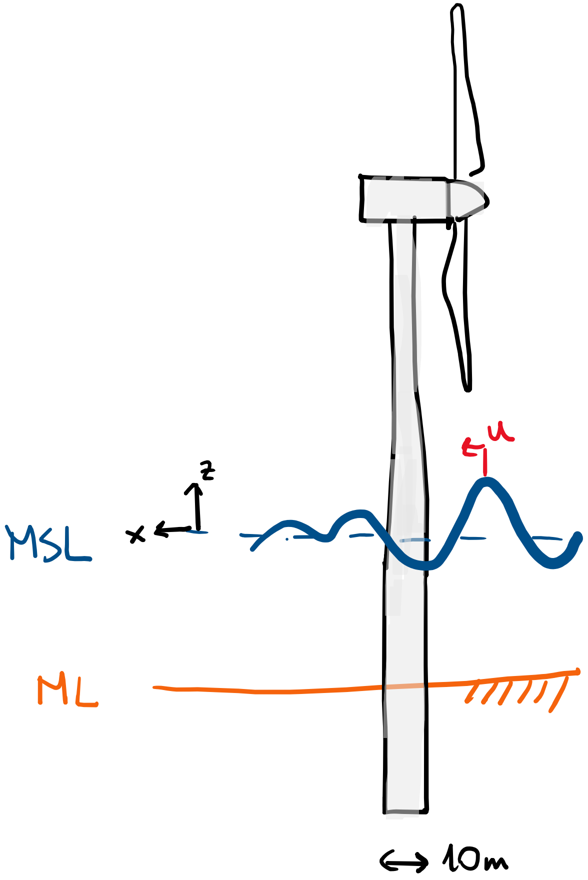


ASSUME

CALIBRATE ON EXPERIMENTS



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



MORISON (1950)

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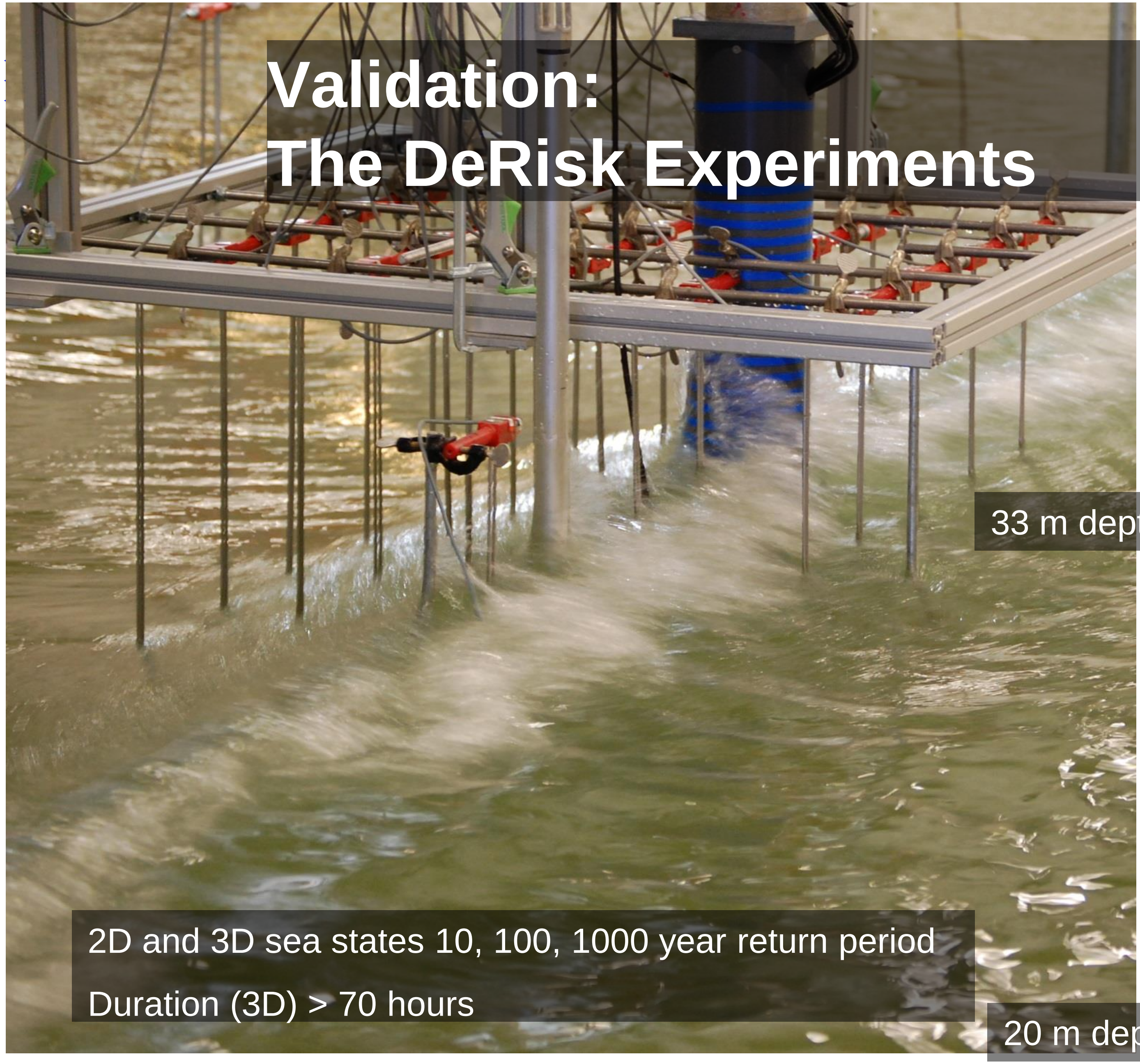
$$F = \int_{-h}^{\eta} f_x \, dz + \frac{1}{2}\rho \pi R^2 C_m \eta_x u^2 + 2\pi\rho u^2 R \eta_B \lambda_B$$

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

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

Validation:
The DeRisk Experiments



33 m depth

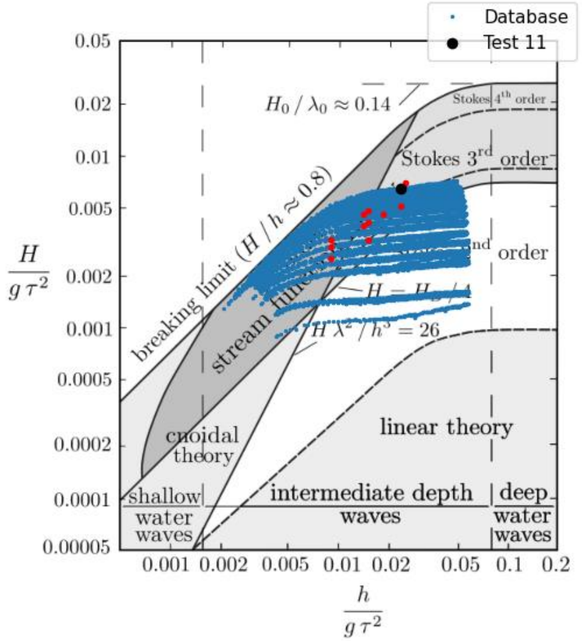
20 m depth

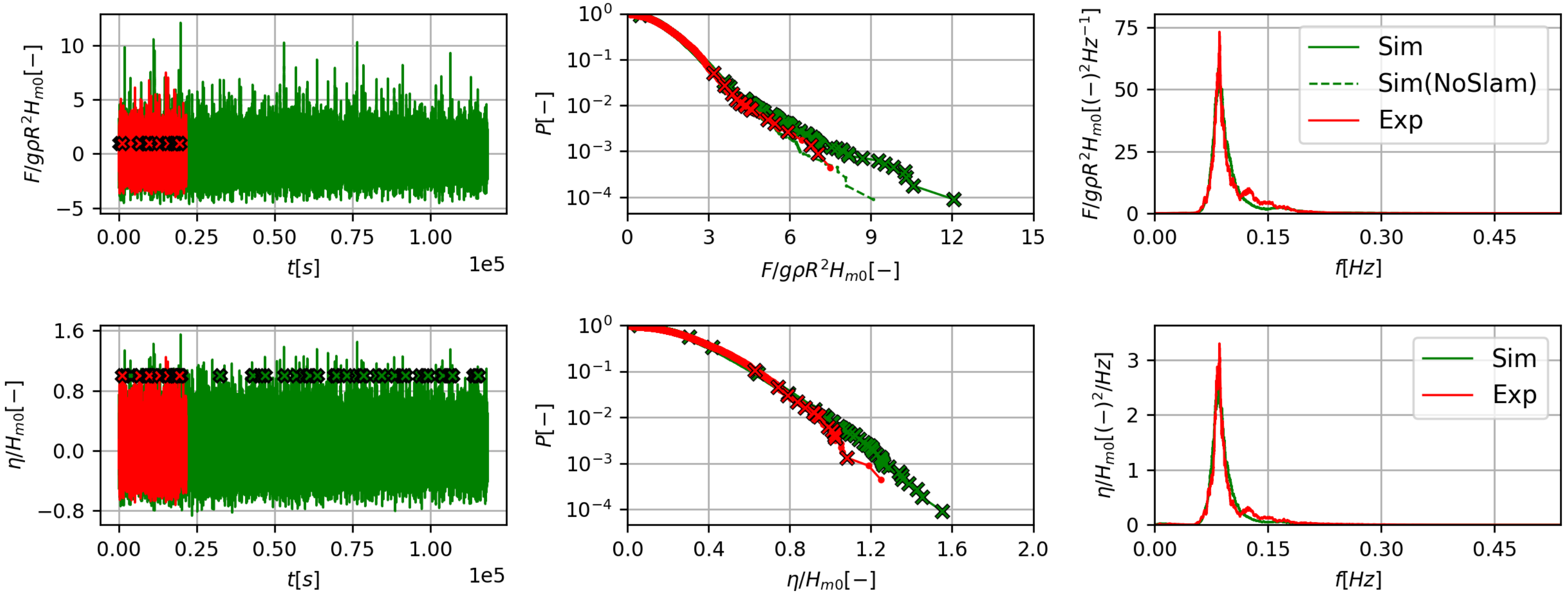
2D and 3D sea states 10, 100, 1000 year return period

Duration (3D) > 70 hours

Test No.	Water depth [m]	H_s [m]	T_p [s]	Directional Spread, σ_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

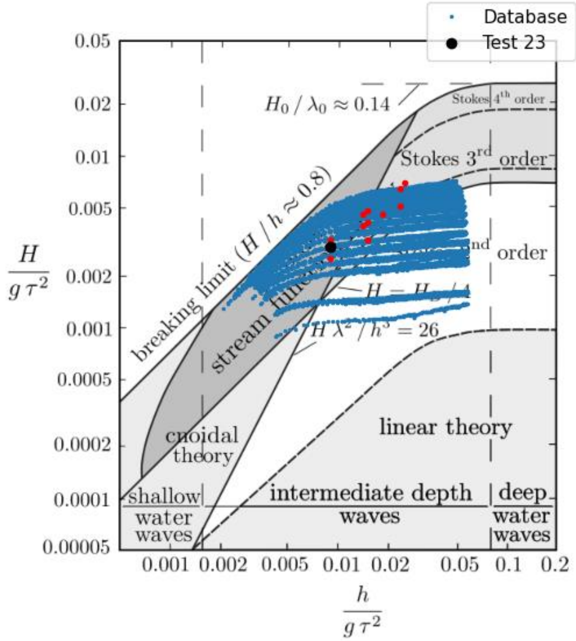
Test 11 (Hs=9.5m, Tp=15.0 s, h=33.0m)

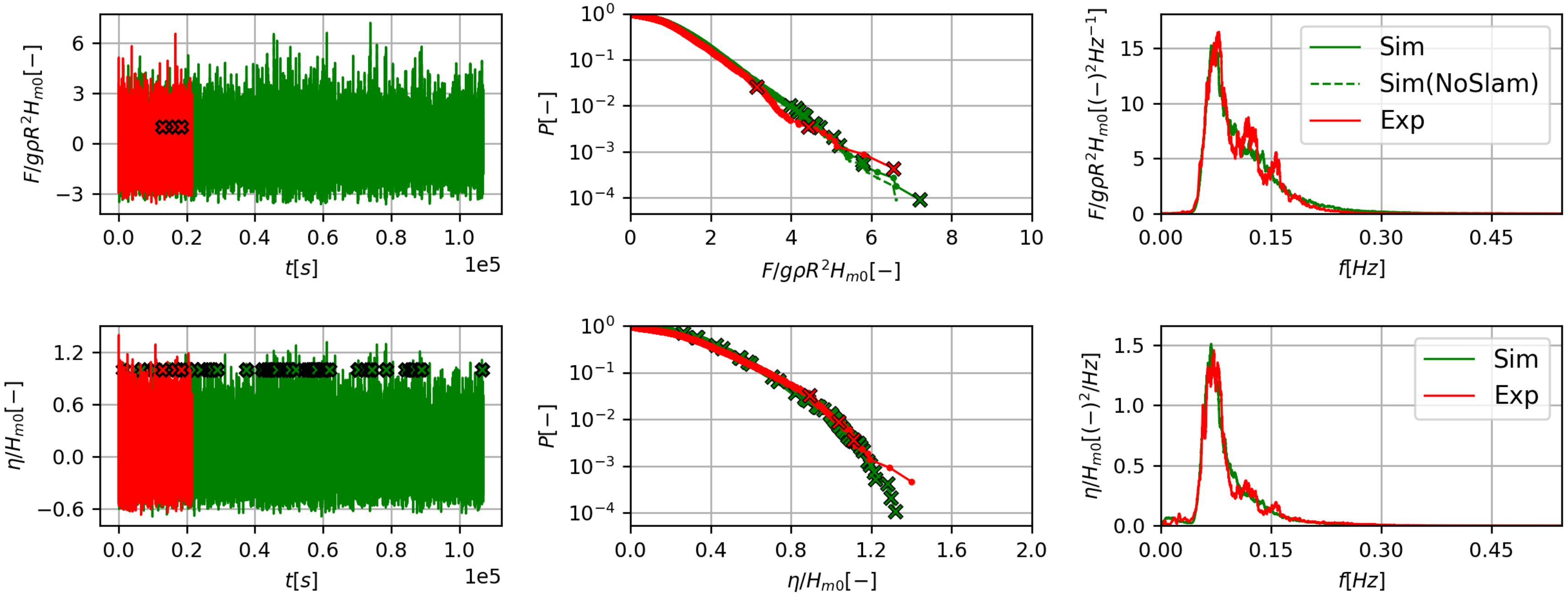




CD=1.0, CM=1.80

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

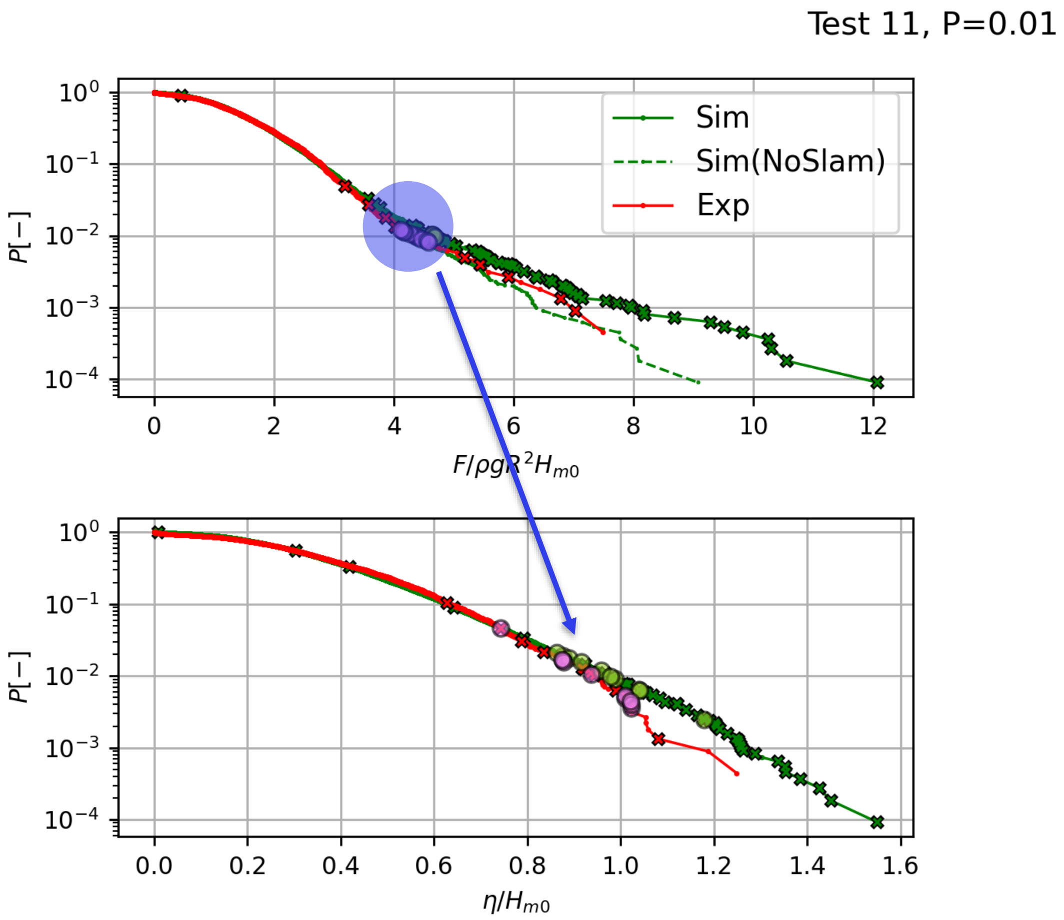




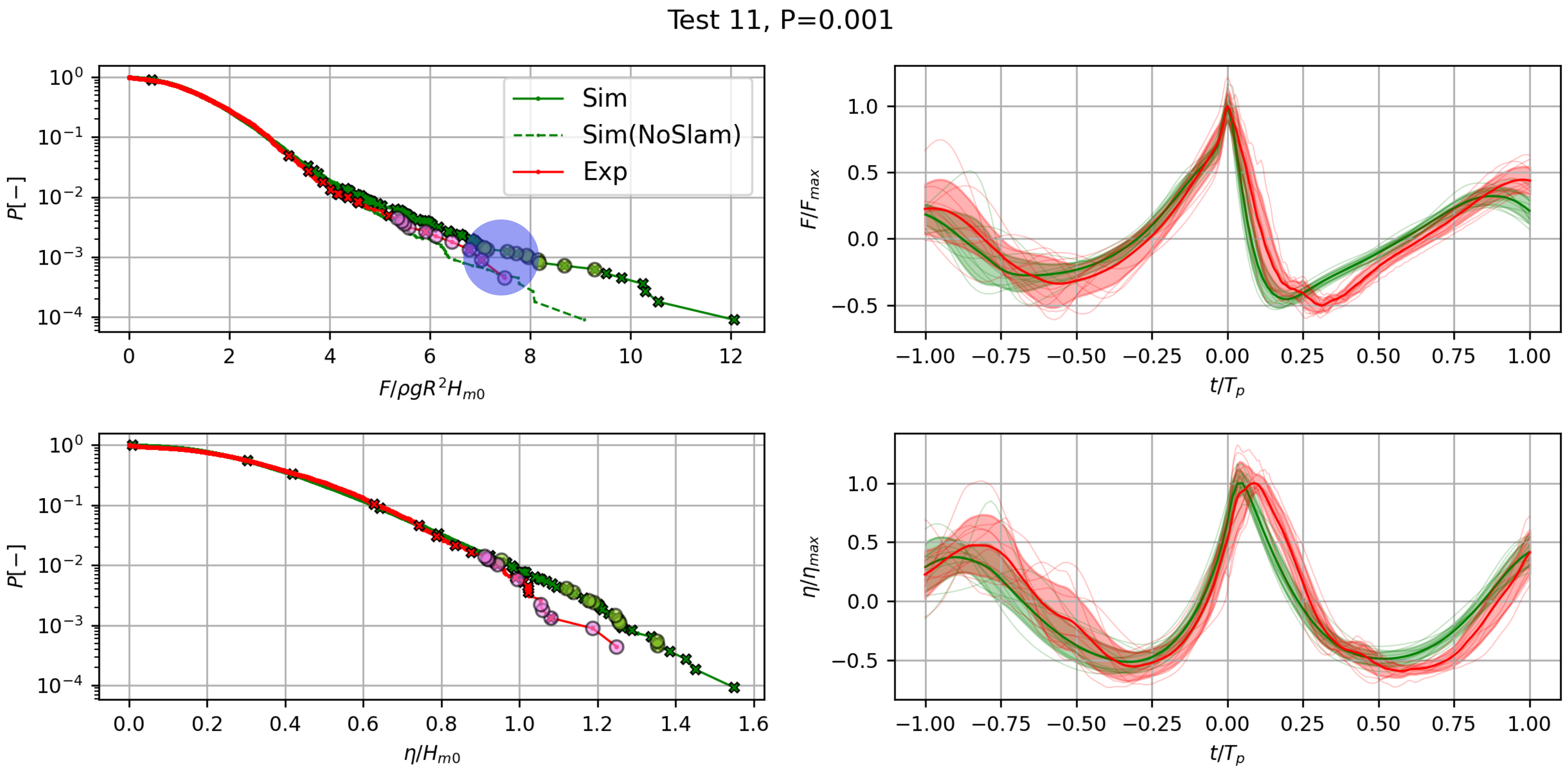
CD=1.0, CM=1.73

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

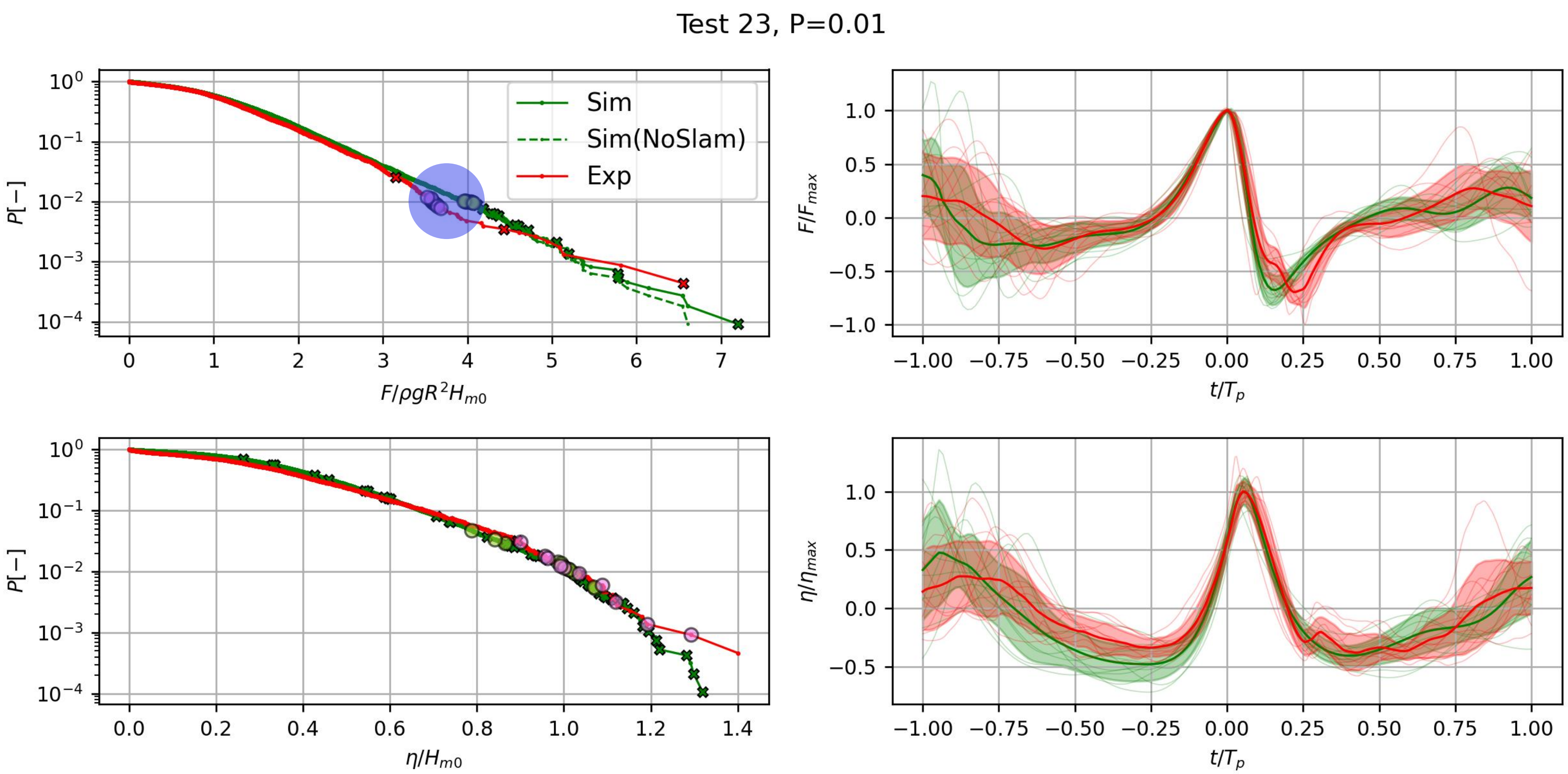
Shapes of the waves for $P_{exc} = 0.01$ Test 11(Hs=9.5m, Tp=15.0 s, h=33.0m)



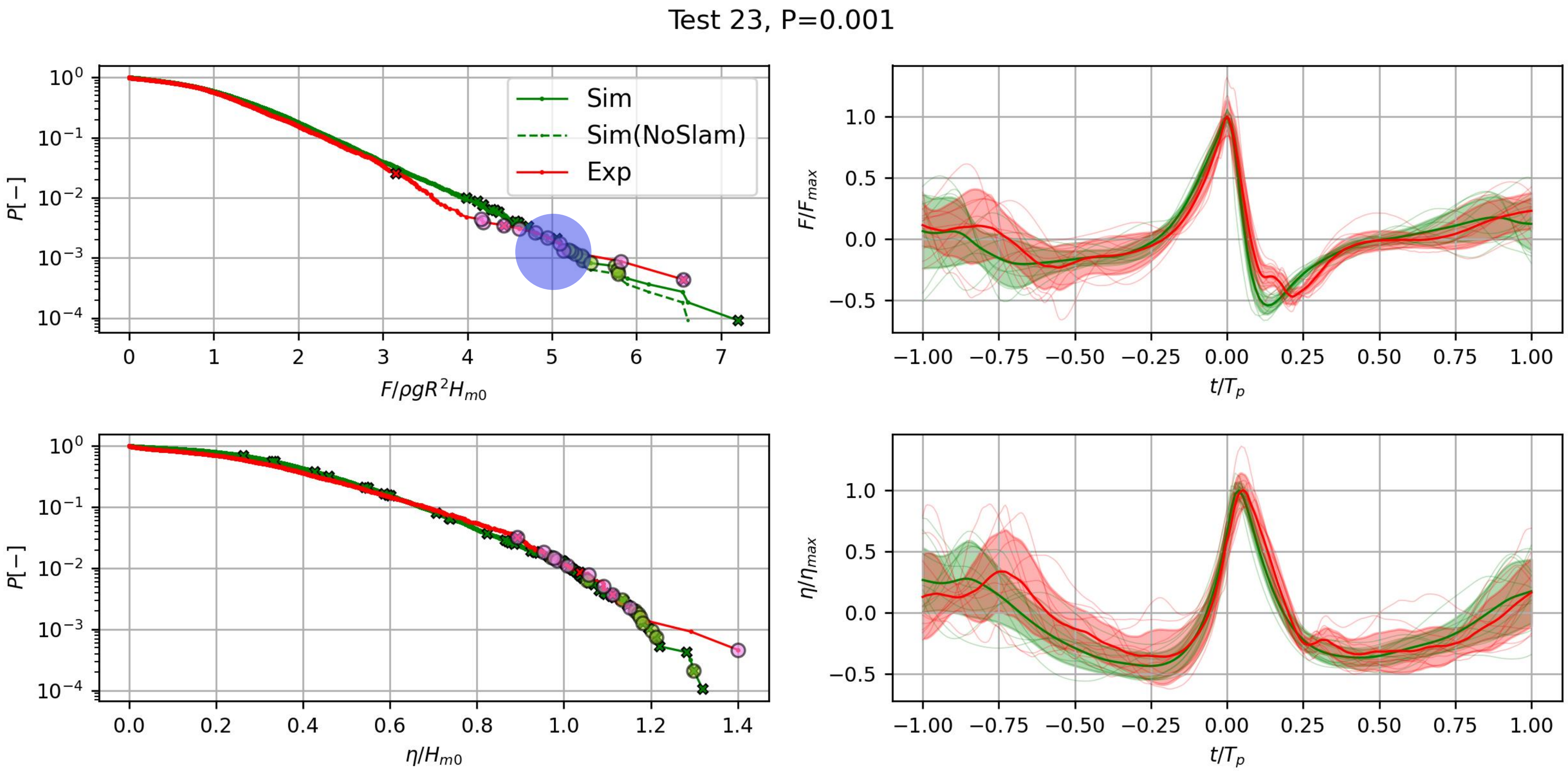
Shapes of the waves for $P_{exc} = 0.001$ Test 11(Hs=9.5m, Tp=15.0 s, h=33.0m)



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

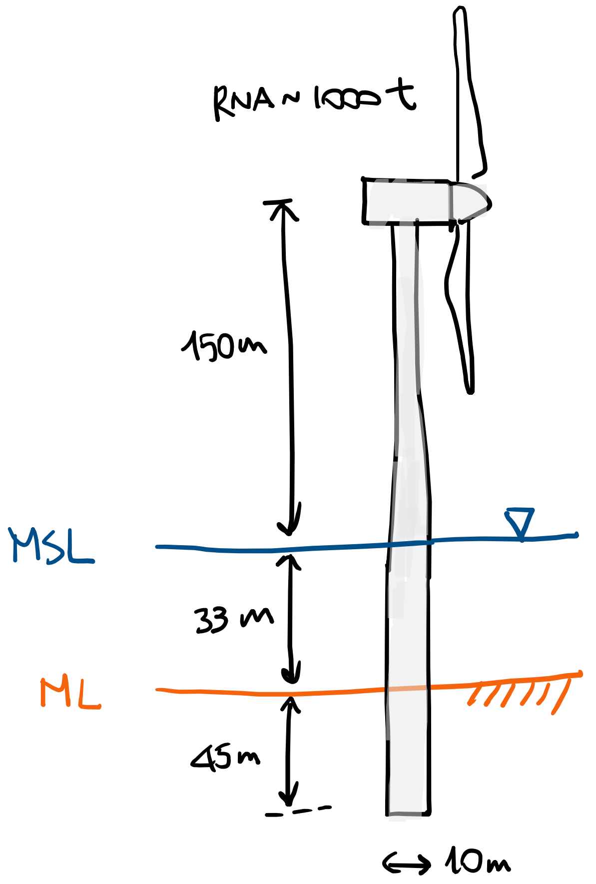


Shapes of the waves for $P_{exc} = 0.001$ Test 23 (Hs=6.8m, Tp=12.0 s, h=20.0m)

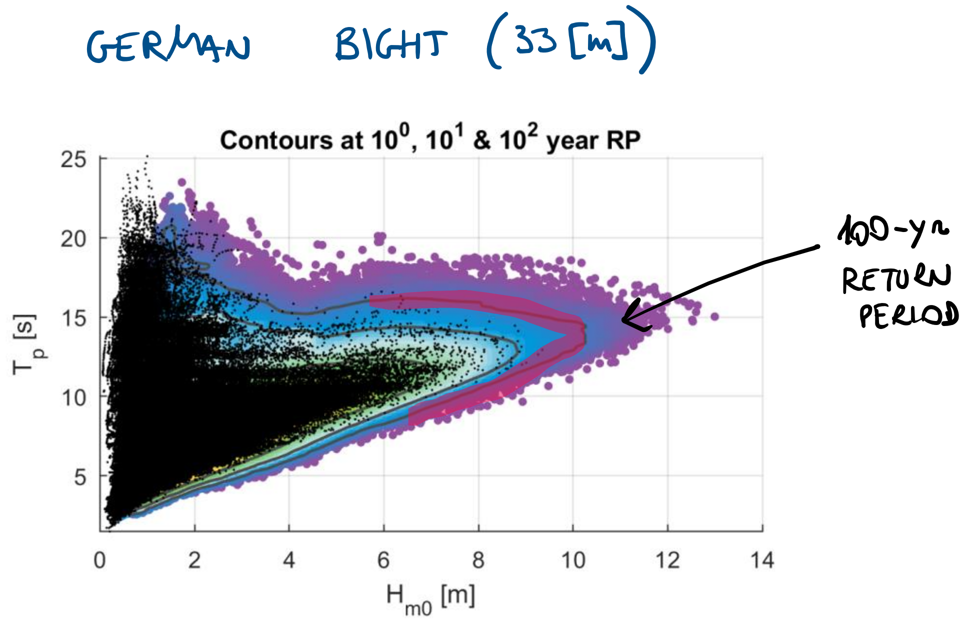


Q3: How can we use this in a design context?

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



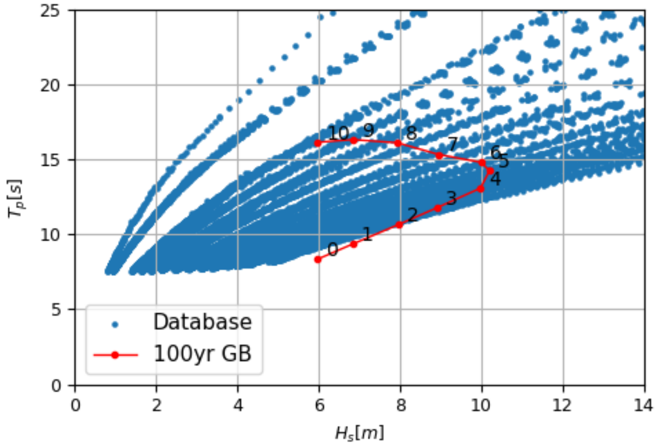
Gaertner et al. (2020)



Sørensen et al. (2021)

Hindcast data (black) + statistical extrapolation (colored)

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

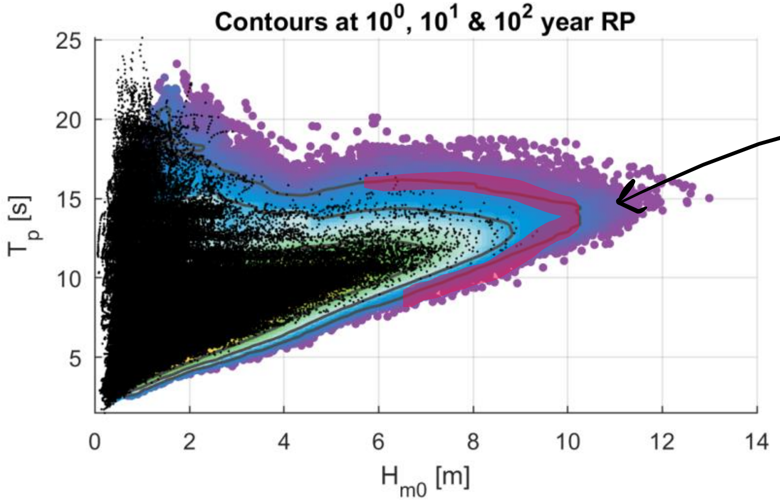


Chosen 10 sea states

Applied force model

$$C_D = 0.6, C_M = 2.0$$

GERMAN BIGHT (33 [m])

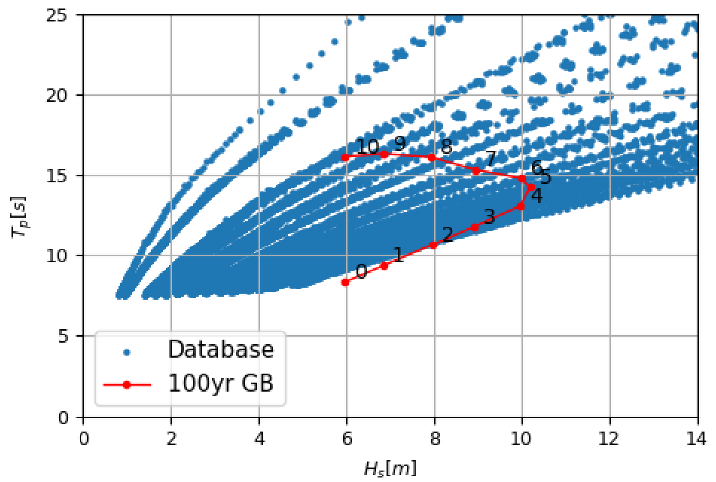


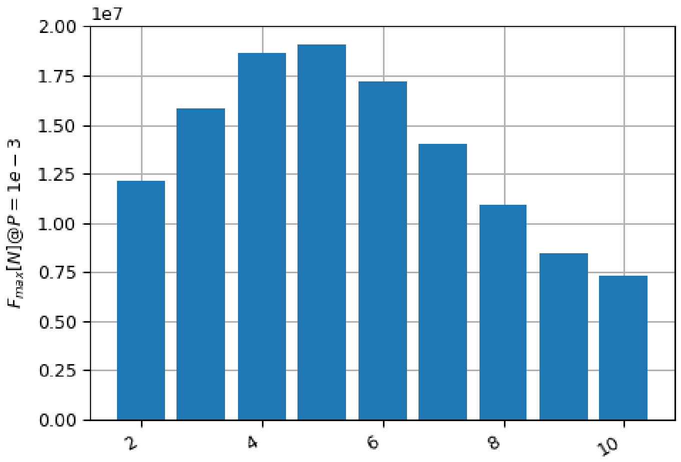
Sørensen et al. (2021)

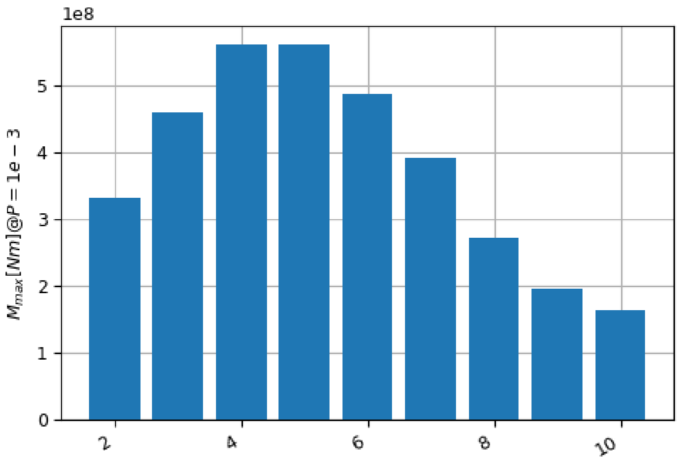
Hindcast data (black) + statistical extrapolation (colored)

We obtain time series of loads

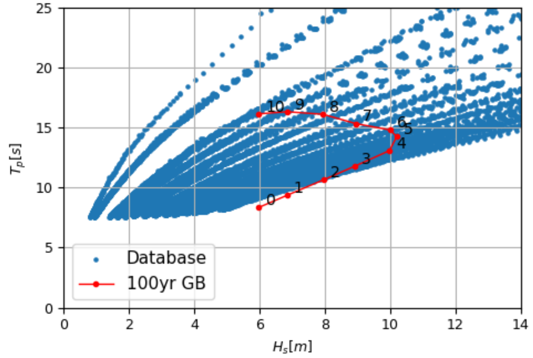
- Where is the force / moment largest?
  - Histogram of max loads P=1e-3



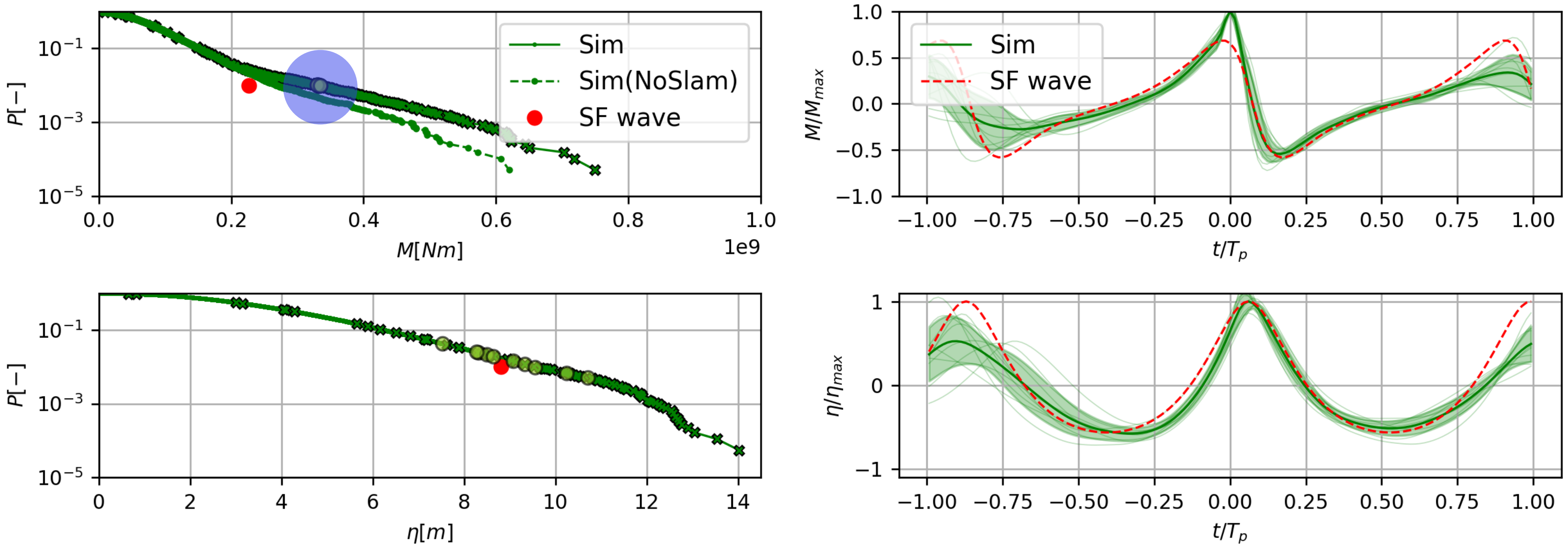


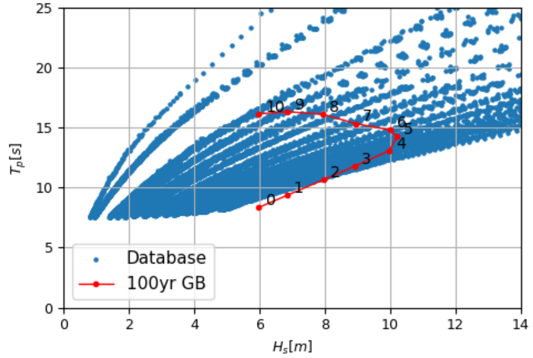


Sea State 4 (Hs=9.97m,Tp=13.1s)



Test 4, P=0.01

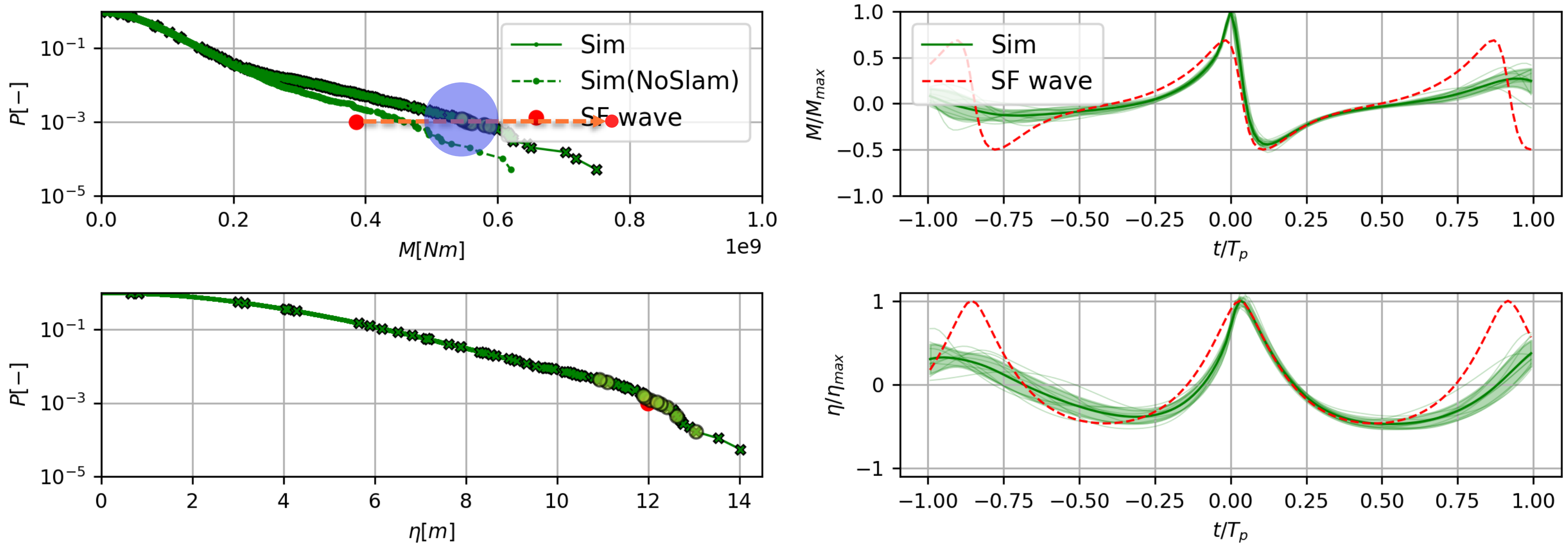




Sea State 4 (Hs=9.97m,Tp=13.1s)

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 η 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