NTNU MARINE CIVIL ENGINEERING DEPARTMENT

HIGH EFFICIENCY AND FULLY NONLINEAR OFFSHORE WIND TURBINE MODELING

REEF3D OPEN-SOURCE HYDRODYNAMICS

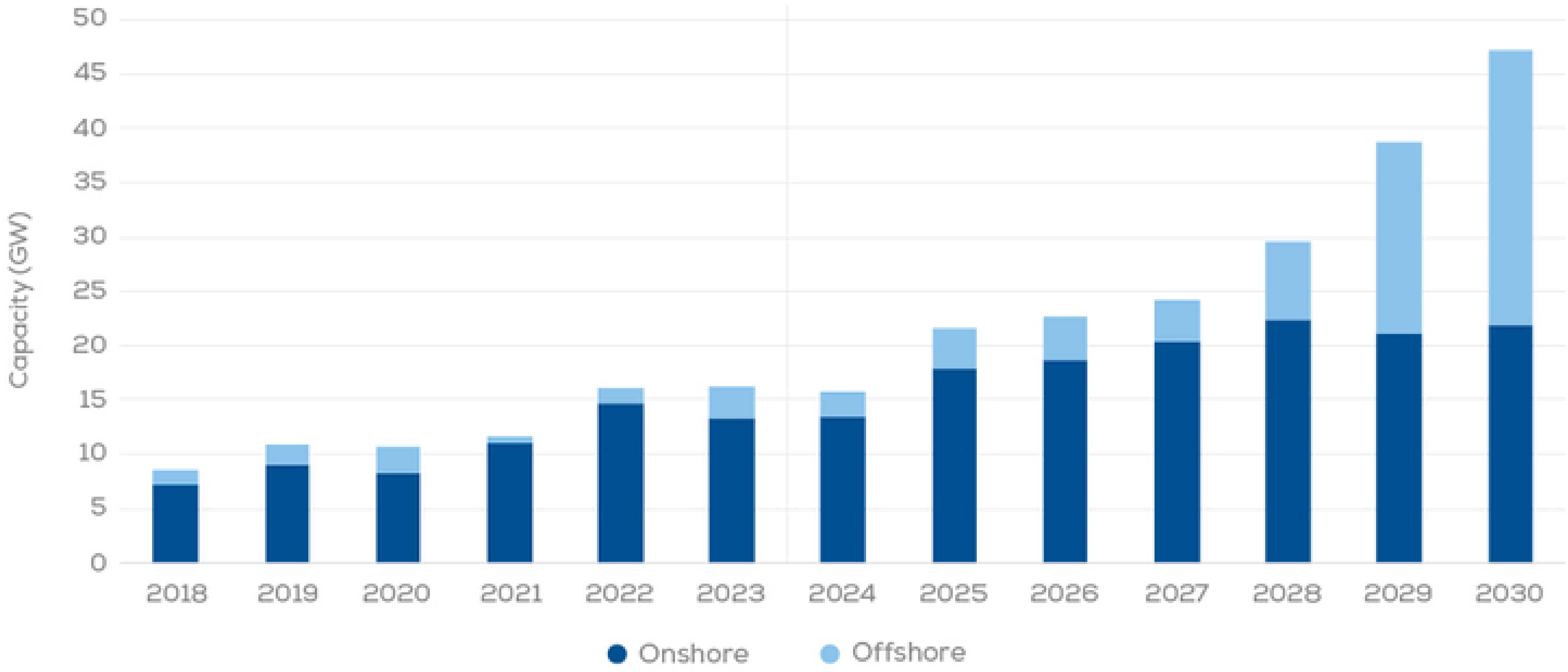
IMAGE SOURCE: COMMERCIAL ALLIANZ. OPPORTUNITIES AND RISKS IN OFFSHORE WIND

Motivation

WE EXPECT EUROPE TO INSTALL 260 GW OF NEW WIND POWER CAPACITY OVER 2024-2030.

WIND EUROPE

FIGURE B. 2024-30 annual onshore and offshore wind power installations in the EU - WindEurope's Outlook



Source: WindEurope

“

Motivation

OFFSHORE WIND PROJECTS OPERATE IN SOME OF THE MOST CHALLENGING AND UNPREDICTABLE ENVIRONMENTS ON THE PLANET.

MARINE SAFETY CONSULTANTS INC

VATTENFALL

One of Europe’s largest producers and retailers of electricity and heat and market leader in wind Energy

Offshore wind portfolio:

- **4.1 GW** → **In operation**
- **13.3 GW** → **Under development**

KRIEGERS FLAK

IMAGE SOURCE: VATTENFALL. WIND TURBINE AT KRIEGERS FLAK WIND FARM

“We want to enable the fossil freedom that drives society forward.”

REEF3D open-source hydrodynamics

Hydrodynamics framework that offers open-source CFD and wave models.

Modular programming approach:

- CFD
- NHFLOW
- SFLOW
- FNPF

FNPF

Three-dimensional fully nonlinear potential flow solver.

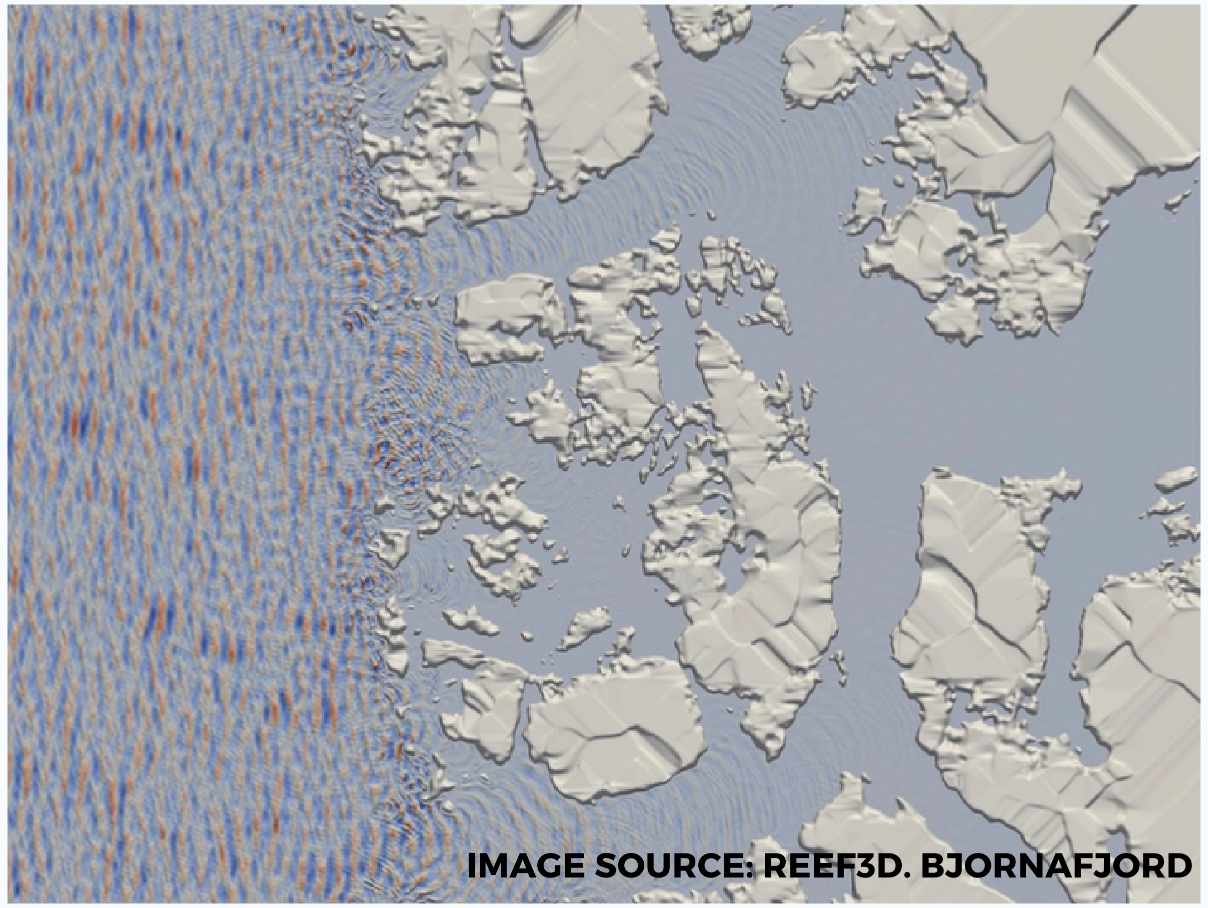


IMAGE SOURCE: REEF3D. BJORNAFJORD

Massively parallelized and can be used to create large-scale phase-resolved sea states at all water depths.

Goal

ANALOGY WITH THE ARBITRARY LAGRANGIAN FORCE CALCULATION

Velocity potential calculated on a σ-grid (REEF3D FNPF)

+

ALE system

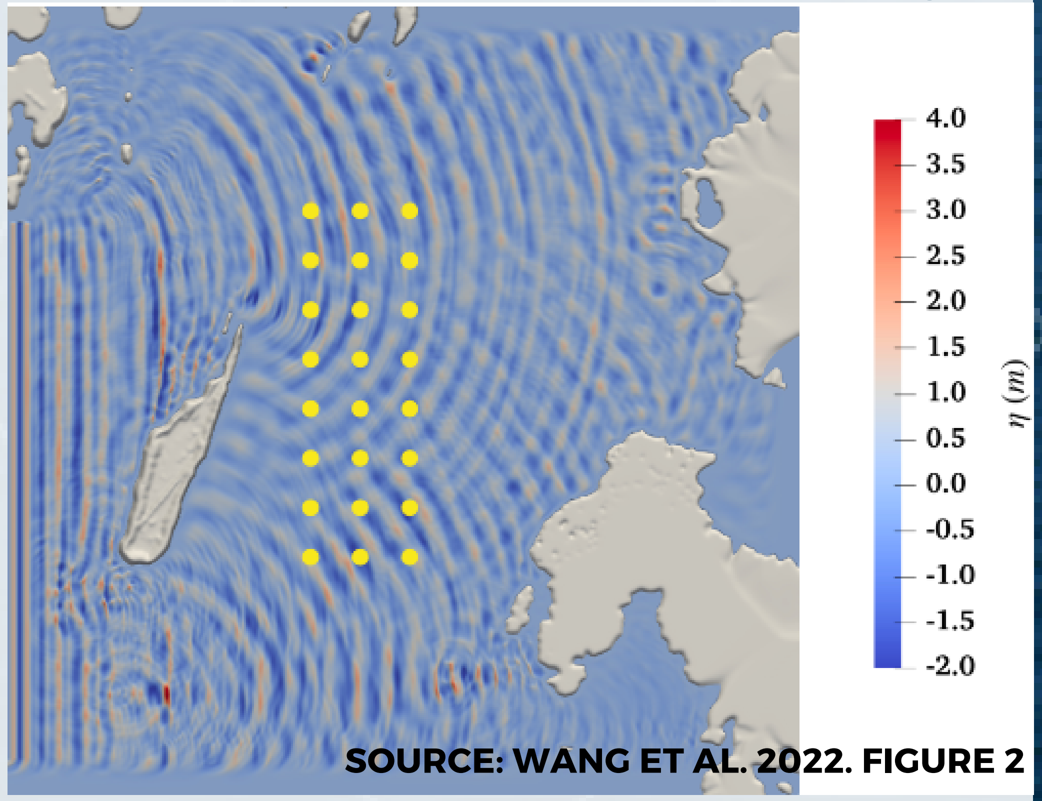
+

Morison equation

$$F_x = \rho(h+\eta) \left[\int_0^1 C_M a_x A_{xy} d\sigma + \int_0^1 C_D u|u| \frac{1}{2} B_p d\sigma\right]$$

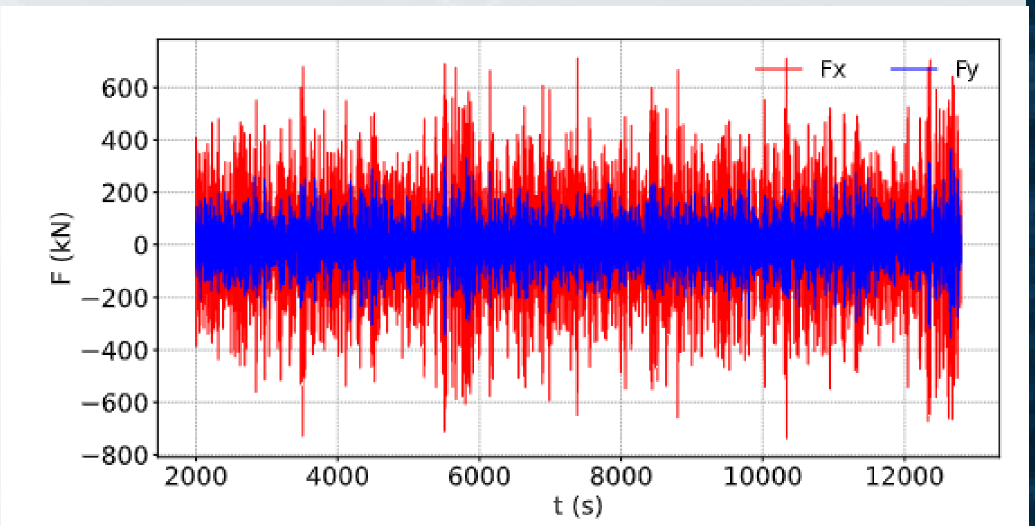
SOURCE: WANG ET AL. 2022. EQ. 25

Study case near Flatøya at the coast of Norway



SOURCE: WANG ET AL. 2022. FIGURE 2

Free surface elevation

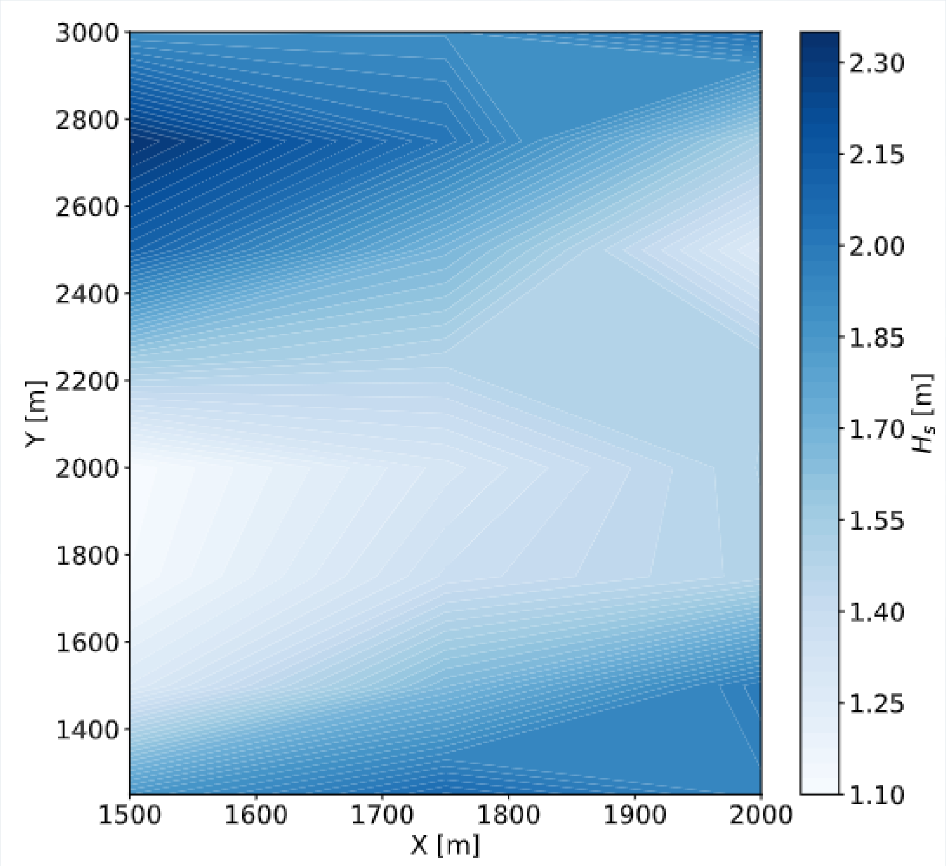


SOURCE: WANG ET AL. 2022. FIGURE 4 a)

Wave forces in x and y direction

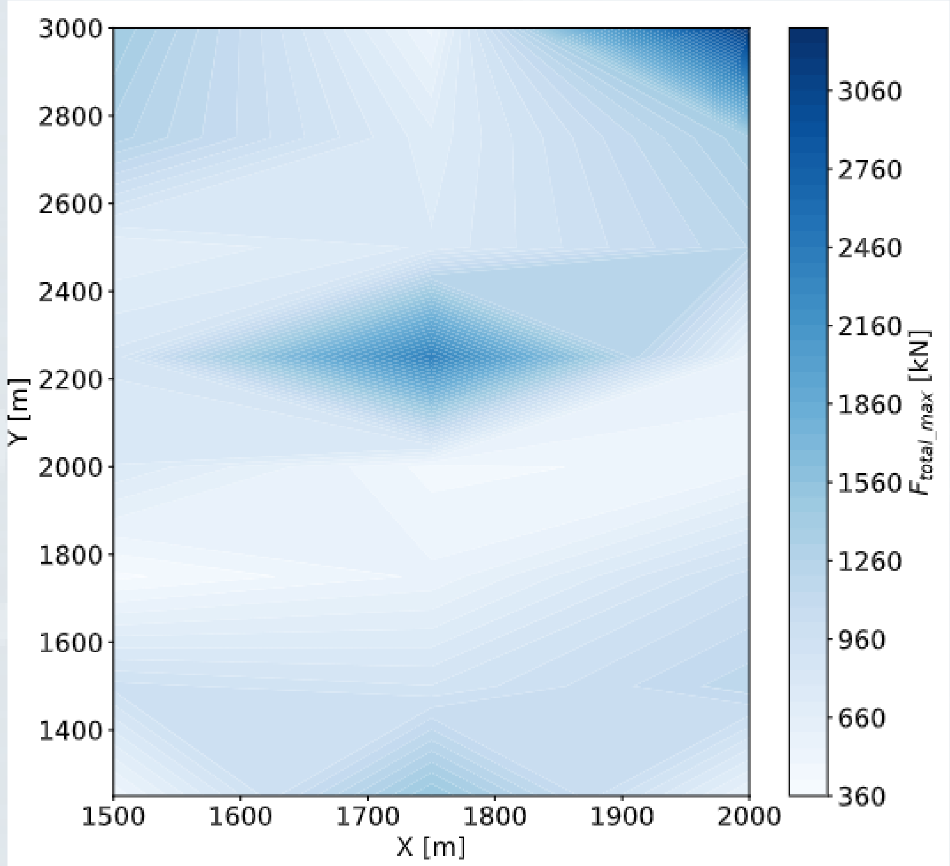
Goal

Study case near Flatøya at the coast of Norway



SOURCE: WANG ET AL. 2022. FIGURE 3 a)

Significant Wave Height



SOURCE: WANG ET AL. 2022. FIGURE 3 b)

Wave Forces

ARTICLE SOURCE: WANG ET AL. 2022. High-efficiency wind-farm-scale wave force estimation for preliminary design of offshore wind installations

IMPACTS

HIGH EFFICIENCY

HYDRODYNAMIC SIMULATIONS AND FORCE CALCULATIONS ARE INTEGRATED AND PERFORMED AT RUN TIME.

IMPACTS

LARGE-SCALE CALCULATIONS

RUN-UP CALCULATION FOR MULTIPLE TURBINES IN ONE SINGLE SIMULATION

RUN-UP CALCULATION

McCamy and Fuchs (1954) - Linear Diffraction Theory

$$\frac{R_u}{\eta_{\max}} = \left(1 + \left(2ka\right)^2\right)^{-0.5}$$

SOURCE: BONAKDAR ET AL. 2016. EQ. 3

Other formulas for different conditions:

Lykke Andersen and Frigaard (2006)	$R_{u,2\%} = \eta_{\max,2\%} + m\frac{u_{2\%}^{2}}{2g}$ for $m = \begin{cases} 4 & s_{0p}=0.02 \\ 3 & s_{0p}=0.035 \end{cases}$
Lykke Andersen et al. (2011)	$R_{u,2\%} = \eta_{\max,2\%} + m\frac{u_{2\%}^{2}}{2g}$ for $m = \begin{cases} 5.6 & s_{0p}=0.02 \\ 4.2 & s_{0p}=0.035 \end{cases}$
Peng et al. (2012)	$\frac{R_{u,2\%}}{h} = 7.39\gamma_D \ln\left(0.27Ur + 1\right)$ for $\gamma_D = 0.004\ln\left(251.8\frac{H}{D} + 1\right)$
Ramirez et al. (2013)	$R_{u,2\%} = \eta_{\max,2\%} + m\frac{u_{2\%}^{2}}{2g}$ for classified wave run-up levels A, B and C Level A: $m = \begin{cases} -66.667s_{0p} + 5.33 & s_{0p}<0.035 \\ 3 & s_{0p}>0.035 \end{cases}$ Level B: $m = \begin{cases} -93.33s_{0p} + 7.47 & s_{0p}<0.035 \\ 4.2 & s_{0p}>0.035 \end{cases}$ Level C: $m = \begin{cases} -200s_{0p} + 16 & s_{0p}<0.035 \\ 9 & s_{0p}>0.035 \end{cases}$
Kazeminezhad and Etemad-Shahidi (2015)	$\frac{R_{u,2\%}}{H_{m0}} = 1.4\left(\frac{H_{m0}}{h}\right)^{0.15}\left(\frac{H_{m0}}{L_{0p}}\right)^{-0.055}$ for $\frac{H_{m0}}{h} \le 0.36$ $\frac{R_{u,2\%}}{H_{m0}} = 1.2\left(\frac{H_{m0}}{L_{0p}}\right)^{-0.055} + 8.5\times10^{-4}\left(\frac{H_{m0}}{h} - 0.36\right)^{0.15}\left(\frac{H_{m0}}{L_{0p}}\right)^{-1.5}$ for $\frac{H_{m0}}{h} > 0.36$

SOURCE: BONAKDAR ET AL. 2016. TABLE 1

ARTICLE SOURCE: BONAKDAR ET AL. 2016. Run-up on vertical piles due to regular waves: Small-scale model tests and prediction formulae

VALIDATION

EXPERIMENTAL DATA

VALIDATION AGAINST EXPERIMENTAL DATA IN COLLABORATION WITH VATENFALL

CFD SIMULATION

VALIDATION USING CFD MODULE IN REEF3D AND AN HYDRODYNAMIC COUPLING WITH THE MODULE FNPF

SUMMARY

MOTIVATION

The growing importance of offshore wind and the challenging conditions where they are developed.

GOAL

Include run-up calculations in REEF3D:FNPF to achieve fast large-scale calculations waves run-up on OWT foundations.

VALIDATION

Use experimental data from collaborator and CFD simulations to validate the results.