Analysis of experimental data: The average shape of extreme wave forces on monopile foundations compared to the New Force model

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Outset of the analysis
Extreme load cases

\[ f = \rho R C_D u^2 + \rho A C_M u_t \]
Outset of the analysis
Extreme load cases

Shape of force?

DeRisk – De-risking of ULS wave loads on offshore wind turbine structures
Outset of the analysis

Extreme load cases

\[
\frac{F}{\rho ghR^2} = f\left(\frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \gamma, \frac{R}{gT_p^2}, \frac{\nu}{\sqrt{ghR^2}}, \frac{t}{T_p}, \{x_j\}\right)
\]

\[
P\left(\frac{F_i}{\rho ghR^2} \leq \frac{F}{\rho ghR^2}\right) = f_1\left(\frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \gamma, \frac{R}{gT_p^2}, \frac{\nu}{\sqrt{ghR^2}}\right)
\]

\[
\frac{F}{F_i} = f_2\left(\frac{F_i}{\rho ghR^2}, \frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \gamma, \frac{R}{gT_p^2}, \frac{\nu}{\sqrt{ghR^2}}, \frac{t}{T_p}\right)
\]

DeRisk – De-risking of ULS wave loads on offshore wind turbine structures
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Extreme load cases

\[ \frac{F}{\rho ghR^2} = f\left(\frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \gamma, \frac{R}{\sqrt{ghR^2}}, \frac{t}{T_p}, \{x_j\}\right) \]

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\[ \frac{F}{F_i} = f_2\left(\frac{F_i}{\rho ghR^2}, H_s, \frac{h}{gT_p^2}, \frac{R}{\sqrt{ghR^2}}, \gamma, \frac{t}{T_p}\right) \]

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\frac{F}{\rho ghR^2} = f \left( \frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \gamma, \frac{R}{\sqrt{ghR^2}}, \frac{\nu}{T_p}, \{x_i\} \right)
\]

\[
P \left( \frac{F_i}{\rho ghR^2} \leq \frac{F}{\rho ghR^2} \right) = f_1 \left( \frac{H_s}{gT_p^2}, \frac{h}{gT_p^2} \right)
\]

\[
\frac{F}{F_i} = f_2 \left( \frac{F_i}{\rho ghR^2}, \frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \frac{t}{T_a} \right)
\]

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\[
\frac{F}{\rho ghR^2} = f\left(\frac{H_s}{g T_p^2}, \frac{h}{g T_p^2}, \gamma, \frac{R}{\sqrt{ghR^2}}, \frac{\nu}{T_p}, \gamma, \{x_j\}\right)
\]

\[
P\left(\frac{F_i}{\rho g H_s R^2} \leq \frac{F}{\rho g H_s R^2}\right) = f_1\left(\frac{H_s}{g T_p^2}\right)
\]

\[
\frac{F}{F_i} = f_2\left(\frac{F_i}{\rho ghR^2}, \frac{h}{g T_p^2}, \frac{t}{T_a}\right)
\]

Functional dependencies of \(f_1\) and \(f_2\) to the wave parameters?
How well can the New Force model predict the force shapes?

DeRisk – De-risking of ULS wave loads on offshore wind turbine structures
Agenda

• The New Force model
• Experimental data
• Exceedance probability distributions of the free surface elevation and force signal
• Average shape of measured inline forces
• Comparison to the New Force model
• Conclusion
The New Force model

\[ \eta_{\text{New Wave}} = \frac{\alpha_\eta}{\sigma_\eta^2} \sum_j \Re \{ S_\eta(\omega_j) \Delta \omega \exp \left( i \left( \omega_j(t - t_0) - k_j(x - x_0) \right) \right) \} \]  

[Lindgren (1976), Boccotti (1983), Tromans (1991)]
The New Force model

\[ \eta_{\text{New Wave}} = \frac{\alpha_\eta}{\sigma_\eta^2} \sum_j \text{Re}\{S_{\eta}(\omega_j)\Delta\omega \exp\left(i(\omega_j(t - t_0) - k_j(x - x_0))\right)\} \]

\[ \Gamma(\omega) = i\rho \pi R^2 C_M \omega^2 / k \quad S_F(\omega) = |\Gamma(\omega)|^2 S_{\eta}(\omega) \]

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The New Force model

\[
\eta_{\text{New Wave}} = \frac{\alpha_\eta}{\sigma^2_\eta} \sum_j \Re \left\{ \eta(\omega_j) \Delta \omega \exp \left( i \left( \omega_j(t - t_0) - k_j(x - x_0) \right) \right) \right\}
\]

\[
\Gamma(\omega) = i \rho \pi R^2 C_M \omega^2 / k \quad S_F(\omega) = |\Gamma(\omega)|^2 S_\eta(\omega)
\]

\[
F_{\text{New Force}} = \frac{\alpha_F}{\sigma^2_F} \sum_j \Re \left\{ |\Gamma(\omega_j)|^2 S_\eta(\omega_j) \Delta \omega \exp \left( i \left( \omega_j(t - t_0) - k_j(x - x_0) \right) \right) \right\}
\]

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The New Force model

$$\eta_{\text{New Wave}} = \frac{\alpha_\eta}{\sigma_\eta^2} \sum_j \text{Re} \left\{ S_\eta(\omega_j) \Delta \omega \exp \left( i \left( \omega_j(t - t_0) - k_j(x - x_0) \right) \right) \right\}$$

$$\Gamma(\omega) = i\rho \pi R^2 C_M \omega^2 / k \quad S_F(\omega) = |\Gamma(\omega)|^2 S_\eta(\omega)$$

$$F_{\text{New Force}} = \frac{\alpha_F}{\sigma_F^2} \sum_j \text{Re} \left\{ |\Gamma(\omega_j)|^2 S_\eta(\omega_j) \Delta \omega \exp \left( i \left( \omega_j(t - t_0) - k_j(x - x_0) \right) \right) \right\}$$

$$\eta_{\text{New Force}} = \frac{\alpha_F}{\sigma_F^2} \sum_j \text{Re} \left\{ \Gamma^*(\omega_j) S_\eta(\omega_j) \Delta \omega \exp \left( i \left( \omega_j(t - t_0) - k_j(x - x_0) \right) \right) \right\}$$

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The New Force model – 2\textsuperscript{nd} order contribution

\[ F^{(1)+(2)} = F^{(1)} + F_M^{(2)} \]

\[ F_M^{(2)} = \rho \pi R^2 C_M \int_{-h}^{0} (u_i^{(2)} + u^{(1)} u_x^{(1)} + w^{(1)} u_z^{(1)}) dz + \rho R C_D \int_{-h}^{0} u^{(1)} |u^{(1)}| dz \]

\[ + \rho \pi R^2 (C_M - 1) \int_{-h}^{0} (u^{(1)} w_z^{(1)}) dz + \rho \pi R^2 C_M \eta_{NF}^{(1)} u_t^{(1)}. \]

Second order wave kinematics based on second order wave theory of Sharma and Dean (1981)
Model tests

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Exceedance probability distributions of the free surface elevation and force signal

\[ P(\cdot) \]

\[ \eta/h \]

\[ F/(\rho gh R^2) \]

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Exceedance probability distributions of the free surface elevation and force signal

\[ P \left( \frac{F_i}{\rho ghR^2} \leq \frac{F}{\rho ghR^2} \right) = f_1 \left( \frac{H_s}{gT_p^2}, \frac{h}{gT_p^2} \right) \]

\[ \frac{H_b}{L_0} = \Lambda \left( 1 - \exp \left( -1.5\pi \frac{h}{L_0} \right) \right) \]

[Goda et al. 1976]

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Exceedance probability distributions of the free surface elevation and force signal

\[ F/(\rho ghR^2) = 0.8 \]

\[ F/(\rho ghR^2) = 1.0 \]

\[ F/(\rho ghR^2) = 1.3 \]

\[ F/(\rho ghR^2) = 1.6 \]

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The average force shape

\[
\frac{F}{\rho gh R^2} = 1.0
\]
The average force shape

DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

\[ \sigma(t) = \frac{F(t)}{F_{\text{max}}(t)} \]

\[ h/(gT_p^2) = 0.009 \quad h/(gT_p^2) = 0.014 \quad h/(gT_p^2) = 0.024 \]

\[ \frac{F}{(\rho ghR^2)} = 0.8 \quad \frac{F}{(\rho ghR^2)} = 1.0 \quad \frac{F}{(\rho ghR^2)} = 1.3 \quad \frac{F}{(\rho ghR^2)} = 1.6 \]

\[ t/T_a \]

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The average force shape

\[
\frac{F}{\rho gh R^2} = 0.8, 1.0, 1.3, 1.6
\]

\[
\frac{h}{(gT_p)^2} = 0.009, 0.014, 0.024
\]
Conclusion

For the considered sea states

- The probability distributions of the force peaks are function of $F/(\rho ghR^2)$, $H_s/(gT_p^2)$, $h/(gT_p^2)$ → possible to estimate the probability distributions of the force peaks from stochastic variables of the sea states.

- The normalised force shapes are function of $F/(\rho ghR^2)$, $h/(gT_p^2)$, $t/T_a$.
- For moderate nonlinear waves The New Force model of second order predicts the shapes of well.

Planned future work

- To predict force shapes of more nonlinear waves, more advanced wave models should be used together with the New Force model.
- Include multidirectional waves in the analysis
Thank you
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