Implementation of a hysteretic 3D soil model in an aeroelastic code. Dynamic analysis of an offshore wind turbine in misaligned wind and waves

EERA DeepWind'2015

12th Deep Sea Offshore Wind R&D Conference

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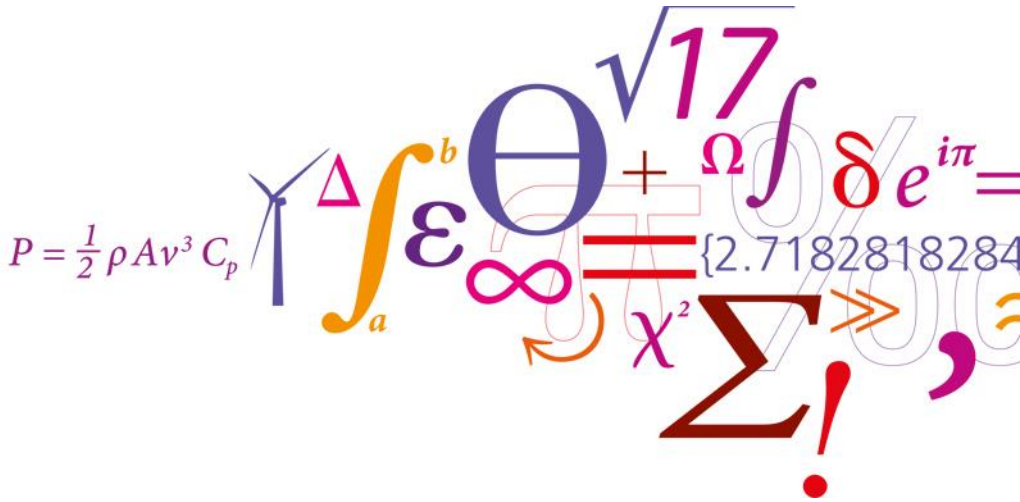


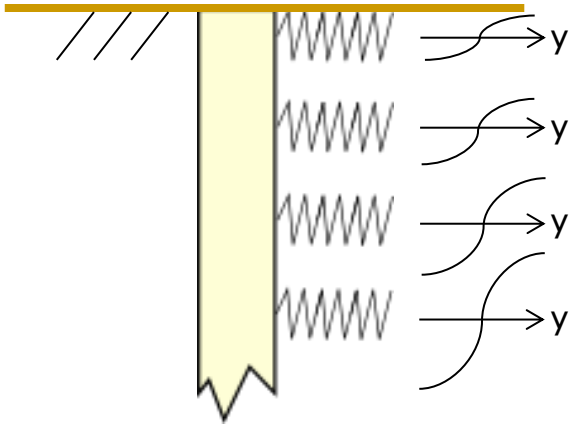
DTU Wind Energy
Department of Wind Energy

Soil models in aeroelastic models

To day

To day:

- Soil stiffness calculated by monotonic *p*-*y*-curves (pressure and displacement) in springs in soil



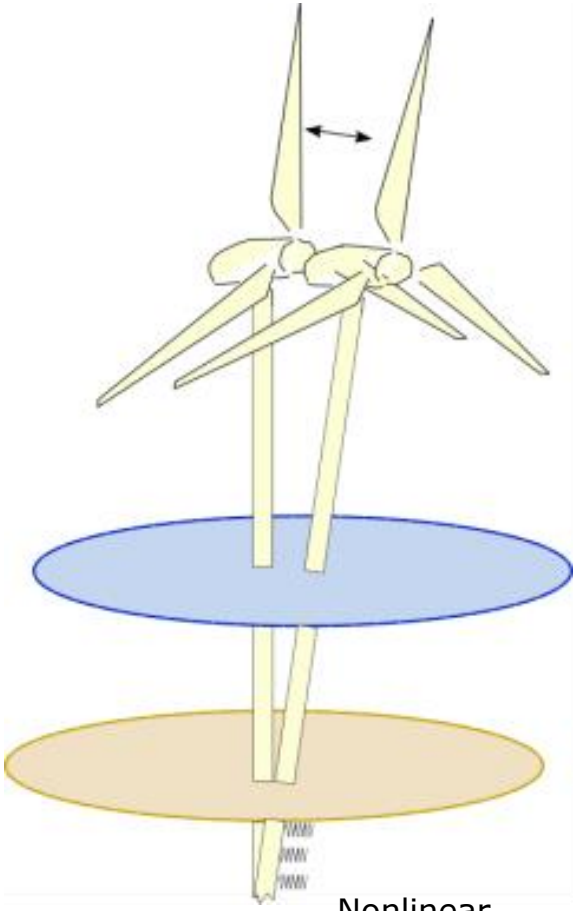
- Soil damping included by constant damping ratio either in springs or as viscous modal damping.

$$\mathbf{M}\underline{\ddot{u}} + (\mathbf{C} + d)\underline{\dot{u}} + \mathbf{K}\underline{u} = \underline{F}$$

Soil damping by a new soil model

Model of Hededal & Klinkvort (2010) and Klinkvort (2012)

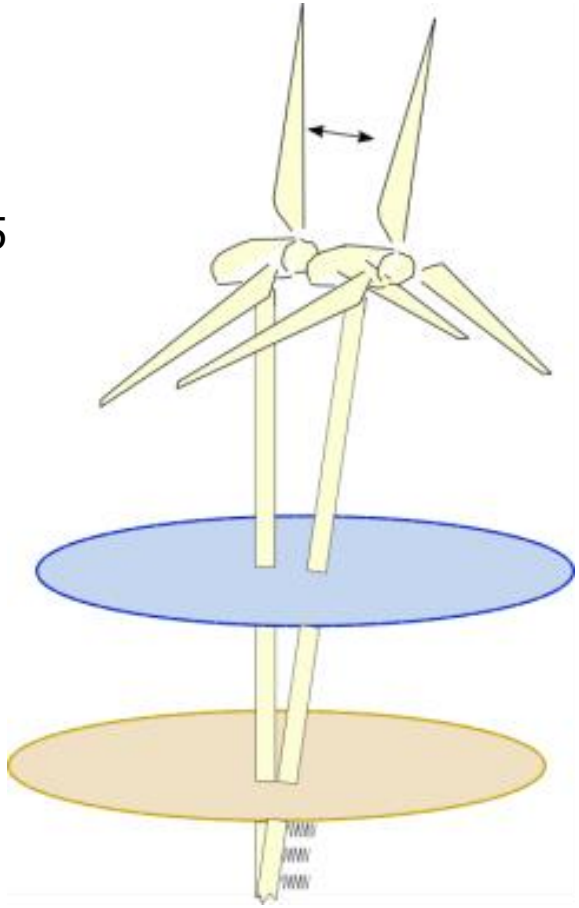
- Cyclic pile-soil interaction
- Hysteretic damping
- Creations of gap
- Only 2D
- "Cyclic model"



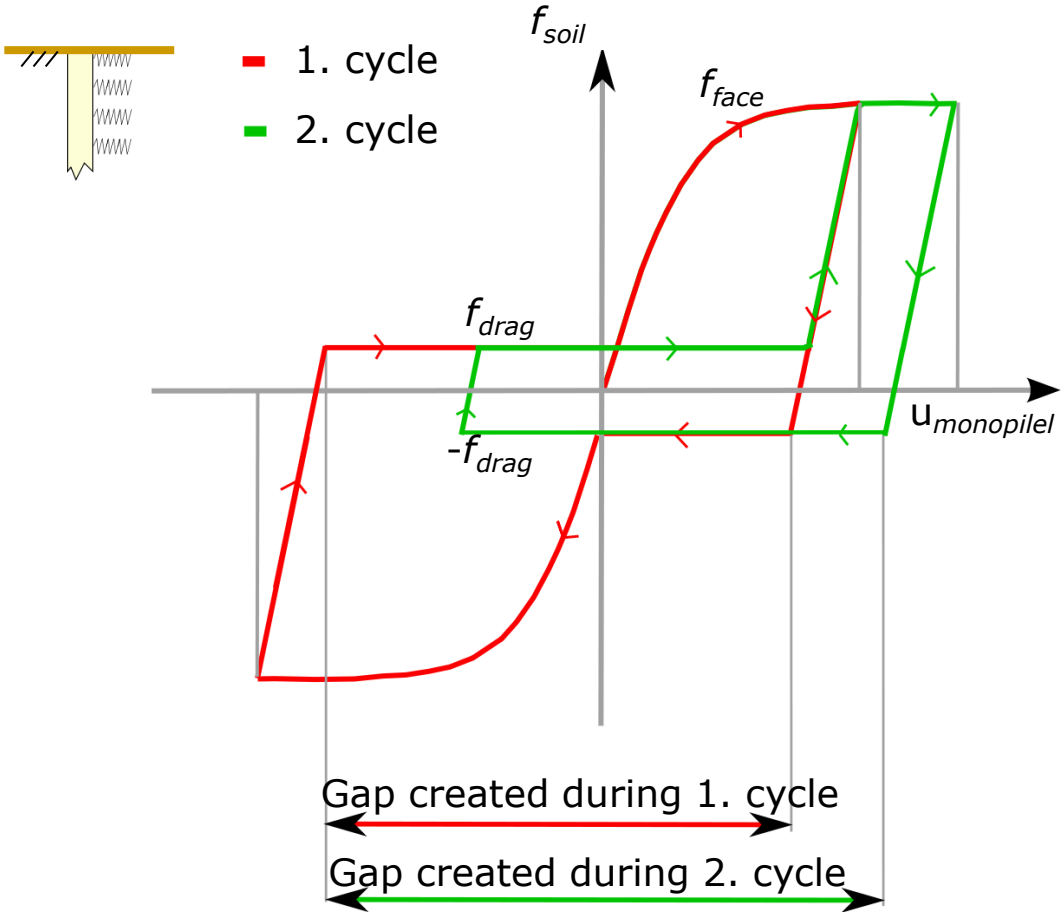
Nonlinear cyclic springs

Agenda

- Explain the new soil model (cyclic model)
- Implemented in the aeroelastic code Flex5
- Extend the cyclic model to 3D
- Compare cyclic model with a *p-y* model
  - 7 wind and sea states
  - Aeroelastic calculatins
  - Equivalent loads
- Discussion



Cyclic model
Winkler model



$$f_{u,virgin} = A_s f_u \tanh\left(\frac{k_m z}{A_s f_u} u\right)$$

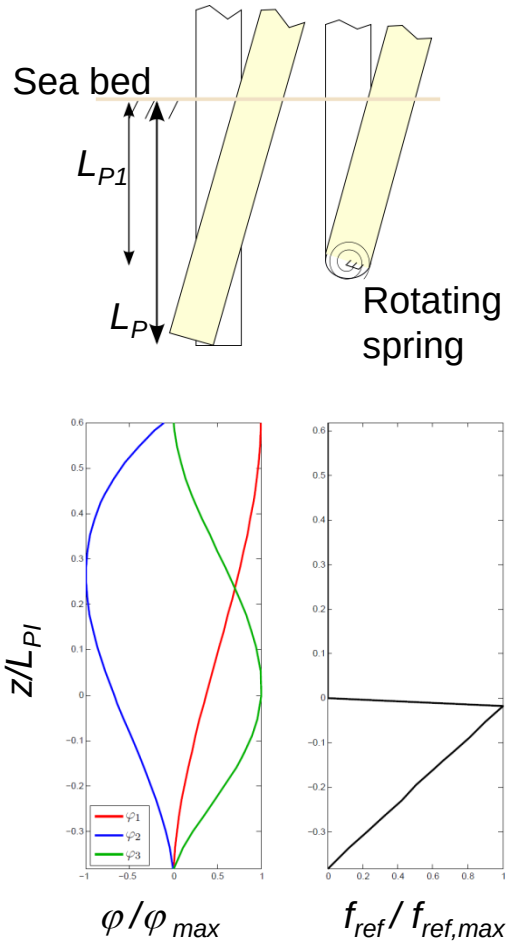
API (2010)

$$f_s = \frac{A_s f_u}{10} \frac{\Delta u}{|\Delta u|}$$

$$f_s = f_{s,old} + \Delta u k_s$$

$$\delta = \frac{1}{2} \frac{W}{\max E_{kin}} = \frac{4 f_{drag}}{m u_0 \omega^2}$$

Cyclic model
Implementation in Flex5



$$u = \sum_{i=1}^{2} \varphi_i(x)\alpha_i$$

Run the soil model: $f_s = f_s(u)$

$$GF_3 = \int_{z_{min}}^{-h} f_s(x)\varphi dz$$

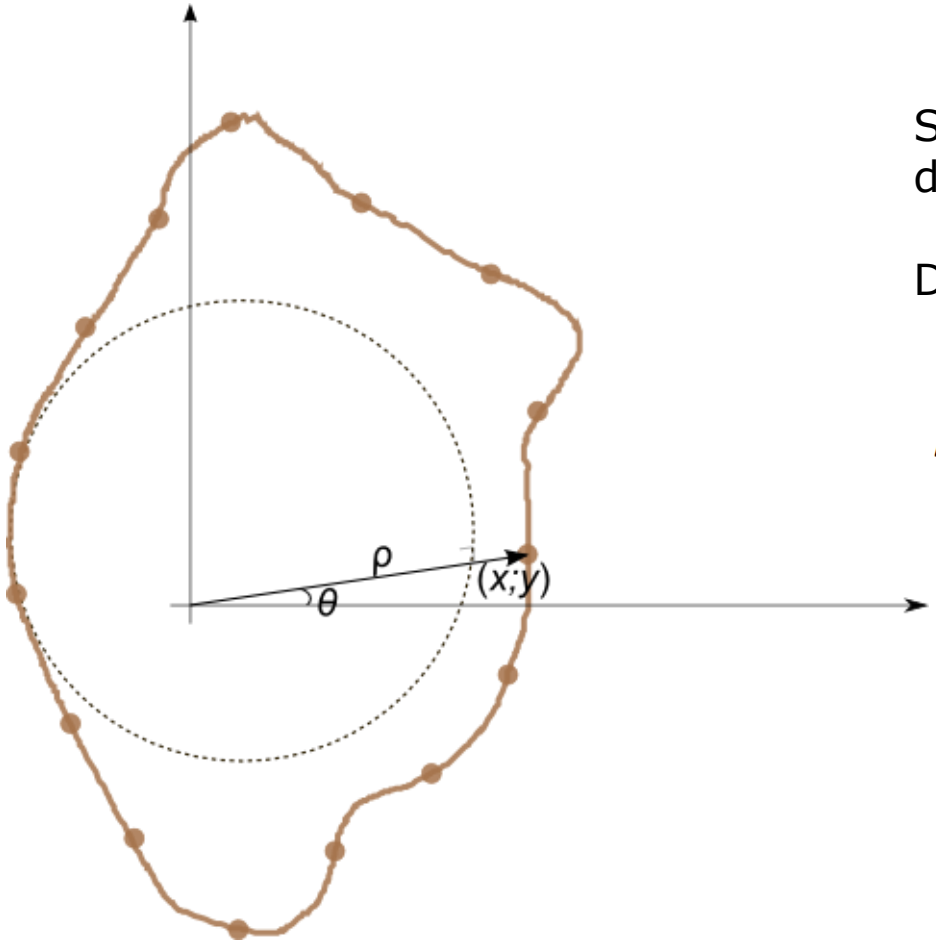
$$\alpha_3 = K_{relax}\frac{GF_3}{GK_3} - (1 - K_{relax})\alpha_3$$

$$GK_3 = \int_{z_{min}}^{-h} f_{ref} dx$$

Iteration

$$u = \sum_{i=1}^{3} \varphi_i(x)\alpha_i$$

Cyclic model
Extension to 3D

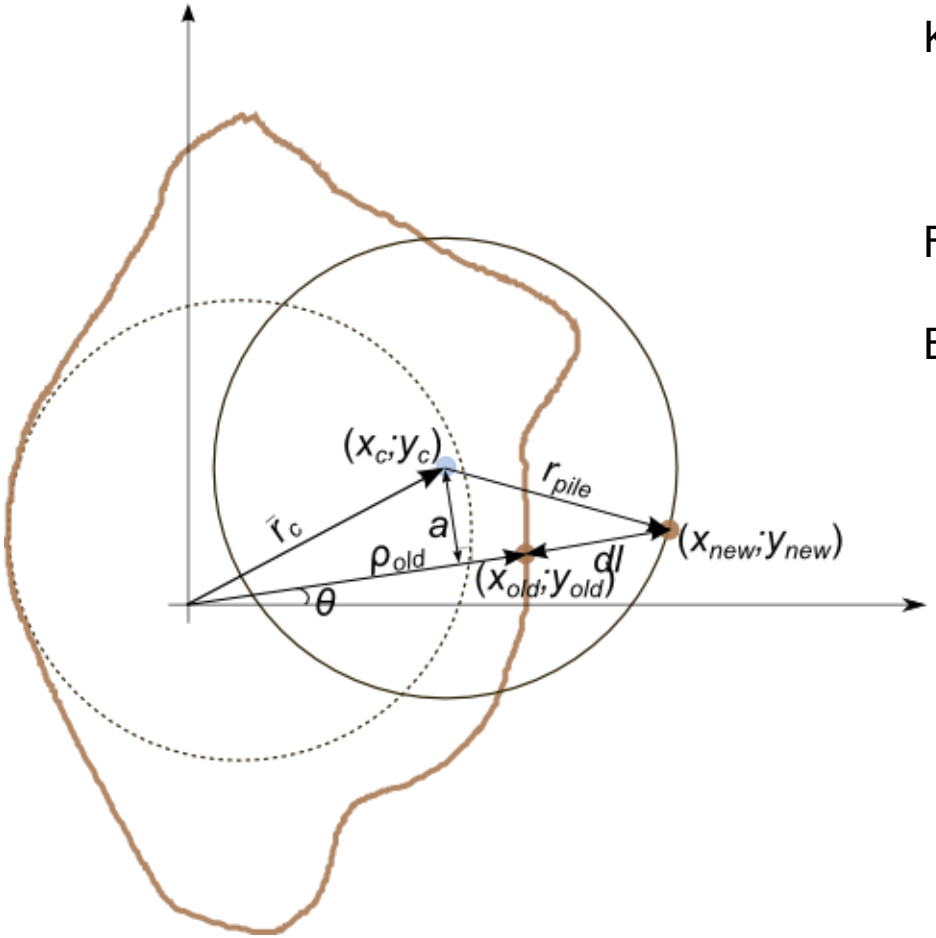


Soil shape described by 21 equally distributed points.

Described by a Fourier function

$$\rho(\theta) = \rho_0 + \sum_{p=1}^{N} \left(A_p \exp(\frac{ip\theta 2\pi}{N}) + CC \right)$$

Cyclic model
Extension to 3D



Known: $\overline{r}_c = (x_c; y_c)$

$\rho_{old}(\cos\theta; \sin\theta) = (x_{old}; y_{old})$

Find: $\rho_{new}(\cos\theta; \sin\theta) = (x_{new}; y_{new})$

By: $l = \frac{\overline{\rho}_{old}}{|\overline{\rho}_{old}|}\overline{r}_c$

$a = \sqrt{|\overline{r}_c|^2 - l^2}$

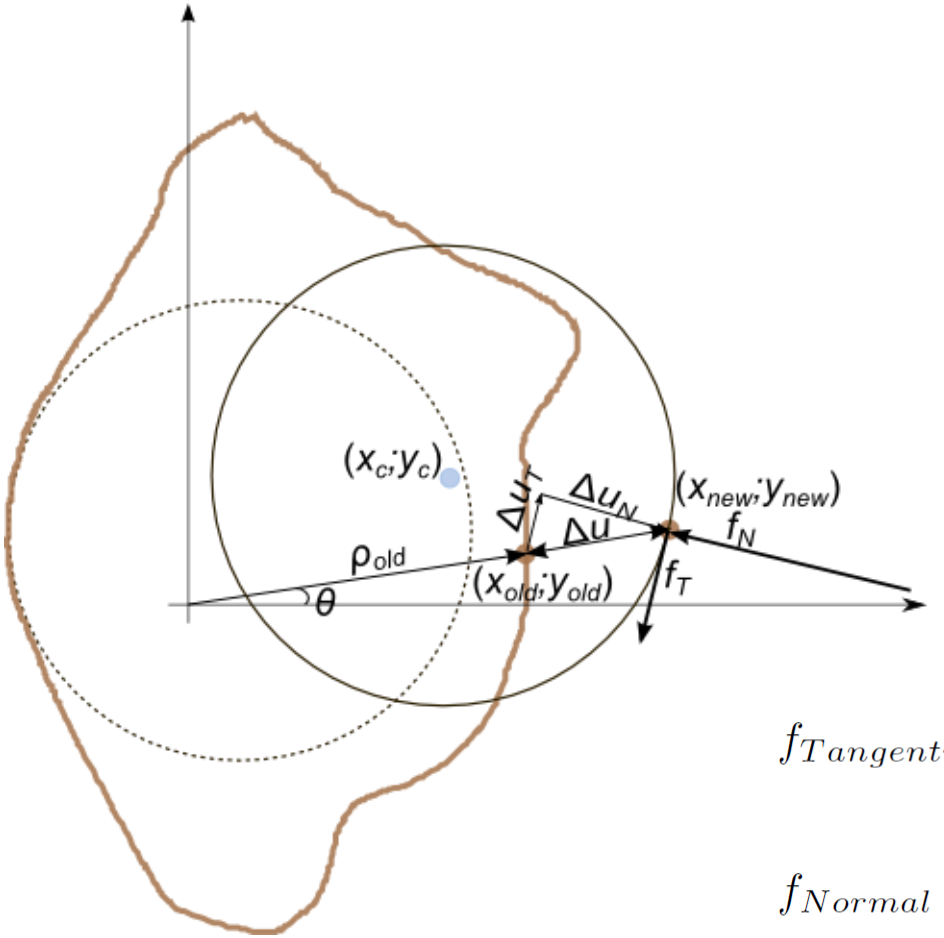
$dl = \sqrt{r_{pile}^2 - a^2}$

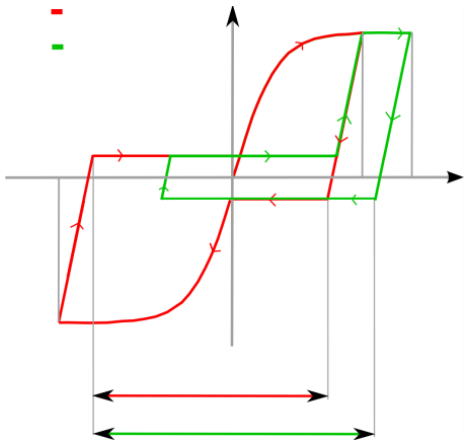
$\rho_{new} = dl + l$

$x_{new} = \rho_{new}\cos\theta$

$y_{new} = \rho_{new}\sin\theta$

Cyclic model
Extension to 3D



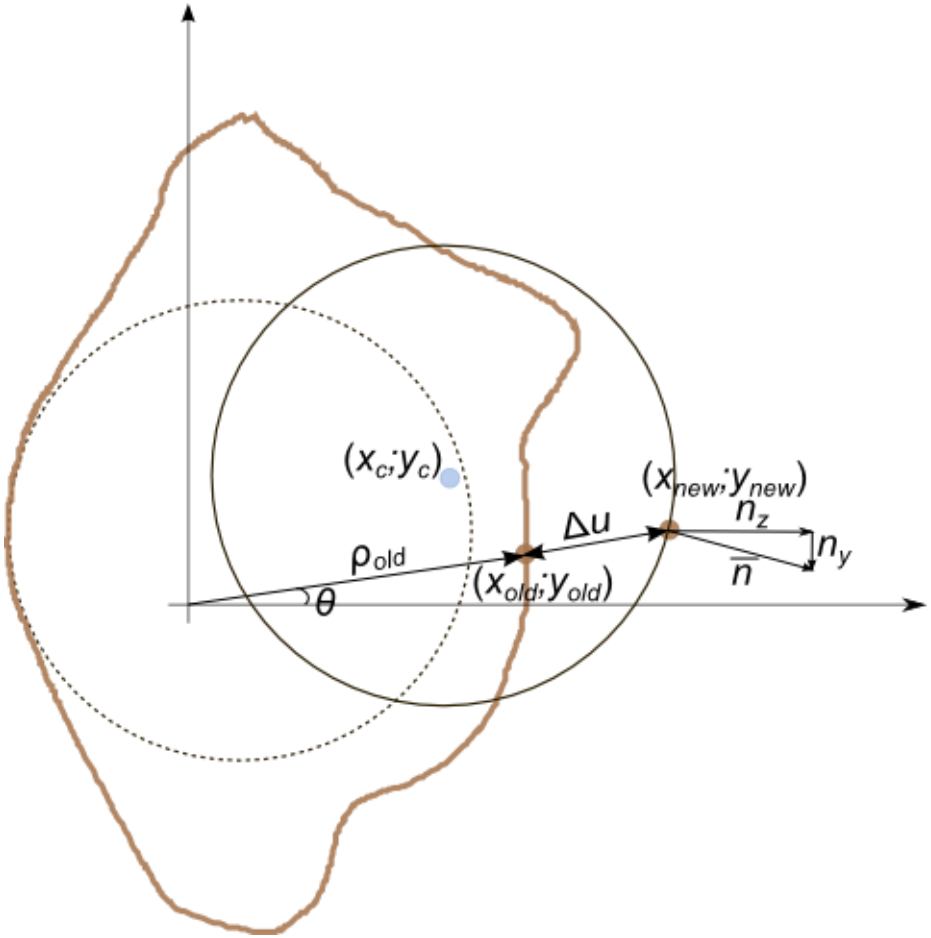


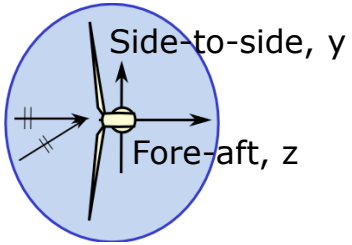
$$f_{Tangential} = \frac{A_s f_u}{10} \Delta u_T$$

$$f_{Normal} = A_s f_u \tanh\left(\frac{k_m z}{A_s f_u}(\rho_{old,x} + \Delta u_N)\right)$$

$$f_{Normal} = f_{Normal,old} + \Delta u_N k_s$$

Cyclic model
Extension to 3D



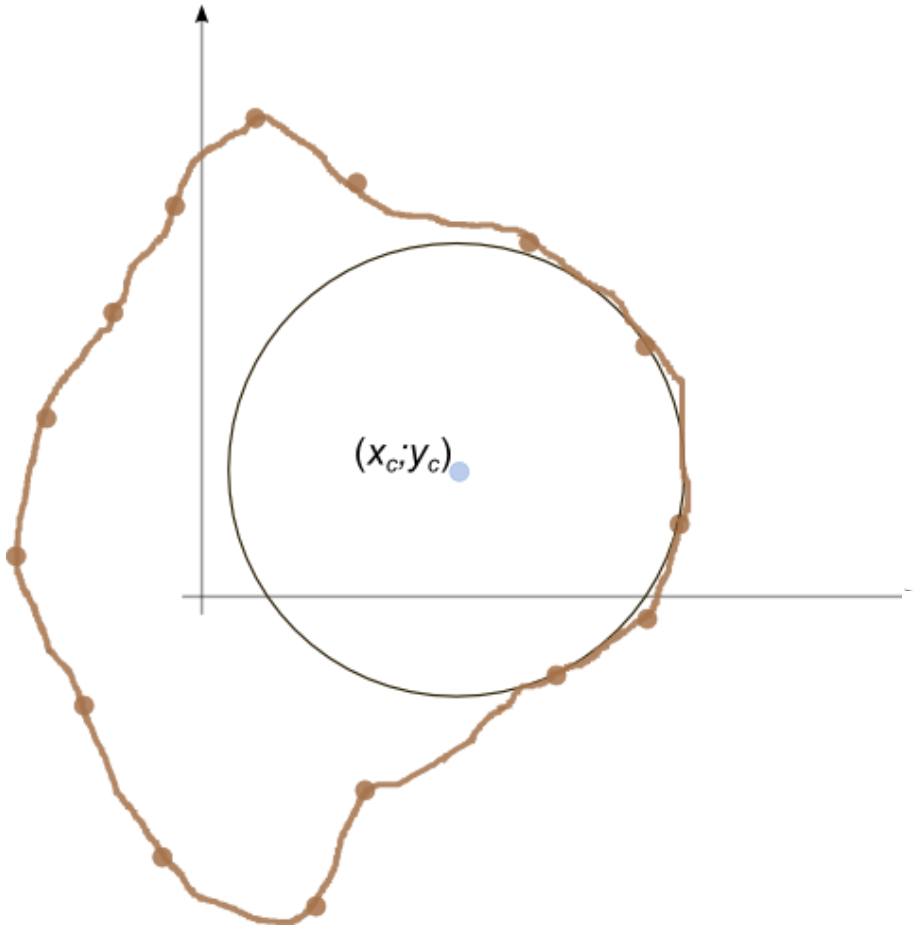


$$f_{Normal,z} = f_{Normal} n_z$$
$$f_{Normal,y} = f_{Normal} n_y$$

$$f_{Tangential,z} = f_{Tangential} t_z$$
$$f_{Tangential,y} = f_{Tangential} t_y$$

$$f_{s,z} = f_{N,z} + f_{T,z}$$
$$f_{s,y} = f_{N,y} + f_{T,y}$$

Cyclic model
Extension to 3D



Update ρ so the points again are equally distributed

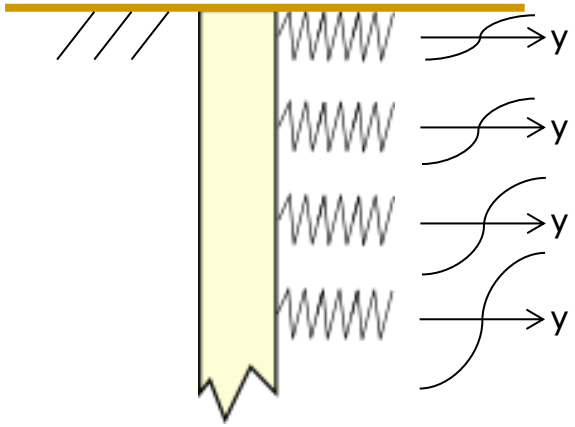
$$A_p = \frac{fft(\rho_{new})}{N_{point}}$$

$$\rho = \rho_0 + \sum_{p=1}^{N_p} \left(A_p \exp(\frac{ip\theta 2\pi}{N_p}) + CC \right)$$

Compare two models

Cyclic model and *p-y* model

p-y model



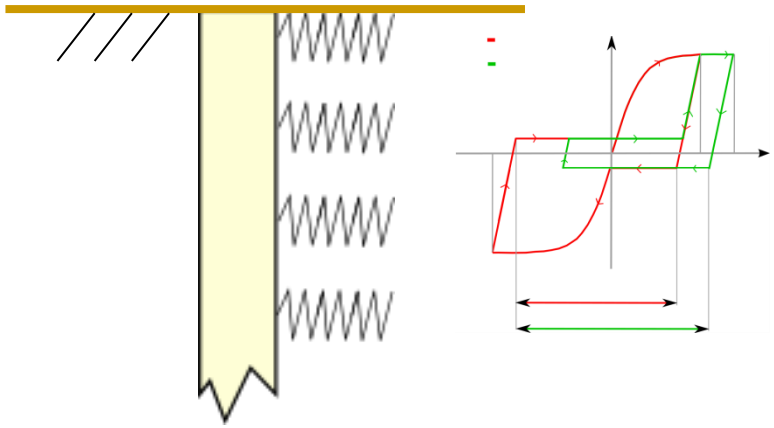
$$f_{u,virgin} = A_s f_u \tanh\left(\frac{k_m z}{A_s f_u}\mathrm{u}\right)$$

API (2010)

$$\mathbf{M}\ddot{\underline{u}} + (\mathbf{C} + d)\dot{\underline{u}} + \mathbf{K}\underline{u} = \underline{F}$$

$$d = \frac{\delta\sqrt{\mathbf{MK}}}{\pi}$$

Cyclic model



$$f_{u,virgin} = A_s f_u \tanh\left(\frac{k_m z}{A_s f_u}\mathrm{u}\right)$$

$$f_s = \frac{A_s f_u}{10}\frac{\Delta\mathrm{u}}{|\Delta\mathrm{u}|}$$

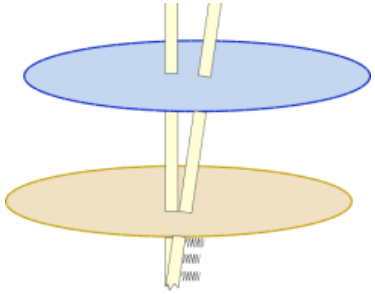
$$f_s = f_{s,old} + \Delta\mathrm{u}k_s$$

$$\delta = \frac{1}{2}\frac{W}{\max E_{kin}} = \frac{4f_{drag}}{mu_0\omega^2}$$

Compare two models

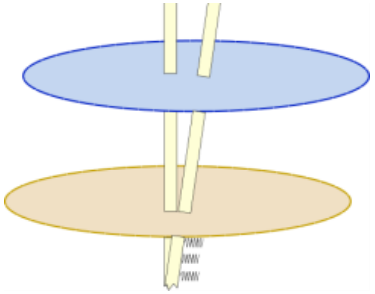
Cyclic model and *p-y* model

p-y model



- Add amount of viscous damping in monopile to represent
  - soil damping
  - hydrodynamic damping
  - structural damping

Cyclic model



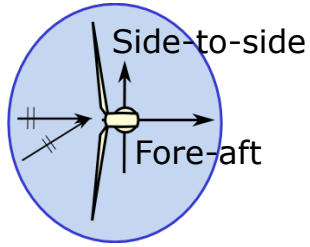
- Soil damping included in model
- Add 2% of logarithmic damping as viscous damping in monopile to represent
  - hydrodynamic damping
  - structural damping

Comparison of the two models

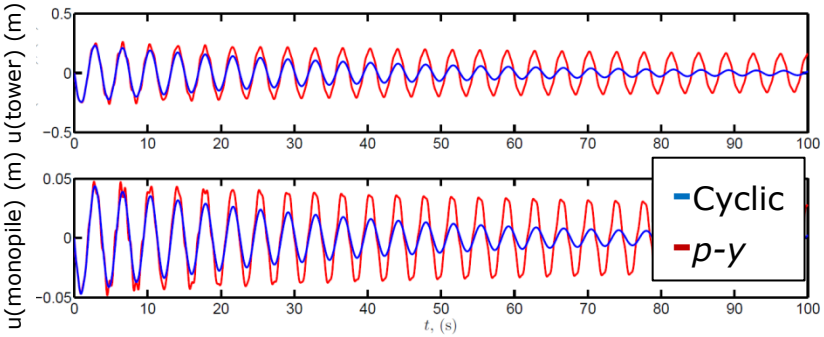
Decay test

$\delta = 30\%$

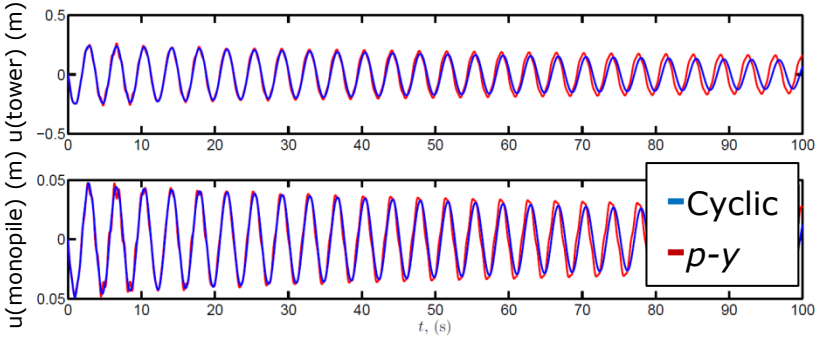
$\delta = 6\%$



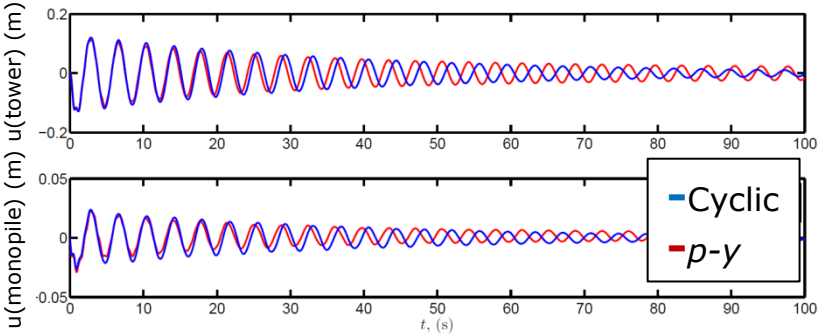
Fore-aft



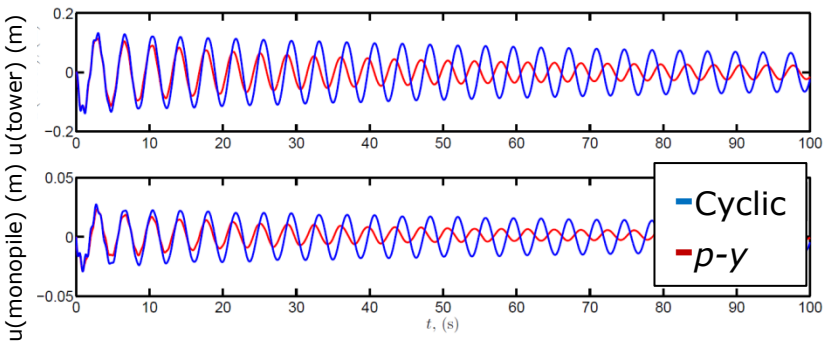
Fore-aft



Side-to-side



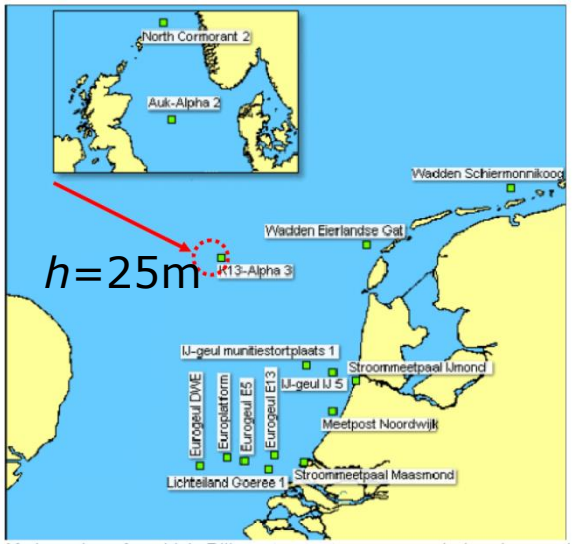
Side-to-side



Comparison of the two models

Metocean data (Upwind-project, Fischer et al. (2010))

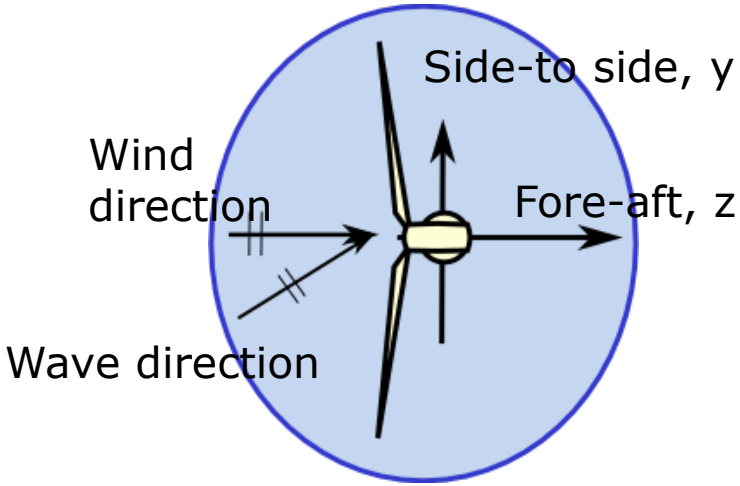
V [m/s]	TI [%]	Hs [m]	Tp [m]	f [−]	f_{rel} [−]
2	29.2	1.07	6.03	0.06071	0.1237
6	17.5	1.18	5.76	0.14048	0.2862
10	15.2	1.48	5.74	0.14654	0.2986
14	14.2	1.91	6.07	0.08381	0.1708
18	13.6	2.47	6.71	0.04186	0.0853
22	13.3	3.09	7.40	0.01534	0.0313
28	11.9	4.17	8.49	0.00202	0.0041



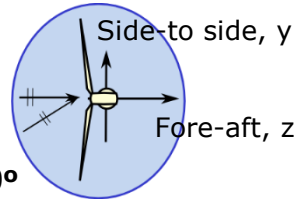
Comparison of the two models

Metocean data (Upwind-project, Fischer et al. (2010))

- NREL 5MW wind turbine
- Monopile extended 21.6 m below sea bed
  - D=6.10 m
  - t=0.085 m
- Water depth: 25 m
- Linear irregular waves
  - JONSWAP spectrum
- Turbulent wind
  - Mann model
- Misalignment between wind and waves
  - 0°
  - 90°

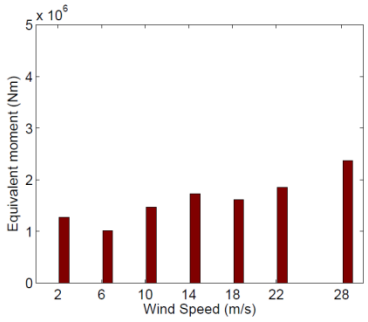


Equivalent loads
p-y model



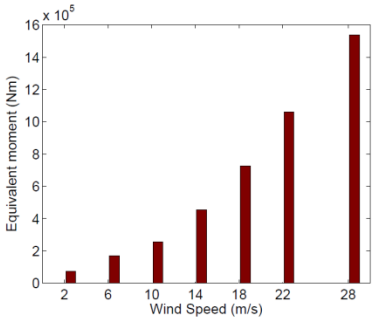
Misalignment 0°

Fore-aft

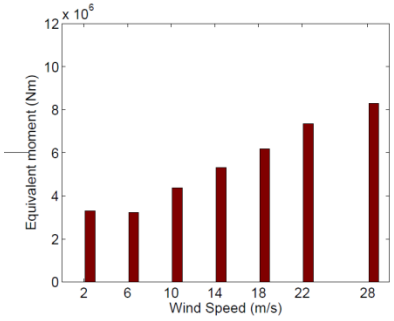


(a) M_y Tower

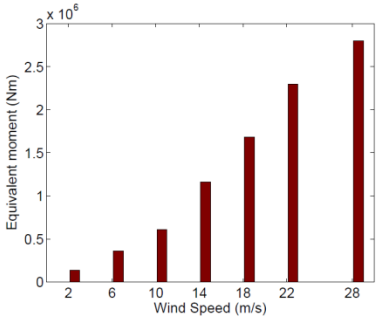
Side-to-side



(b) M_z Tower



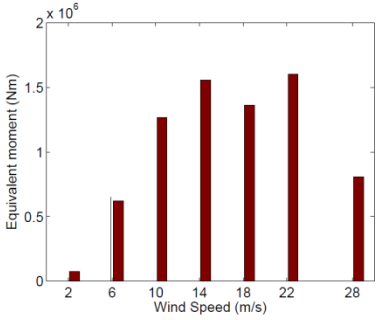
(c) M_y Monopile



(d) M_z Monopile

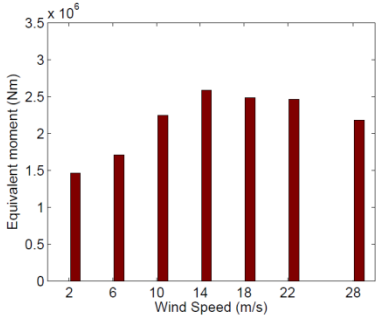
Misalignment 90°

Fore-aft

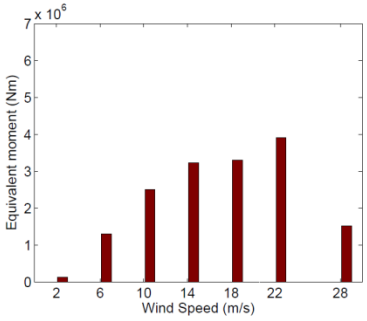


(a) M_y Tower

Side-to-side



(b) M_z Tower



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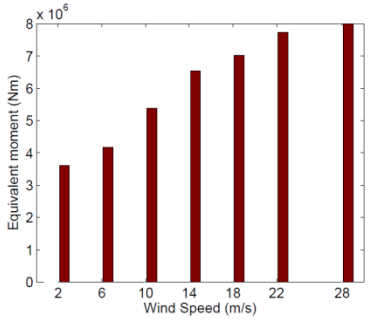
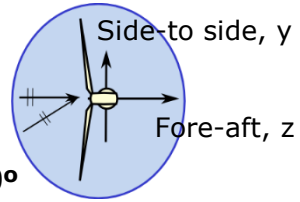


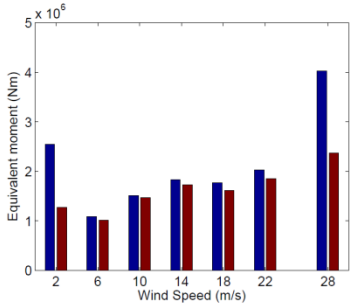
(d) M_z Monopile

Equivalent loads
Both models



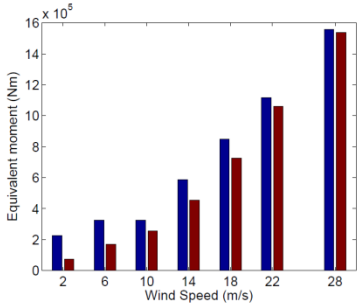
Misalignment 0°

Fore-aft

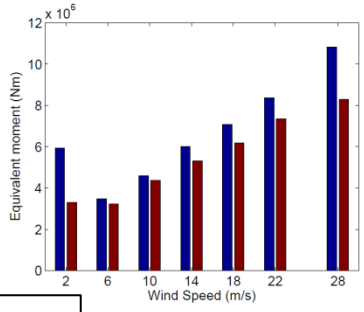


(a) M_y Tower

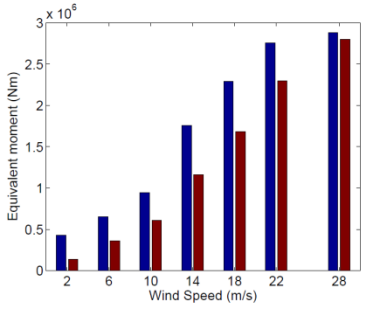
Side-to-side



(b) M_z Tower



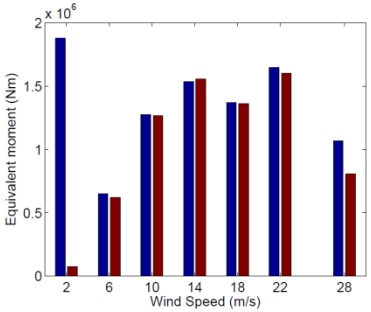
(c) M_y Monopile



(d) M_z Monopile

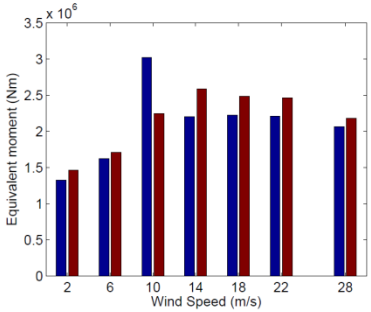
Misalignment 90°

Fore-aft

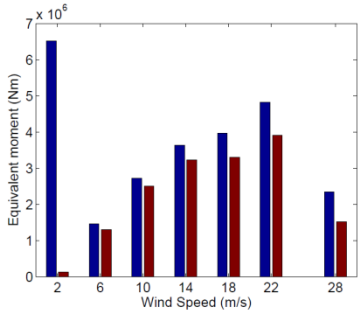


(a) M_y Tower

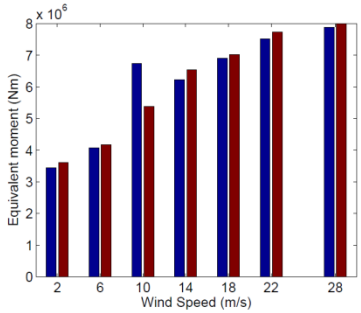
Side-to-side



(b) M_z Tower



(c) M_y Monopile



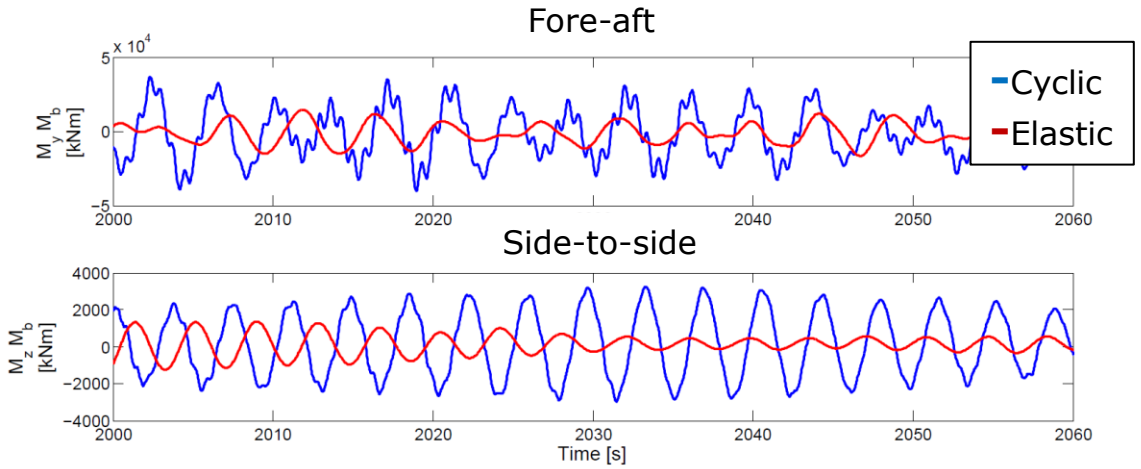
(d) M_z Monopile

Cyclic
p-y

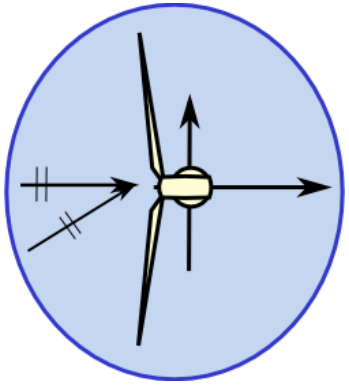
Comparison of the two models

W=2 m/s, *Hs*=1.07m, *Tp*=6.3s, 0°

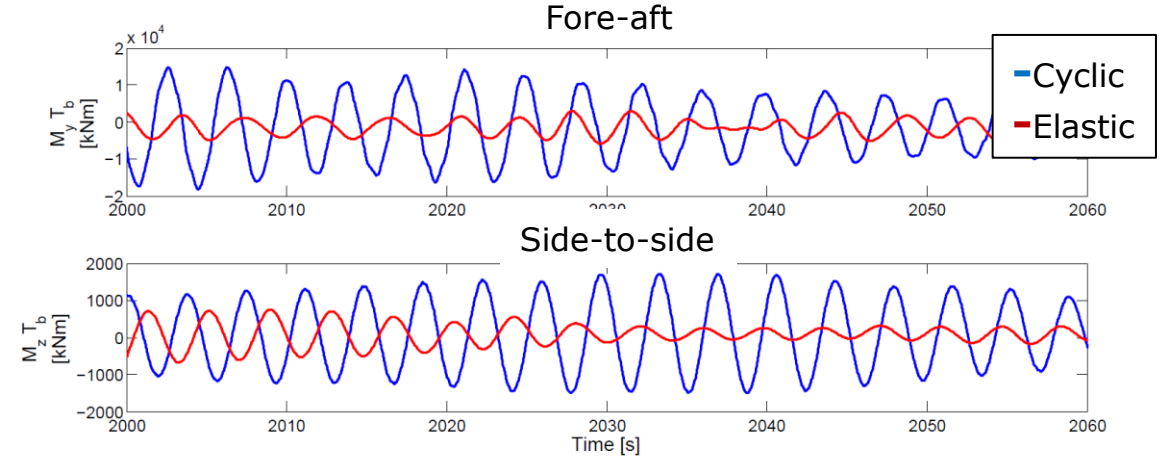
Tower bottom

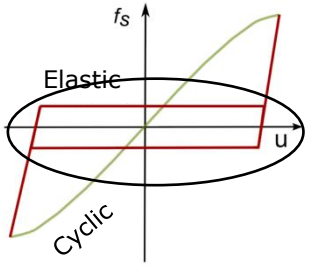


Wave direction: 0°

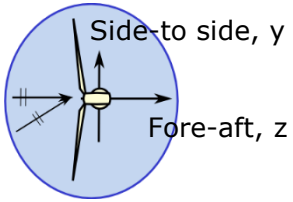


Monopile bottom



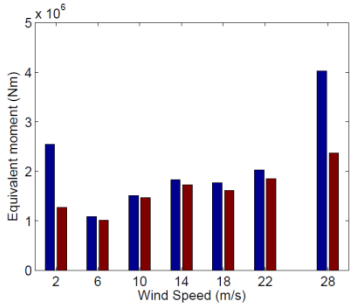


Equivalent loads
Both models



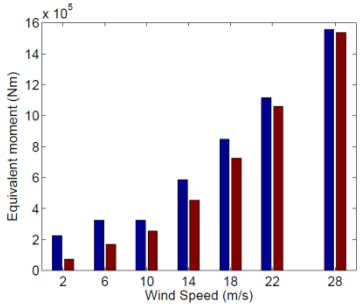
0°

Fore-aft

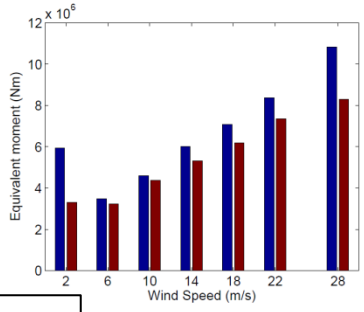


(a) M_y Tower

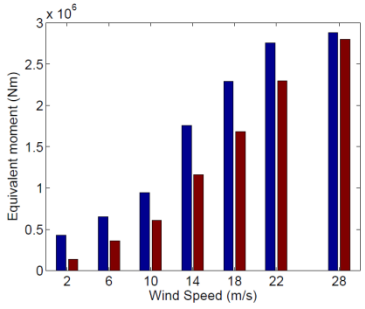
Side-to-side



(b) M_z Tower



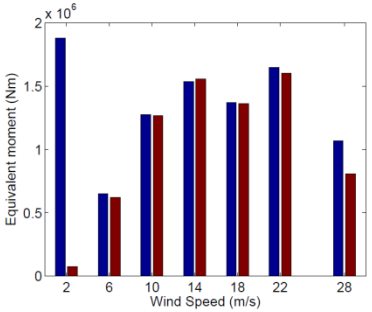
(c) M_y Monopile



(d) M_z Monopile

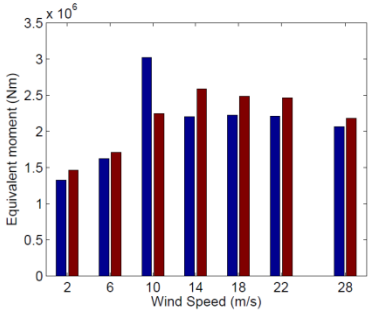
90°

Fore-aft

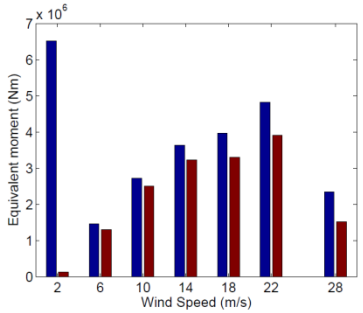


(a) M_y Tower

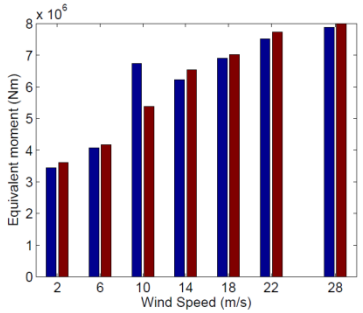
Side-to-side



(b) M_z Tower



(c) M_y Monopile



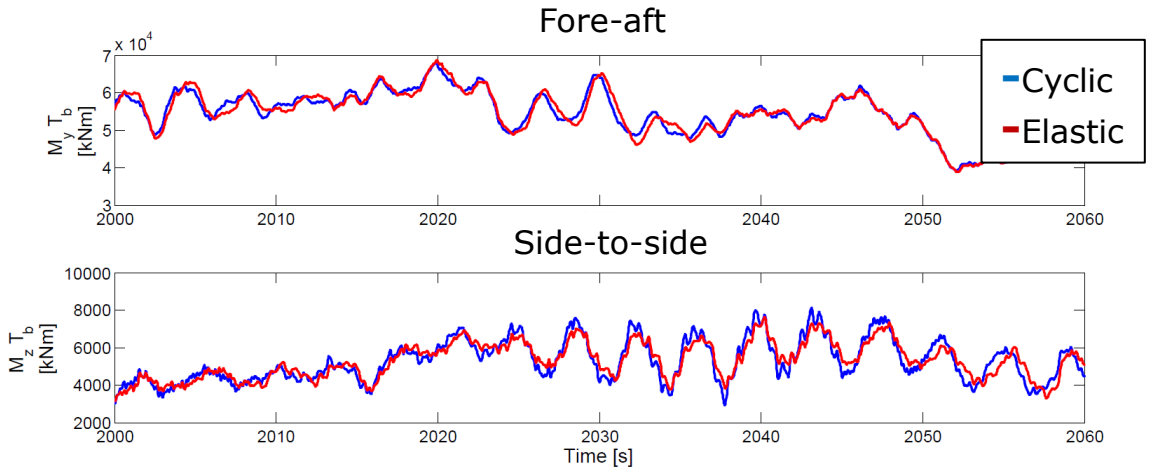
(d) M_z Monopile

- Cyclic
- *p-y*

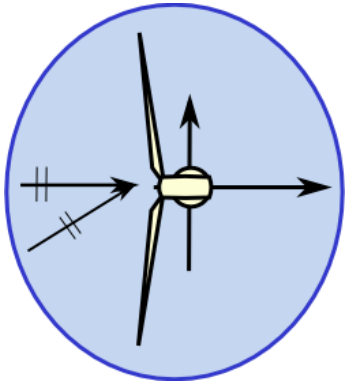
Comparison of the two models

W=10 m/s, *Hs*=1.48m, *Tp*=5.74s, 0°

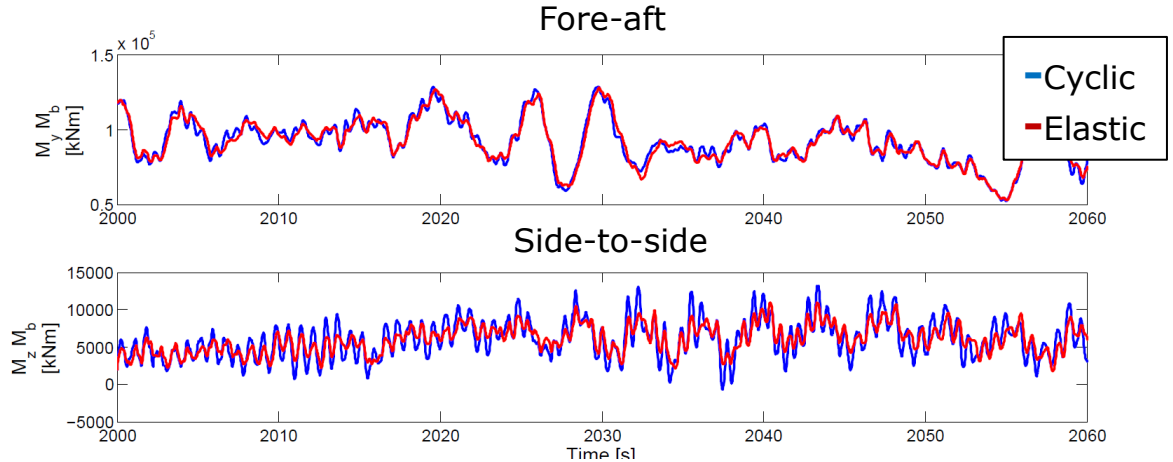
Tower bottom

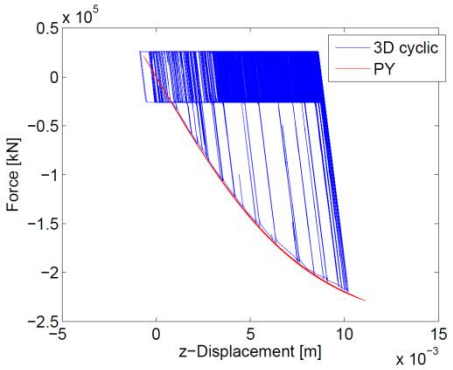


Wave direction: 0°



Monopile bottom

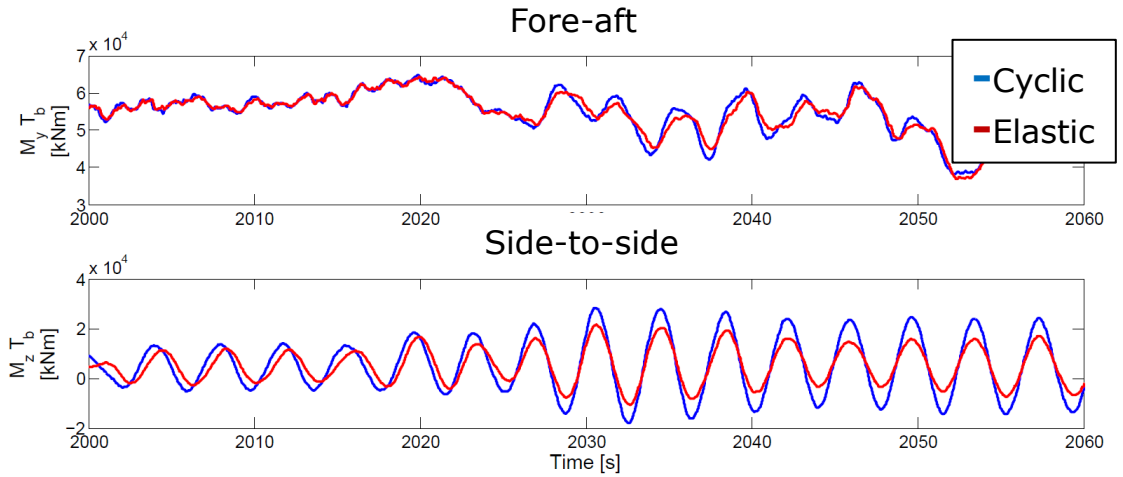




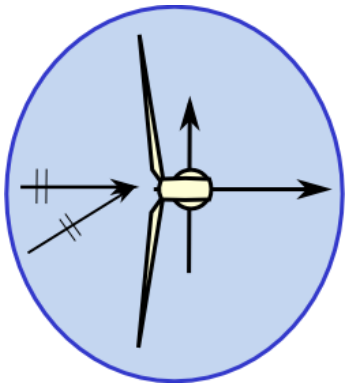
Comparison of the two models

W=10 m/s, *Hs*=1.48m, *Tp*=5.74s, 90°

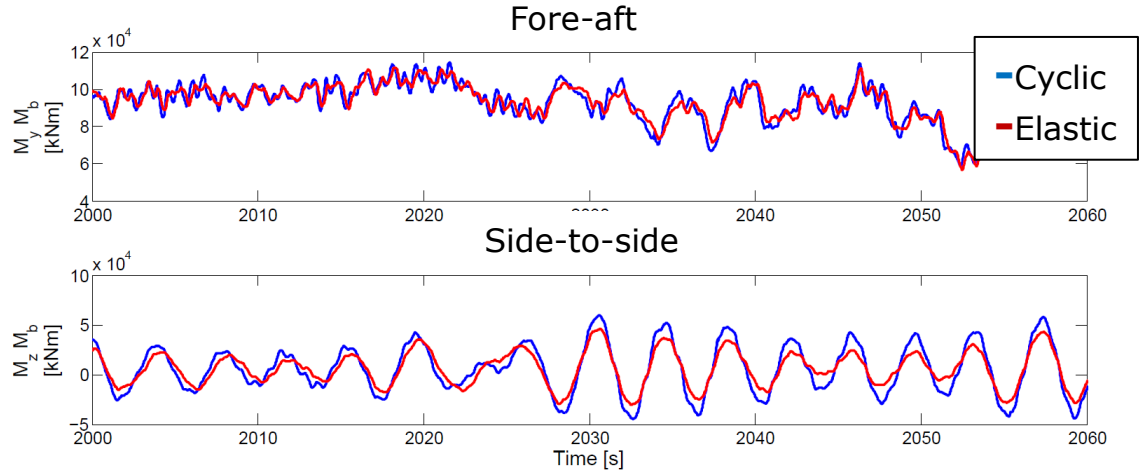
Tower bottom



Wave direction: 90°



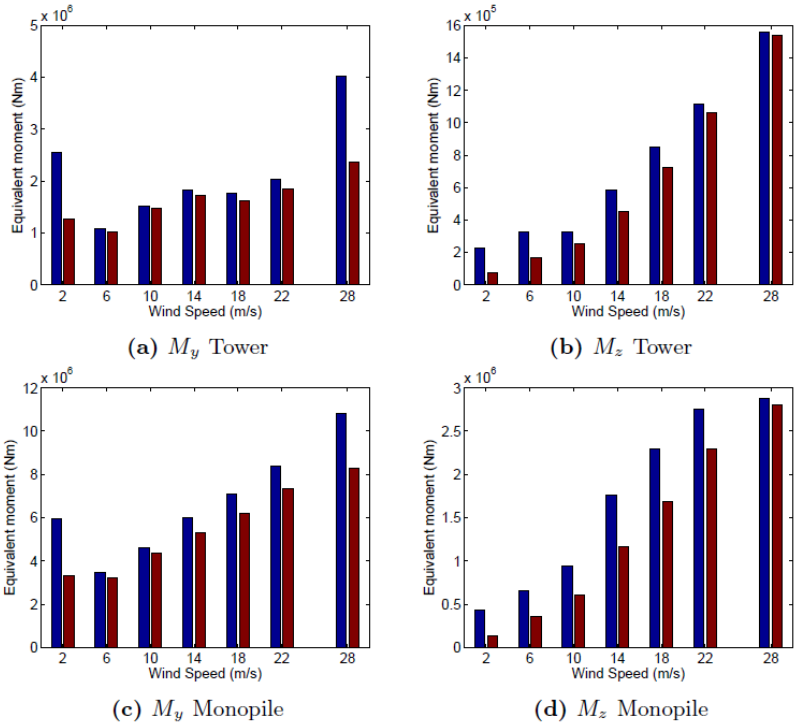
Monopile bottom



Equivalent loads

Both models

0°



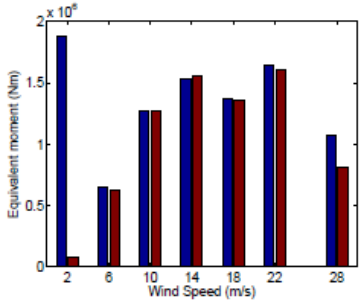
(a) M_y Tower

(b) M_z Tower

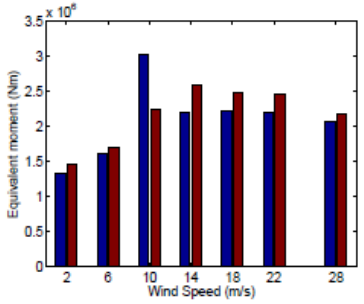
(c) M_y Monopile

(d) M_z Monopile

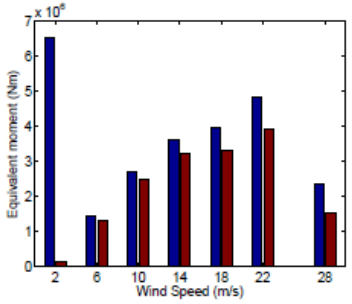
90°



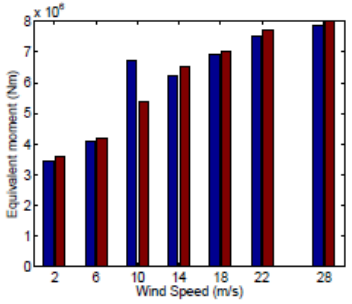
(a) M_y Tower



(b) M_z Tower



(c) M_y Monopile

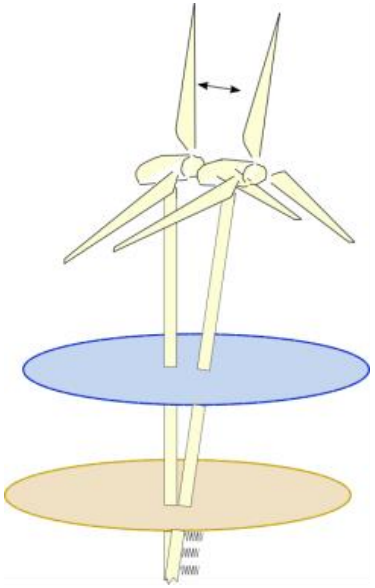


(d) M_z Monopile

Cyclic
Elastic

Conclusions

- Implemented a new soil model in 3D which includes
  - Cyclic pile-soil interaction
  - Hysteretic damping
  - Creations of gap
- Compared with normal p-y model with viscous damping
  - Very small displacements – friction disapears in cyclic model
  - Damping depends on size of the displacements



- Important to calibrate viscous damping in p-y model
- One damping for all wind speeds is not representative