Dynamic behaviour of offshore wind turbines supported on monopiles

Domenico Lombardi & Subhamoy Bhattacharya

Lecturer in Geotechnical Engineering, Edinburgh Napier University
Chair in Geomechanics, University of Surrey

Monday 15th September 2014
International Conference on Offshore Renewable Energy
Glasgow

Content of the presentation

Content of the presentation

- Why 'offshore' wind turbines?

Content of the presentation

- Why 'offshore' wind turbines?
- Why the dynamic behaviour of offshore wind turbines is important?

Content of the presentation

- Why 'offshore' wind turbines?
- Why the dynamic behaviour of offshore wind turbines is important?
- Which are the main design challenges?

Content of the presentation

- Why 'offshore' wind turbines?
- Why the dynamic behaviour of offshore wind turbines is important?
- Which are the main design challenges?
- Present results of tests on scaled model wind turbine supported on monopile

Content of the presentation

- Why 'offshore' wind turbines?
- Why the dynamic behaviour of offshore wind turbines is important?
- Which are the main design challenges?
- Present results of tests on scaled model wind turbine supported on monopile
- Highlight practical implications for the selection of monopile diameter

Content of the presentation

- Why 'offshore' wind turbines?
- Why the dynamic behaviour of offshore wind turbines is important?
- Which are the main design challenges?
- Present results of tests on scaled model wind turbine supported on monopile
- Highlight practical implications for the selection of monopile diameter
- Conclusions

Why **offshore** wind turbines?

European Union climate & energy targets for 2020 (European Union Directive 2009/28/EC:

20% total EU energy consumption from renewable resources

Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009

Why **offshore** wind turbines?

European Union climate & energy targets for 2020 (European Union Directive 2009/28/EC:

20% total EU energy consumption from renewable resources

Offshore wind energy: SWOT analysis

Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009

Why **offshore** wind turbines?

European Union climate & energy targets for 2020 (European Union Directive 2009/28/EC:

20% total EU energy consumption from renewable resources

Offshore wind energy: SWOT analysis

- **S**trength: stronger and more stable wind conditions, higher capacity factors, offshore sites;
- **W**eaknesses: costs, technical challenges, harsh environmental conditions, new foundation options;
- **O**pportunities: new research areas, investments, new jobs; potential progress in technology, economic growth;
- **T**hreat: long-term performance of offshore wind turbines

Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009

Example of technical challenges in the *Atlantic Array project*

Essen/Swindon, 26 November 2013, RWE Innogy

Deutsch

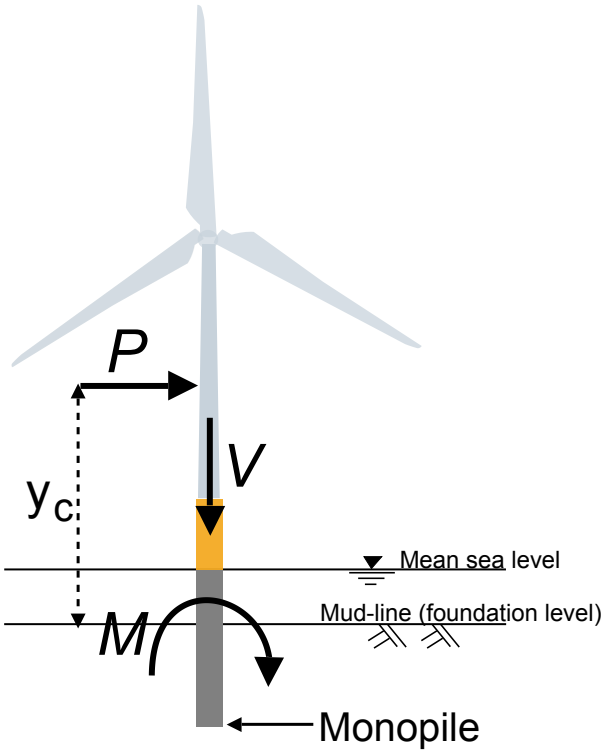
RWE stops development on Atlantic Array due to technical challenges making the project uneconomic at current time

- Technical challenges within the Bristol Channel Zone are significant, including substantially deeper waters and adverse seabed conditions
- Costs to overcome such technical challenges are prohibitive in current market conditions
- RWE to focus on progressing more technically and economically viable offshore projects

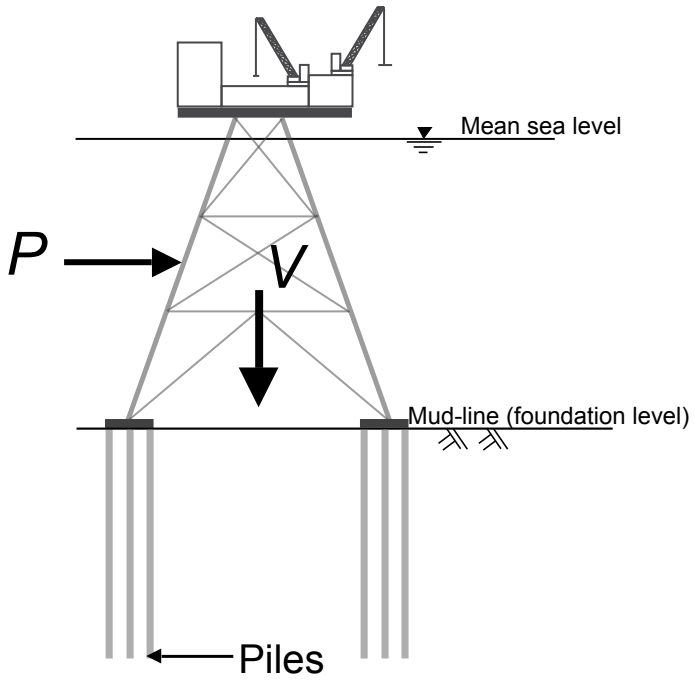
Monopile foundations vs coventional pile foundations

Schematic representation

Offshore wind turbine



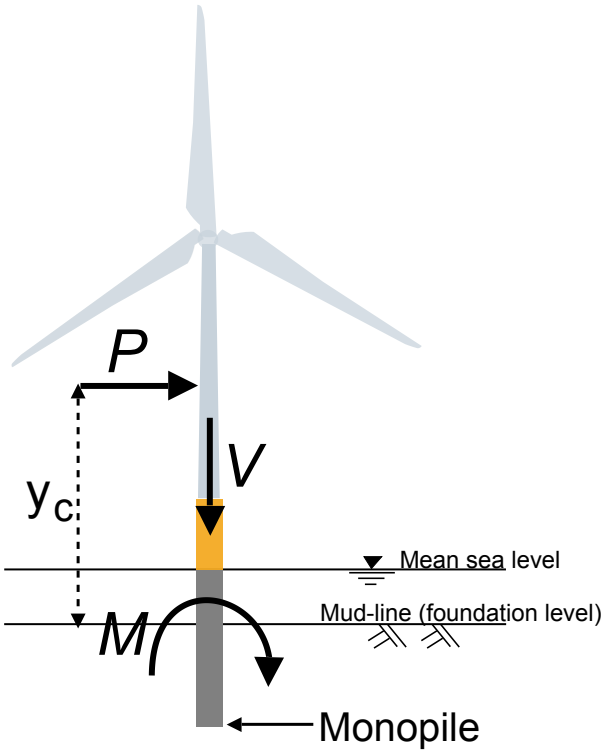
Offshore jacket structure



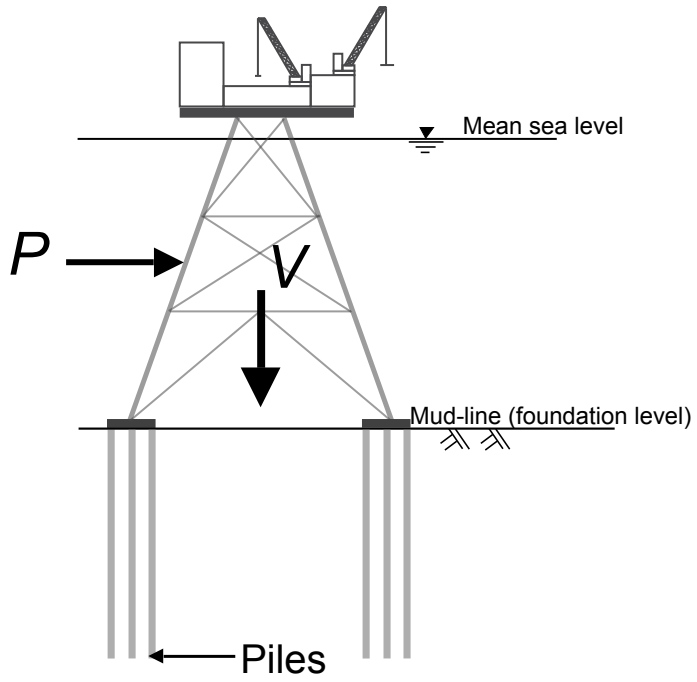
Monopile foundations vs coventional pile foundations

Schematic representation

Offshore wind turbine



Offshore jacket structure



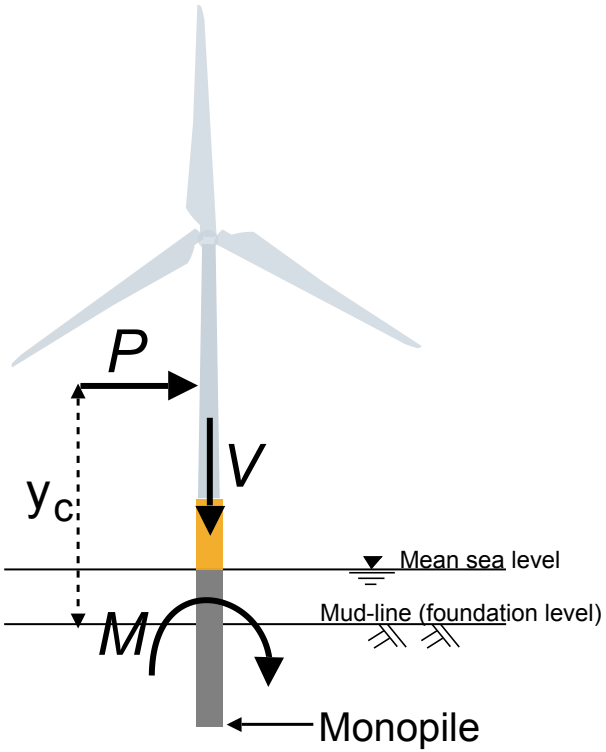
Typical dimensions

$$D = 3.5 - 6.0m \qquad \frac{L}{D} = 5 - 8$$
$$L = 20 - 30m$$

Monopile foundations vs coventional pile foundations

Schematic representation

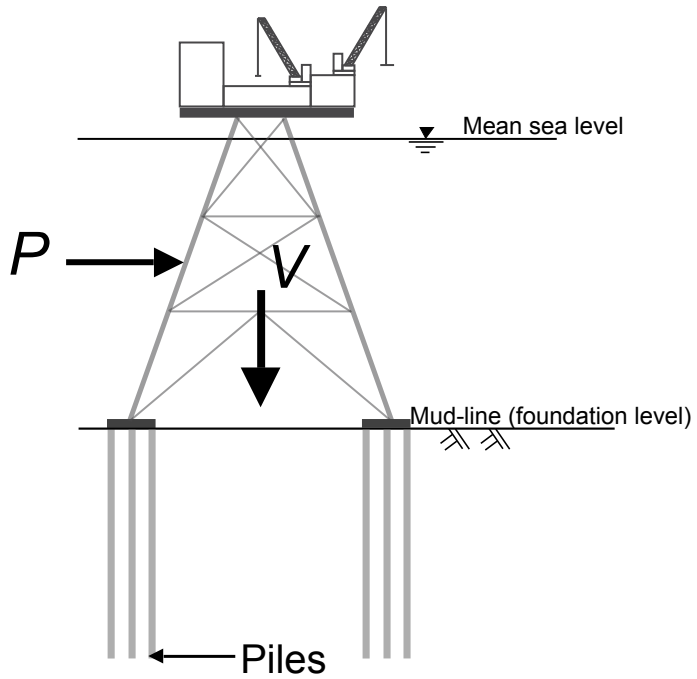
Offshore wind turbine



Typical dimensions

$$D = 3.5 - 6.0m \qquad \frac{L}{D} = 5 - 8$$
$$L = 20 - 30m$$

Offshore jacket structure



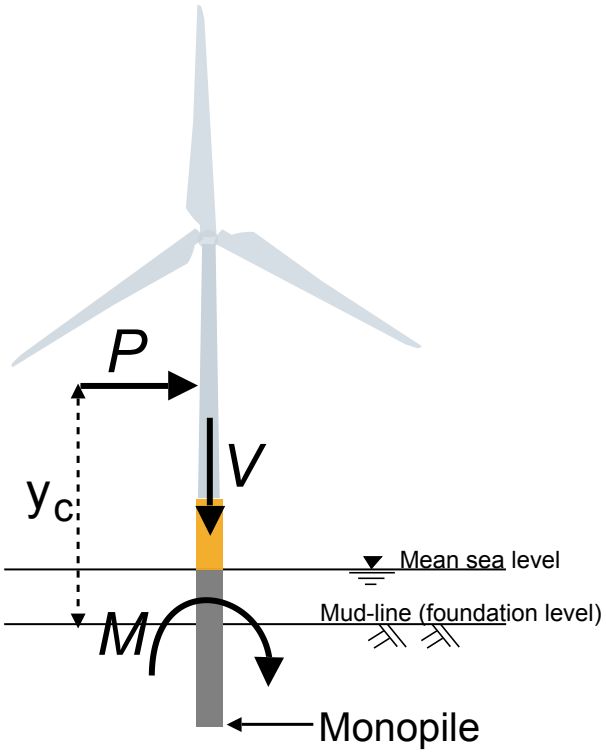
Typical dimensions

$$D = 1.5 - 3.0m \qquad \frac{L}{D} = 10 - 70$$
$$L = 60 - 110m$$

Monopile foundations vs coventional pile foundations

Schematic representation

Offshore wind turbine

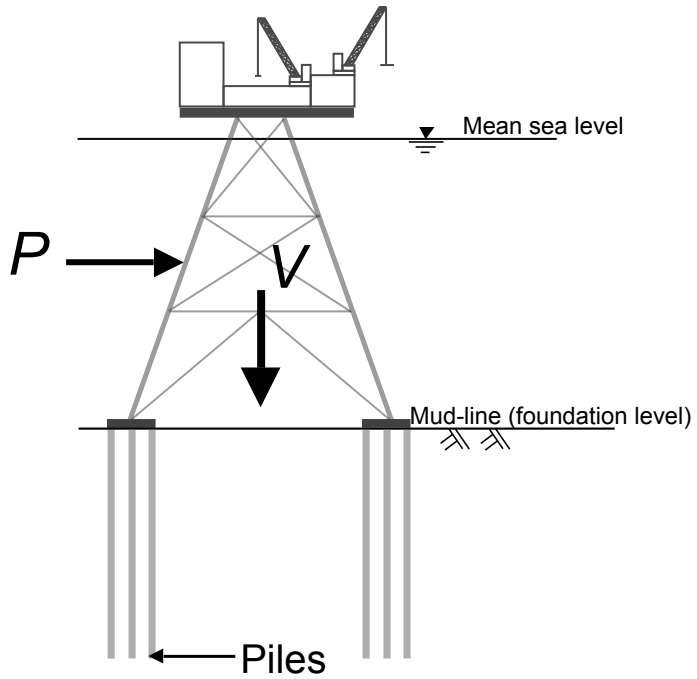


Typical dimensions

$$D = 3.5 - 6.0m \qquad \frac{L}{D} = 5 - 8$$
$$L = 20 - 30m$$

Rigid (or short pile) behaviour

Offshore jacket structure



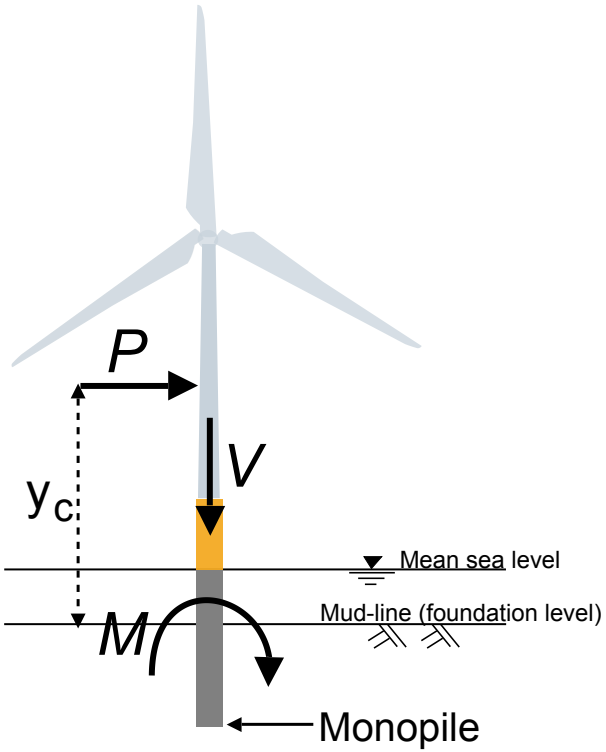
Typical dimensions

$$D = 1.5 - 3.0m \qquad \frac{L}{D} = 10 - 70$$
$$L = 60 - 110m$$

Monopile foundations vs coventional pile foundations

Schematic representation

Offshore wind turbine

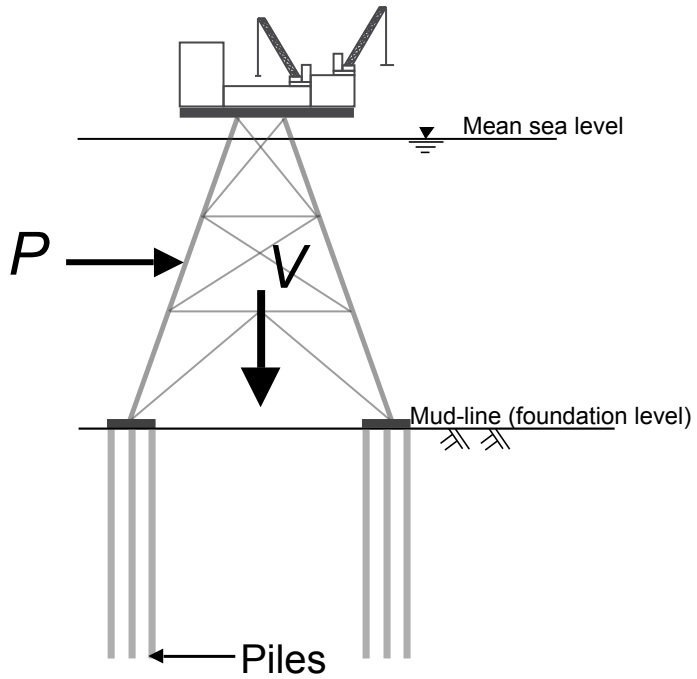


Typical dimensions

$$D = 3.5 - 6.0m \qquad L = 20 - 30m \qquad \frac{L}{D} = 5 - 8$$

Rigid (or short pile) behaviour

Offshore jacket structure



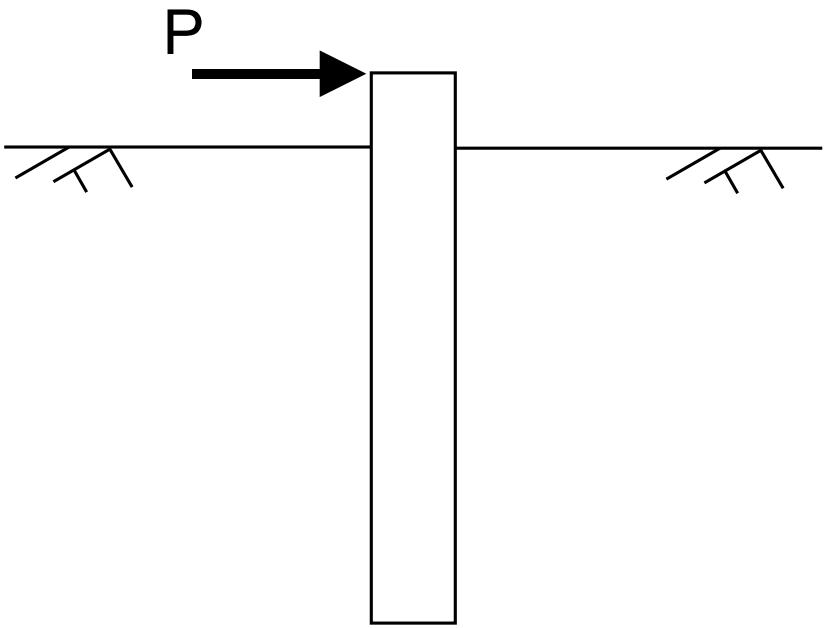
Typical dimensions

$$D = 1.5 - 3.0m \qquad L = 60 - 110m \qquad \frac{L}{D} = 10 - 70$$

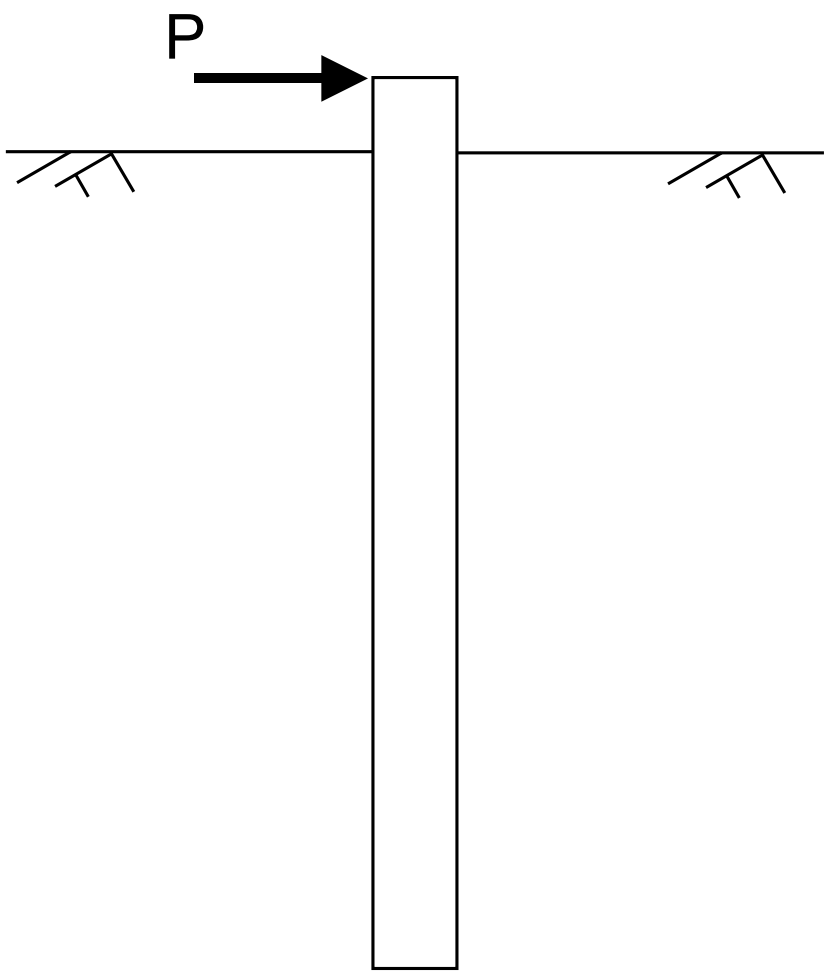
Flexible (or long pile) behaviour

Flexible and rigid behaviour of laterally loaded piles

Rigid failure mode

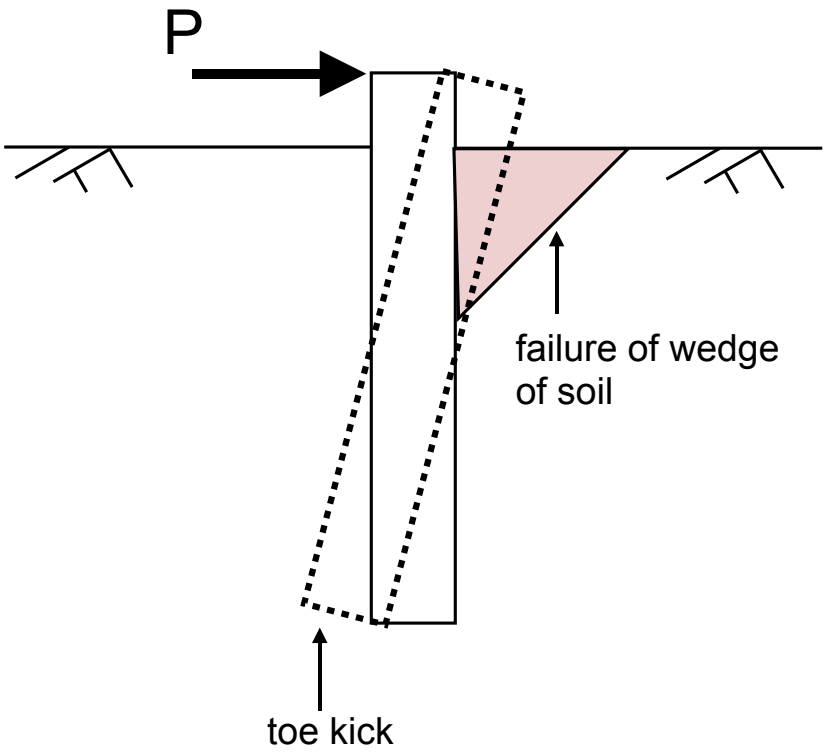


Flexible failure mode

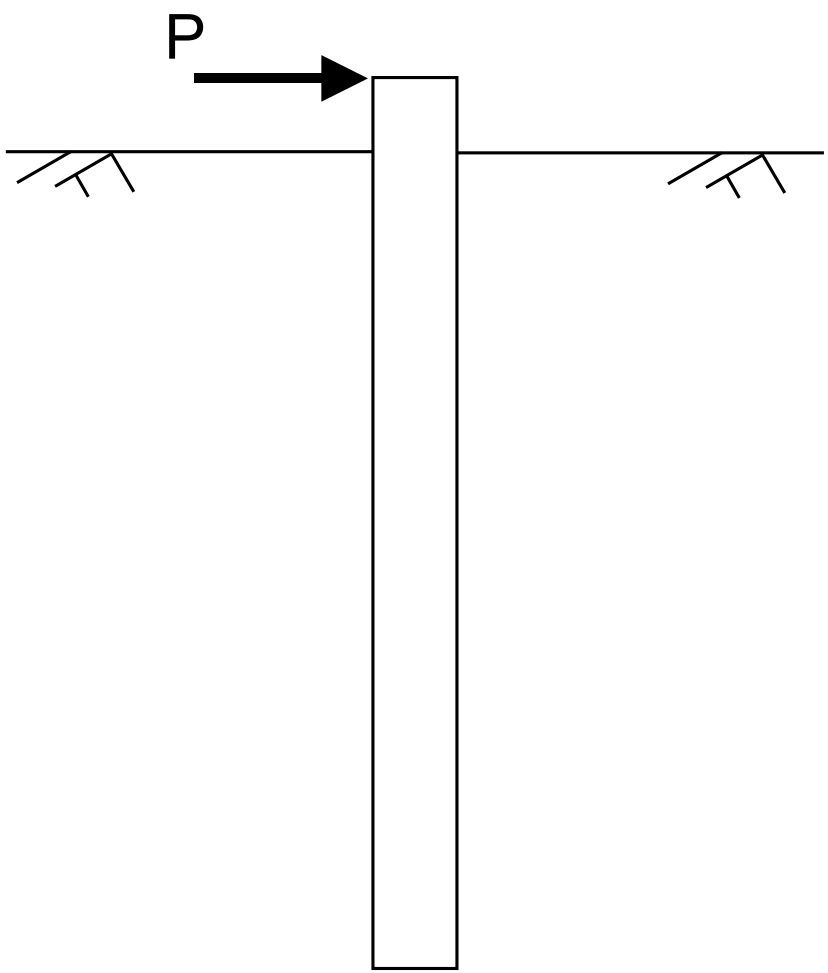


Flexible and rigid behaviour of laterally loaded piles

Rigid failure mode

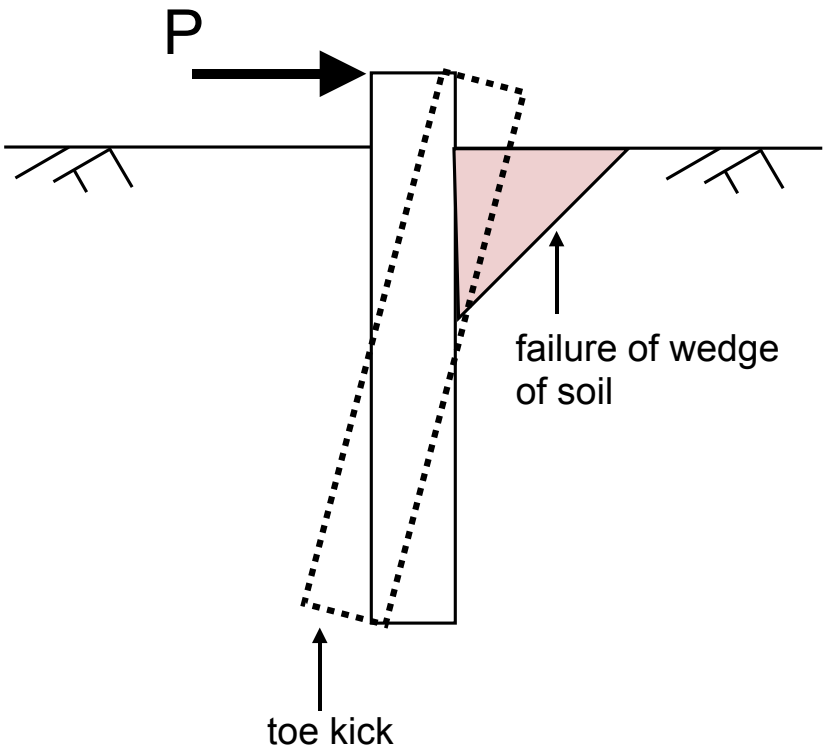


Flexible failure mode

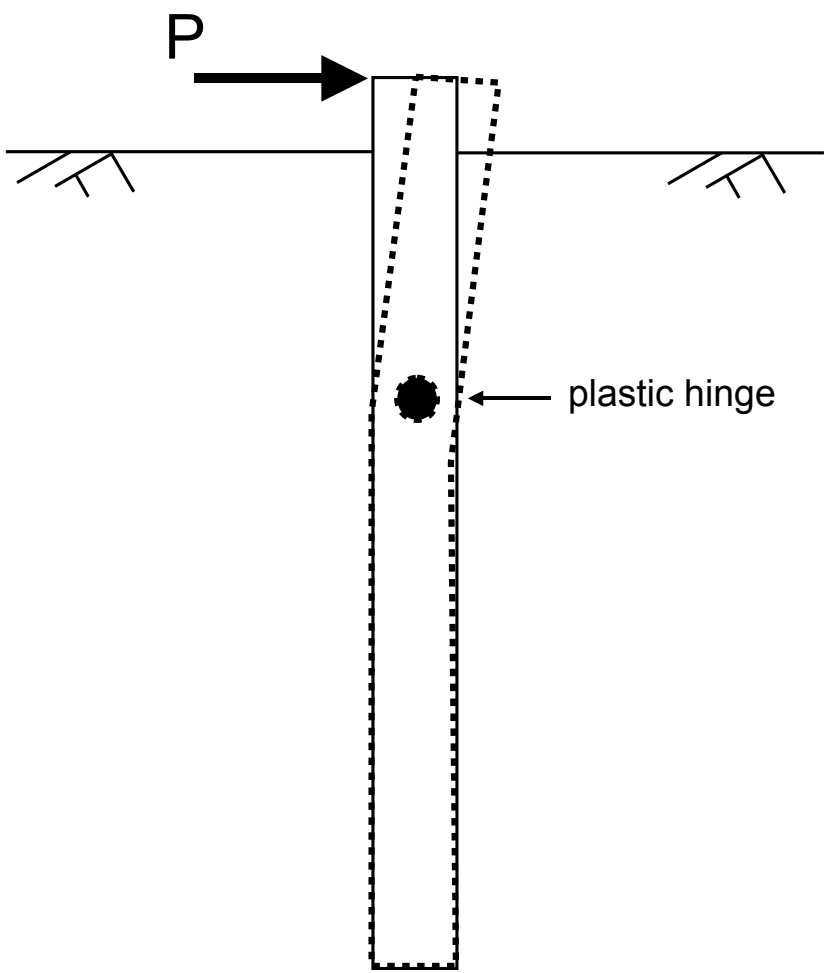


Flexible and rigid behaviour of laterally loaded piles

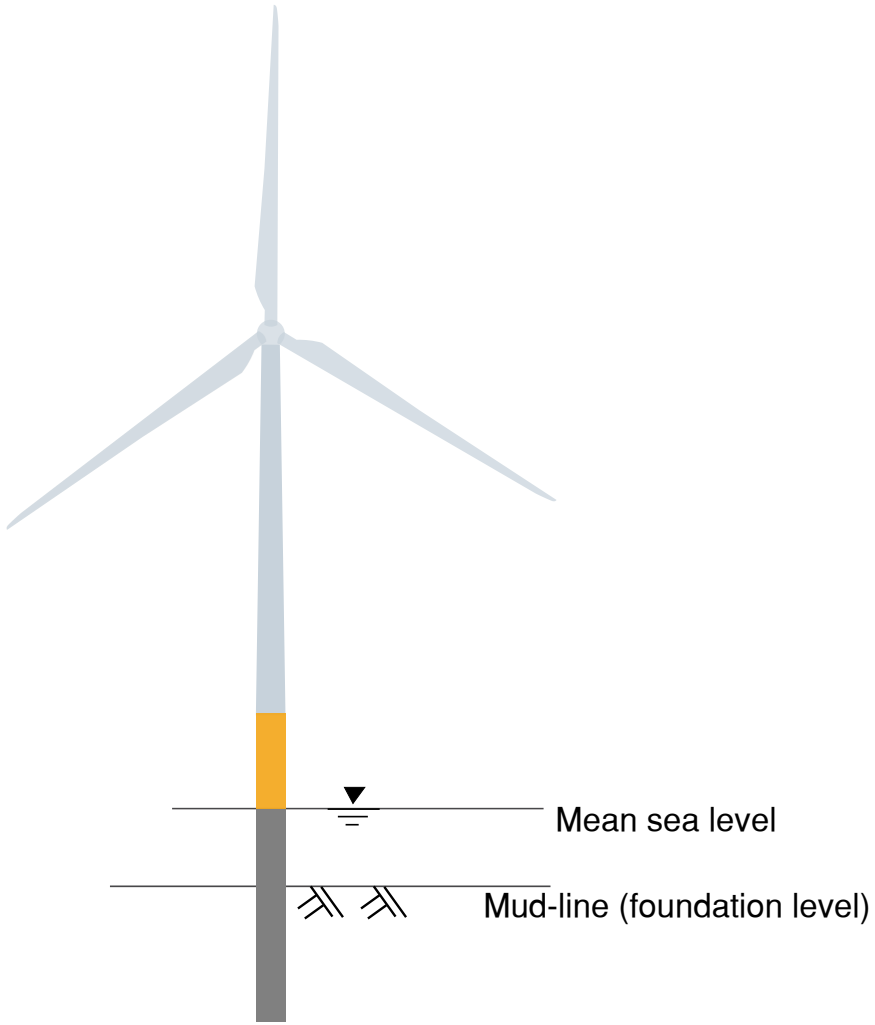
Rigid failure mode



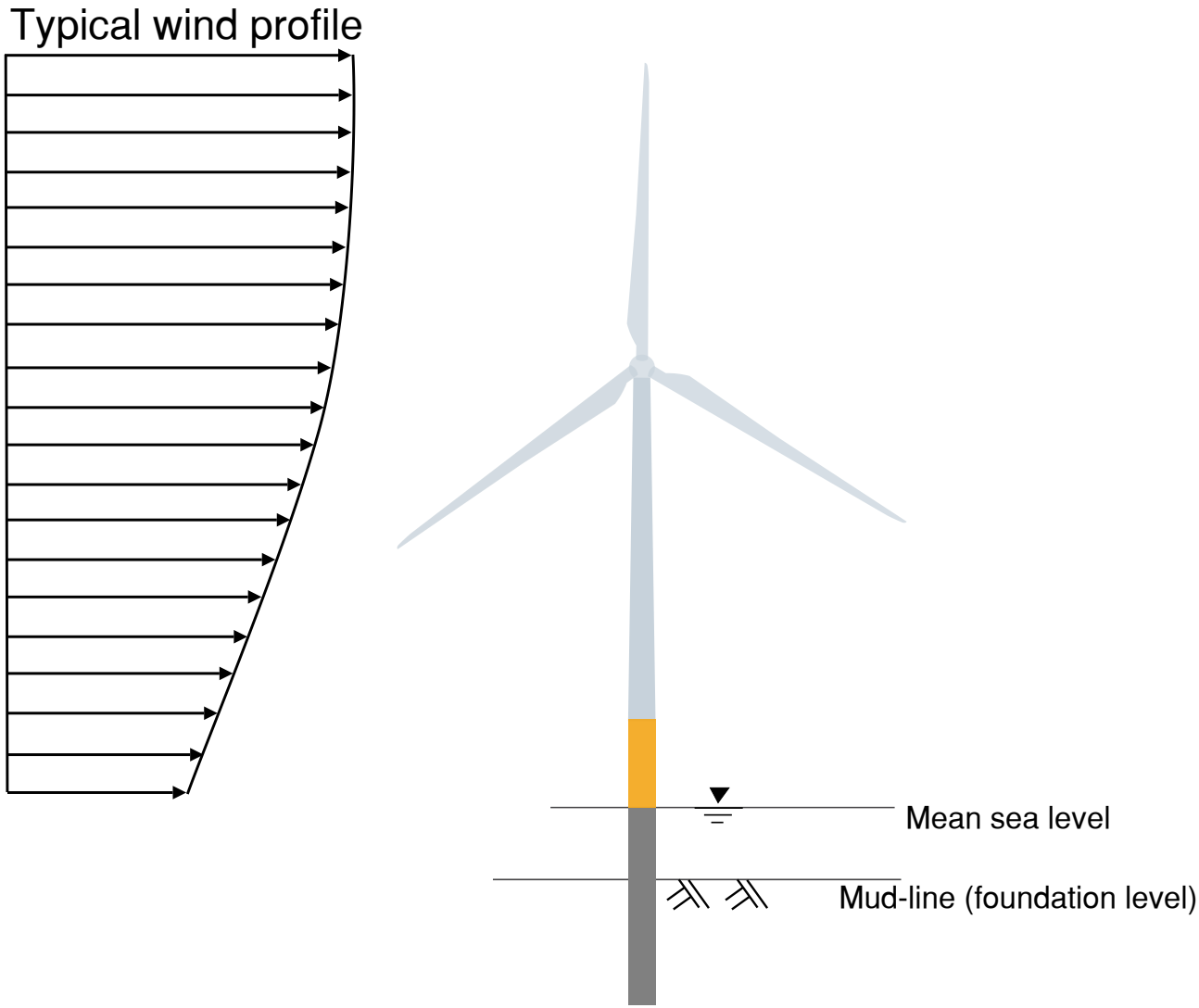
Flexible failure mode



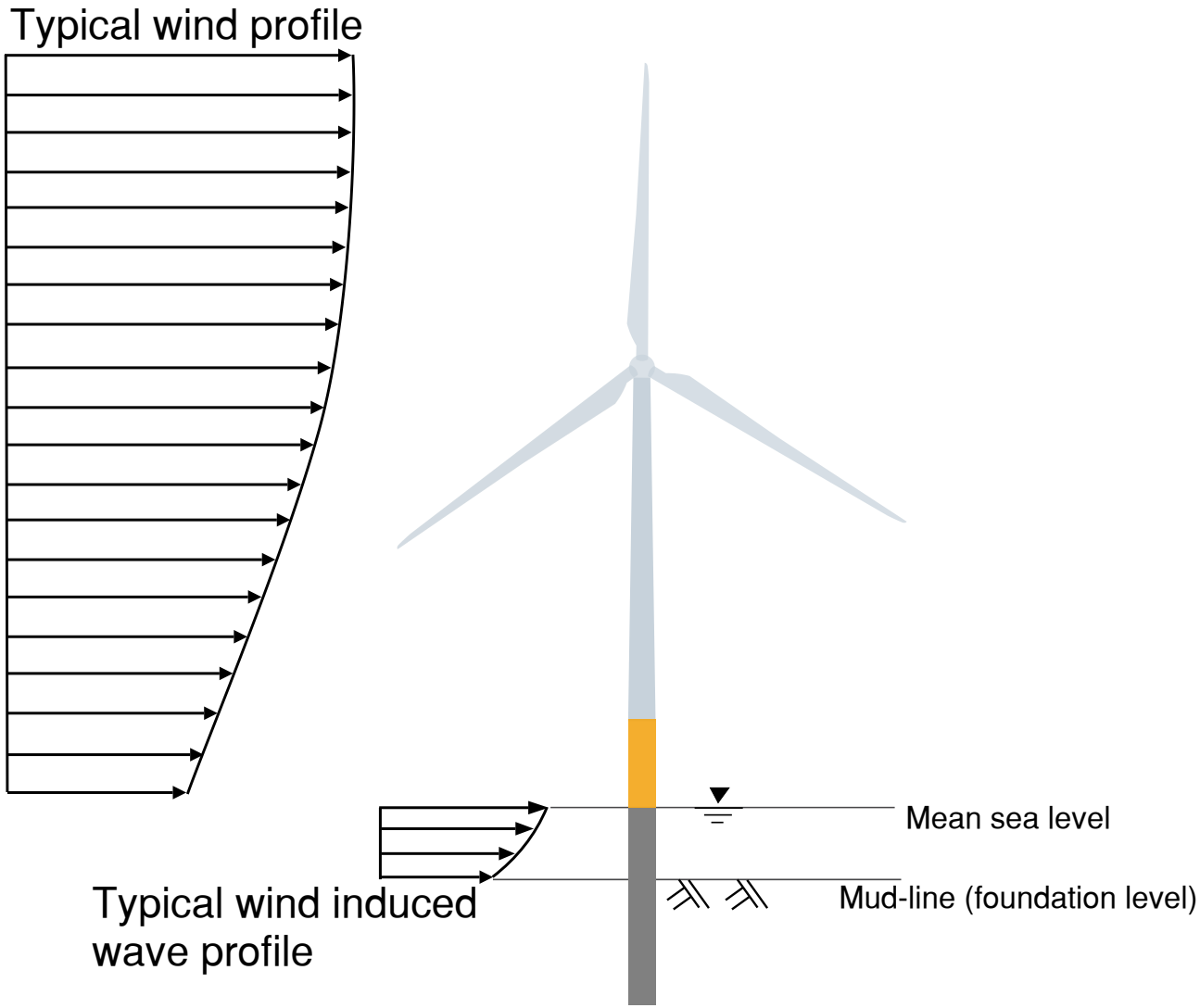
Simplified loading conditions



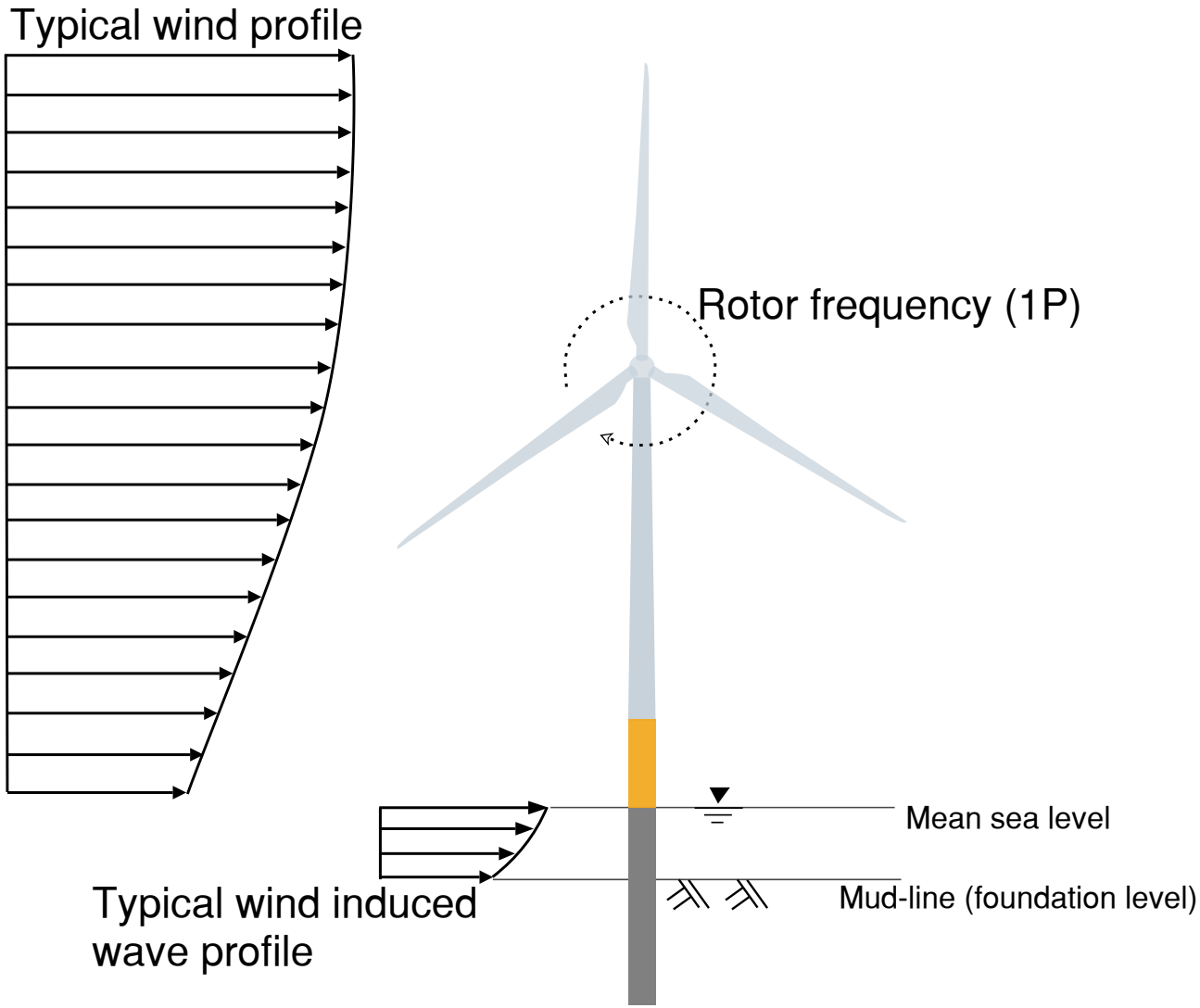
Simplified loading conditions



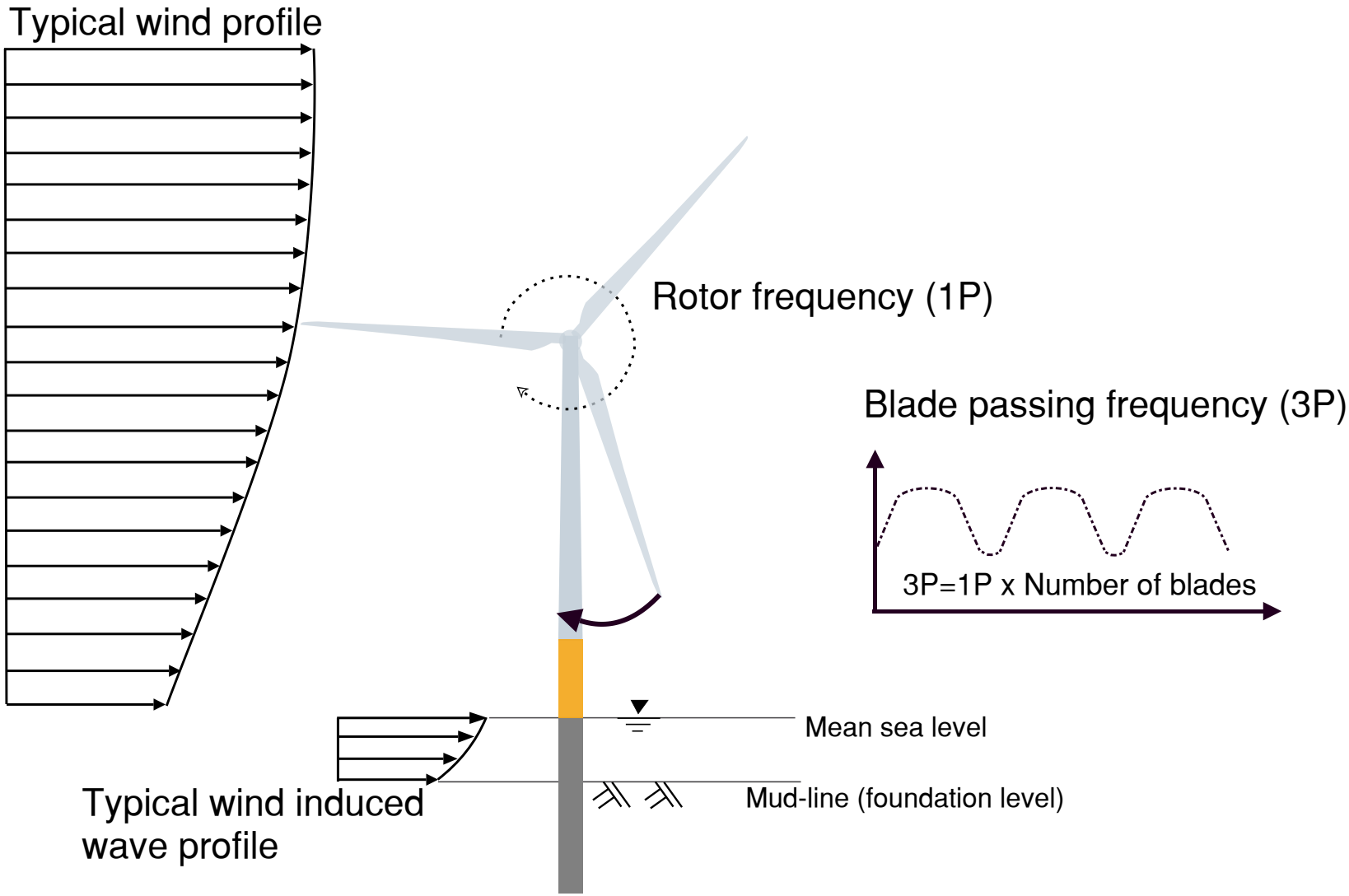
Simplified loading conditions



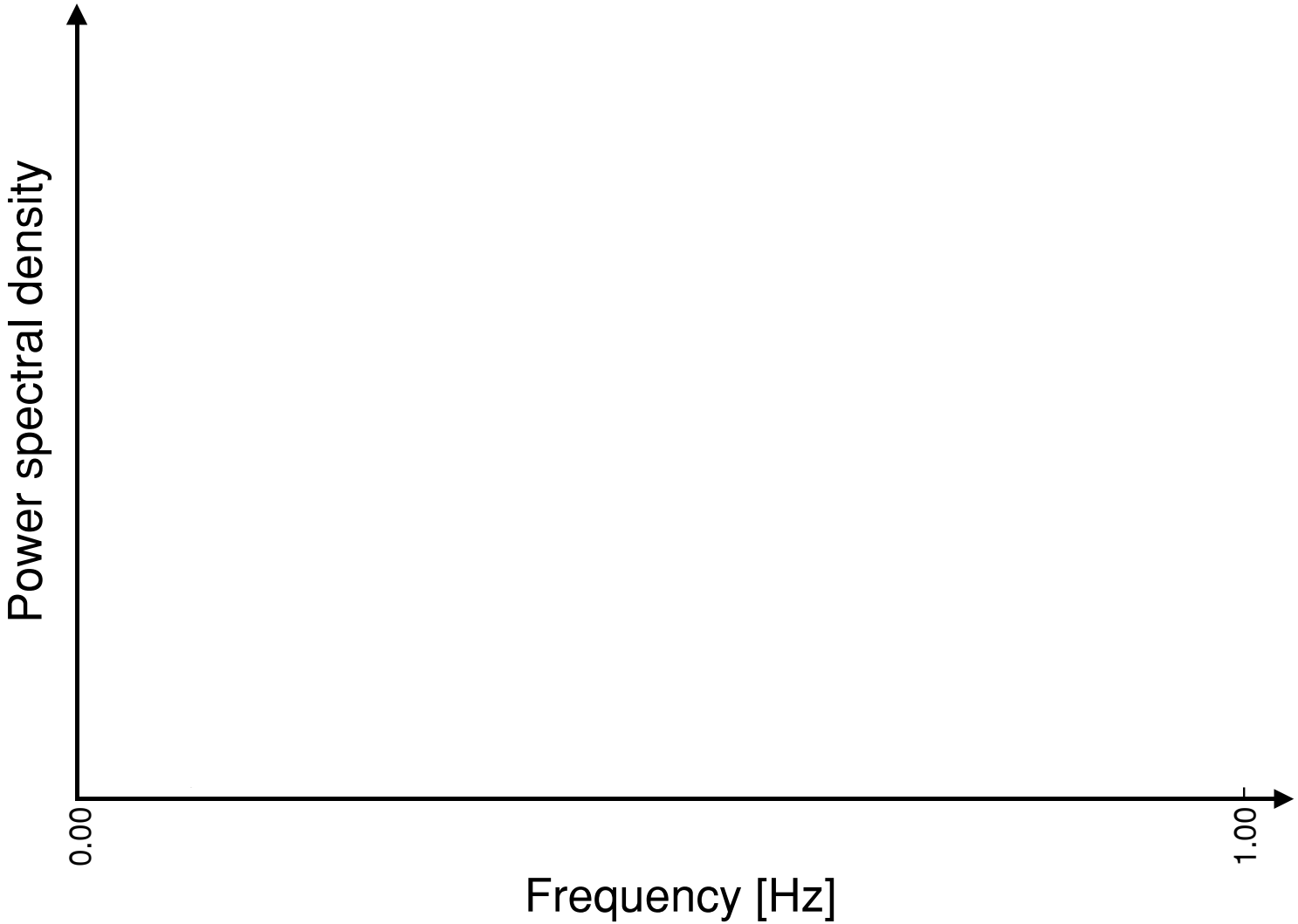
Simplified loading conditions



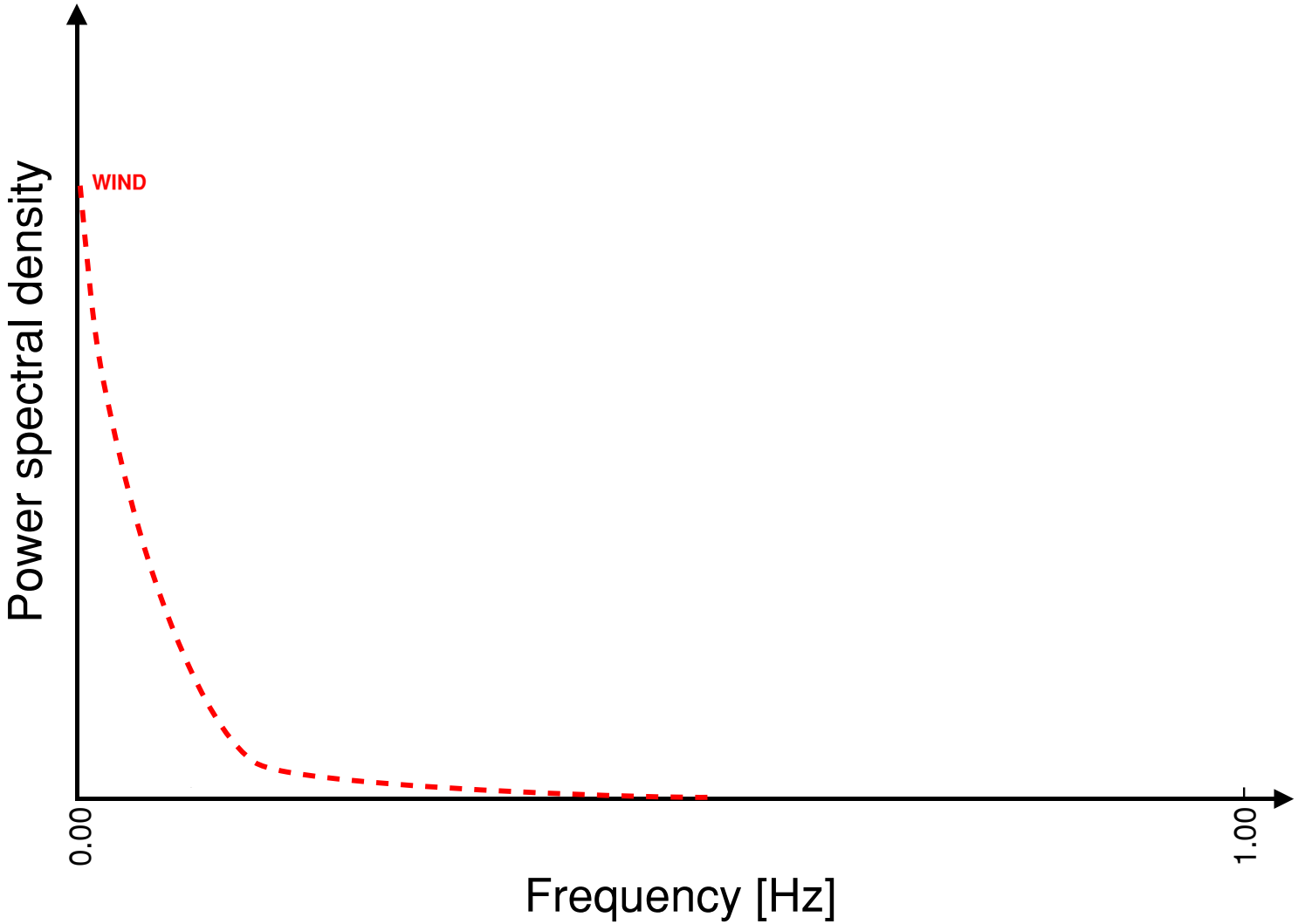
Simplified loading conditions



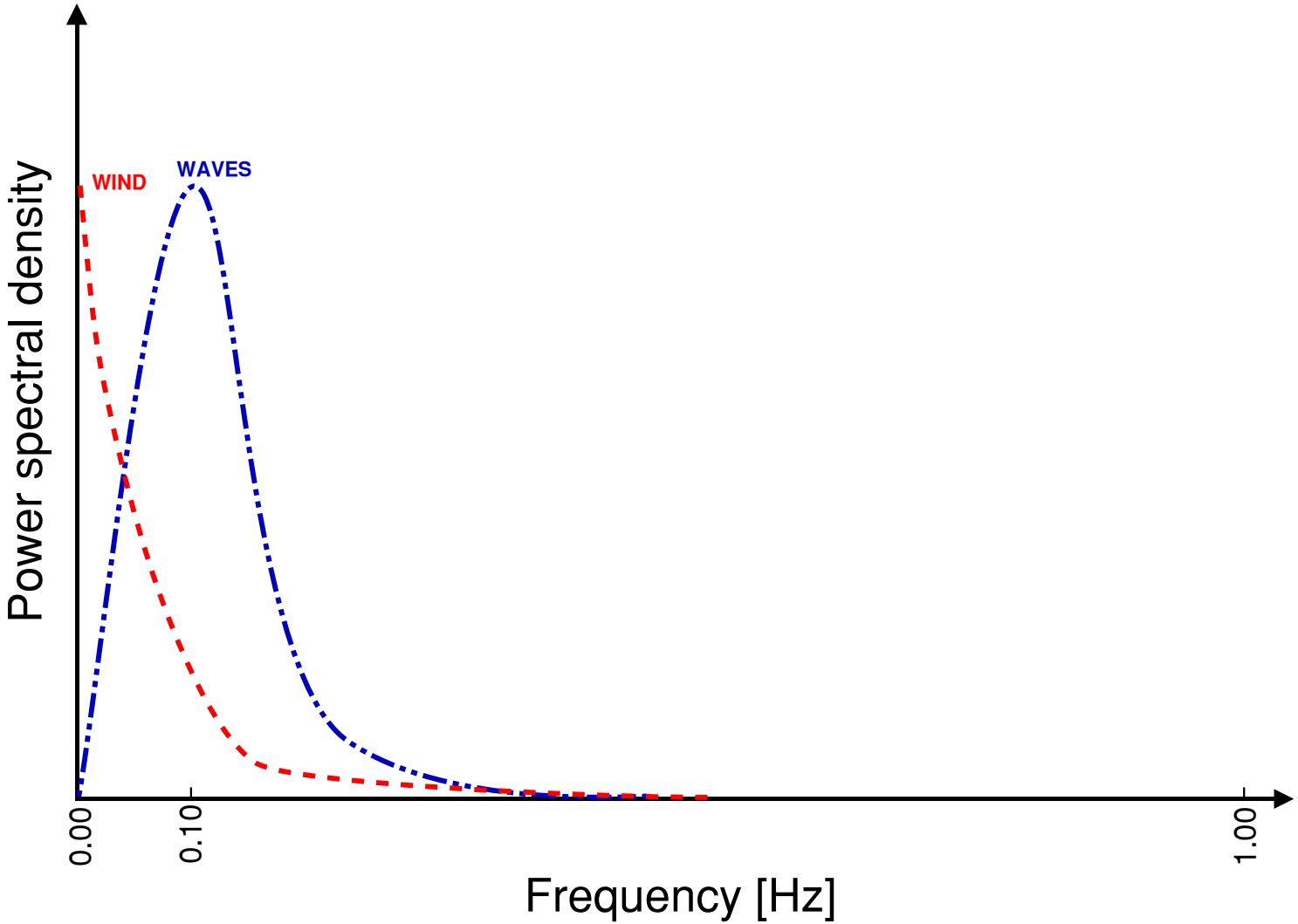
Current design approach



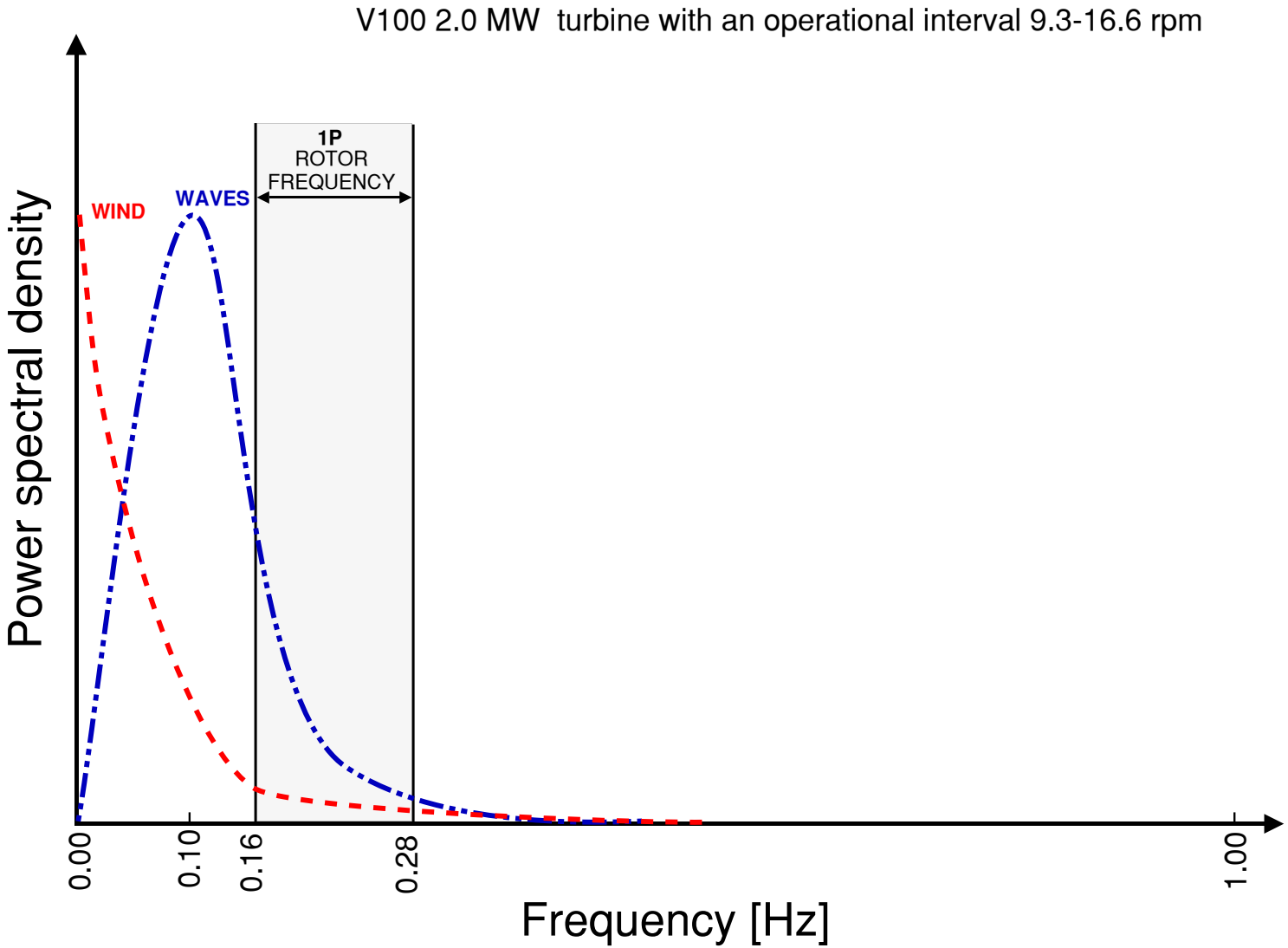
Current design approach



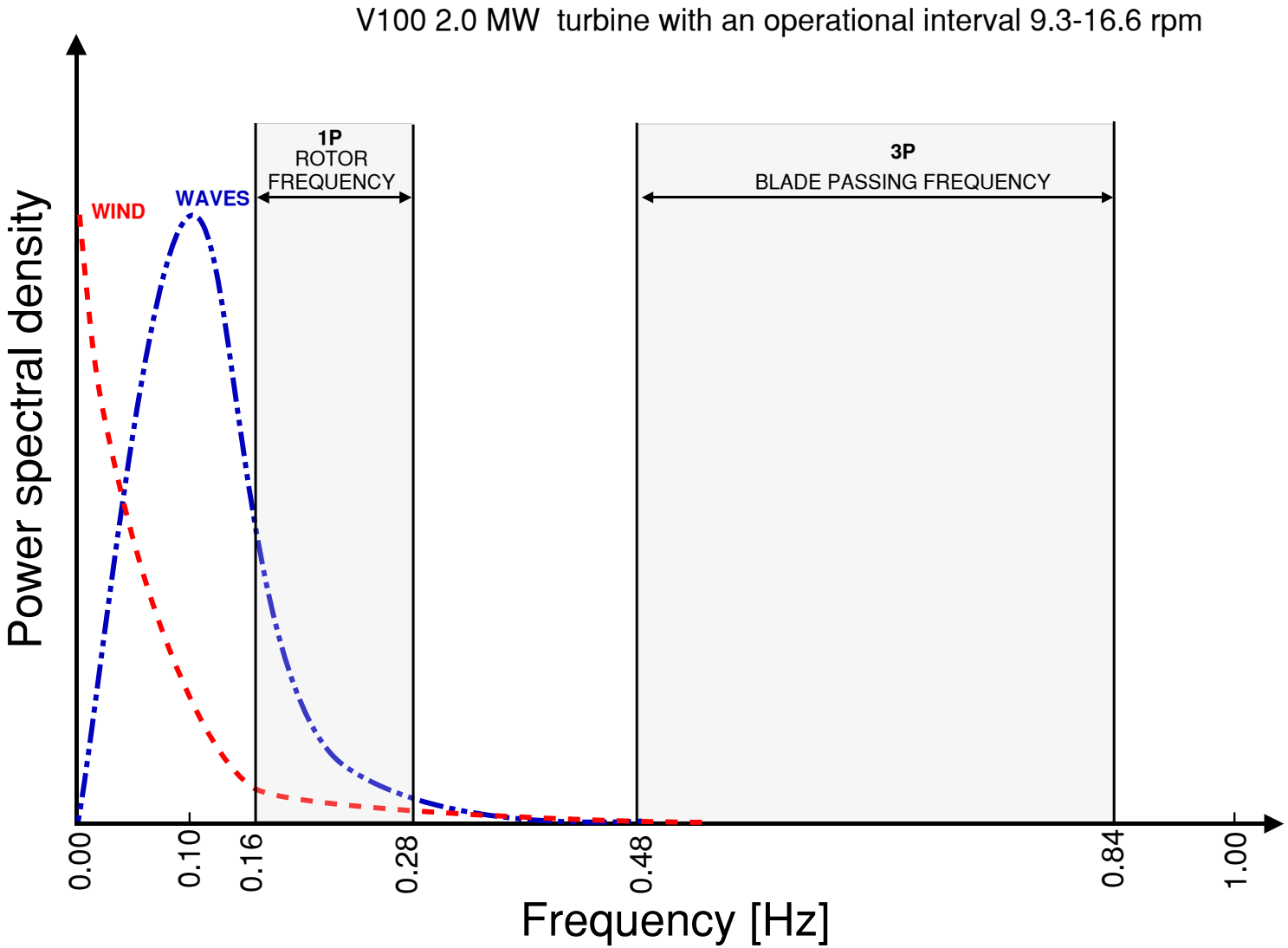
Current design approach



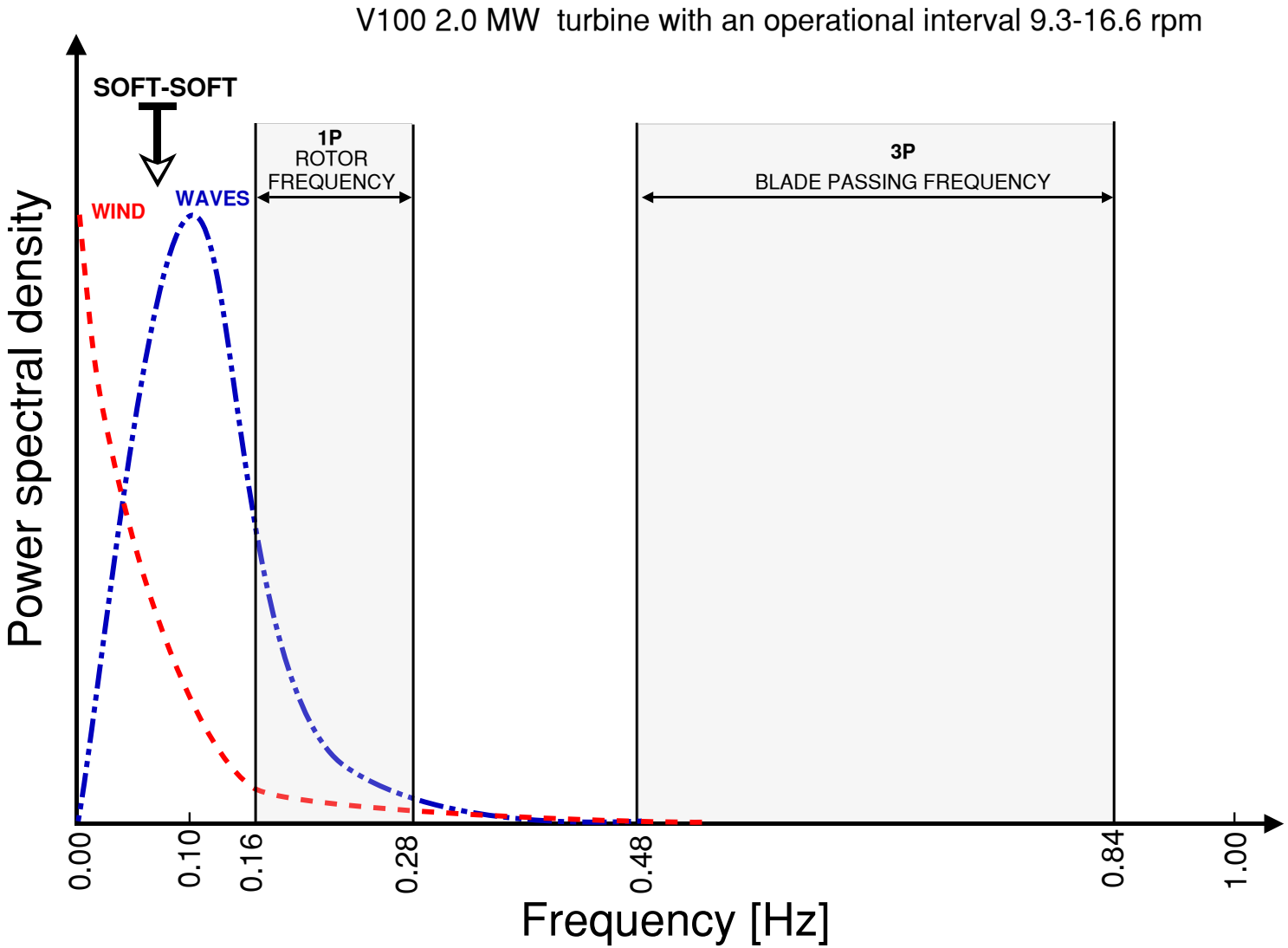
Current design approach



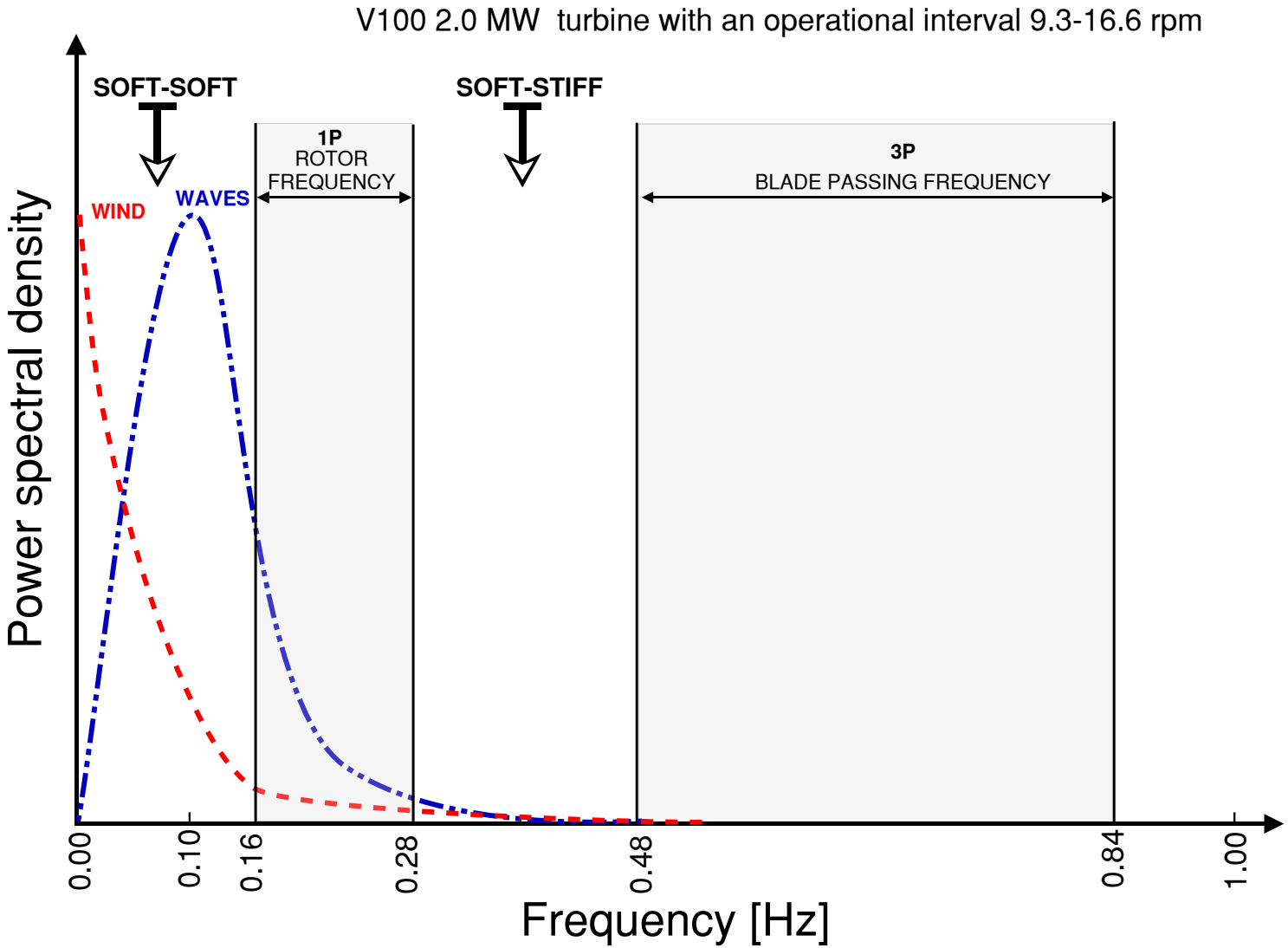
Current design approach



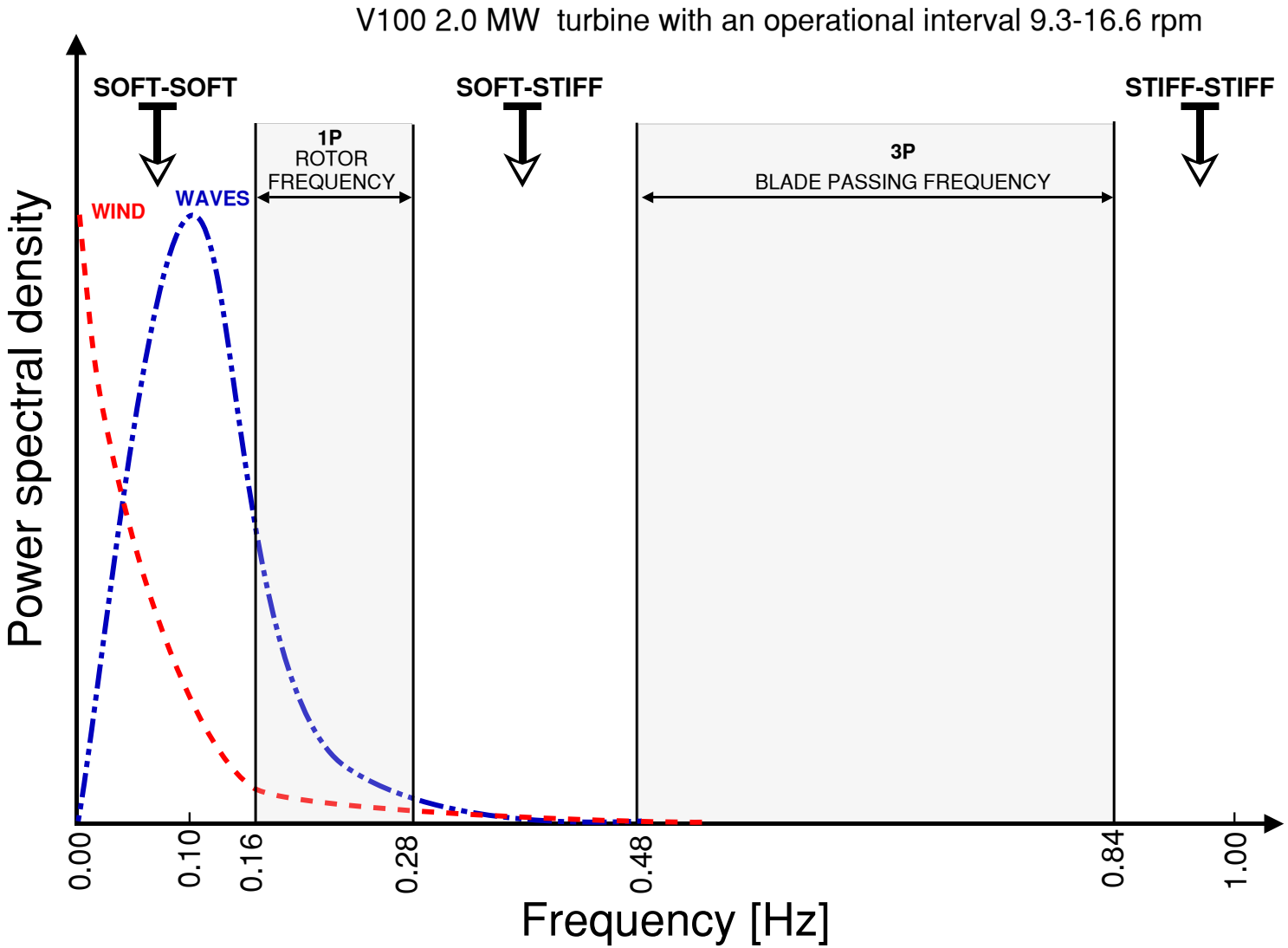
Current design approach



Current design approach



Current design approach



Design challenges

Design challenges

- Accurate assessment of natural frequency of the turbine is required;

Design challenges

- Accurate assessment of natural frequency of the turbine is required;
- Natural frequency is dependent on the support condition (i.e. foundation flexibility);

Design challenges

- Accurate assessment of natural frequency of the turbine is required;
- Natural frequency is dependent on the support condition (i.e. foundation flexibility);
- Degradation in soil stiffness leads to variation in foundation flexibility and consequently change in natural frequency of the turbine;

Design challenges

- Accurate assessment of natural frequency of the turbine is required;
- Natural frequency is dependent on the support condition (i.e. foundation flexibility);
- Degradation in soil stiffness leads to variation in foundation flexibility and consequently change in natural frequency of the turbine;
- Potential resonance phenomena must be avoided throughout the operational life of the turbine, typically 25 years (10^7-10^8 cycles of loading);

Design challenges

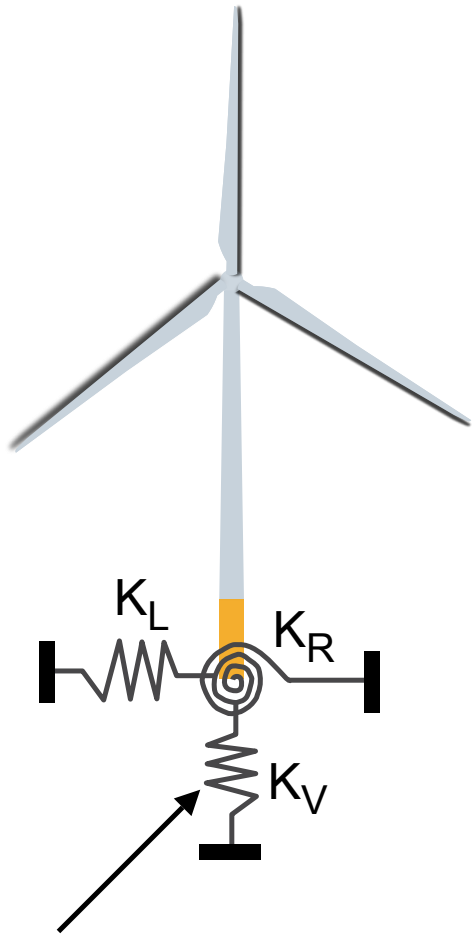
- Accurate assessment of natural frequency of the turbine is required;
- Natural frequency is dependent on the support condition (i.e. foundation flexibility);
- Degradation in soil stiffness leads to variation in foundation flexibility and consequently change in natural frequency of the turbine;
- Potential resonance phenomena must be avoided throughout the operational life of the turbine, typically 25 years (10^7-10^8 cycles of loading);
- Occurrence of resonance phenomena would amplify the dynamic response leading to larger tower deflection and/or rotations;

Design challenges

- Accurate assessment of natural frequency of the turbine is required;
- Natural frequency is dependent on the support condition (i.e. foundation flexibility);
- Degradation in soil stiffness leads to variation in foundation flexibility and consequently change in natural frequency of the turbine;
- Potential resonance phenomena must be avoided throughout the operational life of the turbine, typically 25 years (10^7-10^8 cycles of loading);
- Occurrence of resonance phenomena would amplify the dynamic response leading to larger tower deflection and/or rotations;
- Long-term performance may be jeopardised;

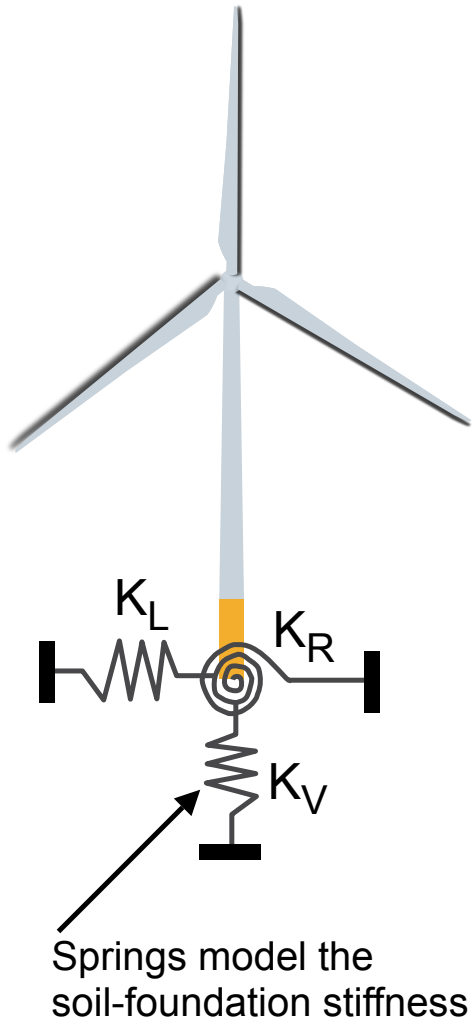
Foundation flexibility: simplified models

Simplified dynamic model

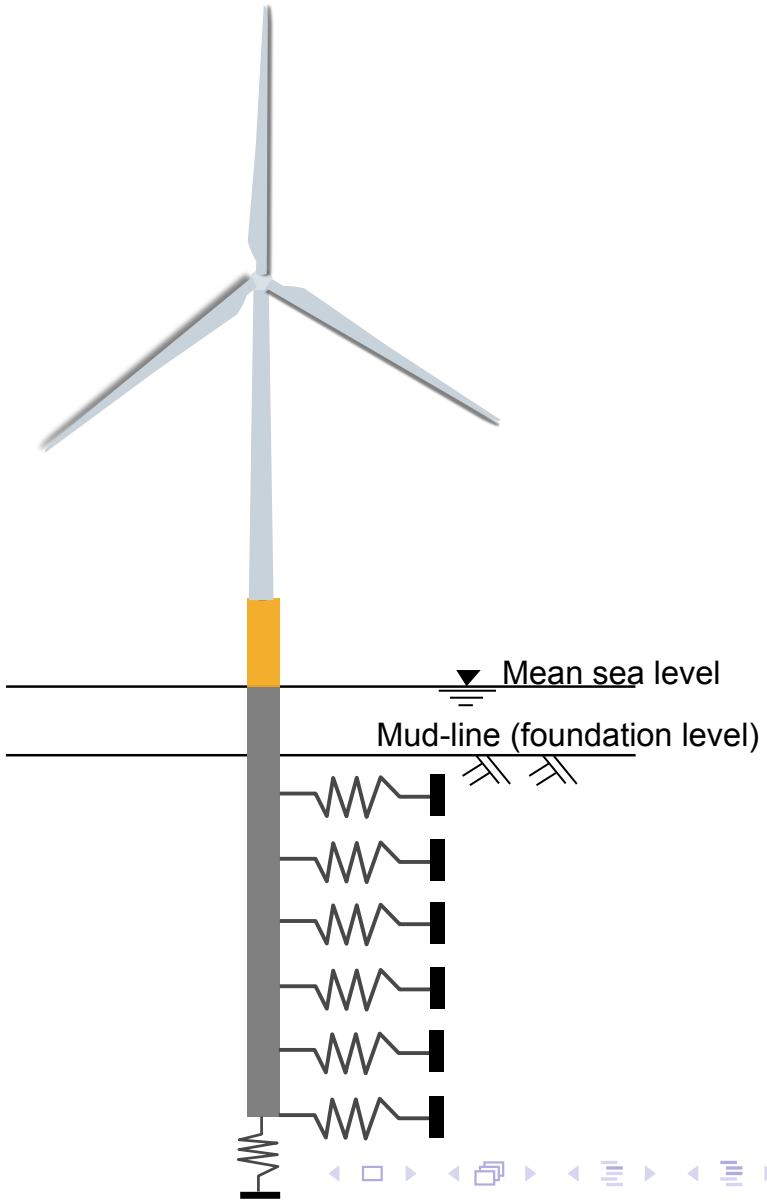


Foundation flexibility: simplified models

Simplified dynamic model



Winkler approach



Variation of foundation flexibility

Variation of foundation flexibility

- Foundation flexibility (i.e. spring stiffness) relies on the stiffness of the surrounding soil;

Variation of foundation flexibility

- Foundation flexibility (i.e. spring stiffness) relies on the stiffness of the surrounding soil;
- When soil is subjected to cyclic loading (for a typical OWT 10^7 - 10^8 cycles), spring stiffness may change as a consequence of soil softening;

Variation of foundation flexibility

- Foundation flexibility (i.e. spring stiffness) relies on the stiffness of the surrounding soil;
- When soil is subjected to cyclic loading (for a typical OWT 10^7 - 10^8 cycles), spring stiffness may change as a consequence of soil softening;
- As a result of the variation in spring stiffness, the natural frequency of the turbine may change over its operational life;

Variation of foundation flexibility

- Foundation flexibility (i.e. spring stiffness) relies on the stiffness of the surrounding soil;
- When soil is subjected to cyclic loading (for a typical OWT 10^7 - 10^8 cycles), spring stiffness may change as a consequence of soil softening;
- As a result of the variation in spring stiffness, the natural frequency of the turbine may change over its operational life;
- Monitoring of a limited number of monopile supported wind turbines has indicated a departure of the overall system dynamics from the design requirements;

Variation of foundation flexibility

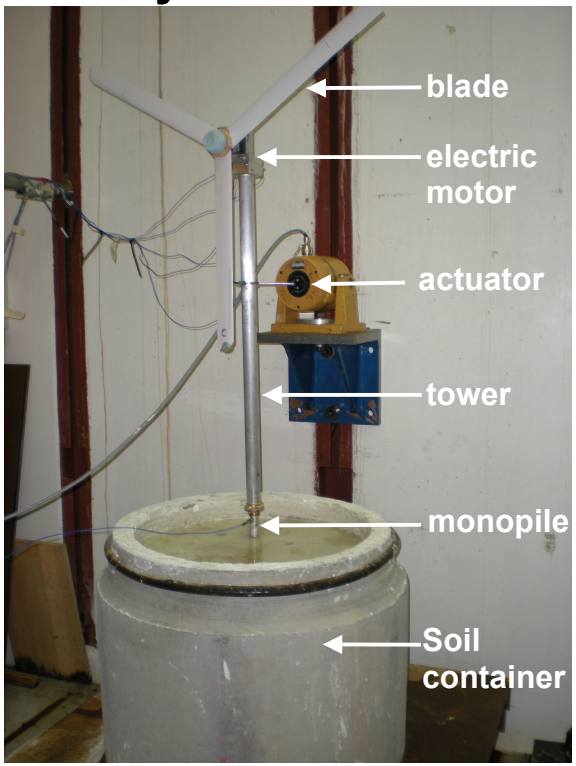
- Foundation flexibility (i.e. spring stiffness) relies on the stiffness of the surrounding soil;
- When soil is subjected to cyclic loading (for a typical OWT 10^7 - 10^8 cycles), spring stiffness may change as a consequence of soil softening;
- As a result of the variation in spring stiffness, the natural frequency of the turbine may change over its operational life;
- Monitoring of a limited number of monopile supported wind turbines has indicated a departure of the overall system dynamics from the design requirements;
- If the natural frequency comes close to any forcing frequencies, resonance phenomena may occur leading to amplification of the system response;

Prototype

Geotechnical physical modelling

Prototype

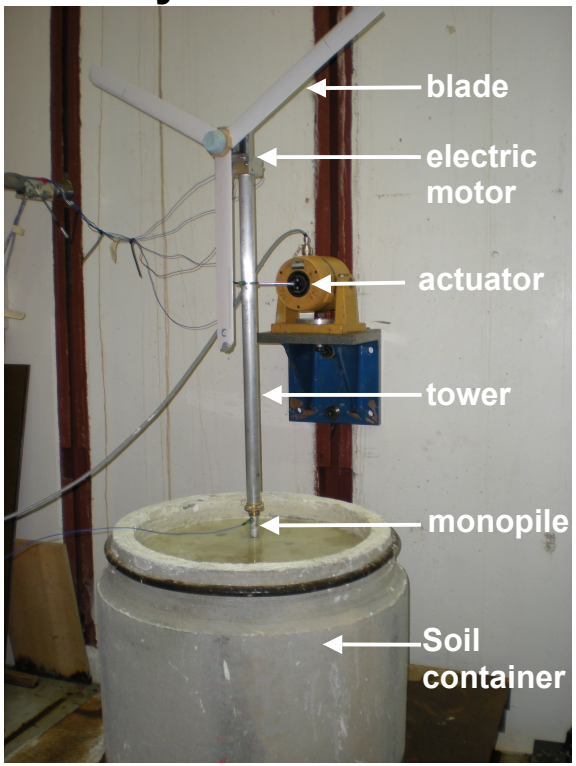
Physical model

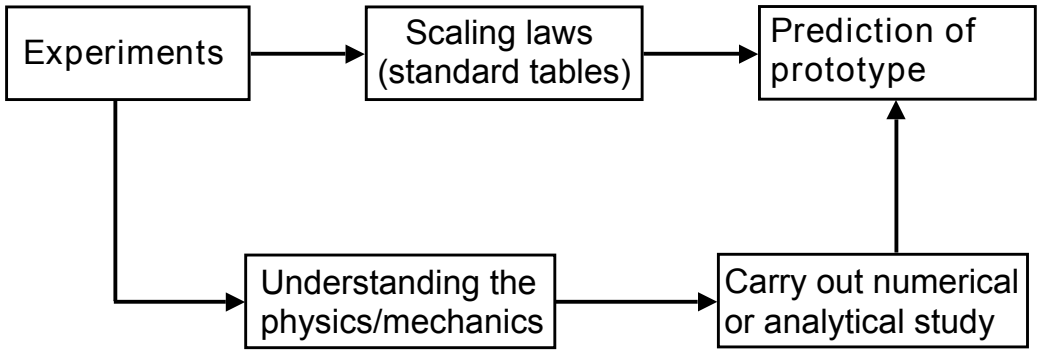


Geotechnical physical modelling

Prototype

Physical model



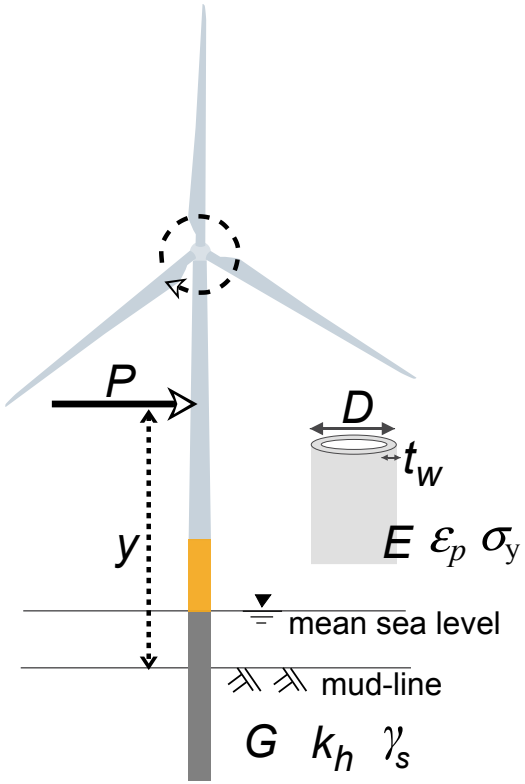


Non-dimensional analysis: scaling laws

Real prototype

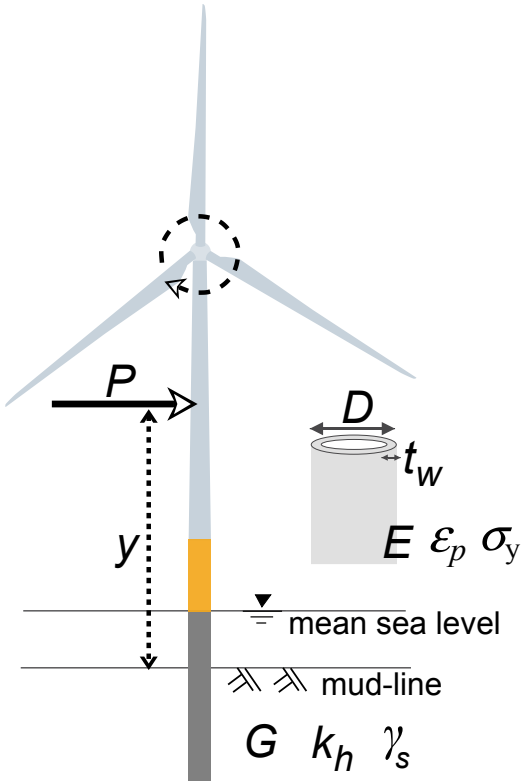
Non-dimensional analysis: scaling laws

Real prototype ⟶ **Simplified prototype**



Non-dimensional analysis: scaling laws

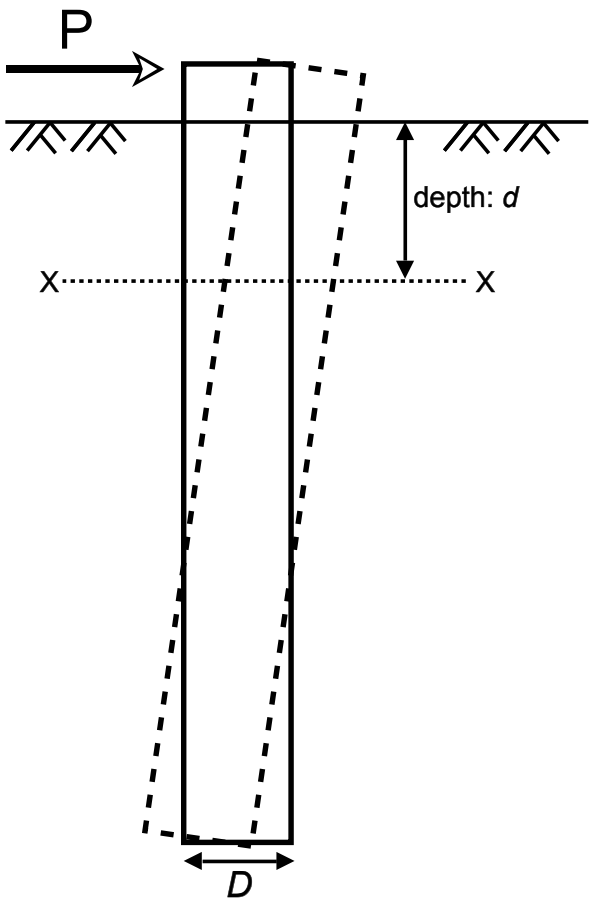
Real prototype ⟶ **Simplified prototype** ⟶ **Non-dimensional analysis**



Physical mechanism	Non-dimensional group
Average strain in soil	$\frac{P}{G \times D^2}$
Rate of loading	$\frac{k_h}{f_f \times D}$
System dynamics	$\frac{f_f}{f_n}$
Bending strain in monopile	$\frac{P \times y}{E \times D^2 \times t_w}$
Fatigue in the monopile	$\frac{P \times y}{\sigma_y \times D^2 \times t_w}$

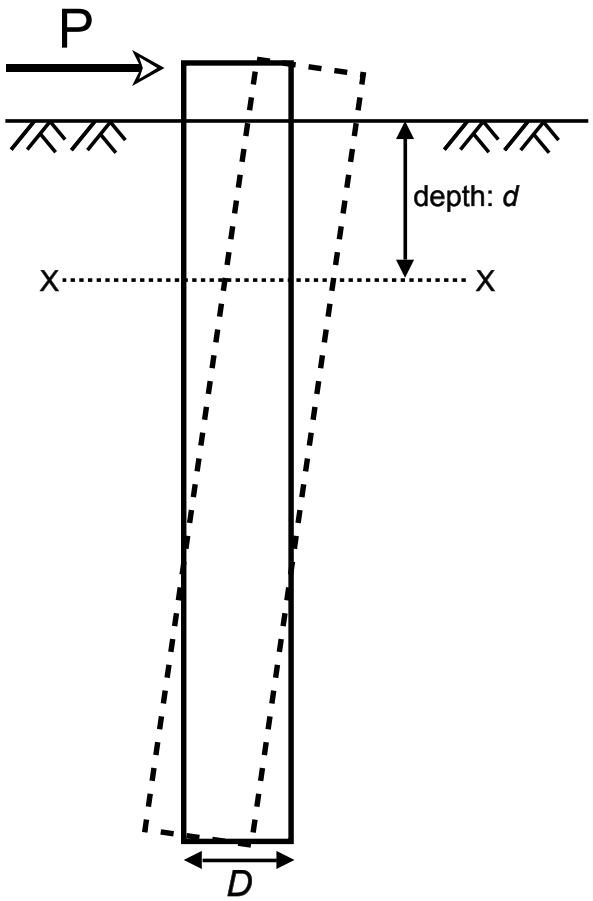
Scaling laws: average strain

$$\varepsilon_s = f(P, G, D)$$



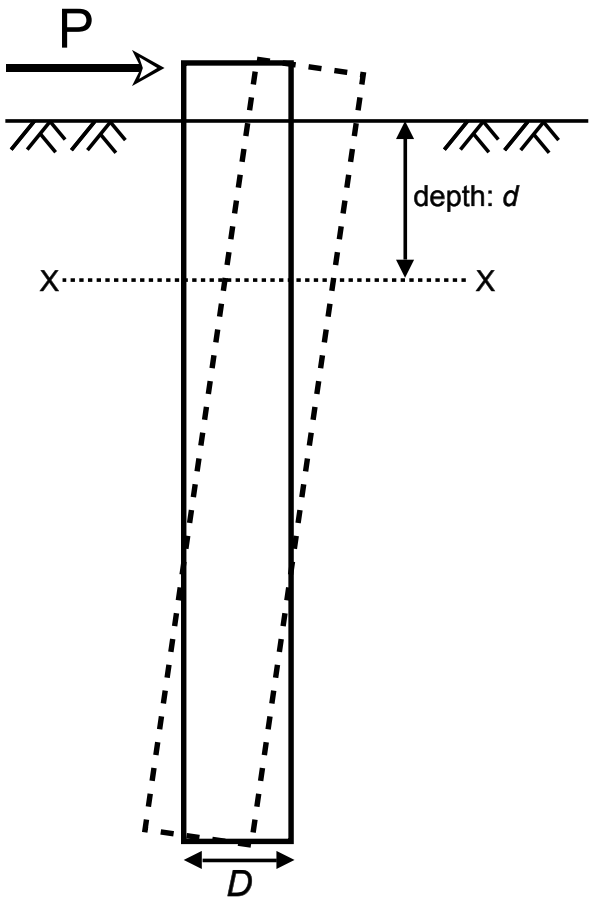
Scaling laws: average strain

$$\varepsilon_s = f\left(P, G, D\right) \longrightarrow \varepsilon_s \propto \frac{P^{\alpha}}{G^{\theta} \cdot D^{\lambda}}$$



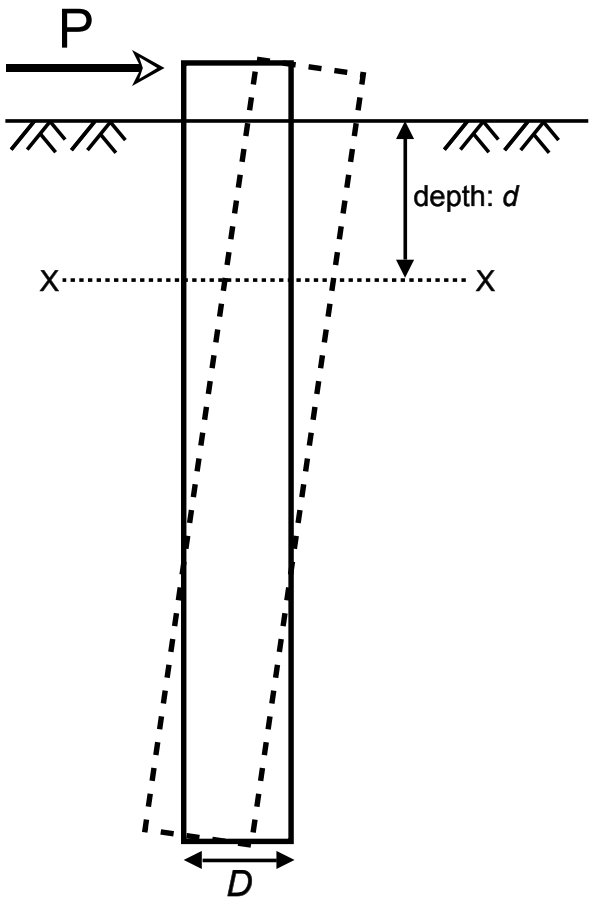
Scaling laws: average strain

$$\varepsilon_s = f\left(P, G, D\right) \longrightarrow \varepsilon_s \propto \frac{P^{\alpha}}{G^{\theta} \cdot D^{\lambda}} \longrightarrow \varepsilon_s \propto \frac{P}{G \cdot D^2}$$



Scaling laws: average strain

$$\varepsilon_s = f(P, G, D) \longrightarrow \varepsilon_s \propto \frac{P^{\alpha}}{G^{\theta} \cdot D^{\lambda}} \longrightarrow \varepsilon_s \propto \frac{P}{G \cdot D^2}$$

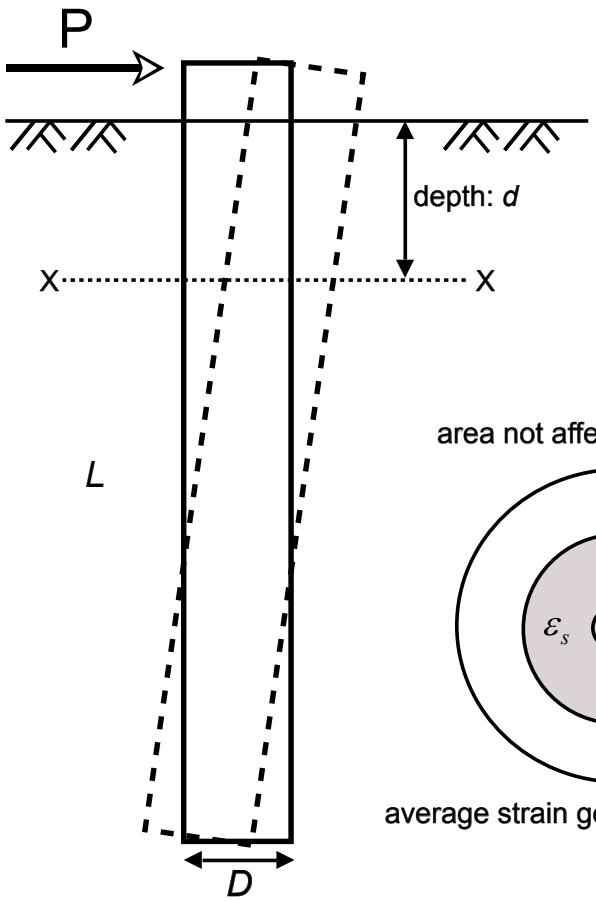


Similitude

$$\left(\frac{P}{G \cdot D^2}\right)_{\text{prototype}} = \left(\frac{P}{G \cdot D^2}\right)_{\text{model}}$$

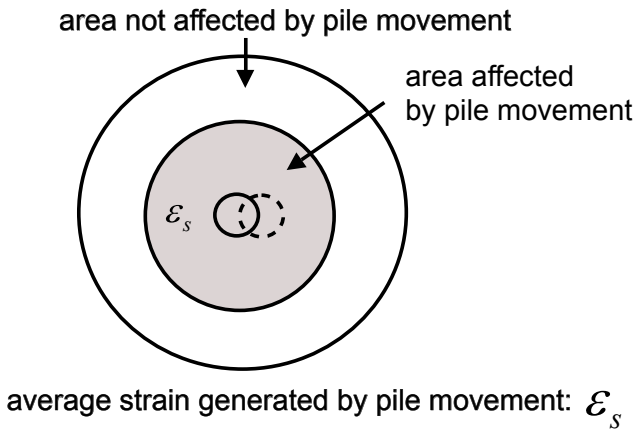
Scaling laws: average strain

$$\varepsilon_s = f(P, G, D) \longrightarrow \varepsilon_s \propto \frac{P^{\alpha}}{G^{\theta} \cdot D^{\lambda}} \longrightarrow \varepsilon_s \propto \frac{P}{G \cdot D^2}$$



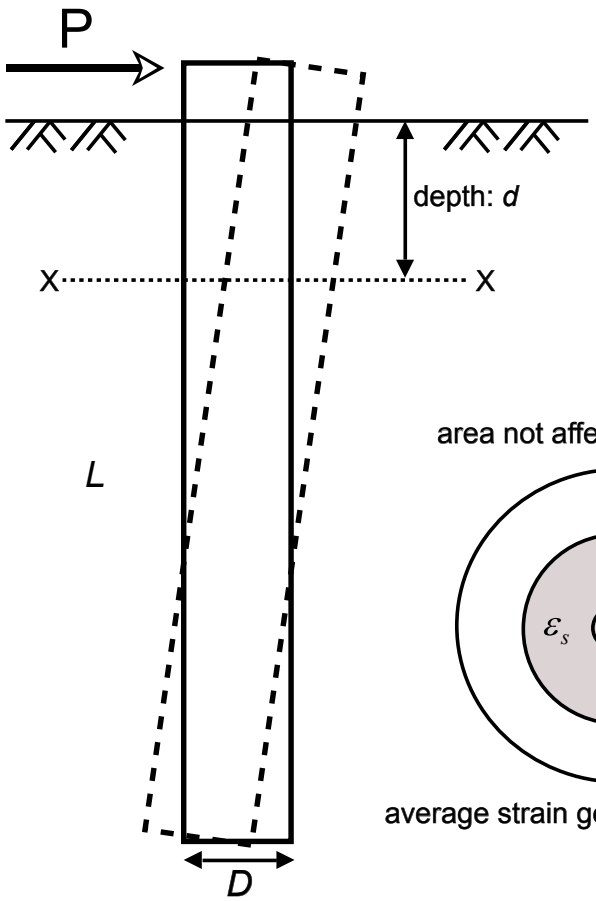
Similitude

$$\left(\frac{P}{G \cdot D^2}\right)_{\text{prototype}} = \left(\frac{P}{G \cdot D^2}\right)_{\text{model}}$$



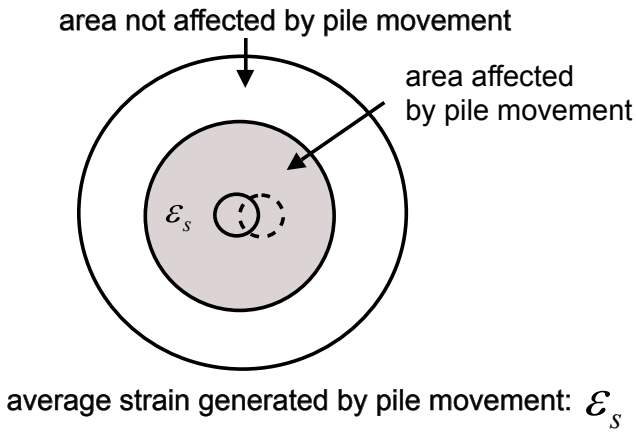
Scaling laws: average strain

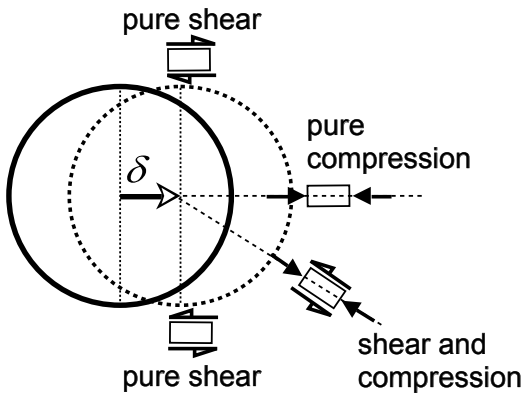
$$\varepsilon_s = f(P, G, D) \longrightarrow \varepsilon_s \propto \frac{P^{\alpha}}{G^{\theta} \cdot D^{\lambda}} \longrightarrow \varepsilon_s \propto \frac{P}{G \cdot D^2}$$



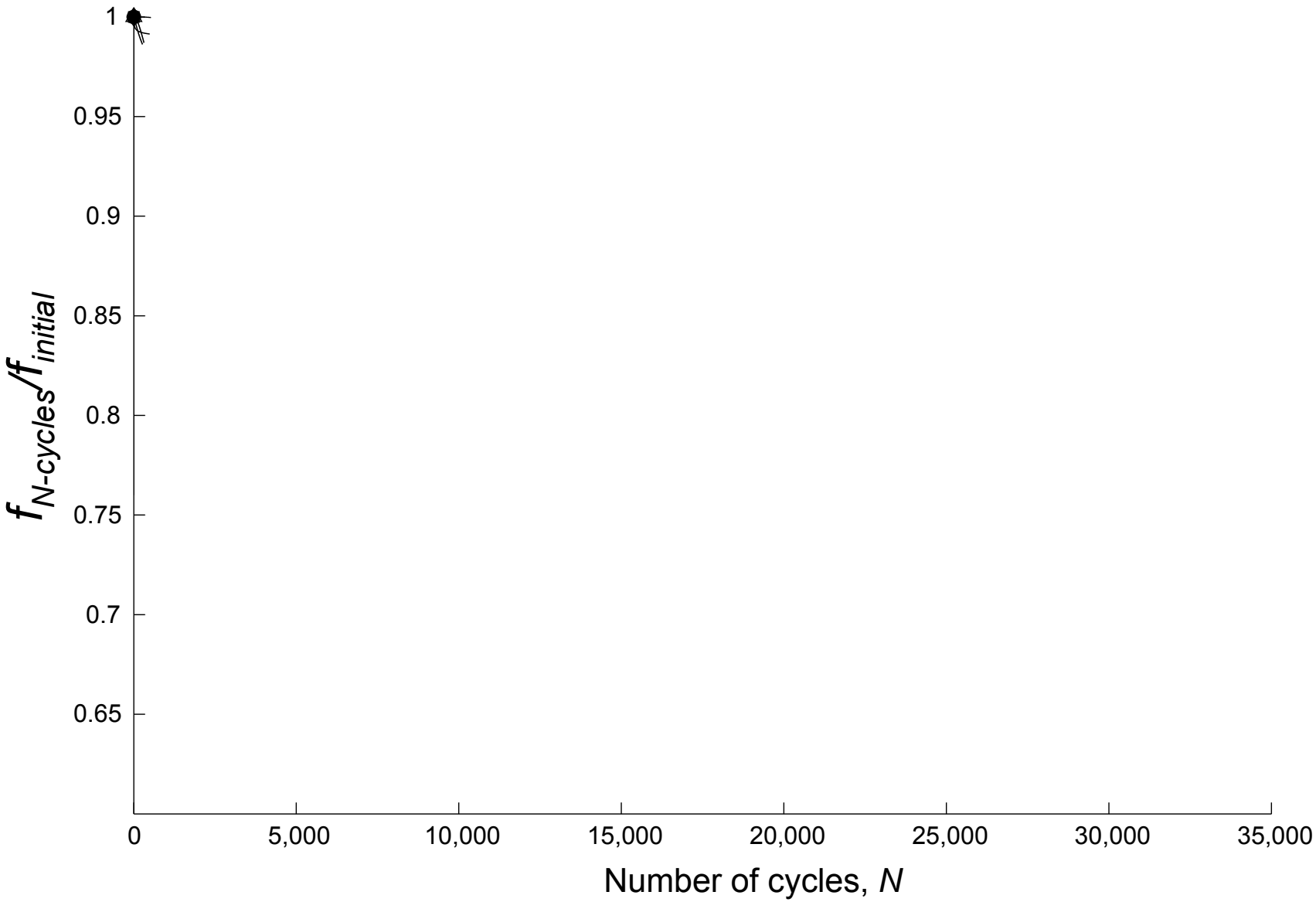
Similitude

$$\left(\frac{P}{G \cdot D^2}\right)_{\text{prototype}} = \left(\frac{P}{G \cdot D^2}\right)_{\text{model}}$$

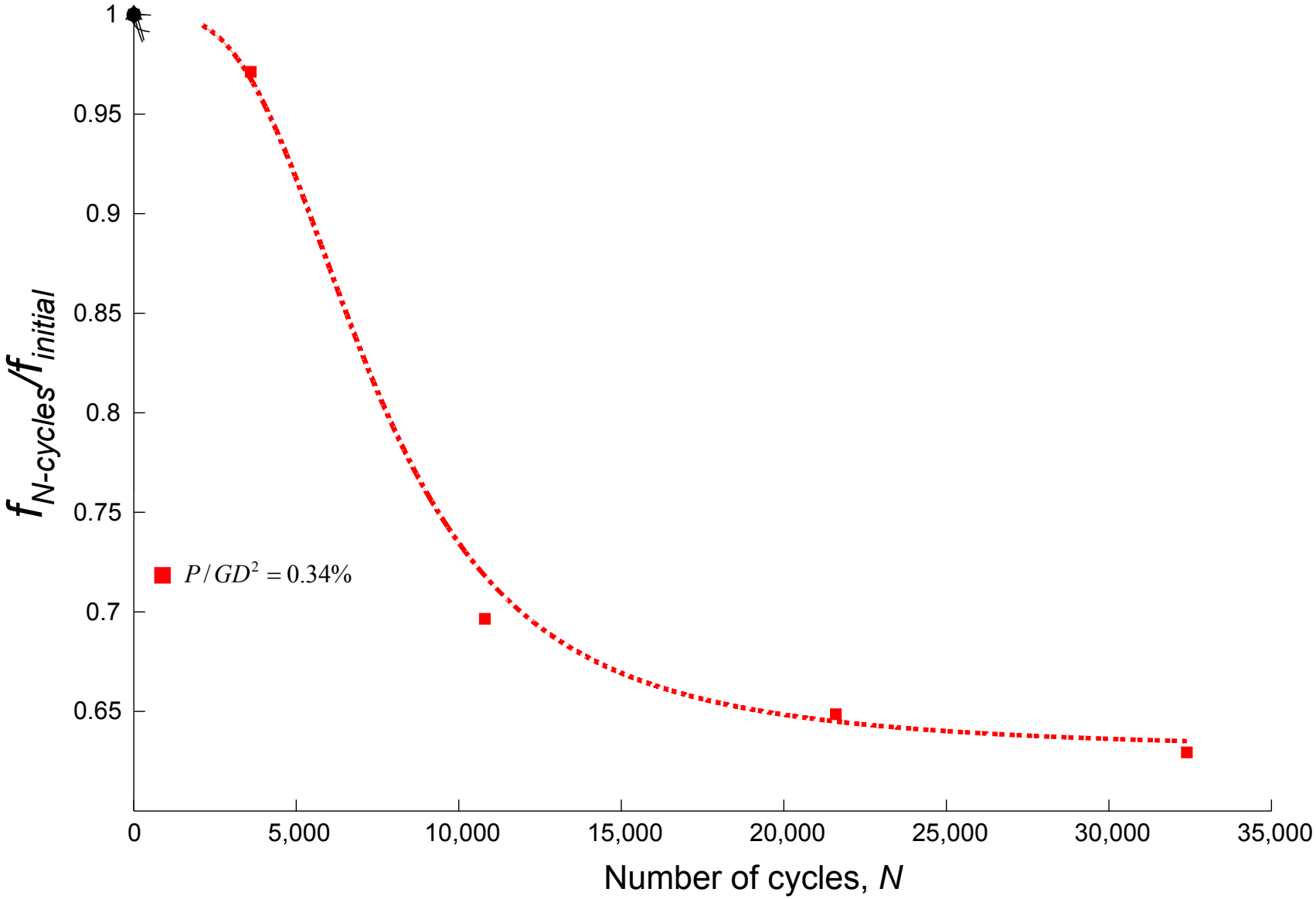




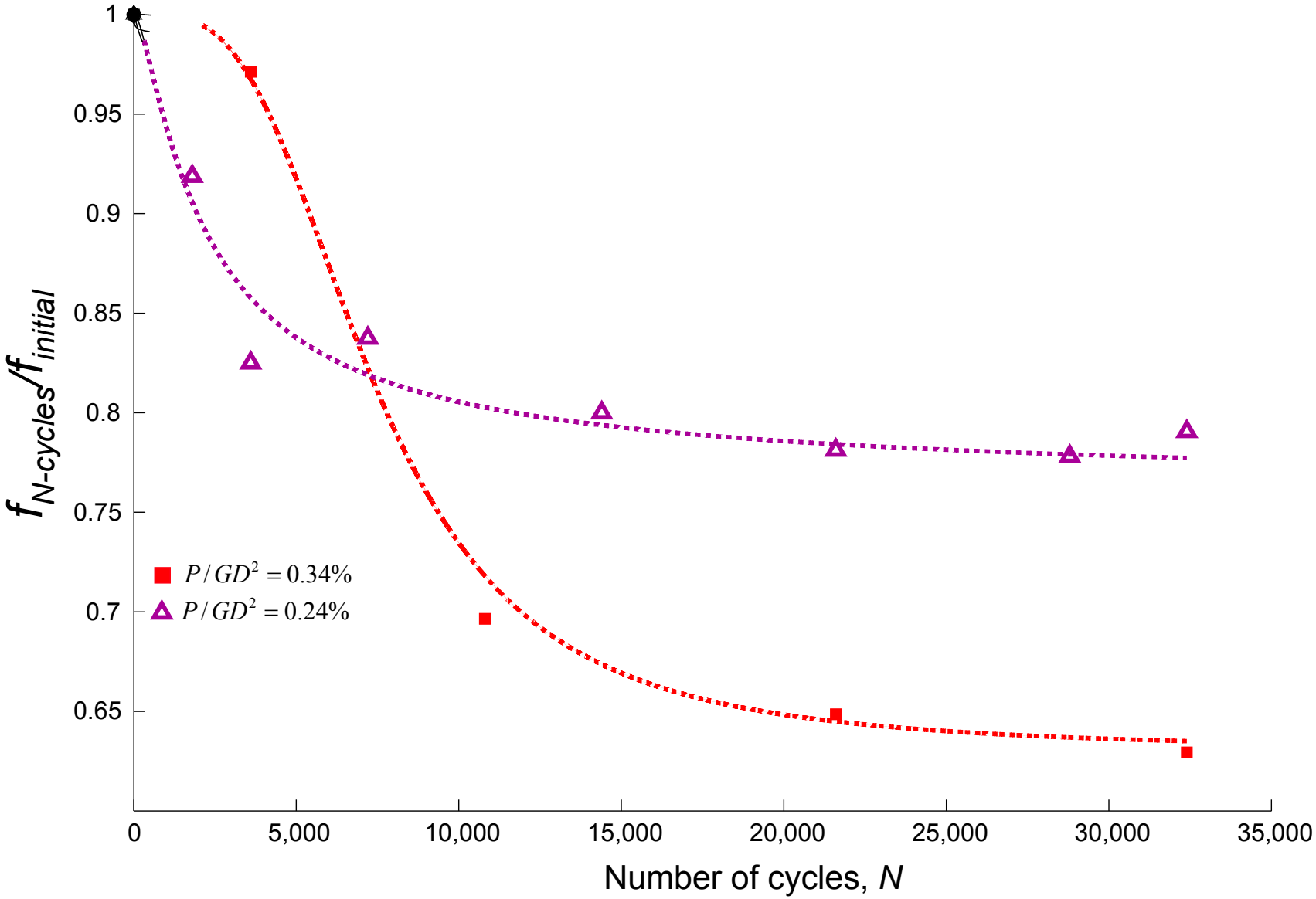
Experimental results



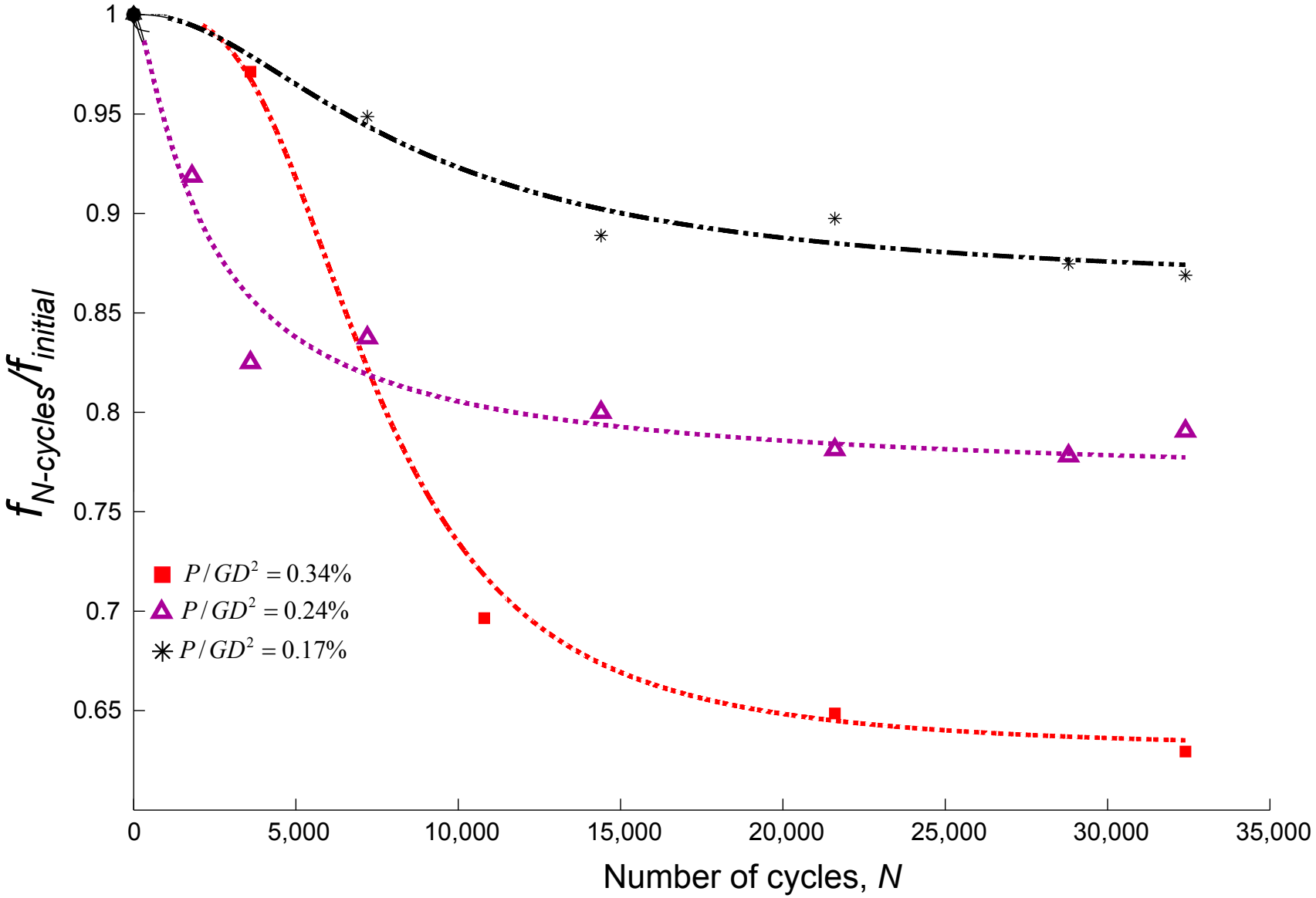
Experimental results



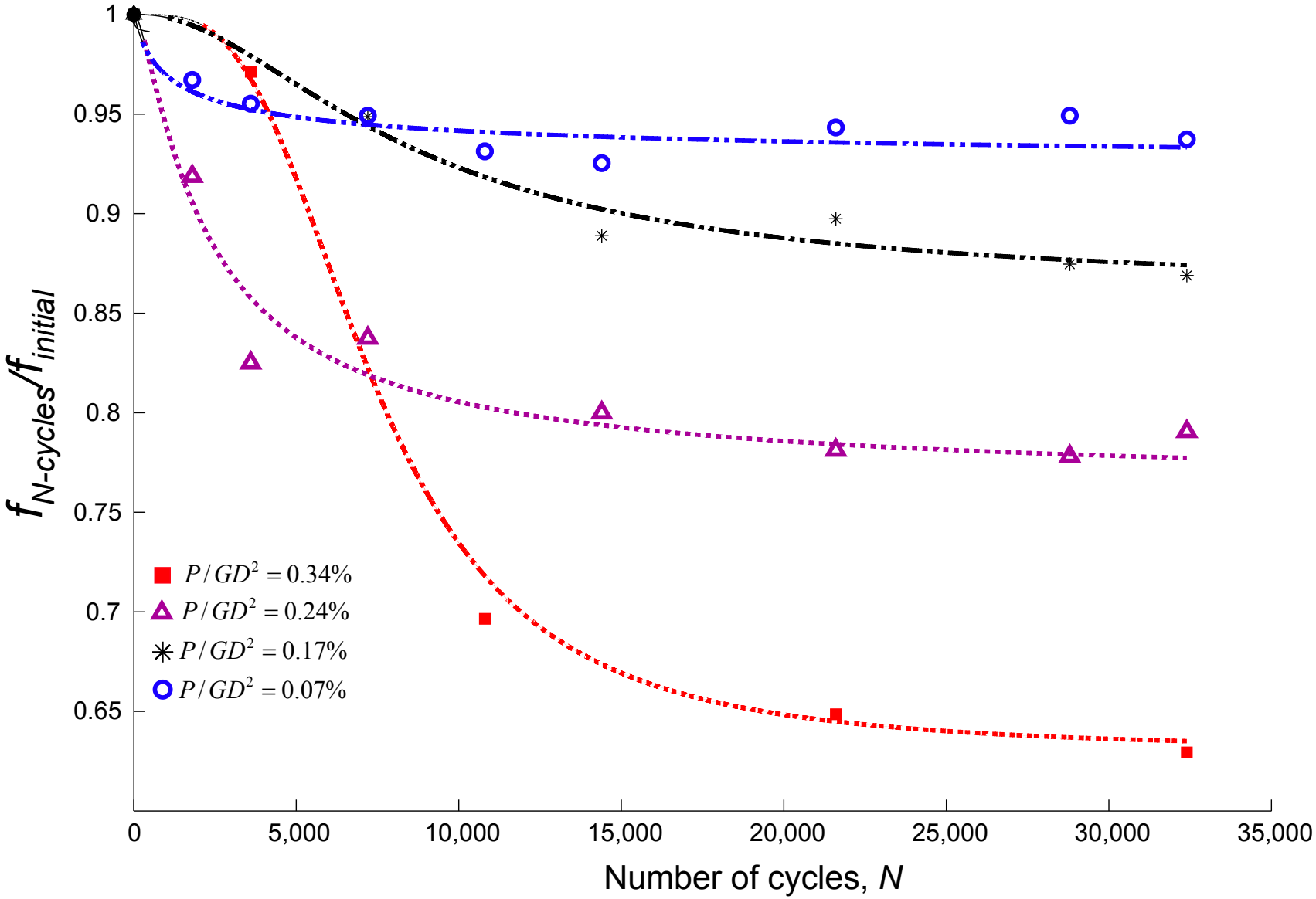
Experimental results



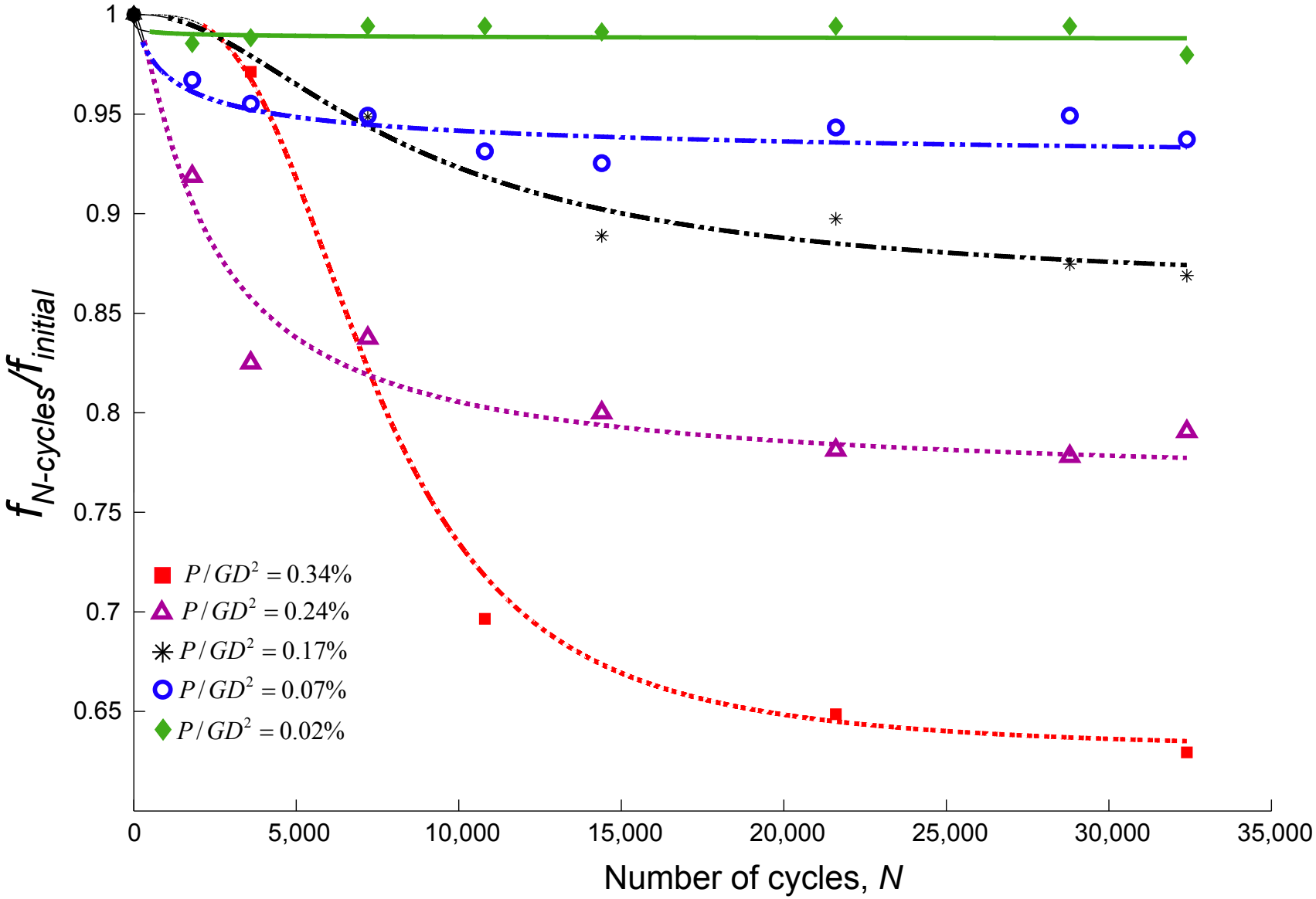
Experimental results



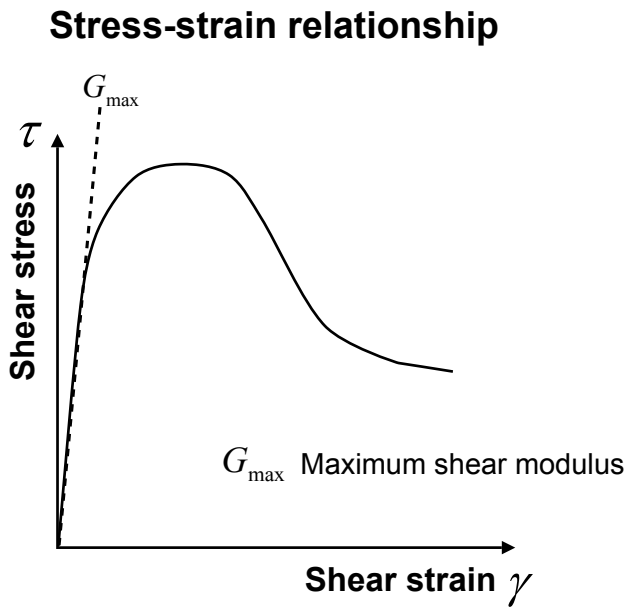
Experimental results



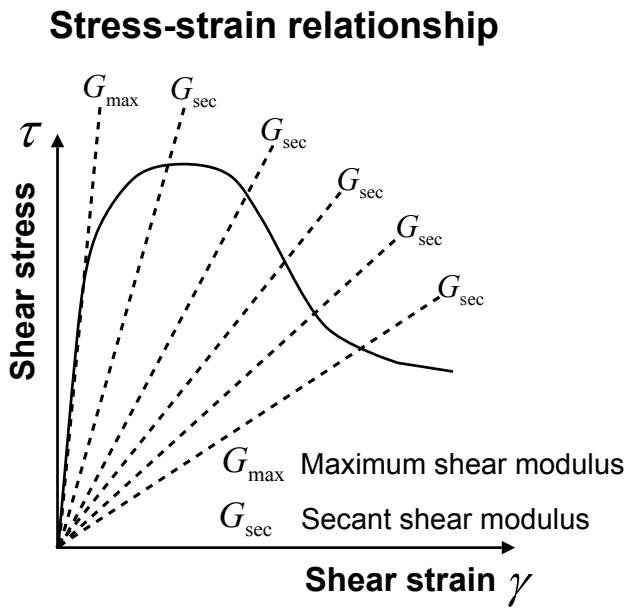
Experimental results



Experimental results and soil stiffness degradation

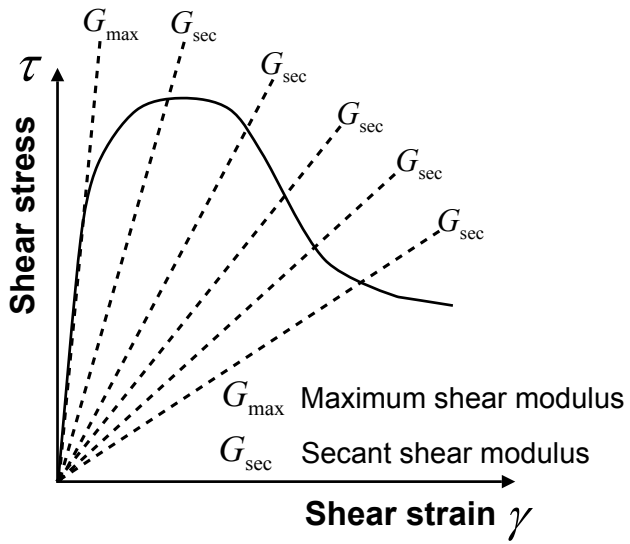


Experimental results and soil stiffness degradation

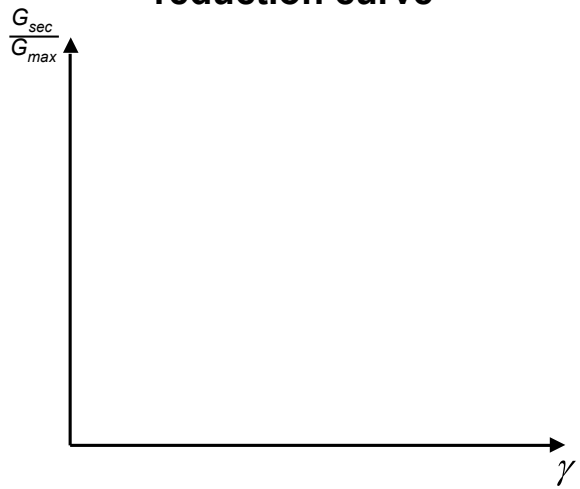


Experimental results and soil stiffness degradation

Stress-strain relationship

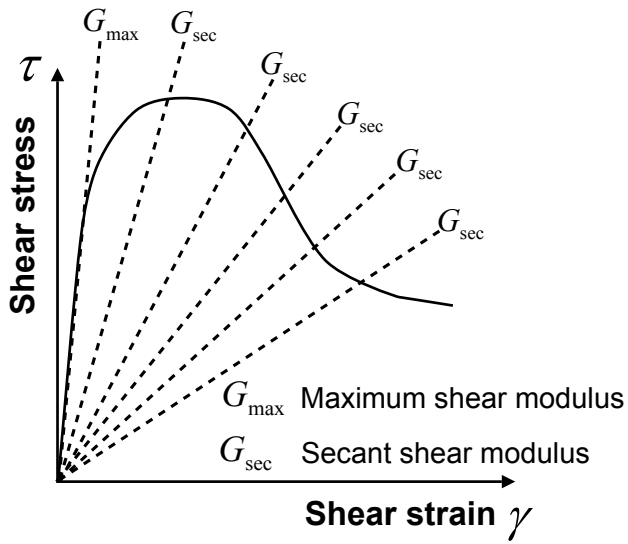


Secant shear modulus reduction curve

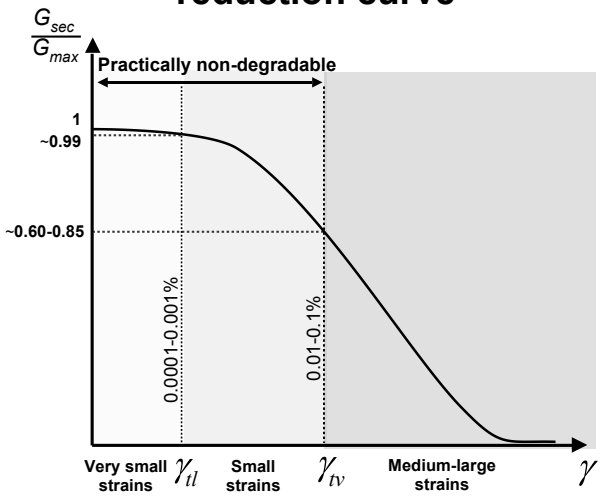


Experimental results and soil stiffness degradation

Stress-strain relationship

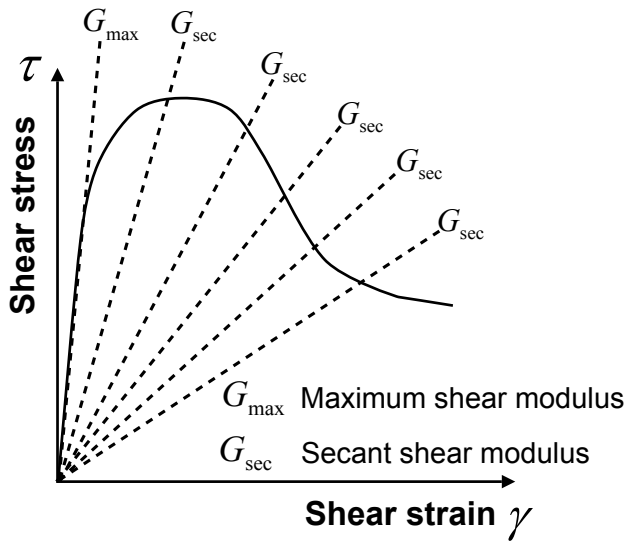


Secant shear modulus reduction curve

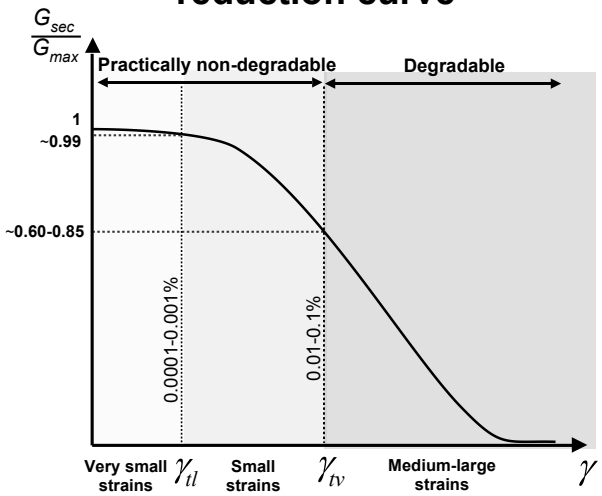


Experimental results and soil stiffness degradation

Stress-strain relationship

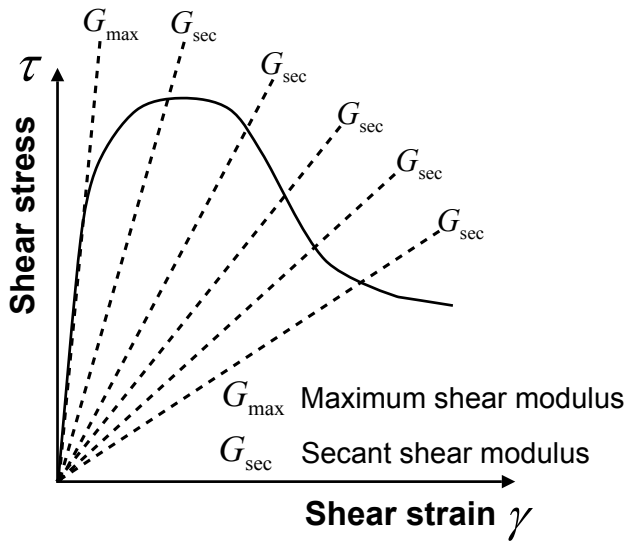


Secant shear modulus reduction curve

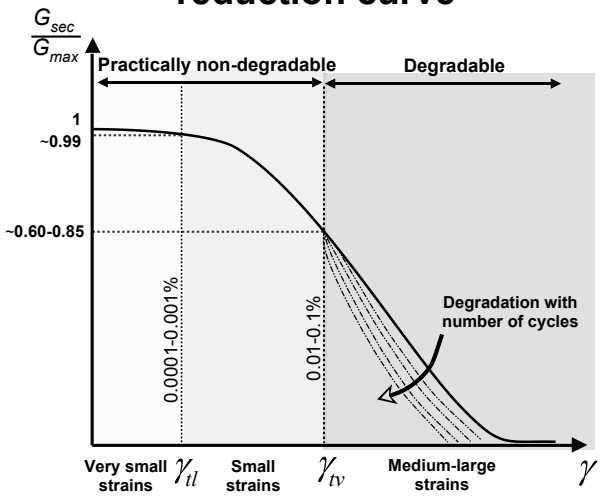


Experimental results and soil stiffness degradation

Stress-strain relationship

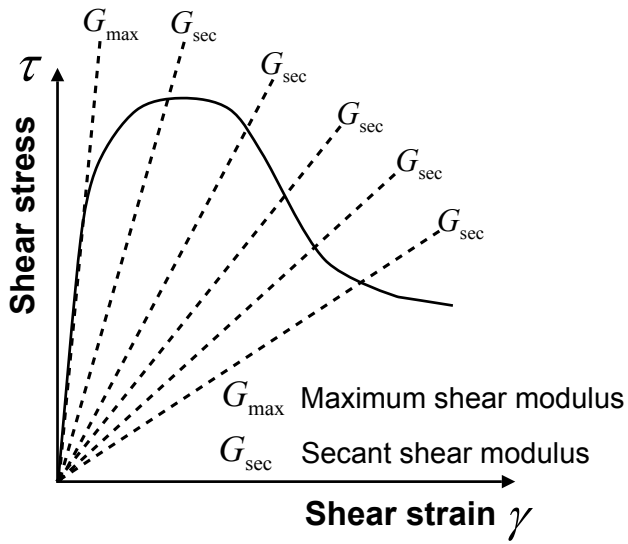


Secant shear modulus reduction curve

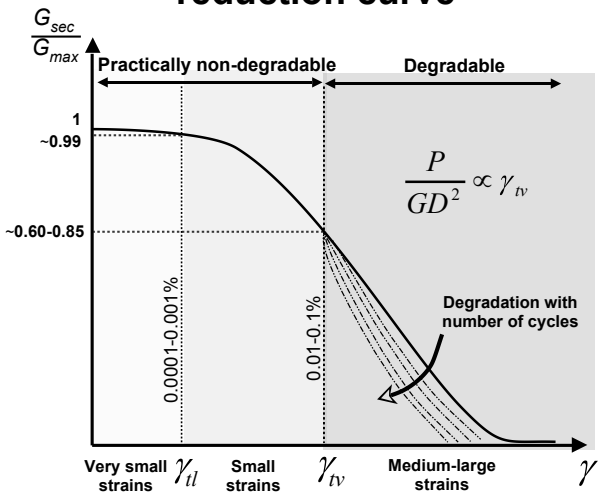


Experimental results and soil stiffness degradation

Stress-strain relationship

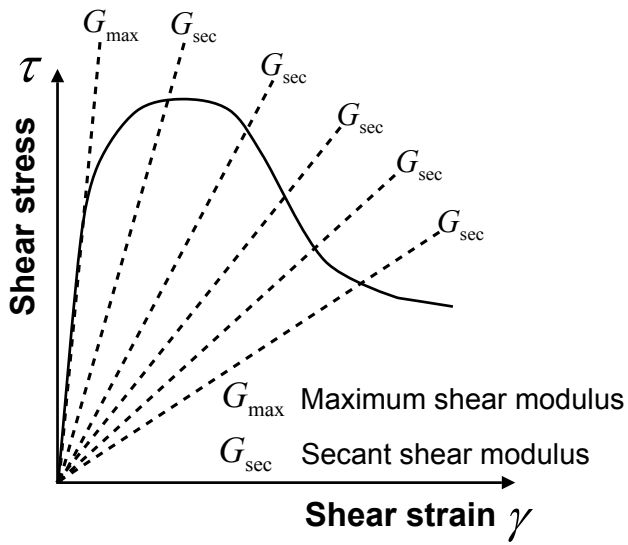


Secant shear modulus reduction curve

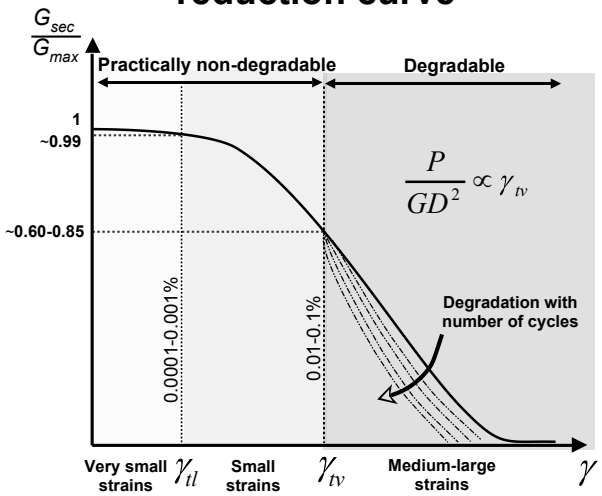


Experimental results and soil stiffness degradation

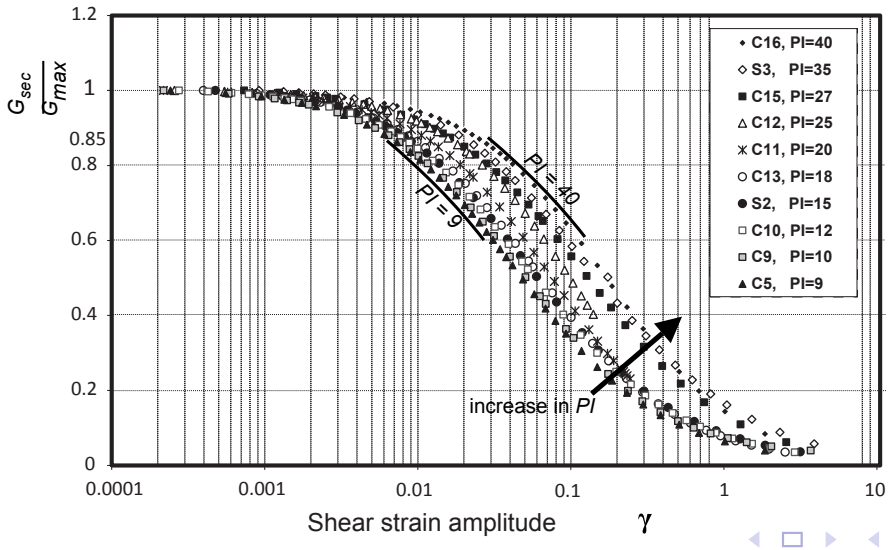
Stress-strain relationship



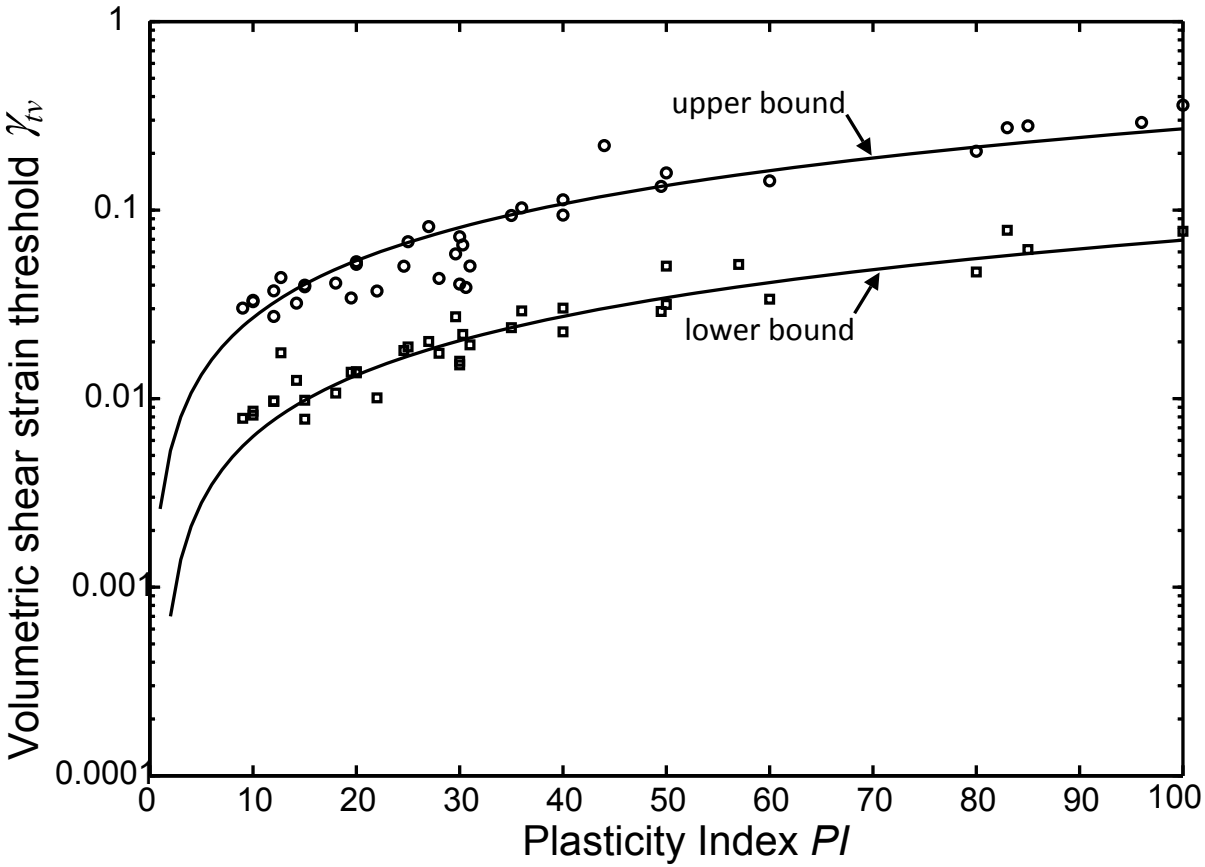
Secant shear modulus reduction curve



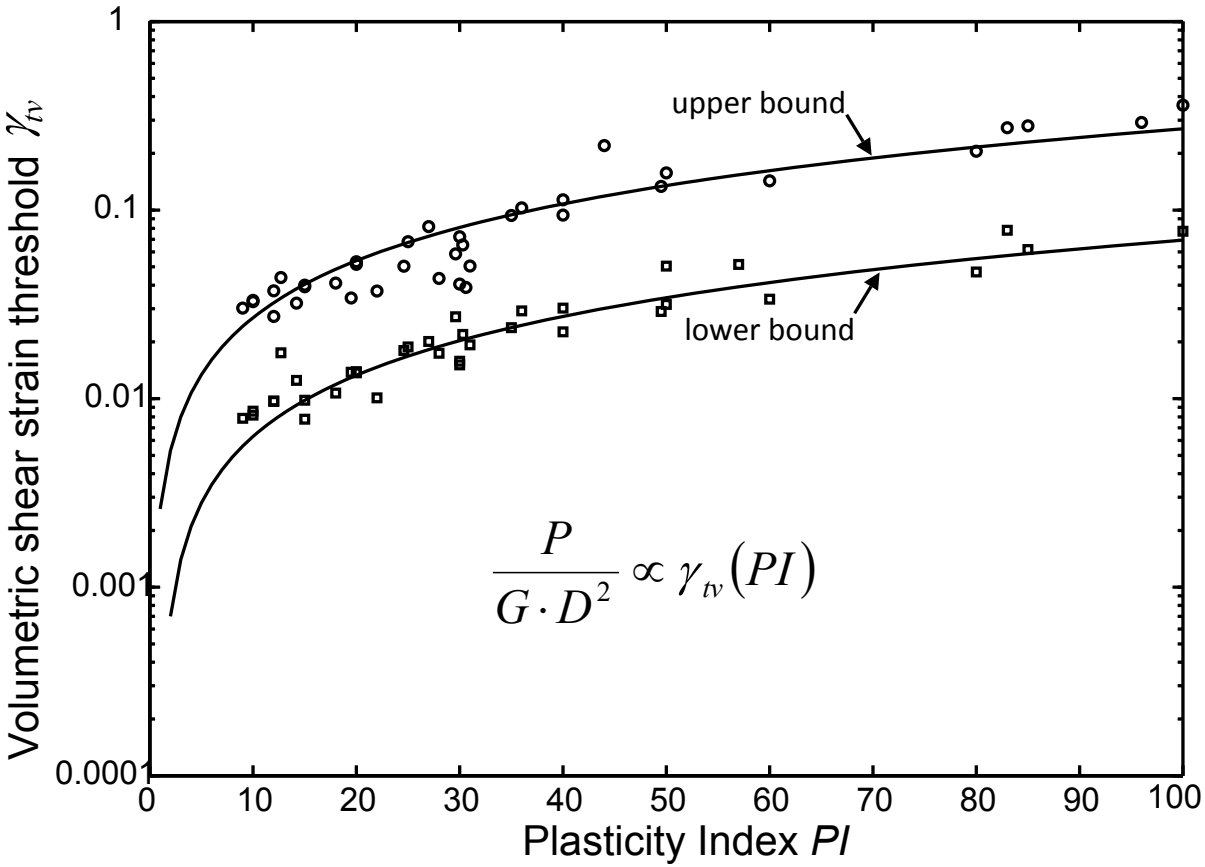
Typical shear modulus reduction curve for clays with different Plasticity Index PI



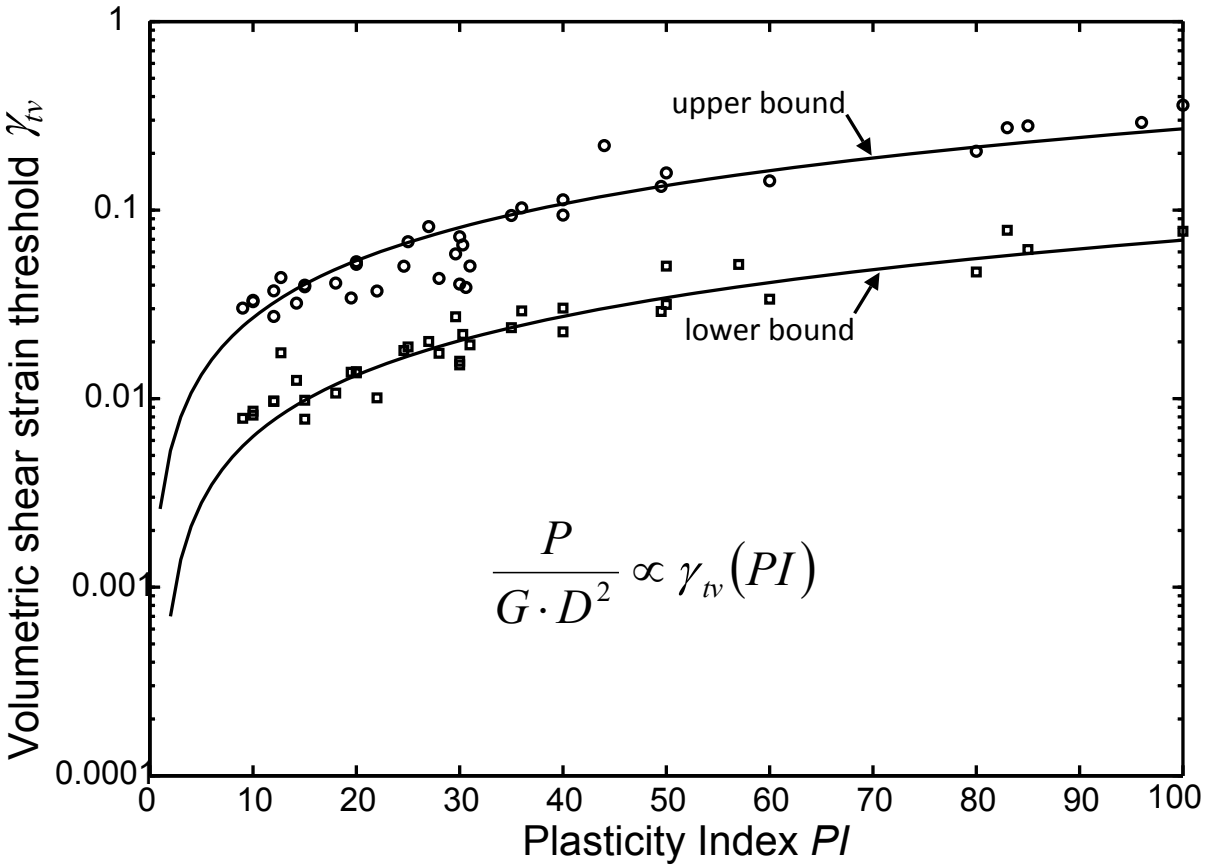
Volumetric shear strain threshold



Volumetric shear strain threshold

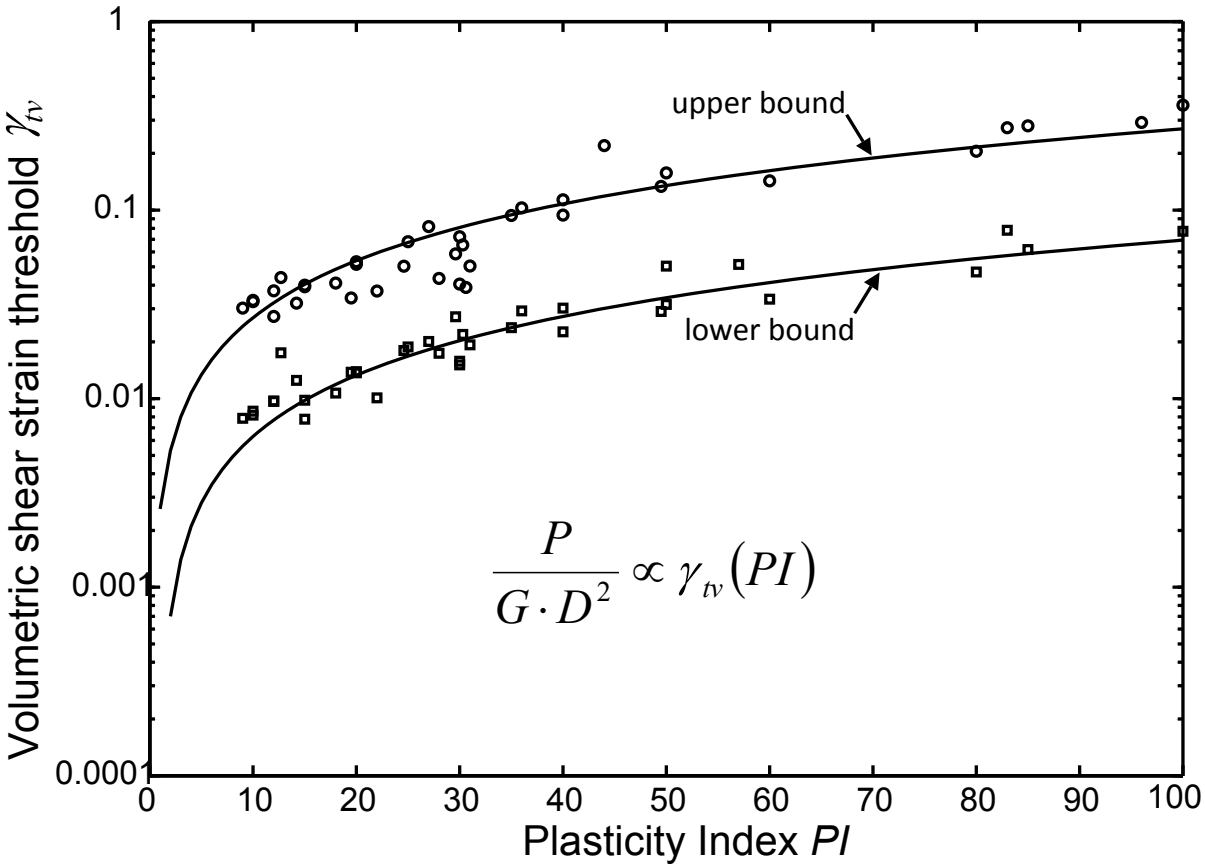


Volumetric shear strain threshold



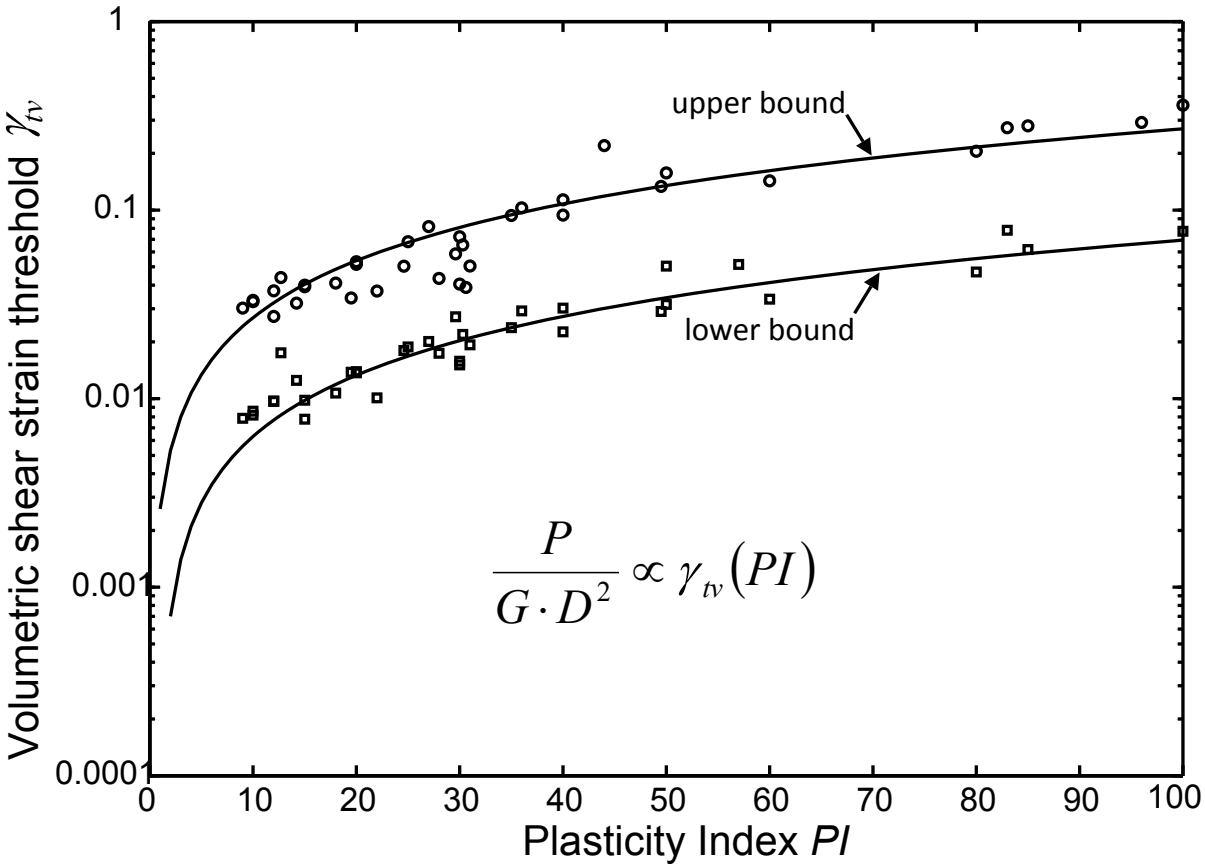
For Kaolin clay (used in this test) γ_{tv} = 0.09%

Volumetric shear strain threshold



For Kaolin clay (used in this test) γ_{tv} = 0.09%

Volumetric shear strain threshold



For Kaolin clay (used in this test) γ_{tv} = 0.09%

Model tests showed no degradation $\frac{P}{G \cdot D^2}$ = 0.07%

Conclusions

Conclusions

- The dynamic response of the physical model is very sensitive to the flexibility of the foundation;

Conclusions

- The dynamic response of the physical model is very sensitive to the flexibility of the foundation;
- The natural frequency of a monopile-supported wind turbine founded on clayey soil may change with the number of cycles of repeated loading;

Conclusions

- The dynamic response of the physical model is very sensitive to the flexibility of the foundation;
- The natural frequency of a monopile-supported wind turbine founded on clayey soil may change with the number of cycles of repeated loading;
- For clay soils, a decrease in natural frequency is expected depending on the strain level in the soil next to the monopile, which was taken into by P/GD^2;

Conclusions

- The dynamic response of the physical model is very sensitive to the flexibility of the foundation;
- The natural frequency of a monopile-supported wind turbine founded on clayey soil may change with the number of cycles of repeated loading;
- For clay soils, a decrease in natural frequency is expected depending on the strain level in the soil next to the monopile, which was taken into by P/GD^2;
- The non-dimensional group P/GD^2 suggests that the higher the diameter D of the monopile, the lower is the average strain in the surrounding soil;

Conclusions

- The dynamic response of the physical model is very sensitive to the flexibility of the foundation;
- The natural frequency of a monopile-supported wind turbine founded on clayey soil may change with the number of cycles of repeated loading;
- For clay soils, a decrease in natural frequency is expected depending on the strain level in the soil next to the monopile, which was taken into by P/GD^2;
- The non-dimensional group P/GD^2 suggests that the higher the diameter D of the monopile, the lower is the average strain in the surrounding soil;
- Lower average strain in the soil reduce the tendency of soil degradation and therefore change in natural frequency;

Reference list

- Bhattacharya, S., Nikitas, N., Garnsey, J., Alexander, N. A., Cox, J., Lombardi, D., & Nash, D. F. T. (2013). **'Observed dynamic soilstructure interaction in scale testing of offshore wind turbine foundations'**. *Soil Dynamics and Earthquake Engineering*, 54, 47-60.
- Lombardi, D., Bhattacharya, S., Muir Wood, D. (2013). **'Dynamic soil-structure interaction of monopile supported wind turbines in cohesive soil'**. *Soil Dynamics and Earthquake Engineering*. 49, 165-180.
- Bhattacharya, S., Lombardi, D., Muir Wood, D. (2011). **'Similitude relationships for physical modelling for physical modelling of monopile-supported offshore wind turbines'**, *International Journal of Physical Modelling in Geotechnics*, 11 (2), pp 58-68;

Thank you for your attention