

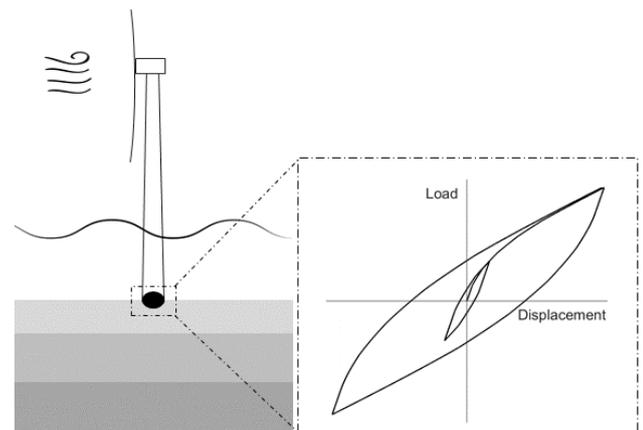
### The Macro-Element Method for Integrated Analyses of Offshore Wind Turbines

Offshore wind energy is considered a necessary renewable energy resource, that may stimulate the transition from fossil fuels. Following the successful development in Western Europe, offshore wind is quickly gaining momentum in the Asia-Pacific region. At variance with North Sea-based offshore wind turbines, structures installed in the Asia-Pacific region are prevalently exposed to typhoons, giving rise to severe wind speeds and, consequently, extreme waves. Such conditions have become design driving for support structures.

Considering that the response of the support structure due to these extreme waves is dependent on soil stiffness, a state-of-the-art foundation model accounting for non-linear, hysteretic soil-monopile behaviour is included in integrated time-domain analyses. Besides considering load-dependent hysteretic damping, the foundation model accounts accurately for the unloading-reloading stiffness. This multi-directional macro-element model has been primarily developed and verified for fatigue limit state analyses. In this thesis, the results of additional 3D finite element verification analyses are presented to identify potential model limitations under ultimate limit state conditions. With regard to different geotechnical and loading scenarios, it is observed that the macro-element model satisfactorily predicts load-dependent stiffness and damping, even for the extreme load levels relevant to the Asia-Pacific region.

To capture the offshore wind turbine dynamic response to extreme loading, time-domain analyses are performed with two foundation models: 1) the current industry standard based on non-linear elastic API  $p$ - $y$  curves, and 2) the non-linear elasto-plastic macro-element model calibrated against the API  $p$ - $y$  curves and also load-displacement curves from 3D finite element analyses.

From the models calibrated against the API standard, the effect of accounting for the load-dependent stiffness and damping on the response at interface for extreme load cases is determined. A reduction of the moment at interface level is observed, due to an improved soil stiffness and damping estimation. Further, as the API  $p$ - $y$  curves do not account for the correct initial stiffness, the response at interface level is additionally evaluated with the macro-element model calibrated to 3D finite element analyses. The results show a further decrease of the response, that may be attributed to the (initial) stiffer response of the monopile at mudline from 3D finite element analyses.



One of the recommendations is to numerically evaluate the contribution of hysteretic damping with regards to the system damping. Therefore, the validity of the often-used linear damping estimation strategy is investigated for the non-linear system. The interference term in the response at mudline has shown to cause a phase difference, with respect to similar response that does not account for the interference term. The applicability of the logarithmic decrement method that is currently used for system damping estimation is therefore questioned. To evaluate this further, it is suggested to perform additional studies that account for a more adequate representation of the response spectrum.

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