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Combination of kinematic and inertial loads acting on monopile foundations for offshore wind turbines

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Due to a growing number of offshore wind farm projects in seismic areas, existing design procedures for slender piles under seismic loading need to be revised to allow for the design of larger and stockier monopiles. This study illustrates how advanced finite element analyses can be used to investigate the combination of seismic loads and may thus inform standard design procedures commonly adopted in practice. In standard design methods, a soil-pile foundation system is represented by a simplified beam-on-nonlinear-springs model [1]. Earthquake loads acting on this system can be decomposed into inertial forces, which originate from the acceleration of a superstructure mass, and kinematic loads due to ground displacements caused by the propagation of seismic waves. Inertial loads are typically derived from modified acceleration spectra which account for the difference between the pile head movement and the soil displacement in the free-field [2, 3, 4]. Maximum displacement profiles can be obtained from site response analyses of the free-field soil column. The distribution of pile bending moments and internal forces can thus be found by superposition of the two loads. However, unless numerical time-domain analyses are carried out, it is not evident whether these components are acting simultaneously on the pile. In the design of long and slender piles, a common assumption is that inertial and kinematic loads may be considered separately, as the former tend to affect only the near-surface zones while the latter dominate at larger depths [2]. However, their combined effect on a far less flexible monopile exhibiting rotational mechanisms is not yet understood, neither is the influence of soil liquefaction triggered by the seismic ground shaking. Experiments on pile groups presented in the literature suggest a dependence of the phase angle on the ratio between the fundamental frequency of the soil deposit and the superstructure [5]. The analogous scenarios are illustrated for a monopile-supported wind turbine in Figure 1.

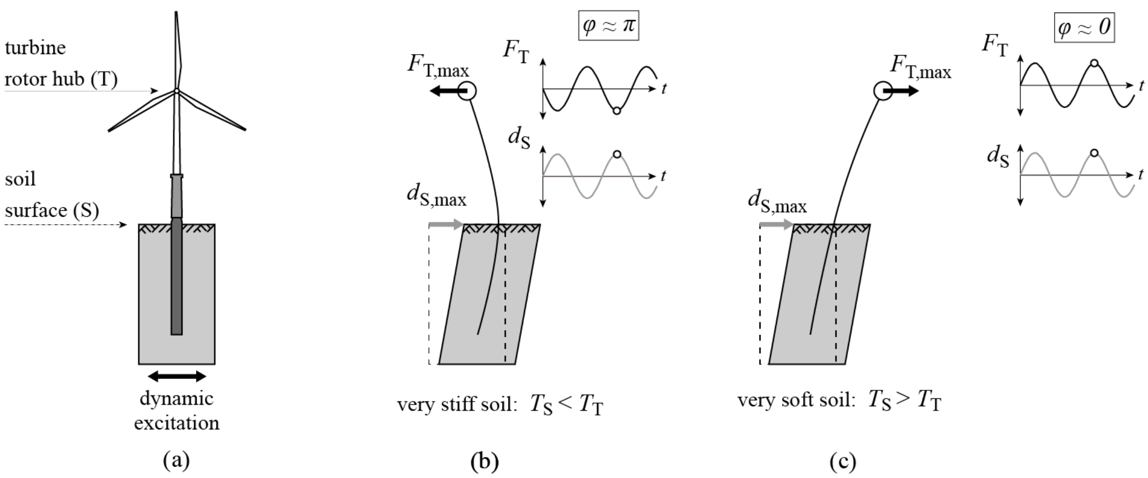

Figure 1: Schematic illustration of kinematic and inertial loads acting in or out of phase.

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The turbine is considered as a single-degree-of-freedom system with the mass off the rotor nacelle assembly lumped together and located at hub height. The time history of the inertial force acting at hub height (F_T), as well as the horizontal ground displacement at surface level (d_S), are schematically shown in Figure 1(b) for a very stiff soil. In this case, the fundamental period of the soil deposit (T_S) is significantly lower than that of the superstructure (T_T), which causes the response of the turbine system to act out of phase with the ground movement by 180°. For a soft soil deposit with much higher fundamental period than the turbine (Figure 1(c)), the kinematic and inertial loads are expected to act in phase.

To investigate the combination of seismic loads acting on a monopile foundation in the time-domain, advanced numerical analyses are carried out on three-dimensional Finite Element models. Soil layers with widely different material properties are considered, including stiff marine clays and liquefiable sands with varying relative densities. The uni-directional motion records adopted as base excitations are sufficiently strong to induce large lateral ground movements and impose significant kinematic loads on the foundation. Through the of use of appropriate constitutive models in a hydro-mechanically coupled formulation, the response of the turbine sub-structure system is simulated while accounting for the degradation of stiffness in the surrounding soil and significant rises in excess pore pressures in the sand layers. An intensely nonlinear material behaviour typically leads to a shift of the fundamental frequency of the deposit [6], which can be deduced from the amplification of accelerations at various depths, with high frequencies dominating in the stiff soil layers and low frequencies in the soft liquefied sand. For a stiff soil deposit prior to liquefaction, local extrema in pile displacements at mudline level are therefore expected to act out of phase with the inertial force resulting from the acceleration of the rotor nacelle assembly at the turbine tower top (Case $T_S < T_T$). As the stiffness diminishes in a soft or fully liquefied ground, pile and free-field ground displacements are expected to move in-phase with the inertial load, as is characteristic for cases where the period of the soil deposit exceeds that of the superstructure (Case $T_S > T_T$). This change in behaviour highlights the influence of soil stiffness degradation and extensive ground liquefaction on the combination of seismic soil-structure interaction effects in the time-domain, which can be captured by advanced numerical methods.

Contributor statement

Conceptualisation: Julia Katharina Möller; Formal analysis: Julia Katharina Möller; Supervision: Stavroula Kontoe and David Taborda; Writing – Original draft: Julia Katharina Möller with contributions from Stavroula Kontoe and David Taborda; Writing – Review & Editing: Julia Katharina Möller, Stavroula Kontoe, David Taborda

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