Abstract

The current research presents a comprehensive investigation into the dynamic response of monopile foundations embedded in homogeneous and layered soil-rock systems under horizontal dynamic loads. The monopile is modeled using visco-elastic springs distributed along its length, representing its interaction with the elastic half-space. The frequency-dependent stiffness and damping of the monopile in various soil-rock conditions are derived through spectral element formulation, demonstrating their variation with frequency. Findings reveal that the depth of rock-socketed monopiles significantly enhances system stiffness, with horizontal amplitudes decreasing and resonant amplitudes for rocking motion increasing as socketing depth grows. Furthermore, the study explores the influence of pile slenderness ratios on natural frequencies and peak amplitudes, providing insights into the dynamic characteristics of pile-soil-rock systems.

Building on this foundation, the research introduces the concept of the "metapile," a monopile integrated with periodically placed spring-mass resonators. A spectral element approach is employed to derive the dynamic stiffness matrix, which is condensed to obtain the system's impedance functions. The dynamic response of the metapile demonstrates reduced amplitudes within specific frequency ranges, owing to the resonators' ability to enhance stiffness near their resonant frequencies. Comparative analysis with monopiles augmented with equivalent lumped masses reveals the unique vibration attenuation capabilities of resonator-based systems, broadening the operational frequency range and improving vibration control.

The application of these principles to wind turbine systems is also investigated. Four configurations namely- conventional turbines, those with resonators in the tower, monopile, or both-are analyzed. Spectral element formulations calculate dynamic responses under harmonic excitations, with experimental validation using a scaled wind turbine model. Results highlight the effectiveness of resonators, particularly when integrated into both tower and monopile, in reducing transmittance near resonant frequencies and mitigating responses at higher excitation frequencies.

The study further examines energy dissipation in monopile systems modeled with visco-elastic springs, focusing on transient response decay. Using Bloch's theorem and dispersion relationships, a novel analytical method estimates dissipation based on damping ratios over the Brillouin zone. Validation with numerical models confirms the efficacy of resonators in enhancing dissipation, termed "metadamping." Parametric studies reveal the impact of resonator characteristics on dissipation, offering a framework for designing resilient pile foundations.

Finally, the research investigates the dynamic interaction of closely spaced pile groups under horizontal vibrations. A detailed framework accounts for primary and secondary wave propagation, soil property variations, and weak zone effects. Results indicate that increasing soil stiffness ratios and boundary zone thickness significantly influences stiffness and damping, providing design guidance for optimizing pile group performance in dynamic environments.

This thesis contributes novel insights into the dynamic behavior and control of monopile foundations, offering practical solutions for improving stability and vibration mitigation in onshore infrastructure systems.