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Centrifuge modelling of offshore monopiles in sloping liquefiable soils: assessment of lateral spreading effects

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ABSTRACT: This study examines the dynamic response of monopile-supported offshore wind turbines subjected to seismic excitation and subsequent liquefaction-induced ground deformations, with a particular focus on the effects of lateral spreading. Centrifuge experiments were conducted to investigate monopile performance on a gently sloping ground and compare it with a flat ground monopile response. The results indicated that lateral spreading induced substantial monopile rotation and led to increased superstructure rotation in the sloping ground condition compared to the flat ground condition. These findings highlight the critical role of lateral spreading in the seismic vulnerability of monopile foundations.

1 INTRODUCTION

As offshore wind energy deployment expands into seismically active coastal and marine regions, the effect of earthquake-induced liquefaction on monopile foundation performance has become a critical design and safety consideration. Existing studies have advanced seismic assessment and design approaches for monopiles in liquefiable soils and have provided valuable centrifuge-based insights into offshore wind foundations (Seong et al., 2023). However, direct experimental evidence that isolates and elucidates the role of mild ground inclination on soil response and the accumulation of permanent foundation deformations remains scarce. This gap is particularly consequential in offshore environments, where fully saturated seabed exhibits reduced shear resistance. Compared with onshore slopes, submarine slopes may become unstable under modest disturbance, with recent findings revealing susceptibility to deformation and failure even at gentle inclinations, often less than 10° (Song et al., 2025). To address this knowledge gap, two centrifuge experiments at 80g were conducted to isolate and systematically compare monopile response on level ground and on a gently inclined seabed (approximately 3°), the latter representative of offshore conditions prone to lateral spreading.

2 EXPERIMENTAL SETUP

The monopile-supported wind turbine model was designed to represent the prototype NREL-5MW wind turbine (Jonkman et al., 2009). The tower and rotor–nacelle assembly (RNA) were simplified as a constant-diameter hollow cylinder with a top lumped mass following the similar simplification procedure stated in (Wu et al., 2025). At prototype scale, the lumped mass was around 410 tonnes. The tower height was 44 m, with an outer diameter of 2 m, and a wall thickness of 0.24 m. The monopile embedded length is around 22.4 m, with an outer diameter of 6.08 m and a wall thickness of 0.24 m. The test setup and instrumentation layout were kept almost identical for both flat ground and sloping ground. Therefore, only the sloping ground test plan is presented in Figure 1.

A sinewave motion with peak ground acceleration (PGA$\approx$ 0.23g) was applied to the base of the model using the one-dimensional hydraulic shaker.

3 RESULTS AND CONCLUSIONS

Figure 2 shows the free-field excess pore water pressure (EPWP) generation during shaking and post-shaking. EPWP developed rapidly after the onset of shaking. In the sloping ground conditions, the free-field transducers show that liquefaction was triggered throughout the soil profile.

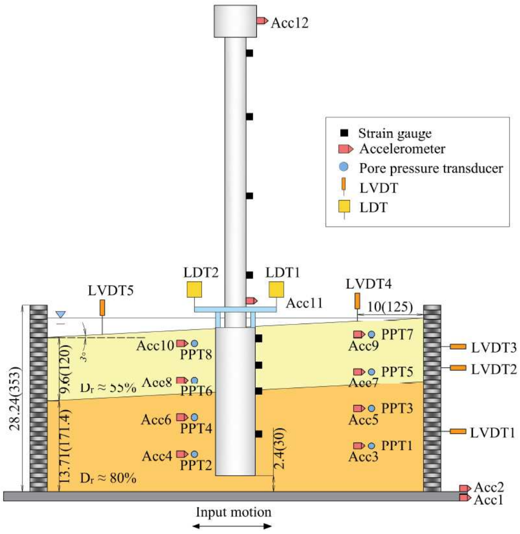

Figure 1. Test setup for monopile in sloping ground.

In contrast, in the flat ground, liquefaction was not observed in the deepest dense layer instrumented by PPT1. The rapid EPWP buildup degraded soil stiffness, monopile shaft and base resistance, which manifests as an abrupt settlement during shaking, as shown in Figure 3, where both tests exhibit a steep settlement drop during the shaking, followed by a slower post-shaking settlement recovery.

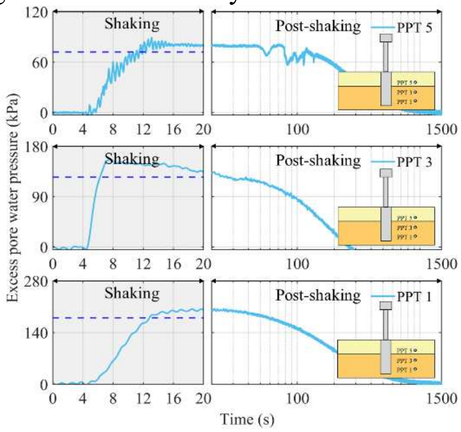

Figure 2. Free-field EPWP recordings in sloping ground.

Despite more extensive free-field soil liquefaction in the sloping ground, the monopile exhibited a relatively smaller settlement than in the flat ground. In contrast, the presence of even a mild ground inclination altered the post-liquefaction deformation mechanism, with lateral ground movement becoming dominant and imparting enhanced kinematic demands on the monopile. As a result, the residual lateral displacement of the superstructure (u_h) increased from 0.114 m in the flat ground to 0.21 m in the sloping ground (Figures 3(b-c)). The superstructure rotation was estimated as $\theta = \tan^{-1}\left(\frac{u_h}{H}\right)$, where H is the sum of tower height and the embedded monopile length. Using this relationship, the permanent rotation increased from 0.098° under flat ground to 0.181° in the sloping ground.

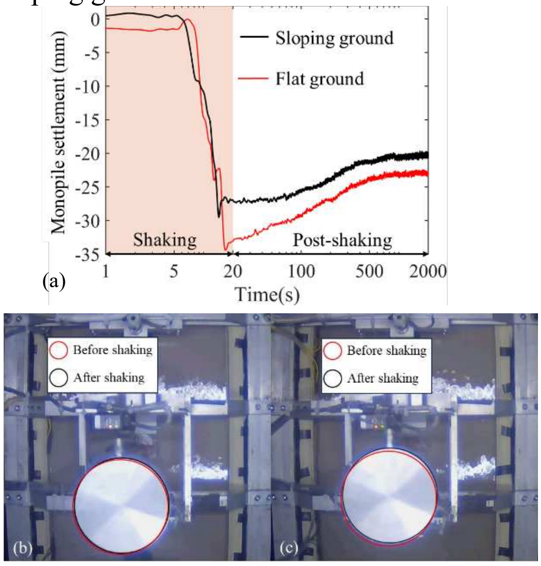

Figure 3. (a) Monopile settlement time histories, (b) lateral displacement in flat ground, (c)lateral displacement in sloping ground.

These observations highlight that even a mild seabed inclination shifts the response toward amplified horizontal displacement and rotation and emphasize the importance of accounting for seabed slope and post-shaking deformation mechanisms in performance-based design frameworks for offshore infrastructure, particularly in seismic active zones.

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