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Interaction Mechanisms between Submarine Landslides and Offshore Monopile Foundations: Centrifuge Modelling

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ABSTRACT: This study investigates submarine landslide-monopile interaction using geotechnical centrifuge modelling of a monopile embedded in a submerged clayey sand slope subjected to long-term water infiltration. Results indicated that monopile response transitioned from an approximately linear, displacement-controlled regime at small slope displacements (≤ 1.0 m) to a strongly nonlinear regime as slope instability developed. Moreover, rapid monopile displacement was triggered once the pore water pressure ratio exceeded a threshold of ~0.35, ultimately leading to global slope failure at slope displacements larger than ~4 m. The observed data demonstrated that monopile response was governed by imposed kinematic demand rather than bearing capacity, highlighting the need for displacement-based design of OWT foundations in hazard-prone seabeds.

1 INTRODUCTION

Offshore wind turbines (OWTs) are increasingly installed in deeper waters and geologically complex seabed environments, where submarine landslides pose a significant threat to monopile foundation performance. Such instabilities may be triggered by the accumulation of excess pore water pressure (EPWP) under different loading conditions, such as long-term seepage, resulting in large seabed deformations (e.g., Nadim, 2006; Lashgari et al., 2025). While documented cases of monopile-landslide interaction remain limited, ongoing expansion of offshore wind farms into deeper and less explored seabeds suggests that such interactions represent an emerging design challenge.

Current offshore design approaches primarily rely on serviceability/ultimate limit state checks and do not explicitly account for coupled soil-slope-structure interaction during seabed deformation. While a displacement-based framework has been proposed (e.g., De Risi et al., 2018), experimental evidence capturing EPWP-driven submarine sliding and monopile response remains limited.

This study presents a centrifuge test to investigate the displacement-based assessment of a monopile OWT embedded in a clayey sand submarine slope subjected to long-term infiltration, with a focus on identifying threshold behaviour linking pore water pressure ratio (r_u), slope, and monopile displacement.

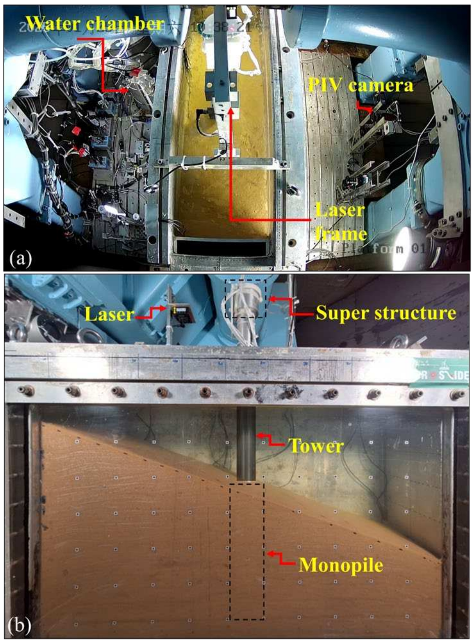

Figure 1. Details of test setup

2 TEST SETUP

A centrifuge test was conducted at the HKUST 400 g-ton Geotechnical Centrifuge Facility, modelling a 20° submarine slope supporting a simplified NREL 5

MW monopile-supported OWT at a 60 g scale (Figure 1). The seabed slope consisted of a clayey sand mixture composed of Toyoura sand with 10% kaolinite at a relative density of 55%. The monopile, tower, and superstructure were fabricated from aluminium (Young's modulus = 70 GPa) based on NREL 5 MW OWT (Jonkman et al. 2009), prototype-scale lengths of 21.6, 36.6, and 4.56 m, and corresponding diameters of 5.56, 3.92, and 6.0 m, respectively. The flexural stiffness (*EI*) of the monopile and tower was 1035.97 × 10^3 and 270.1 × 10^3, respectively. Instrumentation included 10 PPT, laser sensors, and PIV cameras.

3 DISPLACEMENT-BASED ASSESSMENT

Figure 2 shows the relationship between monopile displacement, submarine slope displacement, and r_u measured at mid-slope. Gradual increase of monopile displacement during the early stages, shows an approximately linear response for slope displacements up to ~1.0 m (Figure 2a). In this regime, deformation was governed by progressive soil softening and limited shear localisation.

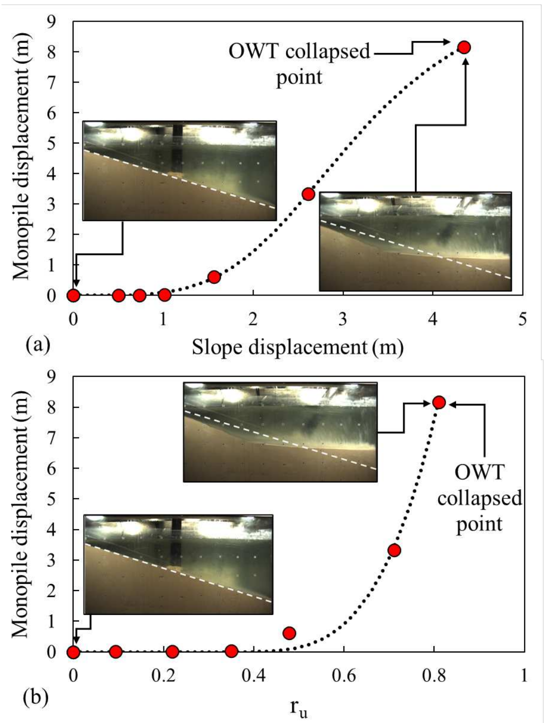

Figure 2. Monopile displacement versus (a) slope displacement (b) r_u (in prototype scale)

As EPWP continued to increase, slope deformation transitioned into a strongly nonlinear regime characterized by rapid sliding and pronounced kinematic interaction with the monopile. At slope displacements exceeding ~4 m, corresponding to global slope instability, monopile displacement exceeded ~8 m, leading to abrupt OWT collapse. This response occurred without classical bearing failure, indicating that monopile performance was controlled primarily by imposed ground displacement rather than foundation capacity in seabed sloping ground.

Figure 2(b) shows that monopile displacement correlates strongly with r_u, with slope deformation initiating at $r_u \approx 0.35$ and rapid monopile movement triggered once r_u exceeds ~0.35-0.4, reflecting abrupt strength degradation and mobilization of the sliding soil mass against the foundation.

4 CONCLUSIONS

This study provides experimental insight into the interaction between submarine landslides and OWT monopile foundation based on centrifuge modelling of a clayey sand slope. The results demonstrate that monopile response evolves from a linear, displacement-controlled regime at small slope movements (≤ 1.0 m) to a strongly nonlinear regime as slope instability develops, with global failure occurring at slope displacements of ~4 m and monopile displacement of ~8 m, without classical bearing failure. Monopile displacement exhibits a clear threshold dependence on r_u, with rapid kinematic response triggered for r_u > 0.35-0.4, underscoring the importance of displacement-based performance assessment for OWT design.

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