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Rate Effects on Cyclic Stiffness and Ratcheting of Monopile Foundations in Clay

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ABSTRACT: The expansion of offshore wind energy requires monopile foundations in varied seabed conditions. The MIDASclay project investigates the cyclic behaviour of monopiles in cohesive soils through a combined experimental and numerical research programme. Laboratory testing provides cyclic characterisation of clay and informs a centrifuge campaign in which monopiles are subjected to cyclic lateral loading. Instrumentation of the monopile and soil bed enables the assessment of stiffness evolution, rotation accumulation, and pore pressure response. Preliminary results show pronounced rate effects, with higher loading frequencies leading to a stiffer response and reduced monopile ratcheting rates.

1 INTRODUCTION

Offshore wind energy continues to expand rapidly, with monopile foundations remaining the dominant support structure, particularly at sites characterised by sandy soils. However, development is increasingly moving towards sites where cohesive soils govern foundation behaviour.

Clay behaviour is governed (among other factors) by cohesion, strain-rate dependency, cyclic degradation, ratcheting, and consolidation processes, all of which can significantly affect monopile stiffness and long-term performance under cyclic loading. While the impact of some of these mechanisms on monopile response has been demonstrated in previous studies (Kementzetzidis et al., 2023; Wu et al., 2022; Lai et al., 2020), their implications for monopile design remain insufficiently quantified.

The MIDASclay project investigates these challenges through a coordinated experimental and numerical research programme on the cyclic lateral response of monopiles in cohesive soils (Kementzetzidis et al., 2025). This paper presents selected experimental findings from centrifuge tests conducted at the Deltares Geocentrifuge in Delft, highlighting strongly rate-dependent monopile behaviour manifested in cyclic stiffness, its evolution during cyclic loading, and monopile ratcheting, with direct relevance to monopile modelling and design in cohesive soils.

2 MODEL PREPARATION AND TESTING

Centrifuge tests were conducted on reconstituted clay samples. The clay (Vingerlink K147; see Kementzetzidis et al., 2025 for details) was placed in the centrifuge strongbox and one-dimensionally consolidated at 1g under a vertical preconsolidation pressure of 600 kPa. Following consolidation to the target pressure, the monopiles were installed in the clay bed, after which the sample was spun at 100g in the centrifuge and allowed to reach pore water pressure equalisation at the elevated g-level. Further details on the instrumentation layout are presented in the companion paper by Cengiz et al. (2026).

The aluminium monopiles (embedded depth L_e = 0.5 m and diameter D = 0.1 m) were instrumented to measure lateral displacement, and bending moment. Lateral loading was applied at 5D above the mudline.

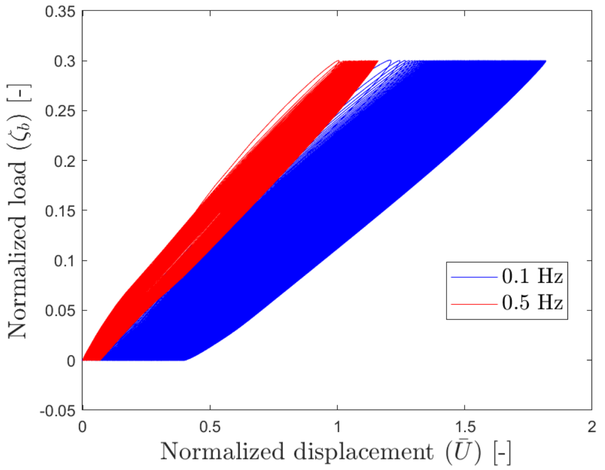

Figure 1. Normalised force (ζ_b) – displacement response. Displacement is normalized by the displacement at $\zeta_b = 0.3$ at the end of the first loading cycle for $f = 0.5$ Hz.

The presented loading sequence, part of a larger loading programme, comprised 500 load cycles at a normalised load level of $\zeta_b = 0.3$, where ζ_b is the ratio between the applied bending moment amplitude and a reference moment capacity corresponding to a monopile rotation of 2° at the mudline. Identical loading sequences were applied at model frequencies of 0.1 Hz and 0.5 Hz, which are considered representative of prototype loading frequencies in this study (see Kementzetzidis et al., 2025). The resulting cyclic response is illustrated in Figures 1–2. The results demonstrate a pronounced influence of loading rate on displacement accumulation (ratcheting) – measured at the elevation of load application, the corresponding cyclic stiffness (i.e., ratio between applied force and displacement amplitude), and it evolution with loading cycles.

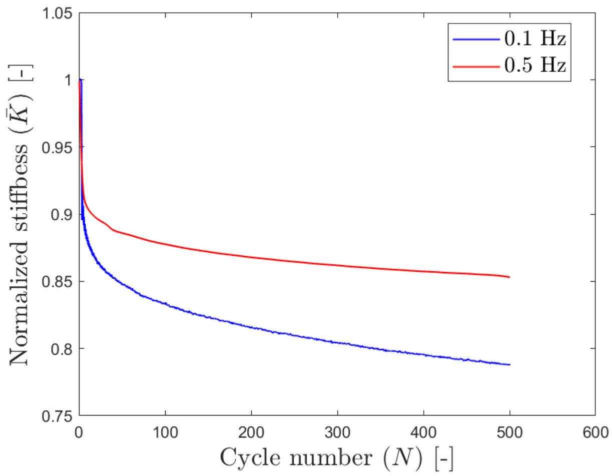

Figure 2. Evolution of cyclic stiffness normalised by the stiffness of each pile at the end of the first loading cycle.

3 CONCLUSIONS

These findings underline the need to account for rate effects in monopile design in cohesive soils, particularly with respect to OWT natural frequency tuning and design against lifetime tilt accumulation. The loading frequency controls monopile velocity and the resulting soil strain rates, which are shown to lead to rate-dependent cyclic stiffness, stiffness evolution, and accumulated rotation.

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