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Physical modelling of monopiles in sand: a generalized scaling law and long-term cyclic response

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ABSTRACT: In this Bright Spark Lecture paper, the author presents two contributions to physical modelling of offshore wind monopiles in sand. First, a generalized scaling law is developed for laterally loaded monopiles in drained sand. The framework links each monopile to an equivalent rigid-pile twin rotating about a centre located approximately 0.75L below the seabed, with dimensionless quantities accounting for pile diameter, embedded length, loading eccentricity, stress level and finite section stiffness. Validation against MIDAS centrifuge tests and literature datasets shows that the framework can unify responses across different geometries, g-levels and testing conditions. Second, a unique MIDAS centrifuge dataset on long-term cyclic loading of monopiles in drained dense sand is interpreted. The dataset includes 2 monotonic and 21 cyclic tests, covering cyclic load amplitude, cyclic load ratio, loading sequence and monotonic preloading. The results show rapid early rotation accumulation followed by stabilization, non-monotonic effects of cyclic load ratio, measurable loading-sequence dependency and relatively stable loading-unloading stiffness. Comparisons with 1g-based empirical models highlight the importance of stress-correct physical modelling for cyclic monopile design.

1 INTRODUCTION

Monopiles remain the dominant foundation for offshore wind turbines, but larger turbines and deeper waters require improved understanding of large-diameter monopile response in sand. Field tests provide direct evidence but are costly and difficult to control, while 1g model tests cannot reproduce prototype stress levels. This is critical because sand stiffness, dilatancy and cyclic deformation are stress- and state-dependent (Bolton, 1986). Centrifuge modelling addresses this limitation, but existing datasets still differ in pile geometry, loading eccentricity, stress level and interpretation method. A generalized framework is therefore needed to compare physical tests across scales and configurations.

2 GENERALIZED SCALING LAW

The first contribution is a mechanism-based scaling law for laterally loaded monopiles in drained sand. The derivation starts from a rigid monopile, for which bending deformation is absent and the response is governed by soil deformation and rigid-body rotation. Previous field tests and finite-element analyses showed that rigid monopiles rotate about a point located approximately 0.75L below the seabed and that the net lateral soil pressure is approximately proportional to vertical effective stress. Moment equilibrium about the rotation centre leads to the normalized resistance $H(h+0.75L)/(DL^3\gamma')$, where H is lateral load, h is loading eccentricity, D is pile diameter, L is embedded length and γ' is effective unit weight (Wang et al., 2022a, 2022b, 2022c).

Stress-dependent sand stiffness is incorporated by normalizing the rigid-pile rotation by $(L\gamma'/p_a)^{0.5}$, where pa is atmospheric pressure. For monopiles with finite flexural stiffness, the additional pile-bending deformation is estimated using a cantilever beam fixed at the rotation centre and corrected for soil restraint. The total response is therefore decomposed into a soil-controlled rigid-body component and a structure-controlled bending component. This enables monopiles with different diameters, embedment lengths, loading heights, stress levels and section stiffnesses to be compared in a common dimensionless space (Wang et al., 2023).

3 VALIDATION AND APPLICATIONS

The scaling law was validated using monotonic centrifuge tests from the MIDAS Deltares programme and independent literature datasets. The MIDAS tests covered different pile diameters, embedment ratios, g-levels and saturation conditions in dense to very dense Geba sand. In model-scale moment-rotation space, the responses differed substantially because of variations in pile geometry, stress level and stiffness. After correction to the rigid twin and normalization using the proposed dimensionless pair, the responses collapsed into a narrow band. Literature datasets that independently varied stress level, aspect ratio and relative density showed similar collapse. Upper- and lower-bound curves derived from MIDAS also provided reasonable first-order estimates for independent dense-sand tests. The framework can therefore support test planning, synthesis of fragmented databases and preliminary prediction before project-specific testing or detailed numerical modelling.

4 LONG-TERM CYCLIC RESPONSE

The second contribution is the interpretation of a unique MIDAS cyclic centrifuge dataset from TU Delft. The programme included 2 monotonic repeat tests and 21 cyclic tests at 100g using the same model pile in dry dense Geba sand. Cyclic loads were defined by $\xi_b = M_{max}/M_u$ and $\xi_c = M_{min}/M_{max}$, where M_u is the reference capacity at 2° mudline rotation. The monotonic repeat tests showed excellent agreement in load-deflection response and bending moment profiles, confirming repeatability.

The cyclic load-displacement curves showed that the first loading branch of each package generally followed the monotonic backbone, indicating limited degradation of post-cyclic capacity when a new peak load was reached. Under one-way loading, rotation accumulated rapidly during early cycles before approaching a stable or quasi-stable state. Cyclic load amplitude was the dominant first-order control, but the normalized trends differed markedly from empirical predictions calibrated from 1g tests.

The cyclic load ratio had a non-monotonic effect because increasing ξ_c increases mean load but reduces cyclic load range. Loading sequence also had a measurable influence. The tests support the idea that severe packages dominate accumulated rotation, but final rotation was not independent of package order; ascending sequences produced the smallest rotation, while descending or severe early packages produced larger responses. The loading-unloading stiffness remained relatively stable for most packages, with temporary reductions under high mean-load conditions that recovered when mean load was reduced. These observations show that cyclic monopile response in dense sand is stress-dependent, path-dependent and only partly compatible with Miner‘s superposition.

5 CONCLUSIONS

The proposed scaling law extends conventional centrifuge scaling by linking different tests through an equivalent rigid-pile response and stress-normalized rotation. The MIDAS cyclic tests show that stress-correct physical modelling is essential for interpreting rotation accumulation and stiffness evolution of monopiles in dense sand. Together, the two contributions provide a basis for improved test design, database synthesis, model validation and cyclic monopile design.

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