Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Integrating Numerical and Centrifuge Modelling to Investigate Shallow Foundation Behaviour

C. U. Ifeobu
University of Cambridge, Cambridge, United Kingdom

C. N. Abadie, Z. Li
Gustave Eiffel University, Nantes, France

S. K. Haigh
University of Cambridge, Cambridge, United Kingdom

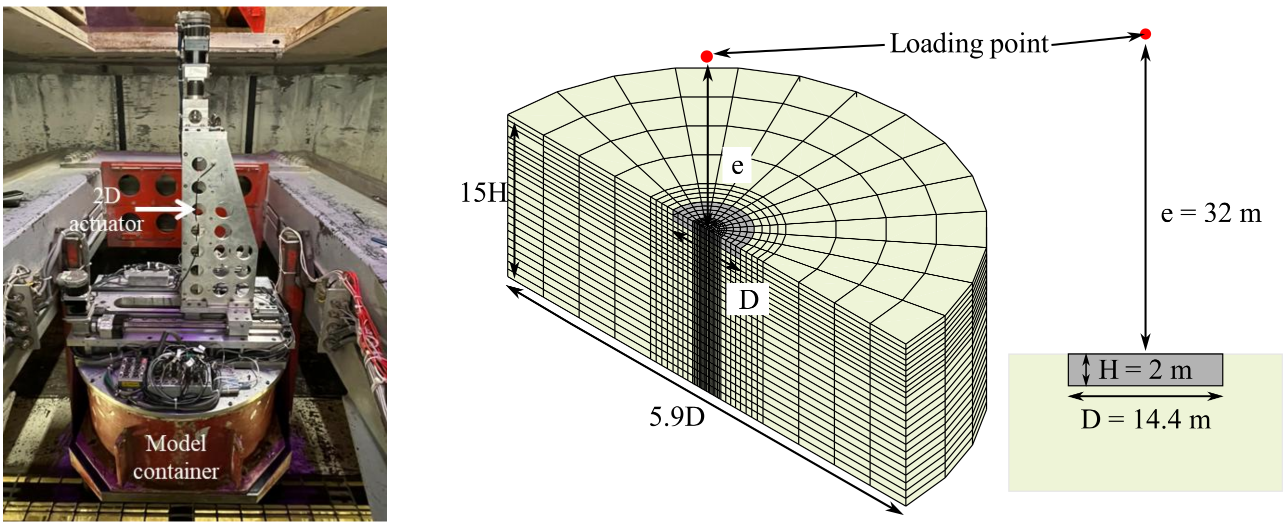
1 INTRODUCTION

The design of wind turbine gravity base foundations (GBF) must satisfy ultimate capacity requirements while limiting settlement and rotation (DNV, 2021). Uncertainty in predicting displacement accumulation over a turbine's lifetime and the “no-gapping“ SLS criterion advised in design guidelines lead to over-conservative designs. This can be remedied by complementing centrifuge modelling with numerical modelling to provide an in-depth understanding of the displacement response and soil-structure interaction under long-term cyclic lateral loading, which is the aim of this paper. This integrative approach shows the value of numerical modelling in enhancing the interpretation of physical test data.

2 METHOD

The centrifuge test presented in this paper was performed at an enhanced gravity of 100*g* on the Turner beam centrifuge at the Schofield Centre, University of Cambridge, and is shown in Figure 1(a). A prototype circular footing with a diameter, D = 14.4 m and a height H = 2 m, representative of a 2 MW wind turbine foundation, was modelled. The centrifuge tests were performed on dry HN31 Hostun sand, poured at a relative density of D_R=90%.
The footing was subjected to a multi-amplitude load-controlled sequence consisting of four packets with 100 cycles each, followed by a monotonic load to failure. The loads were applied at an eccentricity of 32 m above the soil surface at prototype scale. This enables a detailed assessment of the displacement response under cyclic and ultimate loading conditions.

A detailed finite element model was developed to simulate the above experimental test at prototype scale, using the SANISAND-MS constitutive model (Liu et al., 2019) and implemented in ABAQUS (version 2024). The model geometry is shown in Figure 1(b), and a similar loading sequence was applied at an eccentric reference point kinematically coupled to the foundation.
The parameters governing the monotonic response were calibrated using experimental data from the



(a) (b)

Figure 1: Modelling wind turbine shallow foundations (a) centrifuge model (b) Abaqus model geometry

Table 1: SANISAND-MS Parameters for Hostun HN31 sand

Elasticity		**Critical state**					**Yield surface**	**Plastic modulus**			**Dilatancy**		**Memory surface**		
G_0	v	M_c	c	λ_c	e_0	χ	m	h_0	c_h	n_b	A_0	n_d	μ_0	ζ	β
300	0.1	1.265	0.712	0.07	1	0.36	0.05	1.76	0.85	1.63	0.37	3.8	10	100	1

literature and drained triaxial test data collected by Azeiteiro *et al.* (2017) and Benahmed (2001), while the memory surface parameters were obtained through back-analysis of the centrifuge test data (Table 1).

3 RESULTS AND CONCLUSIONS

The numerical predictions of the small-scale behaviour and the global behaviour under monotonic and cyclic loading are shown in Figure 2 and are in good agreement with the experimental results. The numerical model captures the increase in rotation amplitude and accumulation with load level (Figure 2b). However, the model overpredicts the rotation accumulation, which leads to conservative estimates. The use of back-analysis to calibrate the memory surface parameters leads to uncertainties in these results and calibration using element tests is required to ascertain the validity of these results.

The numerical model was used to provide further insights on the evolution of the contact area with load level, which could not be determined during testing (Figure 3). Notably, the variation of contact area under cyclic loading closely matches that of the monotonic response and reduces by 50% at $M \approx 0.62 \times M_R$.

The results shown in Figures 2 and 3 illustrate how the validated numerical model complements the centrifuge test data by providing additional insights into soil–structure interactions that cannot be directly measured during experiments.

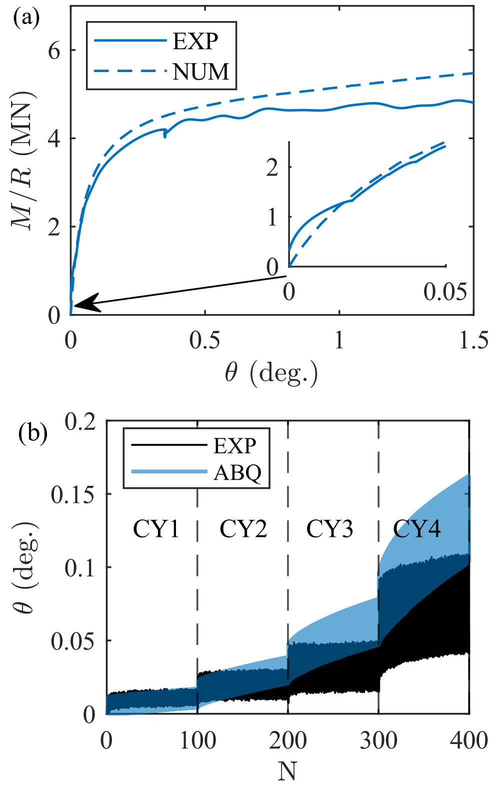


Figure 2: Validation of the numerical model based on the experimental data (a) Monotonic, (b) Cyclic

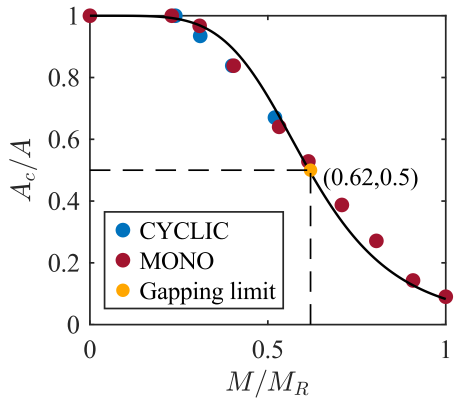


Figure 3: Variation of contact area with load level

ACKNOWLEDGEMENTS

The authors are grateful for the generous support of the Cambridge-Africa Scholarship and Gustave Eiffel University. We also thank the technicians at the Schofield Centre, University of Cambridge.

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