OPTIMISATION OF SHALLOW FOUNDATIONS FOR ONSHORE WIND TURBINES

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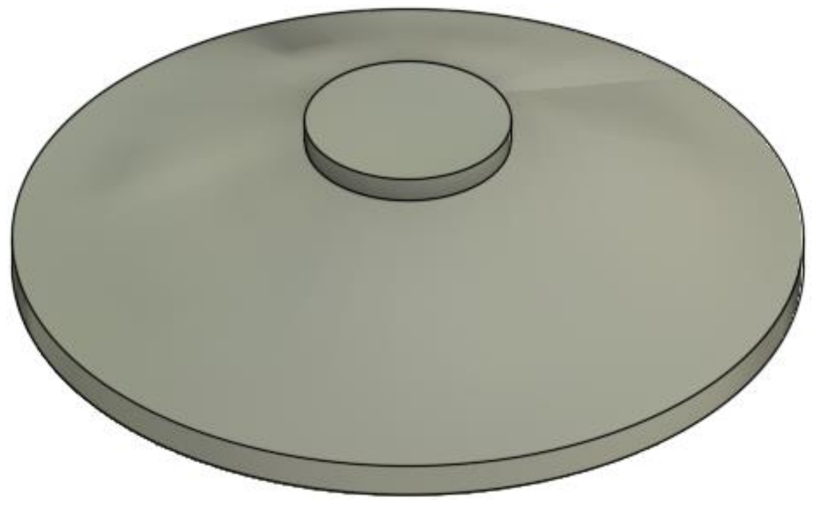
INTRODUCTION

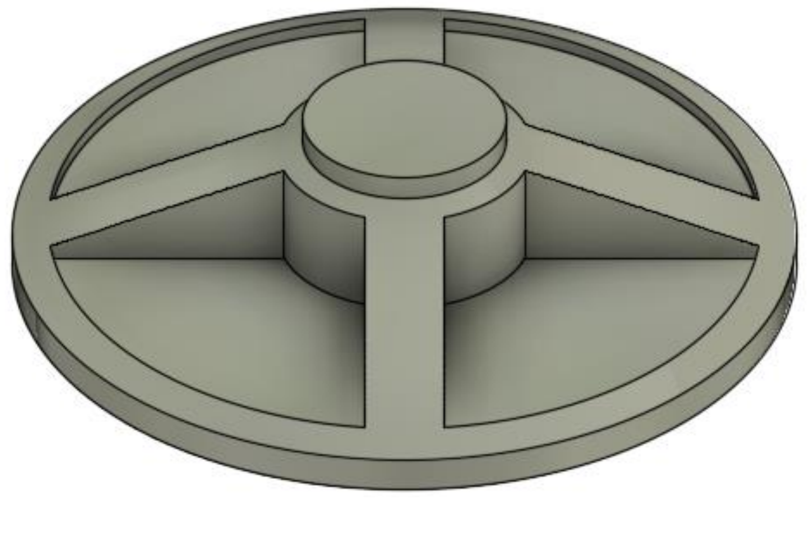
COSTS
£300 million in construction costs
1.176 x 10^6 m³ of concrete
370 x 10^3 tonnes of emitted carbon

POTENTIAL SAVINGS
£70 million in construction costs
292 x 10^3 m³ of concrete
87 x 10^3 tonnes of embodied carbon



CONVENTIONAL DESIGN

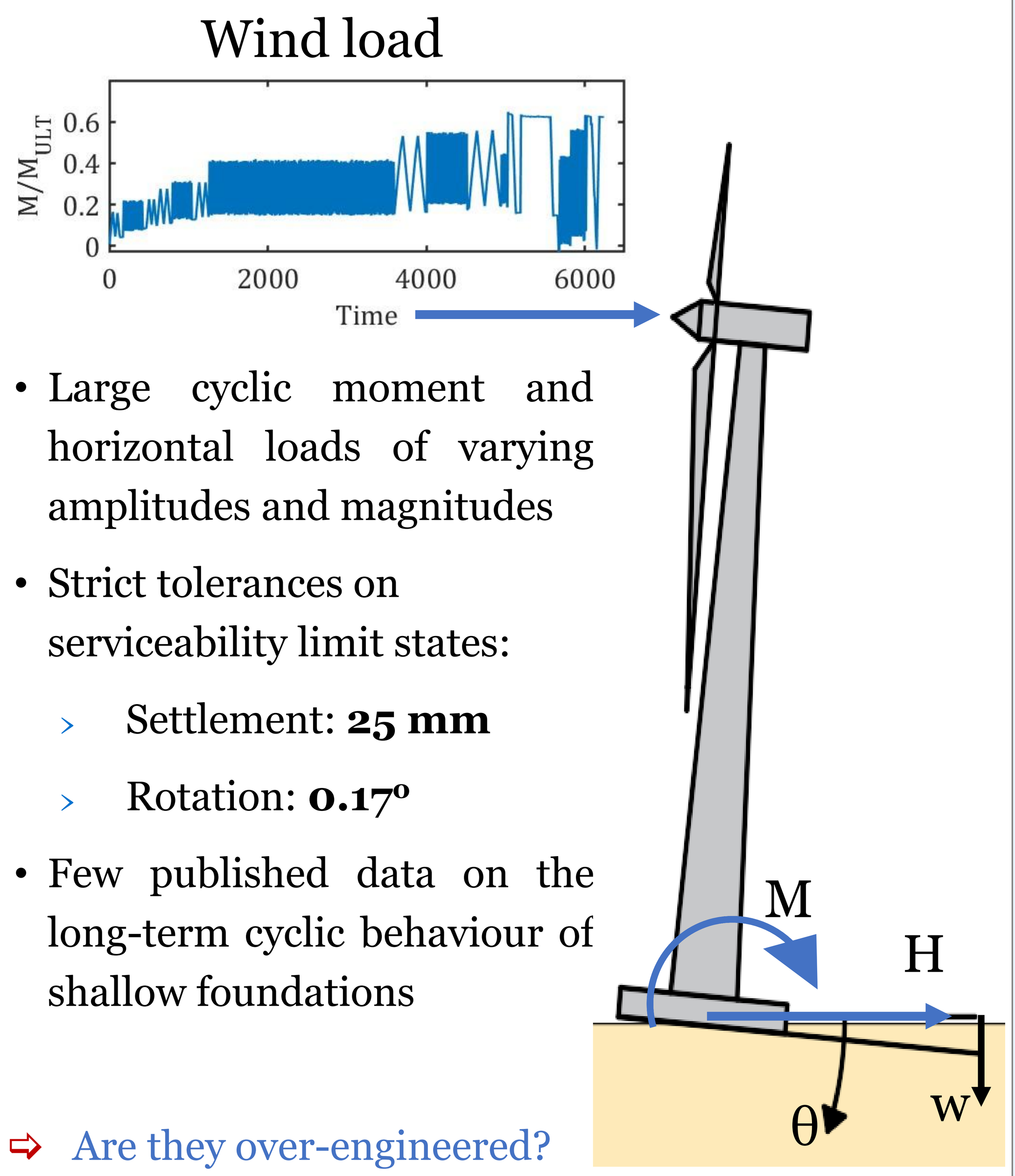
RESEARCH OBJECTIVES:
Understand the geomechanics behind the lifetime performance of shallow foundations to propose an optimised geometry that will:
- Reduce the carbon footprint
- Reduce the cost of scaling up onshore wind energy globally



POTENTIAL OPTIMISED DESIGN(S)

All values are estimated for an onshore wind farm with 1000 6 MW turbines

TECHNICAL CHALLENGES



- Large cyclic moment and horizontal loads of varying amplitudes and magnitudes
- Strict tolerances on serviceability limit states:
  - Settlement: **25 mm**
  - Rotation: **0.17°**
- Few published data on the long-term cyclic behaviour of shallow foundations

⇨ Are they over-engineered?

REFERENCES
Leblanc, C., Byrne, B. W., & Houlsby, G. T. (2010). Response of stiff piles to random two-way lateral loading. Géotechnique, 60(9), 715–721.
Moradi, M., Hosseini, S. M. M. M., & Khezri, A. (2023). Investigation of rocking mechanism of shallow foundations on sand via PIV technique. *Earthquake Engineering & Structural Dynamics*, 52(6), 1762–1784.

METHODOLOGY

- **Centrifuge experiments**: representative stress levels
- Performed at enhanced gravity of **100g**
- Dense Hostun Sand (RD ≈ 75 %)
- Dimensions representative of **2 MW turbine** scaled to plane strain conditions
- Deformation measured with Linear Variable Differential Transformers (LVDTs)
- Soil deformations and deformation mechanisms captured with Particle Image Velocimetry (PIV)
- **Load-controlled** cyclic lateral loading at relevant height
- Aluminium footing with H= 2m and B = 9 m

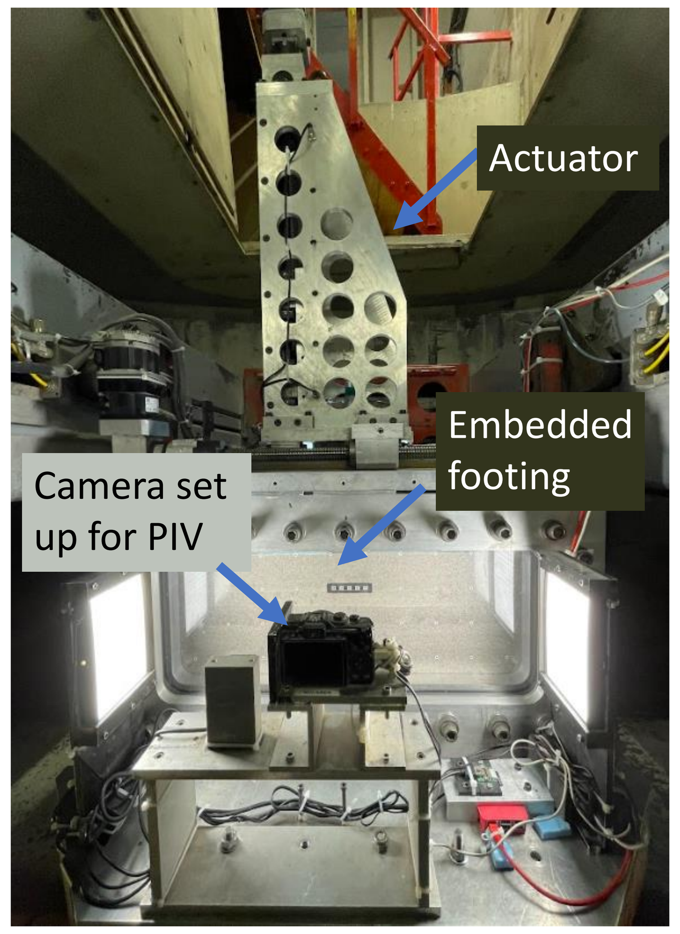


Figure 1. Model container with embedded footing ready for testing

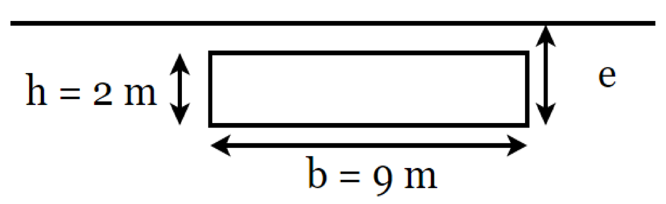


Figure 2. Schematic of footing (prototype scale)

☑ 1ST STEP IN INVESTIGATION:
Effect of embedment depth on cyclic performance of the footing

RESULTS

FOOTING RESTING ON A DENSE SAND (NO EMBEDMENT)

- Applied storm loading (Figure 3a)
  - Ratcheting behaviour observed with accumulation of rotations and settlements caused by cyclic loading (Figure 3b, c);
  - SLS requirements met at low load levels;
  - But exceeded at larger loads

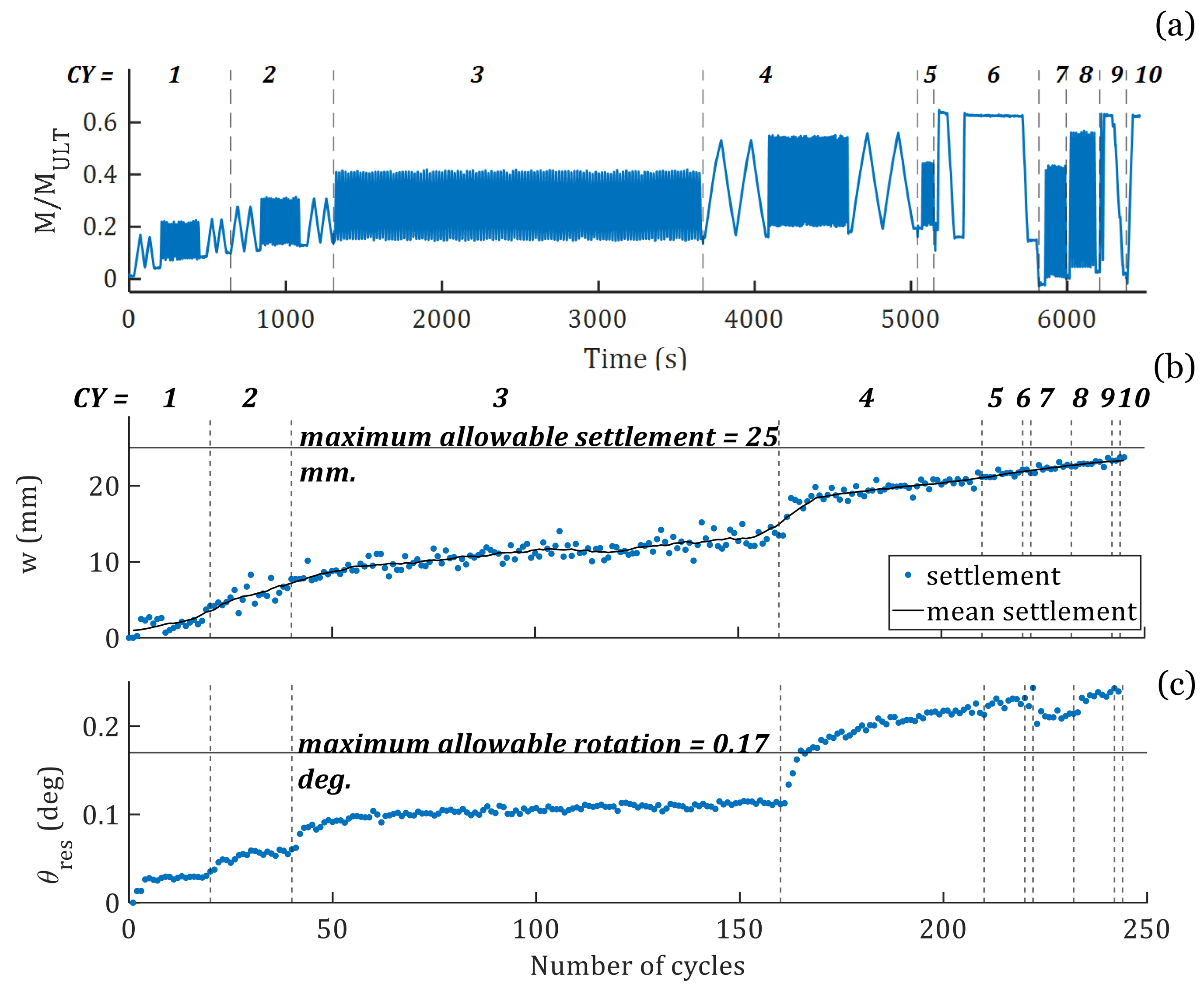


Figure 3. (a) Applied moment history and generated (b) settlement and (c) residual rotation with cycle number (prototype scale).

USING EMBEDMENT TO ENHANCE PERFORMANCE?

- Accumulated rotation follows a power law relationship (Leblanc et al. 2010) independent of embedment depth (Figure 5)

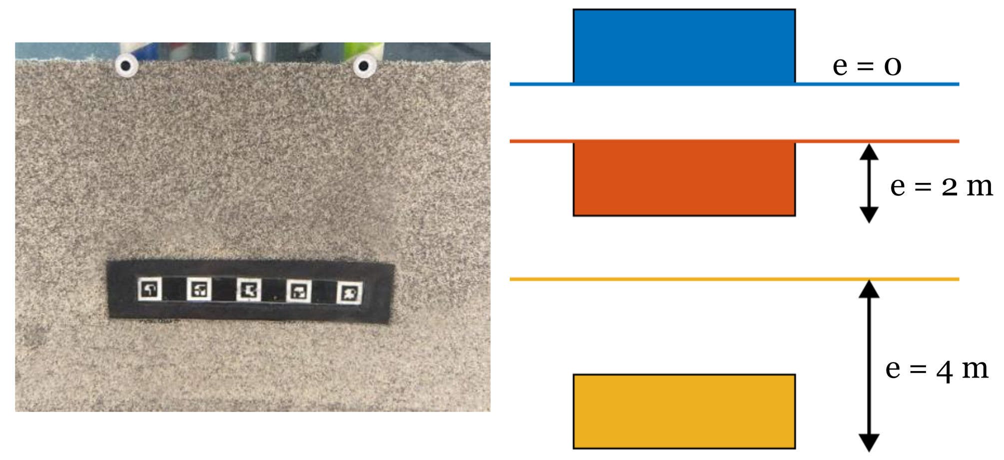


Figure 4. Model footing embedment (prototype scale)

- Reduction in accumulated rotations with embedment by up to **85%** in the tests performed to date

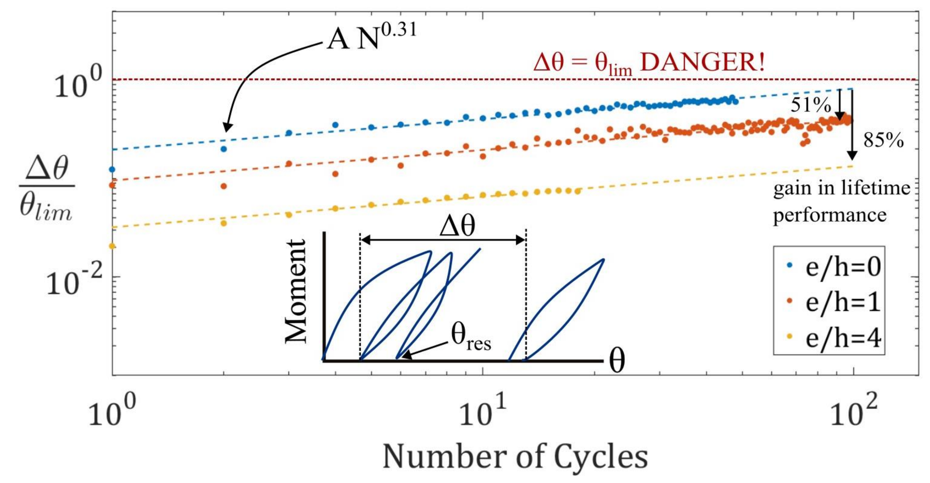


Figure 5. Rotation accumulation for similar load magnitudes and amplitudes for each embedment depth

CONCLUSIONS AND FUTURE WORK

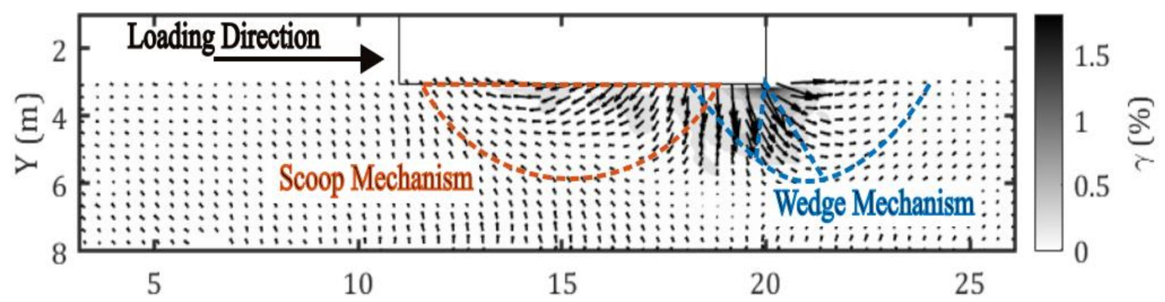


Figure 6. Soil deformation mechanisms at the end of load packet CY4. Displacement field overlain on maximum shear strain contours.

- The design of shallow foundations for onshore wind applications requires careful consideration of the number of cycles and load levels experienced
- The accumulated rotation and settlement over the lifetime of a shallow onshore wind turbine foundation can be large
- Enhanced geotechnical performance can be achieved significantly by increasing the embedment depth

Future work involves further tests on the geotechnical centrifuge in both plane-strain conditions and in 3D to elucidate:

- Can we understand this further by analyzing the soil deformation mechanism at larger plasticity levels (Figure 6)?
- Can this property be exploited to reduce the size of the foundation?
- Can simple design guidelines be recommended to enable more cost effective and less CO_2 intensive scaling up of onshore wind energy globally?