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Discussion: Soil–monopile interactions for offshore wind turbines

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Contribution by B. C. O'Kelly

The purpose of this discussion is to share with the readers some observations gathered from extensive research on lateral cyclic loading of short rigid monopiles for offshore wind turbines (OWTs) performed recently by the geotechnical research group at Trinity College Dublin and which are in support of the authors' findings (Cui and Bhattacharya, 2016), specifically: (*a*) granular convective flow, (*b*) increase in secant stiffness with number of load cycles (N) and (*c*) accumulated rotation of the monopile. The results reported in this discussion are for non-displacement closed-ended model piles (outer diameter (D) of 53 mm) having an embedment depth of 360 mm in dry medium silica sand beds prepared at a density index of 70–74% (i.e. dense state) (Arshad and O'Kelly, 2014). In these investigations, the monopile was directed to move under the action of an external horizontal force acting at the pile head, which protruded 90 mm above the sand bed surface level.

- For all 30+ tests performed, the sand grains surrounding the pile moved downwards, causing ground settlements to occur around the monopile, which was observed as a conical depression (Figure 12) that had almost fully developed by the end of the first ~ 500 load cycles. As described by Arshad and O'Kelly (2017b), the maximum diameter of the cone of depression occurred for balanced two-way (2w) lateral loading, ranging between ~ 200 and 300 mm ($3{\cdot}8$–$5{\cdot}7 \times D$), and depended on the load amplitude. Both one-way (1w) and unbalanced 2w lateral loading produced a smaller but elongated subsidence zone (i.e. ovalisation), with the maximum axis of the depression cone having a total length of between 175 and 225 mm ($3{\cdot}3$–$4{\cdot}2 \times D$), aligned with the direction of loading (Figure 12). The maximum depth of the sand depression (next to the monopile shaft) was limited to 25 mm for 1w and 2w (balanced and unbalanced) loading conditions. This indicated that the extent of the densified region was significantly smaller for 1w and unbalanced 2w lateral loading (as compared with balanced 2w lateral loading), consistent with the experimental observations reported by Brown *et al*. (1988). Further, the size of the depression cones observed (applying up to 42% of the ultimate static lateral load-carrying capacity of the pile, P_u) were in broad agreement with the experimental observations from model studies on monopiles embedded in saturated dense sand beds reported by Cuéllar *et al*. (2012).
- From the experimental investigations, the discusser concurs that the main reason for the measured/computed increase in secant stiffness with cycling is convective sand flow and the resulting densification around the monopile, most likely due to cyclic shear deformation of the soil mass adjacent to the pile, which causes a net contraction of the sand to occur (Gudehus, 2000). As pointed out by Cui and Bhattacharya (2016), the take-home message is that the stiffness of monopiles embedded in granular material is expected to increase with increasing N, which causes changes in the natural frequency of the wind turbine system, with the potential for unplanned system resonances – that is, a 'soft–stiff' structure design will move towards the $3P$ frequency.
- The accumulation of rotation of the experimental model piles produced after many thousands of lateral load cycles was dependent on the cyclic load characteristics, with the initial few cycles substantially contributing to the total accumulated rotation, and was found to increase approximately as a logarithmic function with increasing N (Figure 13 and Equation 2) (Arshad and O'Kelly, 2017a)

$$2. \quad \frac{\Delta\theta(N)}{\theta_0} = \alpha_1 \ln(N) + \beta_1$$

where θ_0 is the rotation for the first load cycle, $\Delta\theta(N)$ is the rotation produced from the second load cycle up to the Nth load cycle, α_1 and β_1 are model parameters (Arshad and O'Kelly, 2017a).

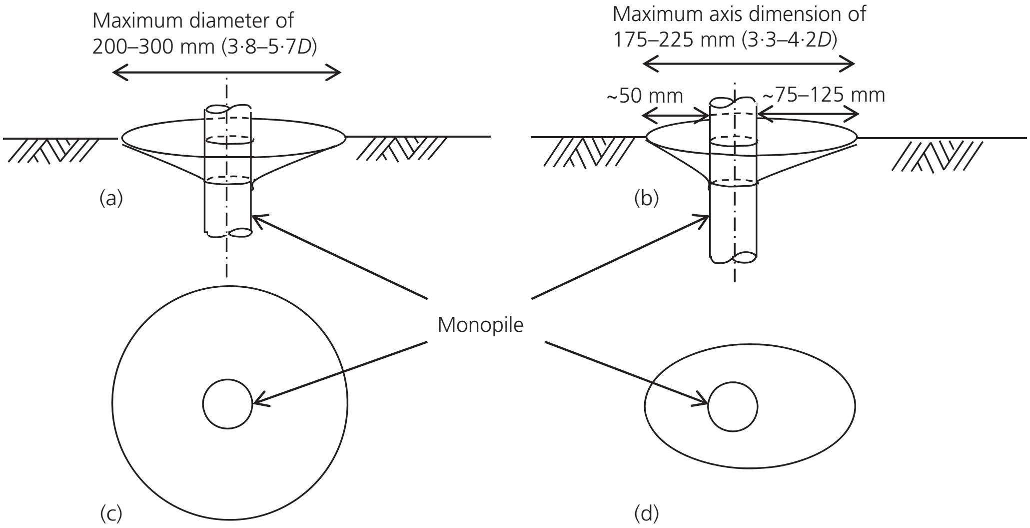

Figure 12. Local subsidence around monopile after application of 6000 lateral load cycles: (a) balanced 2w loading (isometric view), (b) unbalanced 2w loading and 1w loading (isometric view), (c) balanced 2w loading (plan) and (d) unbalanced 2w loading and 1w loading (plan) (Arshad and O'Kelly, 2017b)

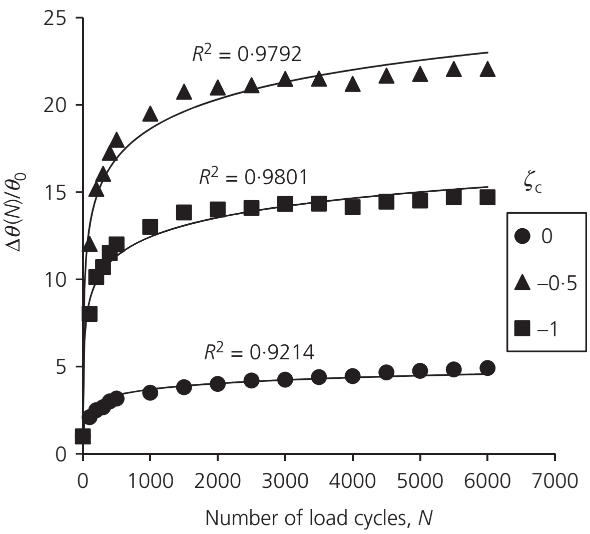

Figure 13. Normalised accumulated rotation against N relationships for different uni-directional lateral loading scenarios, with $\zeta_b = 0{\cdot}28$ (fatigue limit state) and loading frequency of 0·25 Hz (Arshad and O'Kelly, 2017a)

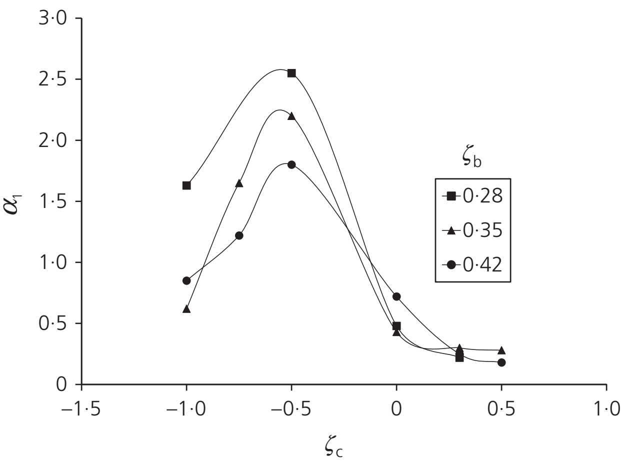

Figure 14. Functions relating model parameter α_1 with cyclic character parameters ζ_c and ζ_b (Arshad and O'Kelly, 2017a)

Figure 14 shows the dependence of α_1 on the magnitude of the cycle and the form of cycling, characterised by parameters ζ_c and ζ_b (Equations 3 and 4), and implies that there will always be a net accumulated rotation, even for balanced 2w lateral loading (i.e. $\alpha_1 > 0$ for $\zeta_c = -1$) (Arshad and O'Kelly, 2017a), with the direction of the first quarter of the 2w load cycle determining the direction of the net accumulated rotation (Rosquoët *et al.*, 2007). What is most conspicuous about this figure is that when compared with 1w, partial 1w and balanced 2w lateral loading (i.e. $\zeta_c = -1$, 0 and 0·5), the maximum accumulated rotation occurs for unbalanced 2w lateral loading ($\zeta_c = -0{\cdot}5$), consistent with experimental findings reported by LeBlanc *et al.* (2010) and Zhu *et al.* (2013). In other words, the largest accumulations occur when the pile is first pushed in one direction, partially pushed backwards and then pushed again in the first direction. Hence, as the authors identified, unbalanced 2w loading may cause excessive tilt and undermine the stability of the monopile more significantly in the long term.

3. $$\zeta_{\mathrm{b}} = \frac{P_{\max}}{P_{\mathrm{u}}}$$

4. $$\zeta_{\mathrm{c}} = \frac{P_{\min}}{P_{\max}}$$

where $P_{\max}$ and $P_{\min}$ are the maximum and minimum lateral loads, respectively, applied to the pile head during the load cycling.

In conclusion, there is much further important work required on the performance of real OWT monopiles, including investigations of the effects of the pile installation method, multi-directional lateral cyclic loading having different magnitudes arising from in-service environmental conditions, comparison between open- and closed-ended pile behaviour and modification of the conventional monopile (e.g. see Arshad and O'Kelly, 2016, 2017b) towards improving its long-term performance. Numerical simulations of the problem, including along the lines presented in the paper by Cui and Bhattacharya (2016), combined with further experimental testing (ideally for field stress conditions) will provide further valuable insights into better understanding of the monopile–soil interaction under the complex loading conditions experienced by the real OWTs in service. Such efforts will provide valuable information for the validation of current and improved design methods/theories for offshore monopiles towards the end goal of significantly reducing the levelised cost of energy for offshore wind.

Authors' reply

The authors agree with the research findings on the granular convective flow, increase in secant stiffness with number of load cycles and accumulated rotations of the monopile obtained by the geotechnical research group in Trinity College Dublin led by Professor O'Kelly. As stated by Professor O'Kelly, there are more important aspects to be investigated including the response of monopile under cyclic loadings with more complex patterns and in multiple directions. Further experimental tests, field tests and complementary numerical simulations will provide key information for improving the current design codes and achieving more affordable wind energy.

REFERENCES

Arshad M and O'Kelly BC (2014) Development of a rig to study model pile behaviour under repeating lateral loads. *International Journal of Physical Modelling in Geotechnics* **14(3)**: 54–67, http://dx.doi.org/10.1680/ijpmg.13.00015.

Arshad M and O'Kelly BC (2016) Piled-cruciform attachment to monopile head reduces deflection. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **169(4)**: 321–335, http://dx.doi.org/10.1680/jgeen.15.00001.

Arshad M and O'Kelly BC (2017a) Model studies on monopile behavior under long-term repeated lateral loading. *International Journal of Geomechanics, ASCE* **17(1)**: 04016040.

Arshad M and O'Kelly BC (2017b) Reducing monopile rotation under lateral loading in sandy soils. *Geomechanics and Geoengineering* **12(1)**: 14–27.

Brown DA, Morrison C and Reese LC (1988) Lateral load behaviour of pile group in sand. *Journal of Geotechnical Engineering, ASCE* **114(11)**: 1261–1276.

Cuéllar P, Georgi S, Baeßler M and Rücker W (2012) On the quasi-static granular convective flow and sand densification around pile foundations under cyclic lateral loading. *Granular Matter* **14(1)**: 11–25.

Cui L and Bhattacharya S (2016) Soil–monopile interactions for offshore wind turbines. *Proceedings of the Institution of Civil Engineers – Engineering and Computational Mechanics* **169(4)**: 171–182, http://dx.doi.org/10.1680/jencm.16.00006.

Gudehus G (2000) Nichtlineare Bodendynamik in der Geotechnik. In *Vorträge der Baugrundtagung 2000 in Hannover*. VGE Verlag GmbH, Essen, Germany, pp. 263–270 (in German).

LeBlanc C, Houlsby GT and Byrne BW (2010) Response of stiff piles in sand to long-term cyclic lateral loading. *Géotechnique* **60(2)**: 79–90, http://dx.doi.org/10.1680/geot.7.00196.

Rosquoët F, Thorel L, Garnier J and Canepa Y (2007) Lateral cyclic loading of sand-installed piles. *Soils and Foundations* **47(5)**: 821–832.

Zhu B, Byrne BW and Houlsby GT (2013) Long-term lateral cyclic response of suction caisson foundations in sand. *Geotechnical and Geoenvironmental Engineering* **139(1)**: 73–83.