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DISCUSSION

Lateral load response of large-diameter monopiles in sand

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Contribution by H. Wang, B. M. Lehane, M. F. Bransby, A. Askarinejad and L. Z. Wang

The authors (Hu *et al.*, 2022a) present a comprehensive numerical study on the lateral response of pile foundations in sands with a constant relative density. The influence of the pile configuration (length (L) diameter (D) and flexural rigidity), load eccentricity (h), sand type and relative density (D_r) were investigated. This discussion provides some additional insights regarding the lateral response of large-diameter monopiles in uniform sand by combining the authors' work with the observations by Wang *et al.* (2021) and Richards *et al.* (2021).

The relationship between normalised displacement and rotation

In the paper, the authors found that the term $y/D^{0{\cdot}88}$ is $0{\cdot}064 \pm 0{\cdot}013$ times the pile rotation (θ), where y is the lateral pile displacement at ground level. As shown on Fig. 20(a), the finite-element analyses of Wang *et al.* (2021) using the hypoplastic model also predicted that the ratio of $y/D^{0{\cdot}88}$ to θ is about 0·064 for 8 m and 10 m dia. piles. However, the predictions indicate that this ratio increases as D reduces. This can be explained by the rigid rotation mechanism of a monopile and the low sensitivity of the location of the rotation centre on the load eccentricity and sand properties illustrated by Wang *et al.* (2021). The rotation centre is located at about $0{\cdot}75L$ in a sand with constant D_r and, therefore, as shown in Fig. 20(b), there is a near-linear relationship between y/L and θ. Consequently, the deflection at the mudline of rigid piles can be approximated as $y = 0{\cdot}75L\theta$. These analyses indicate that pile deflection is better correlated with y/L than with $y/D^{0{\cdot}88}$ for rigid piles, such as the large-diameter monopiles used in offshore wind farms.

The normalised moment–rotation response of rigid piles: a simple way to unify the influence of pile diameter and loading eccentricity

The authors proposed a series of equations for calculating the load–deflection curves of monopiles in sand, which were also validated by the results from finite-element simulations. The discussers would like to show that a simpler normalisation method can be used to unify the influence of pile diameter and loading eccentricity on the load–deflection response of rigid monopiles.

In the same study referred to above, Wang *et al.* (2021) found that the moment–rotation response of rigid piles of different diameters can be unified by the normalisation $M/DL^3\gamma'$, where M is the over-turning moment at the mudline and γ' is the submerged soil unit weight. As shown in Figs 21(a) and 21(b), for rigid piles with the same L and h/L ratio, the moment–rotation of piles with different diameters is almost unified by the normalisation $M/DL^3\gamma'$.

However, this normalisation does not work if the L and h/L ratios of the rigid piles are different, as shown in Fig. 22(a). This is because (*a*) the stiffness of the soil along the pile depends on the stress level, which will change with pile length and (*b*) the normalised moment resistance (i.e. $M/DL^3\gamma'$) of a rigid pile depends on the relative distance of the loading point (i.e. h/L) to the rotation centre (at around $0{\cdot}75L$). To unify the influence of L (i.e. stress level) and h, it is proposed to represent the rigid pile response by relating $M_R/DL^3\gamma'$ with $\theta(P_a/0{\cdot}75L\gamma')^{0{\cdot}5}$, where M_R is the overturning moment relative to the rotation centre at about $0{\cdot}75L$ (i.e. $M_R = H(h + 0{\cdot}75L)$), H is the applied lateral load and P_a is the reference stress and equal to 100 kPa. The adjustment of the rotation (θ) by a normalised stress term $(P_a/0{\cdot}75L\gamma')^{0{\cdot}5}$ allows for the slower degradation of shear modulus (which controls the soil response to rotation) from the small-strain elastic value as the stress level increases. Further discussion of this normalisation is provided by Wang *et al.* (2022, 2023).

As shown in Fig. 22(b), the response of 1 m and 10 m dia. piles in the paper is almost unified by the proposed normalisation, despite different L and h/L ratios. The computed results from the paper for sand with $D_r = 80\%$ and the centrifuge test results in Richards *et al.* (2021) are also included in the same figure. It can be seen that the computed and experimental results show excellent consistency using the proposed normalisation and suggest that it is the D_r value that significantly affects the $M_R/DL^3\gamma'$ variation with $\theta(P_a/0{\cdot}75L\gamma')^{0{\cdot}5}$ for rigid piles in uniform drained sand.

Authors' response

The authors appreciate the discussers' interest in their research. The authors would like to point out initially that the discussers base much of their argument on analyses using a

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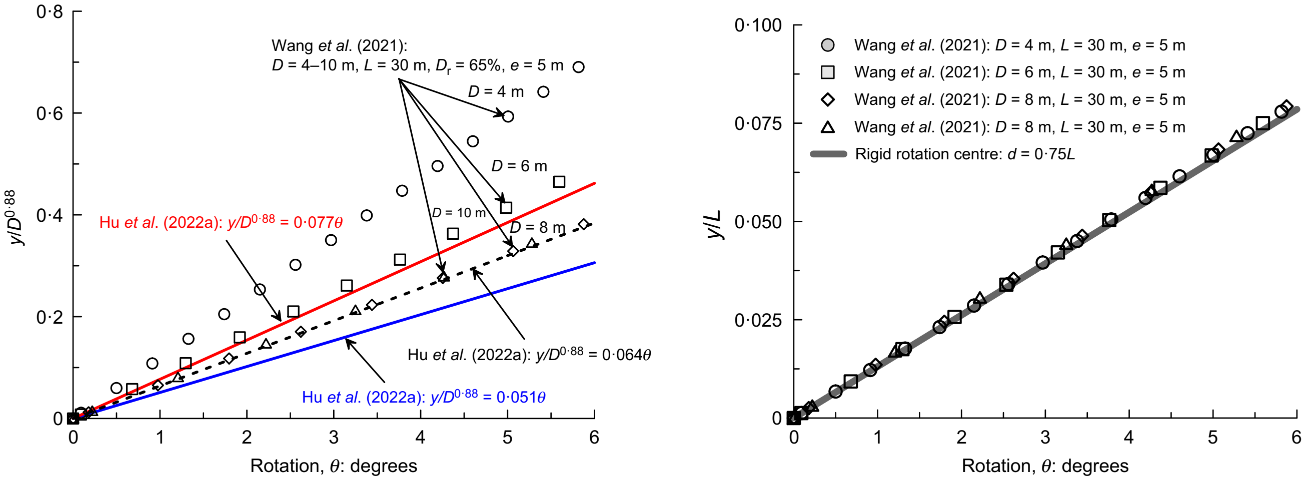
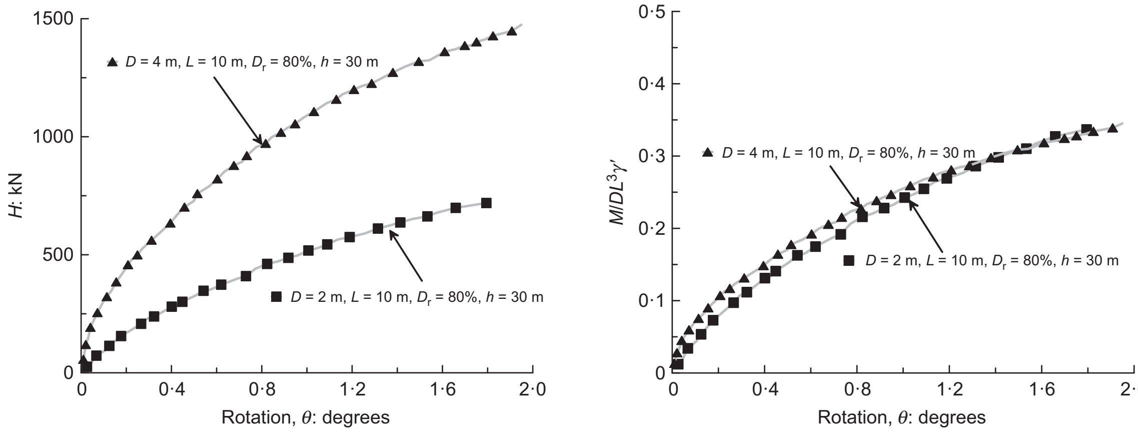


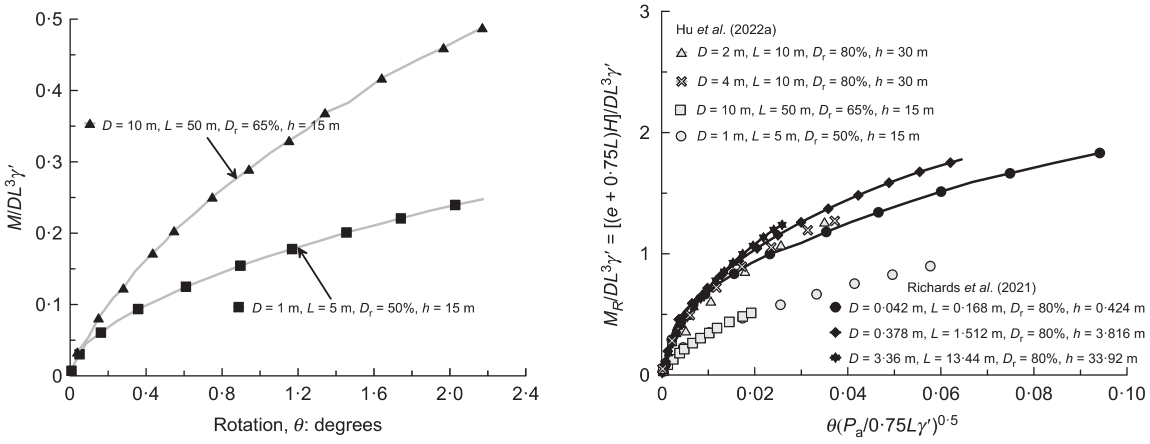
(a) (b)

Fig. 20. The relationship between the normalised displacement and rotation: (a) $y/D^{0{\cdot}88}$ plotted against θ; (b) y/L plotted against θ



(a) (b)

Fig. 21. Moment–rotation response at mudline: (a) M plotted against θ; (b) $M/DL^3\gamma'$ plotted against θ



(a) (b)

Fig. 22. Normalised moment–rotation response: (a) $M/DL^3\gamma'$ plotted against θ; (b) $M_R/DL^3\gamma'$ plotted against $\theta(P_a/L\gamma')^{0{\cdot}5}$

different constitutive model, which may have impacted some of the discussers' observations.

The discussers argued, first, that the pile rotation θ at mudline would be better correlated with length-normalised displacement u/L than with $u/B^{0{\cdot}88}$ (where L is pile length and B is pile diameter) for rigid piles, and, second, a normalisation method could be used to capture the relationship between applied moment and the pile rotation at mudline. The authors will address these two points in sequence.

The relationship between normalised pile displacement and rotation at mudline

The discussers suggested that the pile deflection u and pile rotation θ at the mudline for rigid, large-diameter monopiles can be correlated as

$$\frac{u}{L} = 0{\cdot}75\theta \qquad (10)$$

The equation was proposed based on the numerical study by Wang *et al.* (2023) of rigid, large-diameter (4–10 m) piles of fixed length (30 m) in uniform (Toyoura) sand with a fixed relative density (65%). Based on the results of these analyses, the authors proposed that the rotation centre of laterally loaded rigid piles is located at about $0{\cdot}75L$ below the ground surface for these piles.

In the authors' original paper (Hu *et al.*, 2022a), they proposed the following relationship between pile deflection and rotation at the mudline:

$$\frac{u}{B^{0{\cdot}88}L_{\mathrm{R}}^{0{\cdot}12}} = 0{\cdot}051\theta \qquad (11)$$

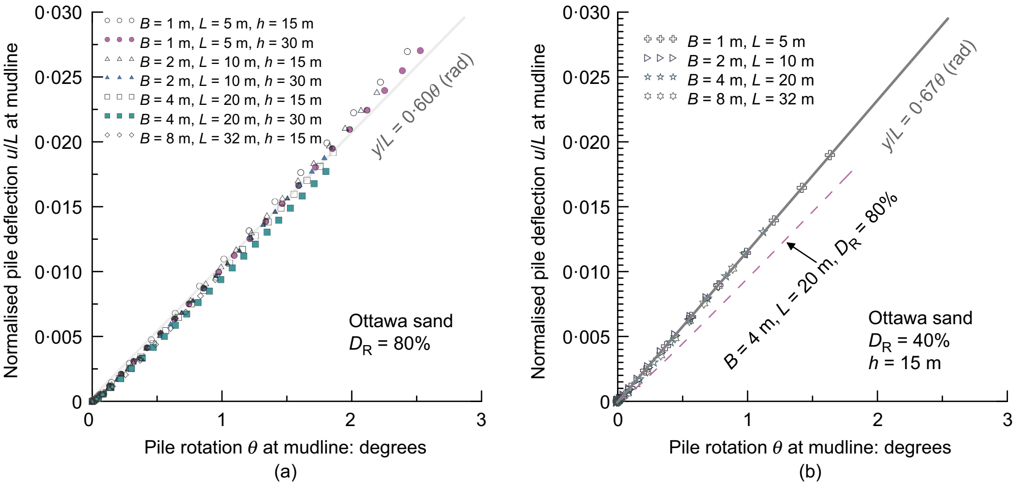
where L_{R} is the reference length = 1 m. The equation, which is applicable for both rigid piles and flexible piles, is based on a wide range of finite-element analyses with pile diameters, B = 1–10 m, slenderness ratio, L/B = 2–20, and load eccentricity, h = 15–30 m with D_{R} = 40–95%.

As shown in Fig. 23(a), the finite-element analyses of the original paper, performed on rigid piles in Ottawa sand, yield a linear relationship between u/L and θ for dense sand with relative density D_{R} = 80%:

$$\frac{u}{L} = 0{\cdot}6\theta \qquad (12)$$

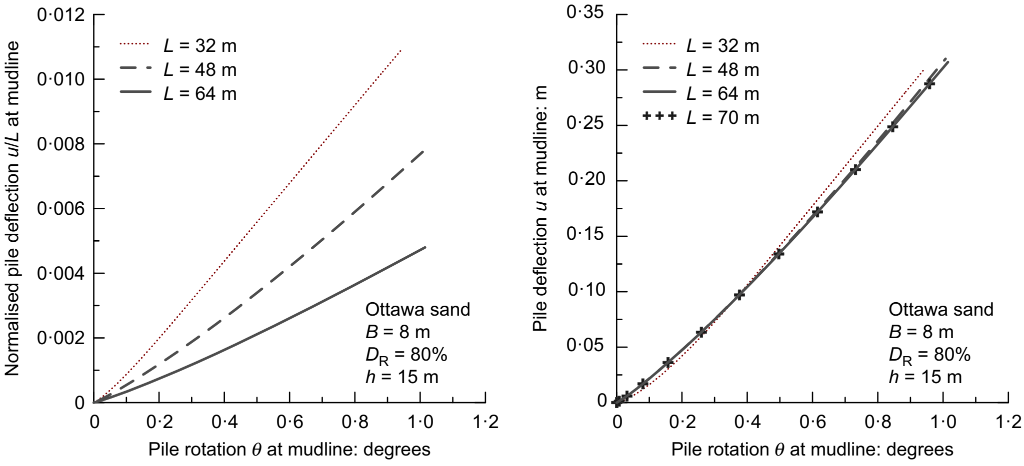
This suggests that the rotation centre is located approximately $0{\cdot}6L$ below the ground surface for dense Ottawa sand with D_{R} = 80%. For medium dense sand with D_{R} = 40% (Fig. 23(b)), the rotation centre is deeper as the soil stiffness decreases, leading to a different relationship between normalised deflection and rotation at the mudline. As load eccentricity has a minimal effect on the normalised relationship between y/L and θ, as shown in Fig. 23(a), only data for piles loaded at h = 15 m are presented in Fig. 23(b). This relationship can be expressed as

$$\frac{u}{L} = 0{\cdot}67\theta \qquad (13)$$



(a) (b)

Fig. 23. Normalised pile deflection *u*/*L* plotted against pile rotation *θ* at the mudline for large-diameter rigid piles for: (a) dense sand; (b) medium dense sand



(a) (b)

Fig. 24. (a) Normalisation of *u*/*L*–*θ* and (b) *u*–*θ* for 8 m dia. piles with different pile lengths in Ottawa sand with D_{R} = 80%, loaded at *h* = 15 m

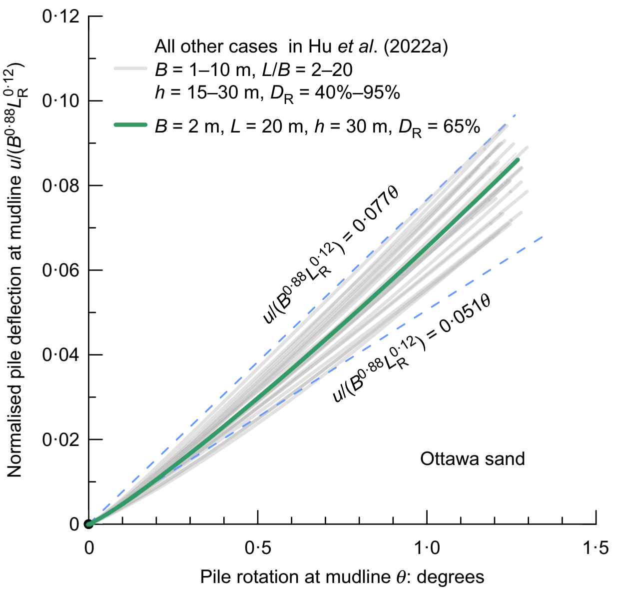


Fig. 25. Normalisation of $u/(B^{0·88}L_R^{0·12})$–θ for both rigid and flexible large-diameter monopiles (after Hu *et al.*, 2022a)

These results confirm the point raised by the discussers that there is a linear relationship between the normalised pile deflection and pile rotation at the mudline for rigid piles. However, the slope of this linear relationship depends on the relative density of the sand: the slope increases as the relative density decreases.

In the original paper, the authors investigated the lateral load response for piles with slenderness ratio L/B ranging from 2 to 20, encompassing the transition from rigid to semi-rigid and then flexible behaviour. A typical monopile used in the North Sea generally has a slenderness ratio in the range of 4–8 (Wang *et al.*, 2023). However, greater slenderness ratios (>8) may be required for monopiles to guarantee sufficient lateral resistance for offshore wind farm foundations when seabed conditions are relatively soft (e.g. medium dense sand or soft clay) and there is susceptibility to typhoon loading, as observed, for example, in China (Wang *et al.*, 2021).

Wang *et al.* (2023) observed that a 30 m long pile with diameters B of 4, 6, 8 and 10 m (resulting in slenderness ratios of $L/B = 3–7·5$) exhibited rigid behaviour. However, the slenderness ratio transition range for monopiles varies with the pile diameter: it decreases as the diameter increases. Detailed information is provided in Hu *et al.* (2022a). As depicted in Fig. 23, the 8 m dia. monopile with a length of 30 m exhibits rigid behaviour. As the slenderness ratio increases from 4 to 8, the pile transitions from rigid to flexible. Consequently, the relationship between lateral displacement u normalised by length L and rotational angle θ varies significantly due to both pile bending and rigid body rotation, as illustrated in Fig. 24(a). In fact, the y–θ curves, without normalisation with respect to L, are almost identical when the pile diameter and relative density are the same, as shown in Fig. 24(b). To account for the effect of pile diameter, slenderness ratio, load eccentricity and relative density, the original paper plots the data for all cases considered in the $u/B^{0·88}$ against θ graph (Fig. 25). All the cases fall in a relatively small range defined by $u/(B^{0·88}L_R^{0·12}) = 0·051\theta$ and $u/(B^{0·88}L_R^{0·12}) = 0·077\theta$. Accordingly, the authors proposed in the original paper (Hu *et al.*, 2022a) the following average relationship between normalised pile deflection $u/(B^{0·88}L_R^{0·12})$ and pile rotation angle θ at the mudline for both rigid piles and flexible piles in Ottawa sand:

$$\frac{u}{B^{0·88}L_R^{0·12}} = 0·064\theta \tag{14}$$

The results of the analyses discussed above confirm that there is a linear relationship between the normalised pile deflection y/L and pile rotation θ at the mudline for rigid piles when the relative density is fixed. However, this relationship does not hold for large-diameter, slender piles, which are frequently used offshore in China. The original paper proposed a relationship between normalised pile deflection and rotation at the mudline that is applicable to $D_R = 40–95\%$, $B = 1–10$ m, $L/B = 2–20$, covering the range from large-diameter rigid piles to large-diameter slender piles.

Normalised moment–rotation relationship for rigid piles

The discussers proposed a normalisation method to unify the moment–rotation response of rigid piles with different values of pile diameter, B, pile length, L, and load eccentricity, h. The method involves substituting the moment M with M_R, where M_R is the overturning moment at the mudline relative to the rotation centre, taken as being at $0·75L$ (i.e. $M_R = H(h + 0·75L)$ and H is the applied lateral load). By doing so, the normalised $M_R/BL^3\gamma'$ plotted against $\theta(P_a/0·75L\gamma')^{0·5}$ curves, where γ' is the submerged soil unit weight, can be unified for a fixed relative density. This normalisation method provides a good alternative to estimate the relationship between the applied lateral load and the pile rotation for rigid piles.

In the original paper, the authors proposed a set of general equations that can be used to obtain the relationship between lateral load, H, and pile rotation, θ, at the mudline for both rigid and flexible piles. The proposed equations are applicable to: a broad range of pile diameters, B, from 1 m to 10 m; slenderness ratios L/B, from 2 to 20; wall thickness-to-diameter ratios, t_w/B, from 1 : 100 to 1 : 50; relative densities, D_R, from 40% to 95%; and load eccentricities, h, from 15 m to 30 m. The design methods were further developed in subsequent studies by Hu *et al.* (2022b), extending their applicability to layered sand profiles for any value of load eccentricity, while also incorporating the impact of overconsolidation.

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