Physical Modelling in Geotechnics

Permanent strains and deflections of reinforced-concrete piles under cyclic lateral loading

H. Louw, E. Kearsley & S.W. Jacobsz
Department of Civil Engineering, University of Pretoria, Pretoria, South Africa

ABSTRACT: In reinforced concrete design it is assumed that, due to the low tensile capacity of concrete, it is unable to resist significant tensile forces and steel reinforcing is required to resist the loads causing tensile stresses. Concrete would thus, for all design purposes, be considered cracked, affecting both the flexural stiffness and sectional properties of reinforced-concrete members, resulting in a construction material that exhibits highly non-linear material behaviour. The behaviour of horizontally loaded piled foundations is an interesting soil-structure interaction problem and is largely dependent on the relative stiffness between the pile and the surrounding soil, amongst other factors. Researchers typically assume linear elastic pile behaviour and focus on the soil component of the soil-structure interaction problem. Changes and non-linear behaviour of the soil surrounding the pile upon load application are studied mostly disregarding the behaviour and response of the pile itself. Often piles are modelled in a geotechnical centrifuge using aluminium alloys. Centrifuge model testing was conducted to determine whether the load-deformation behaviour of a horizontally loaded pile made of reinforced concrete can be compared to that of a metal pile. In this paper, the focus is on investigating the effect of cyclic loading on the permanent strains and deflections developed within aluminium and reinforced-concrete piles with similar uncracked relative pile stiffnesses. Considering permanent responses, significant differences between the two piles were observed due to concrete cracking, which is also discussed.

Keywords: centrifuge modelling, piles, reinforced concrete, soil-structure interaction

1 INTRODUCTION

Reinforced concrete is a strong, durable and versatile construction material that has been widely used in many types of structures for decades. It is also a well-known assumption that, due to the low tensile capacity of concrete, steel reinforcing is required to resist the loads causing tensile stresses. For all design purposes, concrete would be assumed to be cracked, affecting both the bending stiffness and sectional properties of reinforced-concrete members, resulting in a composite material that exhibits highly non-linear material behaviour.

Pile foundations are extensively used to support structures constructed on soft or loose soils, where shallow foundations would be considered ineffective due to low bearing capacities and large settlements. The design of these structures to accommodate horizontally applied loads, usually imposed by winds and water, has gained popularity over the past few decades especially within the renewable energy sector. Typically, considering such foundations, the lateral pile displacement depends on the soil reaction, and in turn, the soil reaction is influenced by pile displacement, complicating the analysis and design of these foundations (Tomlinson, 1980). The behaviour of horizontally loaded piled foundations is an interesting soil-structure interaction problem and is largely dependent on the relative stiffness between the pile and the surrounding soil, as indicated by Poulos & Davis (1980) in Equation 1:

$$K_R = \frac{E_p I_p}{E_s L^4} \tag{1}$$

where E_pI_p refers to the bending stiffness of the pile, E_s to the Young's modulus of the soil and L to the embedment length of the pile. K_R is a dimensionless measure of the pile flexibility, with $K_R > 0.208$ representing a rigid pile and $K_R < 0.0025$ a slender pile according to Poulos (1982).

Researchers typically assume linear elastic pile behaviour when investigating lateral pile response and focus on the soil component of the soil-structure interaction problem. Often piles are modelled in a geotechnical centrifuge using aluminium alloys, raising concern regarding the validity of these assumptions and methodologies for analysing and designing reinforced-concrete piles, as the material behaviour is considerably different than that of metals. Typically, these methods only consider the effects of cyclic lateral loading through the application of degradation factors (Little & Briaud, 1988). However, many researchers have indicated that under long-term cyclic loading, the behaviour of the soil-pile system shows a different response due to the soil around the pile densifying rather than degrading (Leblanc *et al.*, 2010, Li *et al.*, 2010). Long & Vanneste

(1994), Leblanc *et al*. (2010) and Li *et al*. (2010) mentioned that piles typically suffer the greatest horizontal permanent deformation during its first load cycle after which the effect diminished as cycling continued due to an increasing soil stiffness, creating progressive pile lateral permanent displacement.

In order to investigate the effect of permanent deformation due to cyclic loading, Werkmeister *et al.* (2004) indicated, based on triaxial tests conducted on unbound granular materials for pavement design, that each loading cycle can be separated into different ranges. They indicated that, even at small cyclic applied stresses, both resilient and permanent deformations arise, with the stress-strain relationship forming a hysteretic loop upon load removal due to the non-linear response of soils. Furthermore, Werkmeister *et al.* (2004) mentioned that, depending on the magnitude of the applied load, the response of the soil will be different. They indicated that the soil will either become entirely resilient after a 'post-compaction' period for a finite number of load applications, or the response being always plastic, with each additional load application resulting in a progressive increment of permanent strain.

Another important aspect that is typically overlooked and has been initially addressed by Kirkwood & Haigh (2014) is that of permanent bending moments that exists within a horizontally loaded pile after load removal. They argued that this is possibly due to locked in soil stresses that develop due to the applied cyclic loading. More recently Truong *et al*. (2019) also emphasised the presence of permanent bending moments during one-way cyclic lateral load tests. At $z/D = -3.5$, the permanent bending moment had a magnitude of 50% of the maximum bending moment in the pile after 500 load cycles, also indicating an increase in magnitude with increasing load cycles similar to Kirkwood and Haigh (2014). All tests from both publications where conducted on piles constructed from aluminium alloys.

Thus, besides changing soil properties with cyclic loading, the need arises to experimentally determine the effect of changing concrete properties on the relative stiffness of the soil-pile system. Centrifuge model testing was conducted to determine whether the load-deformation behaviour of a horizontally loaded reinforced-concrete pile can be compared to that of a metal pile. In this paper the effect of cyclic loading on the permanent strains and deflections developed within aluminium and reinforced-concrete piles with similar uncracked relative pile stiffnesses is investigated. The effect of concrete cracking is also discussed.

2 EXPERIMENTAL SET-UP

In order to investigate the effect of cyclic lateral loading on the response of reinforced-concrete piles in the geotechnical centrifuge, cyclic lateral load testing was carried out at 30-*g* on both a scaled aluminium and reinforced-concrete pile respectively. The tests were conducted using an aluminium strongbox with inside length, width, and height of 600 x 400 x 400 mm respectively, with the piles pre-positioned in the centre of the strongbox. As the primary problem concerned bending of the piles, the bending stiffnesses (E_mI_m) of the aluminium and reinforced-concrete piles were scaled using the appropriate scaling laws (Schofield, 1980). Pile dimensions were selected to model a 600 mm reinforced-concrete pile at prototype scale (Byrne & Berry, 2008). For the scaled aluminium pile, a hollow aluminium tube was used, with an assumed modulus of elasticity of 70 GPa for calculation purposes. The scaled reinforced-concrete pile was cast from concrete with a compressive strength and modulus of elasticity of 35.8 MPa and 20.5 GPa respectively, measured from standard reinforced concrete test specimens. For modelling the reinforcing cage, 6 x 0.60 mm stainless-steel wires were used, confined by a 0.21 mm stainless steel wire spiral with a pitch of approximately 10 mm and diameter of 17 mm. Table 1 indicates the respective pile dimensions along with the uncracked and cracked bending stiffness of each pile. The cracked bending stiffness of the reinforced-concrete pile was determined from strain compatibility and force equilibrium and represents the stiffness when the steel reinforcing starts to yield. D_m refers to the outside diameter of each model pile, t_m, the model pile wall thickness and E_mI_m, the model pile bending stiffness.

Both piles had a total length of 400 mm with 350 mm ($L/D \approx 17.4$) embedded in the soil. A one-way horizontal cyclic load was applied to an aluminium pile cap that was fixed to each pile head, 37.5 mm above the soil surface. Loads were applied using a linear actuator, with the applied load measured using a load cell attached to the front of the actuator shaft. Horizontal displacement above and below the soil surface was measured using linear variable differential transformers (LVDTs) and bending beam displacement transducers respectively. To evaluate the bending response of the piles, both piles were instrumented using six sets of 120 Ω precision resistance strain gauges on both sides of the pile to obtain independent strain readings (quarter-Wheatstone bridge configuration).

Table 1. Pile dimensions and pile-flexibility factors.

Pile type	D_m (mm)	t_m (mm)	E_mI_m – uncracked ($MNmm^2$)	E_mI_m – cracked ($MNmm^2$)	K_R – uncracked
Aluminium	19.2	1.3	194.3	-	0.00028
Reinforced concrete	21.1	-	316.1	18.0	0.00045

The model set-up and position of all the measuring and testing equipment can be seen in Figure 1.

All centrifuge experimental work was conducted using dry silica sand, with a mean particle size of 138 µm, specific gravity of 2689 kg/m^3 and coefficient of uniformity of 2.97. Soil models were prepared through a method of pluviation from a constant height into the strongbox around the pre-positioned instrumented piles to obtain a density of approximately 1700 kg/m^3 (80% relative density). A representative Young's modulus at this relative density was determined from oedometer tests as 47 MPa, assuming a Poisson's ratio of 0.3. A friction angle of 32˚ was obtained from triaxial tests.

Using the abovementioned soil properties and the sectional properties of each model pile, the pile-flexibility factors, K_R, for the scaled aluminium and reinforced-concrete piles were calculated as indicated in Table 1. According to Poulos (1982) both piles are classified as slender. Due to the low tensile capacity of concrete, the bending stiffness of the concrete pile would decrease significantly once the section cracks, as seen in Table 1. In order to access the magnitude of the applied horizontal loads to each pile, the magnitude was expressed as a function of the horizontal capacity of each pile, also referred to as the cyclic magnitude ratio, ζ_b, (Leblanc *et al.,* 2010). The horizontal capacity of each pile was calculated as 695.1 N for the scaled aluminium pile and 76.6 N for the scaled reinforced-concrete pile using Broms (1964). Table 2 indicates ζ_b along with the corresponding number of load cycles, N, at each load for each pile type. The magnitudes of the applied loads were determined to model both serviceability and ultimate limit state conditions of the reinforced-concrete piles.

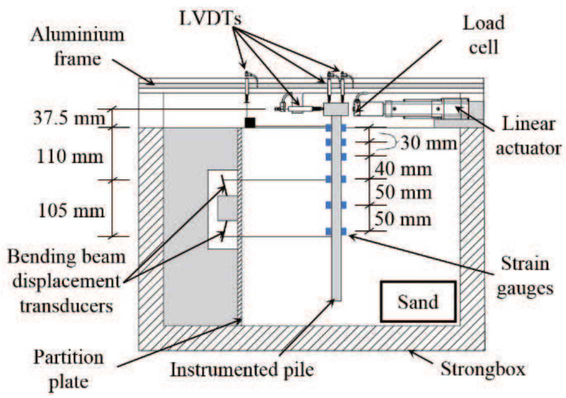

Fig. 1. Centrifuge test set-up.

Table 2. Cyclic load ratio and number of load cycles.

Aluminium		Reinforced concrete	
ζ_b	N	ζ_b	N
0.07	300	0.39	150
0.13	1000	0.85	1000
0.16	1000	1.31	1000

3 RESULTS AND DISCUSSIONS

3.1 Permanent bending moments

Figures 2(a) and 2(b) indicate the permanent bending moments, M_{per}, with depth for the scaled aluminium and reinforced-concrete piles respectively. The position of each M_{per} is presented relative to the diameter of the pile (z/D), with the soil surface taken as z = 0 mm and downwards as negative. In each figure cycle 1, cycle 100 and the last cycle at each load magnitude (ζ_b) are indicated. It can be seen that, in the case of the scaled aluminium pile, the maximum M_{per} occurred at approximately 8 pile diameters below the soil surface with the magnitude increasing as the applied load magnitude and the number of load cycles increased. This differs from the scaled reinforced-concrete pile, where the maximum M_{per} was measured between 7 and 10 pile diameters below the soil surface. After about 200 load cycles at ζ_b = 1.31 the reinforced-concrete pile cracked and started to yield. Values beyond this point, at a depth of z/D = -4.7 were not included, as the crack in the concrete section formed close to the strain gauge, resulting in the measured values not being representative of the pile behaviour.

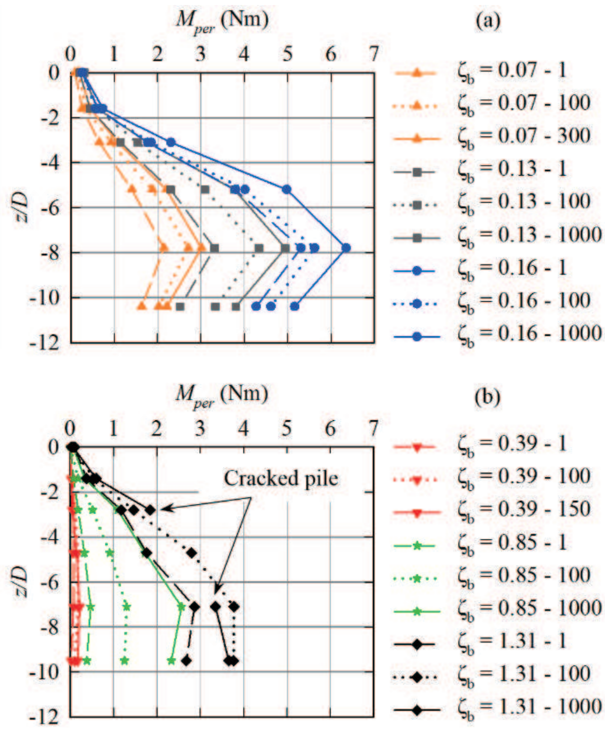

Fig. 2. Permanent bending moment with depth: (a) aluminium; (b) reinforced concrete.

The permanent bending moments observed were as a result of changing soil conditions due to applied cyclic lateral loading. A reduction in permanent bending moments below the position of the crack ($z/D \approx$ -4.7) seems to indicate crack growth, with permanent bending moments measured above the position of the crack still increasing with number of load cycles after cracking.

3.2 Permanent pile displacement

The effect of load magnitude and the number of load cycles on the permanent pile displacement, y_{per}, were also considered. Figures 3(a) and 3(b) shows y_{per} for the scaled aluminium and reinforced-concrete piles respectively. The figure presents the displacement measured along the length of the pile, with $z/D > 0$ indicating displacement measurement above the surface of the soil. For both piles, the maximum increase in y_{per} occurred within the first load cycle at each load magnitude and position, except towards the bottom of the pile. After the first load cycle, y_{per} increased slightly with number of load cycles, indicating possible resilient response of the soil. However, it should be noted, in the case of the scaled reinforced-concrete pile, once the concrete had cracked (after about 200 load cycles at ζ_b = 1.31), the pile experienced a significant increase in y_{per} with number of load cycles above the crack formation ($z/D \approx$ -4.7). The soil towards the top of the pile experienced progressive increments of permanent displacement with each additional load application indicating plastic behaviour.

4 CONCLUSIONS

Significant differences between the behaviour of the scaled aluminium and reinforced-concrete piles were observed. Considering permanent pile response upon load removal, it can be concluded that the response of reinforced-concrete piles subjected to lateral loading causing cracking, will not be captured using materials that cannot capture the reduction in bending stiffness due to cracking. Densification of the soil surrounding the pile occurred with increasing number of load cycles, with soil becoming resilient. Once cracking occurs, a progressive incremental increase in permanent displacement indicated plastic soil behaviour.

ACKNOWLEDGEMENTS

The financial support of The Concrete Institute and the Concrete Society of Southern Africa is gratefully acknowledged.

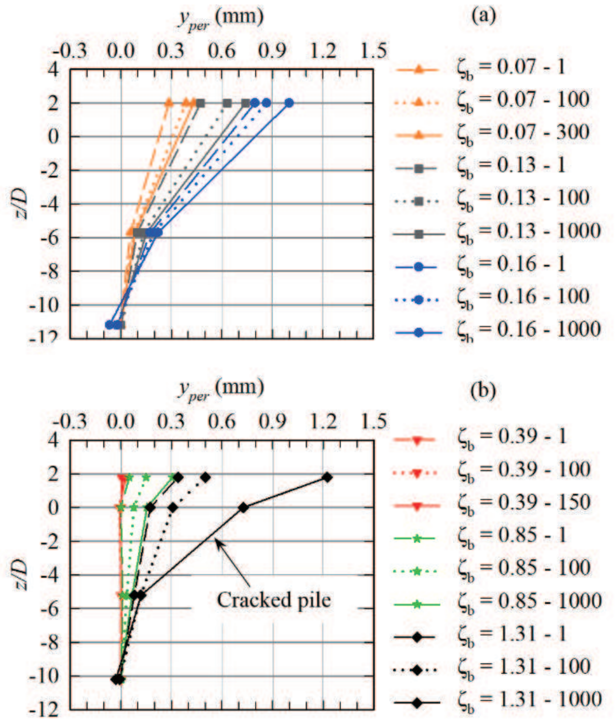

Fig. 3. Permanent pile displacement with depth: (a) aluminium; (b) reinforced concrete.

REFERENCES

Byrne, G. & Berry, A.D. 2008. *A Guide to Practical Geotechnical Engineering in Southern Africa.* Franki, Johannesburg, SA.

Kirkwood, P.B. & Haigh, S.K. 2014. Centrifuge testing of monopiles subject to cyclic lateral loading. In Gaudin & White (eds), *Physical Modelling in Geotechnics; Proc. of the 8th int. conf., Perth, 14-17 January 2014*. Boca Raton: CRC Press.

Leblanc, C., Houlsby, G.T. & Byrne, B.W. 2010. Response of stiff piles in sand to long-term cyclic lateral loading. *Geotechnique* 60 (2): 79-90.

Little, R.L. & Briaud, J.L. 1988. *Full Scale Cyclic Lateral Load Tests on Six Single Piles in Sand.* Geotechnical Division, Department of Civil Engineering, Texas A & M University, College Station, TX, USA, Miscellaneous Paper GL-88-27.

Li, Z., Haigh, S.K. & Bolton, M.D. 2010. Centrifuge modelling of mono-pile under cyclic lateral loads. In Springman, Laue & Seward (eds), *Physical Modelling in Geotechnics; Proc. Of the 7th int. conf., Zurich, 27 June - 2 July 2010.* London: CRC Press.

Long, J.H. & Vanneste, G. 1994. Effects of cyclic lateral loads on piles in sand. *Journal of Geotechnical Engineering* 120 (1): 225-244.

Poulos, H.G. 1982. Single pile response to cyclic lateral load. *Journal of Geotechnical and Geoenvironmental Engineering* 108 (GT3): 355-375.

Poulos, H.G. & Davis, E.H. 1980. *Pile Foundation Analysis and Design*. Toronto: John Wiley & Sons.

Schofield, A.H. 1980. Cambridge geotechnical centrifuge operations. *Geotechnique* 30 (3): 227-268.

Tomlison, M.J. 1980. *Foundation Design and Construction*. United Kingdom: Pitman Publishing.

Truong, P., Lehane, B.M., Zania, V. & Klinkvort, R.T. 2019. Empirical approach based on centrifuge testing for cyclic deformations of laterally loaded piles in sand. *Geotechnique* 69 (2): 133-145.

Werkmeister, S., Dawson, A.R. & Wellner, F. 2004. Pavement design model for unbound granular materials. *Journal of Transportation Engineering* 130 (5): 665-674.