Centrifuge Modelling of the Influence of Size and Geometry of Hybrid Foundations on Bearing Capacity

J.P. PANCHAL
Research Student, Department of Civil Engineering City, University of London, London, United Kingdom
A.M. MCNAMARA
Senior Lecturer, Department of Civil Engineering City, University of London, London, United Kingdom
Email: a.mcnamara@city.ac.uk
R.J. GOODEY
Senior Lecturer, Department of Civil Engineering City, University of London, London, United Kingdom

ABSTRACT

Piles have been used widely on commercial developments in London for about the last 60 years. The life of a commercial building is about 25 – 30 years and as each building is demolished and rebuilt, the piles from the previous buildings remain in the ground. These cause obstructions to the new foundations because removal is difficult, time-consuming and expensive. Published research has shown that sheet piled foundations are a genuine and viable alternative to cast in-situ concrete piles. Individual sheet piles have relatively low capacity when axially loaded, therefore it is necessary to consider their use as a pile group in conjunction with a pilecap. In this paper these are defined as hybrid foundations. An increase in bearing capacity was observed when the geometry of the sheet pile group was varied from a circular arrangement to square formation. This research aimed to understand the influence of the geometric shape and the dimensions of sheet pile groups on their bearing capacity.

Key words: *Bored piles, Sheet piles, Re-use, Physical modelling, Sustainability*

1. Introduction

Early bored cast in-situ concrete piles were typically about 12m long and up to 0.5m in diameter. It was usually necessary to group together a large number of small piles to support the load from the structure. Now it is normal practice to construct one deep large diameter pile under each column of a building.

At the end of their lifespan these structures are decommissioned however the foundations are often left in place. Developers are left with the task of removing or avoiding existing piles which incur additional costs and delays to the programme. As expected, this is an environmentally damaging and unsustainable means of managing construction waste.

In contrast, steel piles are easily removable and can be recycled but have low axial capacity. Recent studies have been conducted to design more sustainable foundation solutions by means of improving the axial capacity of pressed in sheet pile group foundations.

2. Background

Sheet piles arranged as a hybrid pile group achieve higher capacity; which combines deep (sheet pile) and shallow (pilecap) foundations. A series of published centrifuge tests (Panchal *et al.*, 2016; Panchal *et al.*, 2018) aimed to confirm whether this foundation type provided comparable bearing capacity to the conventional straight shafted concrete pile and whether the shape of the sheet pile foundation influenced its performance.

A range of pile types were investigated in an overconsolidated clay sample. These piles included conventional rough and smooth circular solid shafted piles; representative of driven or cast in-situ piles. Three sheet pile variations were also studied which comprised circular and square plan formations, with and without perforations along the shaft. **Fig. 1** depicts the range of piles that have been tested as part of this research project.

Fig. 1 Model piles used in previous centrifuge tests

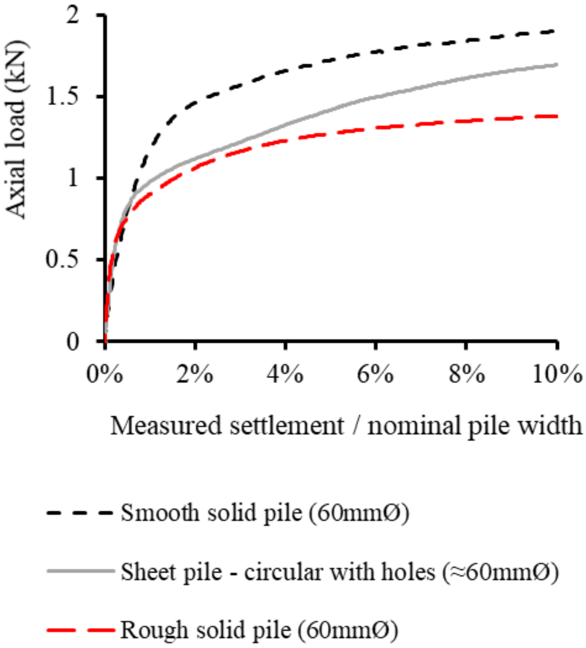


Fig. 2 Centrifuge results of circular sheet pile with holes compared against rough and smooth solid circular shafted piles (Panchal *et al*., 2016)

The literature showed that hybrid foundations offer significantly improved capacity and is a worthwhile and sustainable foundation solution. For solid circular piles and circular sheet pile groups of comparable diameters Panchal *et al*. (2016) demonstrated that the sheet pile group capacity was much improved over a smooth shafted solid pile but was approximately 10% lower than a rough solid shafted pile (**Fig. 2**).

The experiments emphasised the viability and relevance of the hybrid foundation as a construction solution. However, there were concerns over its buildability. Further tests were later conducted modelling a square hybrid sheet pile group which would be considerably easier to set-out and construct on site (Panchal *et al*., 2018). Results showed that for comparable base areas the ultimate axial bearing capacity of a square sheet pile was equal to that of a rough concrete pile.

3. Objectives

Previously published material suggests that the shape of the sheet pile group influences the bearing capacity of a pile.

This paper aims to back analyse new centrifuge data to determine values of the adhesion factor (α) for a reduced aspect ratio. The purpose of this is to evaluate the impact of dimension on sheet pile group foundations capacity.

4. Soil Model

The tests were conducted in a 300mm deep stainless steel centrifuge tub, 420mm in diameter. The final sample was required to be flush with the top edge of the tub hence a 300mm deep extension was bolted to the top such that an oversized sample could be trimmed to size. Speswhite kaolin clay was mixed with distilled water to a water content of 120%. This was approximately twice its liquid limit and produced a workable slurry.

Water pump grease was thinly applied to the walls of the centrifuge tub. Sheets of porous plastic and filter paper were placed at the base of the tub over channels that had been machined into the base of the tub to facilitate drainage. Slurry was carefully placed in the tub to a depth of 550mm using a scoop and was regularly agitated using a palette knife to prevent air entrapment before being sandwiched between another layer of porous plastic and filter paper.

The sample was transferred to a hydraulic press where a tightly fitting platen was lowered onto the sample. The pressure was gradually increased from 25kPa to

500kPa over the period of a week. Pipes fitted to the drainage taps directed water into a bucket and holes drilled through the platen allowed water to drain from the top of the sample. This aided in accelerating the consolidation of the sample. he sample was swelled back to 250kPa the day prior to testing producing a highly overconsolidated sample with an overconsolidation ratio (OCR) of 19.6 at 50*g* at the pile base following in-flight consolidation.

5. Apparatus

The experiments were conducted on the Acutronic 661 beam centrifuge at City, University of London. The centrifuge tub and loading apparatus were designed by Gorasia (2013). It comprised a lead screw actuator connected to a stiff loading beam to which load cells and LVDTs were secured.

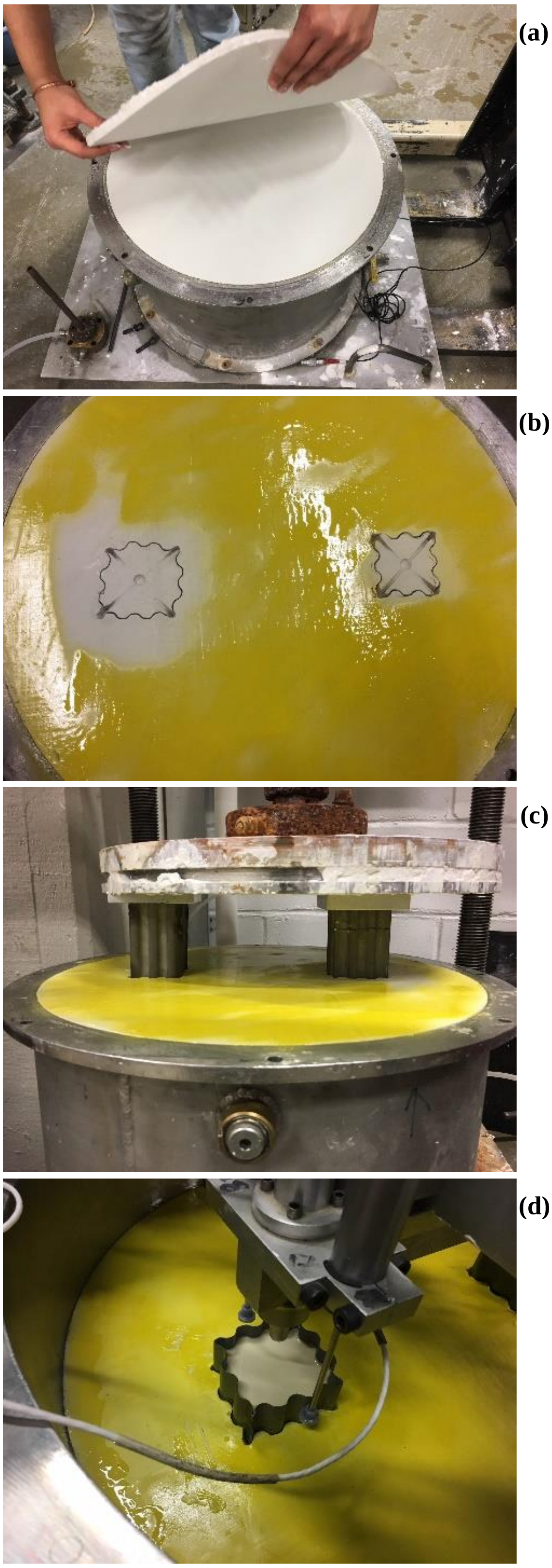
The sheet piles used in these tests were formed from a 0.5mm thick stainless steel plate pressed into a corrugated profile. The sheets were folded and welded so that they were square in plan and nominally 53mm and 43mm wide along the central axis of the ribs.

A pile and loading cap were machined from aluminium that served the purpose of securing the shape of the sheet piled foundation and providing a platform on which the LVDTs and load cell could sit.

6. Test procedure

The sample was swelled back to 250kPa the day prior to testing. A pore pressure transducer (PPT) was installed to the centre of the model 100mm below the soil surface and backfilled with kaolin slurry mixed to a water content of 120%.

In preparation for the test the sample was recovered from the hydraulic press and the extension lifted off before a wire cutter and palette knife were used to trim the sample flush with the top of the tub (**Fig. 3a**). A thin layer of PlastiDip, a synthetic rubber membrane, was sprayed across the clay surface to prevent the sample from drying out excessively, whilst leaving the area for the sheet pile groups uncovered. The apparatus frame was aligned above the sample and the loading frame lowered until it indented the clay surface. Having marked out the centres of the piles the frame was removed and sheet piles centrally aligned (**Fig. 3b**). A hydraulic press (**Fig. 3c**) was used to press the piles into the soil and embed them to a depth of 180mm, protruding 20mm above ground surface.



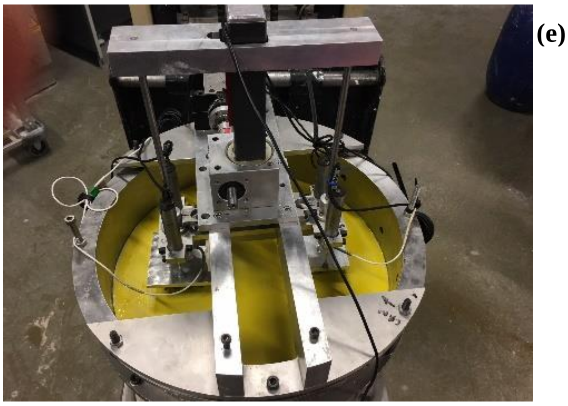


Fig. 3 Images taken during model making include (a) trimmed sample flush with top of tub, (b) pile centres marked out and surface sealed with PlastiDip, (c) embed piles to correct depth, (d) resin pile caps, (e) complete model prior spin up.

Two-part Sika Biresin was poured within the sheet pile upstand to form a pile cap that was approximately 15mm deep, shown in **Fig. 3d**. This was left to cure before securing the loading caps to each pile group. The loading frame was bolted to the centrifuge tub and the loading mechanism lowered until it was approximately 2mm above the caps. The model, immediately prior to spin up, is depicted in **Fig. 3e**.

The package was weighed and transferred to the centrifuge swing. A standpipe was connected to the base drain to maintain a water table 30mm below the clay surface. The sample was left to consolidate at 50*g* for a period of 24 hours to allow the excess pore pressures to dissipate; equilibrium conditions were confirmed by the pore pressure transducer readings. The piles were loaded at a rate of 1mm/minute whilst measuring loads and settlements.

7. Test results

Two square sheet pile groups; nominally 53.5mm and 43mm wide were tested as part of this investigation. Both sheet piles groups were embedded 180mm into the soil and a 15mm deep resin pile cap was cast above ground level. A water table was established 30mm below ground level. Shear vane readings taken immediately after the test showed that the average undrained shear strength along the piles was 32kN/m^2.

Fig. 4 illustrates the axial load against the settlement normalised by the nominal sheet pile width. At a working load of 1% normalised settlement the larger square pile group gave 52% greater capacity compared with the small pile. At the ultimate state the larger square pile offered 71% greater ultimate bearing capacity.

Test piles, either with comparable base areas or perimeters, were plotted to understand the influence of geometry and dimension on the behaviour of the pile. **Table 1** summarises the nominal pile widths/diameters, the perimeter/circumference and the area of the pile base.

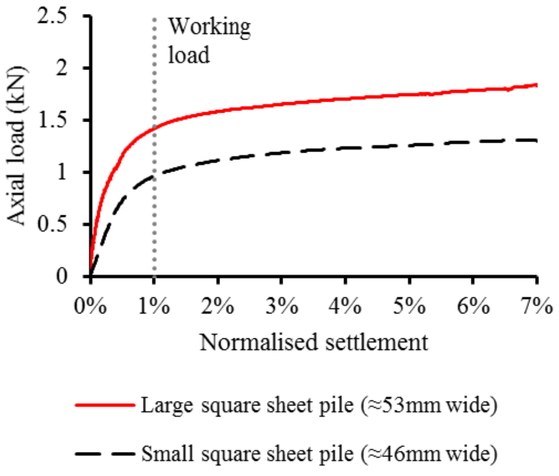


Fig. 4 Results from centrifuge test comparing a large square sheet pile group against a small square

Table 1. Summary of pile geometry used in the centrifuge tests

	Solid circular pile	Sheet pile groups		
		Circular	Large square	Small square
Nominal width (mm)	60	60	53.5	43
Measured perimeter (mm)	188	217	246	214
Area of pile base (mm^2)	2827	2827	2862	1849

Fig. 5 explains how the nominal widths were obtained for each of the piles tested in these experiments, where the average width was taken between maximum and minimum widths between the ribs. The perimeter was measured and the area was calculated using the nominal width or diameter.

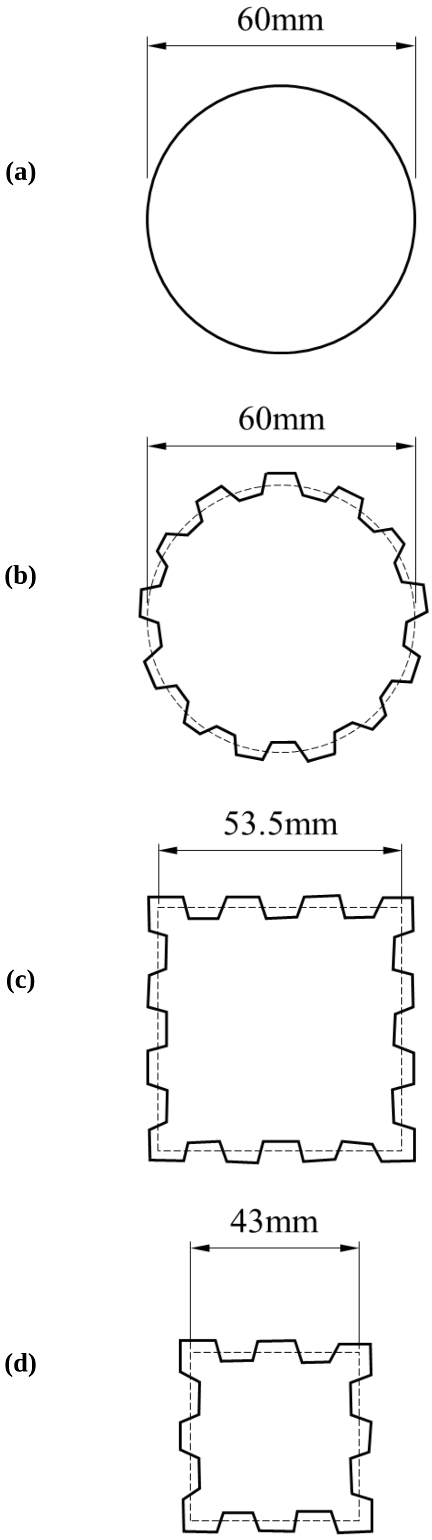


Fig. 5 Nominal widths of the various piles (a) solid shafted pile, (b) circular sheet pile, (c) large square sheet pile and (d) small square sheet pile

Fig. 6 was plotted to explore the influence of pile dimension on the working capacity of a square sheet pile group. It shows that a 15% increase in the perimeter of the sheet pile more than doubles the magnitude of normalised axial load/S_u. The initial pile response of the larger square pile was also shown to be approximately twice as stiff as the small square pile group.

For comparable base areas **Fig. 7** considers the behaviour of a rough solid shafted circular pile, the large square sheet pile and the perforated circular sheet pile. The rough solid pile exhibited similar behaviour to the circular sheet pile with holes. However, the large square sheet pile was considerably stiffer at the initial loading stages and continued to withstand higher loads during the test.

A final comparison was drawn between the small square sheet pile group and the circular sheet pile, 43mm wide and 60mm in diameter respectively. These foundations were regarded as similar owing to similarities in the pile perimeter. **Fig. 8** shows that up to 0.25% normalised settlement the stiffness of the circular sheet pile was equal to that of the small square pile. However, the circular sheet pile tends towards the ultimate capacity whereas the square sheet pile continues to transfer load into the soil. Subsequently, the working load of the small square sheet pile was 36% higher than the circular pile of comparable shaft area.

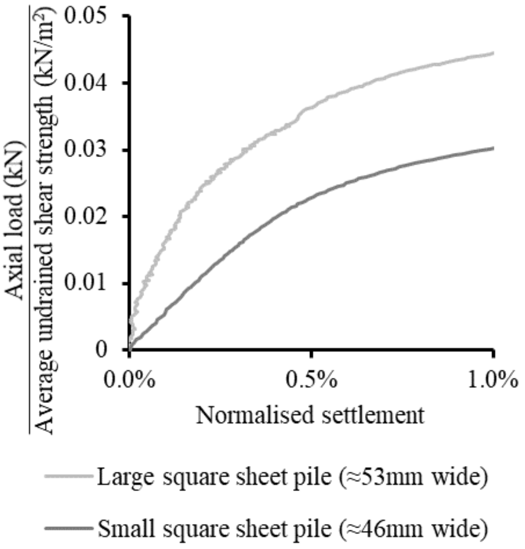


Fig. 6 Comparison between pile response of large and small square sheet pile groups.

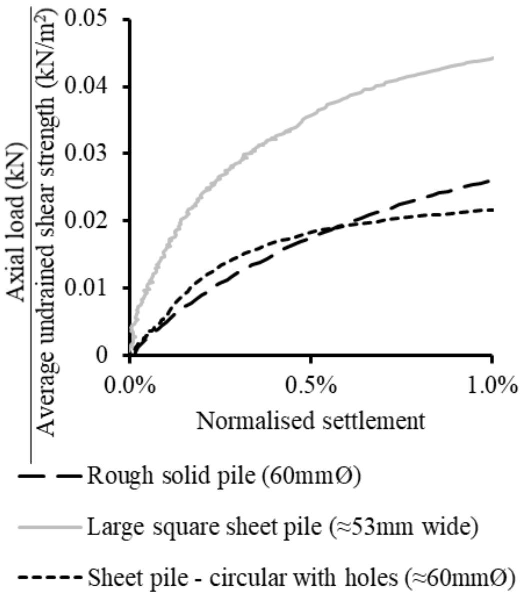


Fig. 7 Comparison between pile response of a rough solid circular pile and small square sheet pile group of comparable base area.

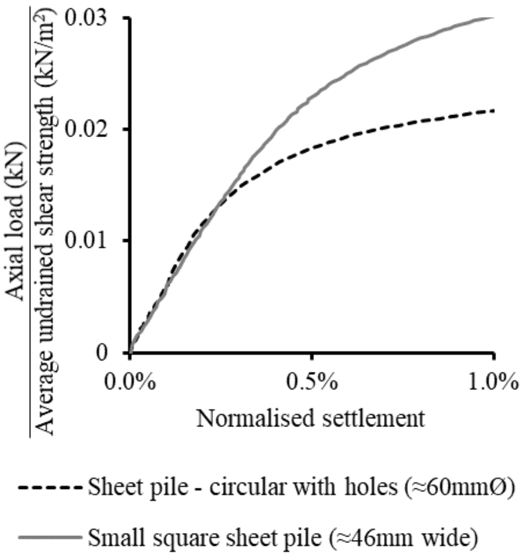


Fig. 8 Comparison of pile response of a large diameter circular sheet pile group and small square sheet pile group of comparable perimeter.

8. Analysis

Terzaghi (1943) presented a method of assessing the bearing capacity (Q_{ult}) of a pile as a summation of the base capacity (Q_b) and shaft friction (Q_s), as defined in **Eq. (1)-(3)**. Where Q_b is reduced by a factor of two owing to the foundation being analysed as an open ended tubular pile in clay (Jardine *et al.*, 2005).

$$Q_{ult} = Q_b + Q_s \quad (1)$$
$$Q_b = [A_b(N_c S_u + \gamma H)] / 2 \quad (2)$$
$$Q_s = A_s \alpha S_u \quad (3)$$

Where A_b is the basal area in contact with the soil, A_s is the shaft area in contact with the soil, N_c is the bearing capacity factor, S_u is the undrained shear strength of the clay, γ the bulk unit weight of soil, H the total length of the pile and α the adhesion factor.

The α values of the sheet pile groups from this test, and previously published tests, were back calculated. Comparisons were made between these values and those calculated for the same plan area but shallower piles. The adhesion factor is influenced by the strength of the soil and the surface roughness of the pile. In addition, the α factor tends to be lower in stiff clays than in soft soils. It also stands true that the smoother the pile the lower the α value.

This research tested two square sheet pile groups of varying dimensions. Theory dictates that similar α values should be obtained. The results from this centrifuge test were used to back analyse α for the two sizes of square sheet pile groups.

Table 2 summarises the α values obtained at 1% normalised settlement and at the ultimate state. The analysis from this experiment are compared against the values obtained from previously published data. The results show that α for the same pile geometry, irrespective of pile size, is reasonably similar.

Table 2. Summary of back calculated α values at 1% normalised settlement

	α (1% normalised settlement)	α (ultimate normalised settlement)
Large square sheet pile	0.310	0.584
Small square sheet pile	0.236	0.516
Large square sheet pile (Panchal *et al.*, 2018)	0.305	0.815

9. Discussion

Previous research (Panchal *et al.*, 2018) concluded that at the ultimate state the square sheet pile α was 0.815 whilst the circular sheet pile was 0.567. It was suggested that this variation was owing to the shape of the sheet pile group, see **Fig. 9**. For instance, the ribs in the square sheet pile were closer and may have become plugged during loading, whereas the circular sheet, having been stretched to form a circle had more open ribs, which enabled the soil to shear against the entire sheet pile surface. This spacing of the re-entrant corners influenced the shearing interface of the square and circular sheet piles resulting in a higher α value for the square sheet pile group.

In practice however, each sheet pile would be installed individually to make the sheet pile group. Therefore, the plugging effect is not likely to reduce the magnitude of the ultimate bearing capacity of a pile in the field.

The difference in α between the large and small square sheet pile group may be influenced by the number of external ribs on the two squared sheet piles. **Fig 10** shows the outlines of both the large and small square sheet pile groups. The smaller of the two piles (**Fig 10a**) has eight external ribs and nine soil/pile shearing interfaces. On the other hand, **Fig 10b** illustrates twelve external ribs and approximately nine pile/soil shearing interfaces. The large square is 25% larger in plan than the small pile, however the additional ribs increase the area of soil/soil shearing area by 50%. This results in an increase in the α value for larger sheet pile groups.

Upon disassembling the model, it was found that the silicone grease used to seal the gap at the top of the pile and prevent the soil from drying out, had in fact seeped down and coated the top half of the sheet piles. This would inevitably reduce the magnitude of the α value.

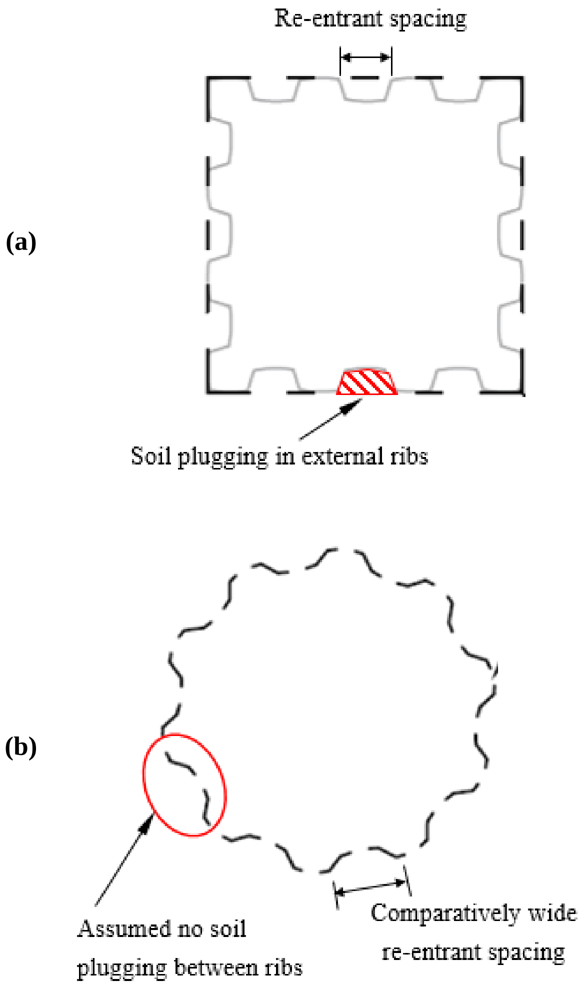


Fig. 9 Assumed shear zones around (a) square sheet pile and (b) a circular sheet pile (after Panchal *et al.*, 2018)

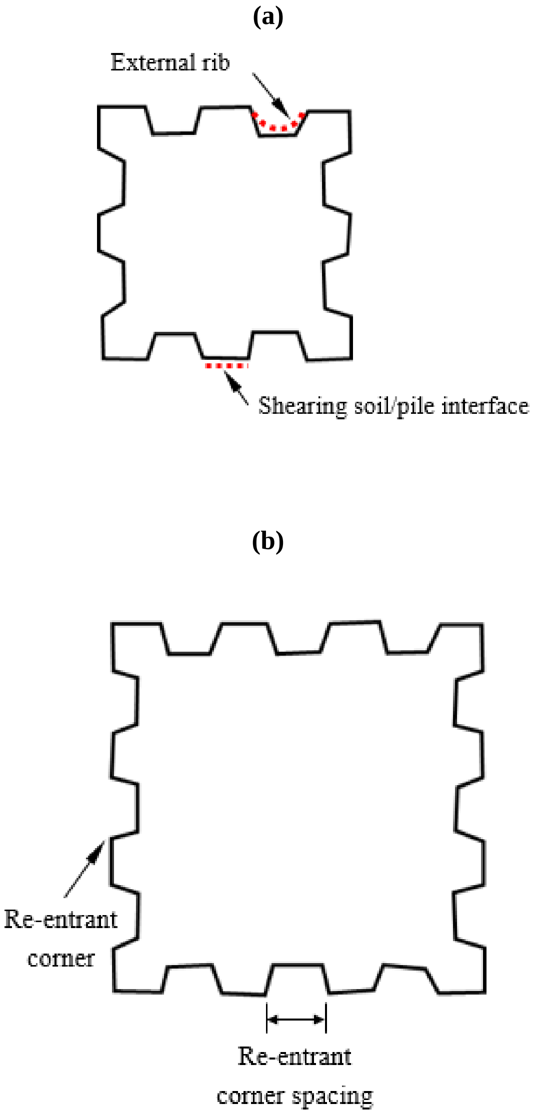


Fig. 10 Outline of (a) small and (b) large square sheet pile group used in centrifuge tests

10. Concluding remarks

To date, a number of centrifuge tests have been conducted investigating the behaviour of corrugated circular and square sheet pile groups against conventional solid shafted smooth and rough circular bored piles. The size of the square sheet pile group has been varied and the influence of perforations has been briefly explored.

The results highlighted that square sheet piles offer comparatively higher capacity than the circular sheet pile group, owing to reduced re-entrant corner, this resulted in a higher α value.

Smaller square sheet piles, although less than half the area of rough solid shafted bored piles exhibited similar ultimate capacity. The capacity of a square sheet pile was shown to be influenced by the number of soil/soil shear interfaces. Ensuring soil plugging between the sheet pile ribs forces a soil/soil failure and can significantly increase the capacity of a square sheet pile group.

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