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Modelling small RC piles for geotechnical centrifuge testing

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ABSTRACT: The conventional way to model piles in geotechnical centrifuge experiments is to use aluminium hollow sections, whose lateral surface may be rendered rough, e.g., by gluing a layer of sand, to simulate a realistic pile-soil interface. As long as the normal stiffness of the prototype pile is matched, this type of model pile is adequate to examine the behaviour of piles and pile groups under vertical loads. However, to address problems with significant lateral loads, also both the bending stiffness and the plastic moment of the pile section must be simulated correctly. Moreover, the anisotropic behaviour of a reinforced concrete section under tensile and compressive stresses cannot be achieved using an aluminium section. This led the authors to develop miniature reinforced concrete (RC) piles for use in geotechnical centrifuge testing. The requirement for a particularly small pile diameter of 10 mm was an added challenge to the problem. This paper describes the method followed to finalise the miniature RC section in terms of materials. Concrete and gypsum-based mortars with varying binder/water and sand/binder ratios were examined. The reinforcement was created using galvanized steel wire mesh. The corresponding mechanical tests show that the gypsum-based model piles have very ductile behaviour and particularly low plastic moments, whereas the cement-based ones tend to replicate the behaviour of an actual RC section more accurately both in terms of plastic curvature and plastic moment.

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

1 INTRODUCTION

As a very common and complex type of foundations, piles have been experimentally examined under different directions of loading in monotonic or cyclic conditions. Because of its benefits among the other physical modelling techniques, centrifuge modelling has been employed as a small-scale modelling alternative offering the ability to capture the actual stress-strain soil behaviour (Madabhushi, 2017). Tests on piles at an increased gravity field have been successfully implemented (Horikoshi & Randolph, 1996; Conte *et al*., 2003; Nguyen *et al*., 2013; Park & Lee, 2015).

The conventional way to model the piles in a geotechnical centrifuge test is to use aluminium hollow sections. As far as the stiffness of the section and the friction of the pile surface are ensured, this methodology is adequate when examining pile-soil interaction problems under vertical loads. However, simultaneous scaling of both deformation and strength behaviour is not possible. This could be acceptable in cases of small strains, but in cases where both the failure mechanism and the relative soil-structure strength are important parameters, the aluminium section is insufficient (Knappett *et al*., 2011). More specifically, when the pile is laterally loaded it is important that the plastic moment of the pile section be correctly simulated, as well as the anisotropic behaviour of the actual reinforced concrete section under tensile and compressive stresses. This cannot be achieved with an aluminium section, marking the importance of the materials used to model the pile section. Therefore, miniature reinforced concrete (RC) piles were developed by the authors for use in geotechnical centrifuge testing. Although concrete of the same consistency as in full-scale cannot be used for such small-scale models (Knappett *et al*., 2011; Harris & Sabnis, 1999), concrete of modified consistency has been recently used in model elements for centrifuge tests (Louw *et al*., 2020). Gypsum-based mortars have also been developed as model micro-concrete (Knappett *et al*., 2011).

In this paper, both gypsum and concrete are examined as binders in the reinforced mortar in terms of ductility and moment capacity. The particularly small pile diameter adds an important challenge to the process of casting the model RC piles.

Fig. 1. Steel-perspex mould.

2 SMALL PILE CONSTRUCTION

The prototype pile is 1-m diameter and 20-m long. The prototype pile is characterized by a plastic moment M_{pl}=1100kNm that corresponds to 20×Ø20 B450C reinforcement bars in a C20/25 concrete section. For an increased gravity level of 100*g* in the centrifuge, the model pile dimensions are 10-mm diameter and 200-mm length.

2.1 Mould

Based on the geometrical requirements, the mould consists of three “sandwich” plates with drilled half-holes, as illustrated in Figure 1. Because of its relatively low adhesion to concrete, steel is preferred to aluminium as the material for the middle plate. Perspex material for the two external plates allows the inspection of concrete while pouring and control of air voids that could easily take place in such narrow moulds.

2.2 Reinforcement

The miniature RC pile consists of mortar and reinforcement. Because of the very small pile diameter, reinforcement-making requires delicate handling. The reinforcement cage is made of galvanized steel wire mesh (Ø0.20 mm, 1.4×1.4 mm^2 cell size) rolled to the desired geometry (~6.5mm OD), as shown in Figure 2. After a series of mechanical tests on sample piles of different mortars and rebar cages, the initial rebar cage was modified in an improved version with less transversal wires, to make the rebar cage more flexible, and with no overlapping between the two edges of the wire mesh, to achieve a more isotropic behaviour of the cage by intervening in the symmetry of its section. The two edges of the rolled mesh are stitched together with wires that also work as spacers to keep the rebar cage in place and at the desired distance from the mould surface during installation.

2.3 Mortar

A typical mortar consists of a binder, aggregates, water and potentially chemical admixtures. In this study, both cement and gypsum were examined as binders.

Very fine sand was used as aggregate in some of the mixtures. Clean de-aired water was added in varying water-binder ratios. The particularly small distance between the wires and the mould required the use of plasticizer to make the mortar more workable and easier to flow through all paths.

Fig. 2. Sample rebar cage.

Table 1 lists the materials used in this study along with their main properties. Based on the suggested standards and the workability of the mixture, different by weight ratios of water-binder (W/B), aggregate-binder (A/B) and plasticiser-binder (P/B) were examined. The samples were left to set for 7 days before testing, which is a period longer than the final setting time of the binders as per manufacturers data sheets. More specifically, it was observed that, regardless of the A/B ratio, two days setting time before demoulding was sufficient for the gypsum-based mortars, whereas cement-based mortars required at least four days. In all samples, the initial version of the rebar cage was used. Ten different mixtures were examined with an average of four samples per mixture. Table 2 lists the proportions of the different mixtures used in this study. In case of low workability the W/B or the A/B ratio was modified.

Table 1. Materials used in this study and their properties.

Material	Properties
Cement	• Ordinary Portland cement CEM I 52.5 N • Density: 3.13 g/cm^3 • Final setting time: 223 min
Gypsum	• Dental Plaster • Wet compressive strength: 10 MPa • Bulk Density (compacted): 1.3 g/cm^3 • Final setting time: 12 min
Fine Aggregate	• Leighton Buzzard Fraction E sand • D_{10}=0.095 mm • D_{50}=0.12 mm • Uniformity coefficient D_{60}/ D_{10}=1.39
Admixture	• Polymer-based superplasticizer • Density at 20°C: 1.08 ± 0.02 g/cm³ • pH: 7.0 ± 1

Table 2. Pile sample composition and pouring method.

Binder	**Mixture**	**W/B**	**A/B**	**P/B**	**Pouring technique**
Cement	CA	0.50	0.0	1%	PD
	CB	0.50	0.5	1%	PD
	CC	0.50	1.0	2%	PD
	CA*	0.50	0.0	1%	PDP
	CK	1.00	1.0	1%	PD
Dental plaster	DA	0.50	0.0	1%	PD
	DB	0.64	0.5	1%	PD
	DC	0.74	1.0	2%	PD
	DA*	0.50	0.0	1%	PDP
	DK	1.00	1.0	1%	PD

2.4 Pouring technique

In the “Pour-Drive in” (PD) technique, the mortar is poured almost from the top of the hole. Immediately after the hole is filled with mortar, the rebar cage is driven into the hole. This method does not cause formation of air-bubbles and any air-bubbles are destroyed while the cage is driven-in. Sediment may be created at the bottom of the mould, if the cage is not driven in right after pouring and/or the proportion of aggregates is high.

In the “Pour - Drive in - Pour” (PDP) technique, the mixture is poured until the middle of the hole, the rebar cage is driven in and the rest of the hole is then filled with mortar. Sediment is not observed. In some cases, extended voids at the top half may be created if not destroyed right after pouring.

3 4-POINT BENDING TEST

3.1 Assembly

The samples were tested in a four-point bending assembly using the 2-kN Electromechanical Universal Testing System in the NRFIS Materials Testing and Characterisation Laboratory, University of Cambridge. The load measurement accuracy is +/- 0.5%. The top piston pushes the specimen at the thirds of the effective length under a displacement control actuation until failure. The total load and the displacement of the piston are recorded and the plastic moment of the section is calculated. Figure 3 illustrates deformed shapes of gypsum- and cement-based specimens after the 4-point bending test and the detail of the main crack.

3.2 Varying mixtures – Results

Figure 4 illustrates the moment-rotation curves for the cement- and gypsum-based mortar specimens. As regards the cement-based specimens, increasing A/B ratio causes a decrease in the plastic moment by about 18%. Additional increase of the W/B ratio causes further decrease in the plastic moment by almost 12%. Important amount of aggregates (A/B=1) to the gypsum-based specimens results in a decrease in the plastic moment from around 1.1 Nm to 0.8 Nm. Increase in the W/B ratio causes further reduction of the plastic moment to 0.65 Nm. All in all, the cement-based mortars resulted in higher plastic moments, whereas the gypsum-based ones reached values much lower than 1.5 Nm.

From a performance perspective, the gypsum-based mortars resulted to a more ductile behaviour than the cement-based materials, which presented a rather brittle behaviour with the failure being more abrupt. Most gypsum-based specimens required at least 6.0 deg curvature to fully mobilise their moment capacity, the failure being progressive from that point on allowing higher curvature to take place before the final breakage of the section. On the contrary, the cement-based specimens required 4.0-6.0 deg curvature for the moment to be fully mobilised and the failure happened suddenly at the point where the ultimate load was recorded.

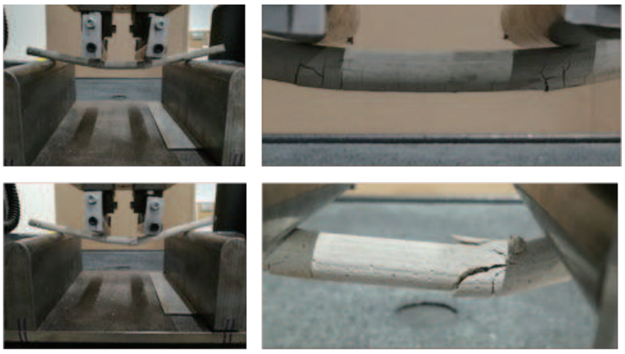

Fig. 3. Deformed shapes of samples DK.II and CA.II.

Considering that (i) qualitatively the behaviour of the cement-based specimens resembles more the actual brittle behaviour of a RC section, (ii) the addition of aggregates often leads to a sedimented layer at the bottom of the mould making the casting process less controlled and, (iii) the target plastic moment is 1.1 Nm, the mixture adopted is as presented in Table 3.

There is an unquestionable variation in the results. A factor causing this is the manual process of pile construction. However, further investigation proved that the initial version of the rebar cage adds an important uncertainty factor to the process, *i.e.*, the position of the overlapping edges of the cage. Two batches of 27 samples in total made of the adopted mixture and the initial cage were casted and tested in the 4-point bending assembly. All 27 samples had minor visible voids out of the effective length or no visible voids at all and thus were considered homogeneous within their section and along their length. The variation in each of the two batches was quite high, with a coefficient of variation CoV ≈ 22%.

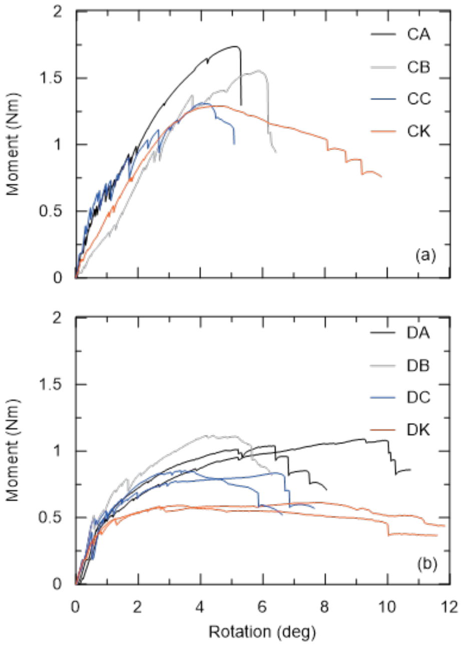

Fig. 4. Bending moment – rotation curves for (a) cement- and (b) gypsum-based specimens.

Table 3. Adopted mixture composition.

Binder	Mixture	W/B	A/B	P/B	Pouring technique
Cement	CA_ZK-02	0.55	0	1%	PDP

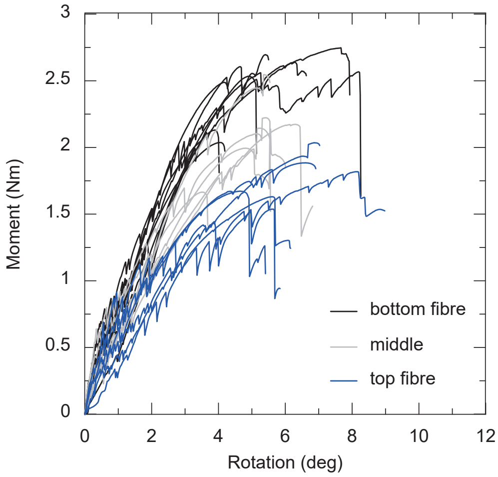

Fig. 5. Moment – angle curves for overlapping position at the bottom fibre, in the middle, at the top fibre of the section.

Grouping of the samples based on the position of the overlapping, as illustrated in Figure 5, shows that the plastic moment of the section is higher when the edges of the rebar cage overlap at the bottom fibre of the section, which is in tension for the existing loading conditions. This is explained by the fact that overlapping corresponds to higher amount of reinforcement.

CoV is about 10% in each group. This means that of the initial 22% CoV, 12% is related to the overlapping edges of the rebar cage and only the remaining 10% is a result of the manual process of pile casting. Moreover, some of the samples have a rather ductile behaviour, possibly related to the amount of reinforcement. The percentage of the reinforcement, considering both the longitudinal and the transversal wires, is so high as to govern failure. It affects both the moment at failure and the failure mode. Lower percentage of reinforcement, for instance coarser transverse wires, should result in lower strength and more brittle behaviour of the section. Therefore, in the improved version of the rebar cage, both the overlapping and some of the transversal wires were eliminated to give a more flexible cage.

3.3 Lighter rebar cage – Results

Targeting to a plastic moment of around 1.1 Nm, a lighter and more flexible rebar cage is constructed by using an alternative wire mesh with Ø0.18 mm and by reducing the transversal wires by 30%. Furthermore, the overlapping is minimized aiming to the most possible isotropic behaviour.

Two new batches of 10 samples in total were tested in bending. The samples were made of the adopted mixture composition and the lighter rebar cage. The first group underwent 7 days of curing and the second 14 days. The two groups present an average plastic moment of 1.0 and 1.1 Nm respectively. Therefore, the target prototype plastic moment of 1100 kNm is achieved. The discrepancy in the results is quite low, at 11% and 13%, this confirming the conclusion that the manual process accounts for around 10% uncertainty. The improved rebar cage is sufficient to almost diminish the uncertainty caused by the cage itself, encouraging the construction of miniature piles for use in geotechnical centrifuge applications.

Further tests also showed that varying curing time at 7, 14, 21, 28 days had no effect on the plastic moment of the section, this varying between 1.1 Nm and 1.2 Nm among the four examined groups. In centrifuge tests, the use of miniature RC piles with varying curing time, between 7 and 28 days, is therefore considered safe.

4 CONCLUSIONS

Piles under lateral loads can quite accurately be modelled in centrifuge tests using reinforced concrete miniature piles. Even small-diameter miniature piles can be constructed using the methodology described, to match the bending stiffness and the plastic moment of the prototype pile section, as well as to match the anisotropic behaviour of the prototype. The miniature piles can be integrated into more complex foundation systems, such as piled rafts, to be tested in the centrifuge (see Katsanevaki et al., 2022).

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