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Cyclic performance of driven minipile group system in sand

Performance cyclique d'un système dirigé par un groupe de micropieux dans le sable

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ABSTRACT: A new concrete-free footing system has been developed recently in Australia as an alternative to shallow foundations with certain advantages such as cost-effectiveness; quick installation and versatile arrangement. Number and embedment depth of minipiles and their configuration are varied to meet the design requirement. While the field performance of this new system under monotonic compression and pullout loadings in cohesive and non-cohesive material has been studied, its field performance under cyclic loads especially in non-cohesive material has not been thoroughly investigated. This is in particular important since the risk of loss of soil/pile interaction can be significant in granular soils. This paper reports on the field test results under cyclic compression and pullout loadings for two different footing configurations and embedment depths in a relatively medium to dense sandy material. The field test results are discussed in terms of force-deformation curves, accumulation of plastic deformations and change in soil/system stiffness. It was understood that although soil/system stiffness decreased to some extent, no considerable degradation in bearing and pullout capacities was observed. The permanent deformation was also found to be less than four mm if the applied cyclic loading is kept below the back-calculated ultimate capacity.

RÉSUMÉ: Un nouveau système de base sans béton a récemment été mis au point en Australie. Il constitue une alternative aux fondations peu profondes offrant des avantages certains, tels que la rentabilité, une installation rapide et un agencement polyvalent. Le nombre et la profondeur d'ancrage des minipiles ainsi que leurs configurations varient en fonction des exigences de conception. Bien que les performances sur le terrain de ce nouveau système sous compression monotone et charges de retrait dans des matériaux cohésifs et non cohésifs aient été étudiées ; ses performances sur le terrain sous charges cycliques, en particulier dans des matériaux non cohésifs, n'ont pas fait l'objet d'études approfondies. Ceci est particulièrement important car le risque de perte d'interaction sol / pieu peut être significatif dans les sols granulaires. Ce document présente donc les résultats des essais sur le terrain du système sous compression cyclique et charges de retrait pour deux configurations différentes de base ainsi que leur profondeur d'encastrement dans un matériau moyennement à fortement sableux. Les résultats des tests sur le terrain sont discutés en termes de courbes de force-déformation, d'accumulation de déformations plastiques et de modification de la rigidité sol / système. Il a été entendu que, bien que la rigidité sol / système ait diminué dans une certaine mesure, aucune dégradation considérable des capacités de charge et de traction n'a été observée. La déformation permanente s'est également avérée inférieure à quatre mm si la charge cyclique appliquée est maintenue au-dessous de la capacité finale calculée préalablement.

Keywords: Driven minipile; Minipile cyclic performance; Pile field load test; Pile bearing

1 INTRODUCTION

A new driven minipile group system is getting attraction because of its time- and cost advantages. This new footing system consists of a series of steel hollow piles (small diameter of 40 mm and typical thickness of 2.6 mm) driven into the ground at the angle of 25 degrees to the vertical direction using a handheld jackhammer through a steel top plate and its guiding sleeves. The embedment depth of minipiles varies from 1200 mm to 2500 mm depending on the soil condition and the required capacity (Figure 1).

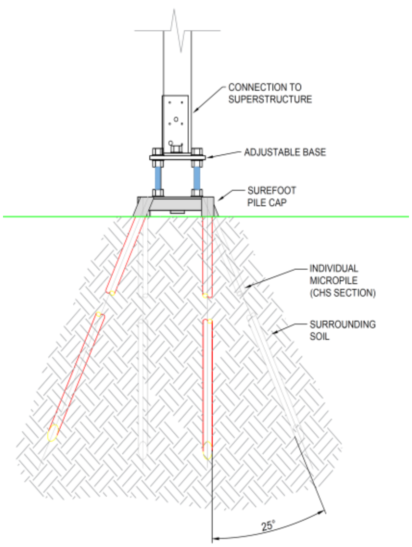

Figure 1. Installed footing in the ground (After Mehdizadeh et al., 2016)

Monitoring of the this new battered minipile group under monotonic pullout and compression loadings (Mehdizadeh et al., 2018 and Disfani et al., 2018) confirmed that it can be used as an alternative to shallow footings considering the achievable capacity with minimal installation effort and soil disturbance. However, the impact of cyclic loading specially in non-cohesive materials on its performance has yet to be fully understood as cyclic behaviour of deep foundations has been a topic of controversy. For instance, Schwarz (2000) reported that for five m long micropiles with diameter of 130 mm, installed in sand, the cyclic loading tends to reduce the bearing capacity when compared with monotonic loading. This reduction was also found to be dependent on the number and amplitude of load cycles. This finding was in agreement with research conducted by Chan and Hanna (1980), Briaud and Felio (1986) and Turner and Kulhawy (1990). In another research conducted by Cavey et al. (2000), pressure-grouted minipiles were installed in a cohesionless soil and subjected to reversal loads with increasing amplitude. It was found that there was a critical level of repeat loading which was well below the ultimate capacity under static conditions. This trend was also observed by Turner and Kulhawy (1990). El Naggar and Wei (2000) established characteristics of cyclic response of tapered piles from experimental investigation. A steel chamber was filled with soil and pressurized using an air bladder to simulate the confining pressure. Piles were subjected to two-way cyclic axial loads and the result indicated that the pile stiffness increased under cyclic loading due to the densification of sand surrounding the pile. Cyclic performance of open-ended steel pile (0.5 m in diameter and 1 m in length) was investigated by Thomassen et al. (2016). To minimize the scaling effects in the laboratory tests, a large circular sand box with a diameter of 2.5 m and a height of 1.5 m was used. The tests result showed that the shaft capacity increased with cyclic loading with small amplitudes. However, increase of the cyclic amplitude can lead to large accumulated displacements and a decrease in cyclic reloading stiffness. Cyclic performance of single and group micropiles in loose sand was also studied by Matos et al. (2015) and (2017) using a cylindrical soil container with 2.5 m diameter and 3.5 m height. The test results indicated that micropiles that experienced cyclic loading showed much higher post-cyclic stiffness. It is evident that there is no clear conclusion on impact of cyclic loading on the performance of deep foundations in the literature. It mainly depends on the soil condition, number and amplitude of load cycles and type of the footing. Since this new driven minipile group cannot be classified as a micropile group or a traditional pile group as it is concrete-free and it has small diameter, the field load test helps to determine its performance under cyclic loading. Therefore, it was decided to conduct cyclic pullout and compressive tests on two group footings with two different embedment depths.

2 SITE DESCRIPTION

The test site was located in Fingal; Victoria; Australia. To classify the soil condition, a series of in-situ geotechnical tests including Standard Penetration Test (SPT), Cone Penetration test (CPT) and Plate Load Test (PLT) were conducted. Test results indicated that the soil consisted of loose to medium silty sand with organic root matters in the first 400 mm. The soil density and relative density were found to vary between 16.3 to 18.7 kN/m^3 and between 45 to 77 percent, respectively, from the ground surface down to 3 m. Water table was not observed down to the bottom of the deepest borehole (10 m deep). Back-calculated soil parameters from in-situ tests are shown in Tables 1 and 2.

Table 1. Variation of internal friction with depth

Depth (mm)	φ' (°)		Es (MPa)		
Test	SPT[1]	CPT[2]	SPT[3]	CPT[4]	PLT
0-500	-	37	-	9	10
500-1000	-	36	-	11	-
1000-1500	-	38	-	15	-
1500-2000	32	39	10	24	-
2000-3000	38	42	25	52	-

[1]: Dunham (1954)
[2]: Kulhawy and Mayne (1990)
[3]: Gallanan and Kulhawy (1985)
[4]: Robertson and Cabal (2015)

3 TESTS PROGRAM

The cyclic performance of this new driven minipile footing system under pullout and compression was monitored according to procedures G and F suggested by ASTM-D1143 (ASTM 1994) and D3689 (ASTM 1990), respectively with some modifications. Two group configurations with four and six piles with two embedment depths of 1200 and 1500 mm were selected for the field testing. Table 2 and Figure 2 show the footings specification studied in this research.

Table 2. Specification of tested footings

Footing Type	Number of Minipile	Embedment Depth (mm)	Top Plate Width (mm)
S250-1200	4	1200	260
S250-1500	4	1500	260
S400-1200	6	1200	380
S400-1500	6	1500	380

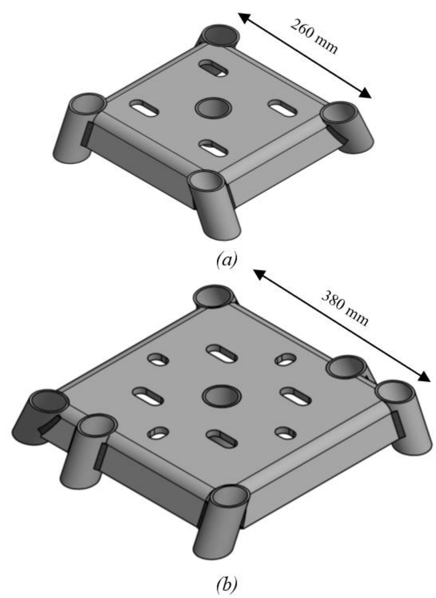

Figure 2. Top plate and piles configuration (a) S250 and (b) S400

Four reaction footings (S500 with 9 piles of 2000 mm embedment depth of much higher capacity) were used to provide enough reaction for compression tests. The impact of organic root matters in top 400 mm was eliminated by installing the footings at the bottom of a 400 mm deep excavated trench. Footings were subjected to 50, 100, 150 and 200 percent of the anticipated design load for 5 minutes and then were fully unloaded. After removing each maximum applied load, the next proceeding load was applied. At the end of the last cycle of loading, test was continued to fail the footing and get the ultimate capacity. Continuous jacking to maintain the applied load was considered as failure and termination criteria. Figure 3 shows setup of a pullout test on S400.

Figure 3. Pullout tests setup

4 TESTS RESULT AND DISCUSSION

Load-settlement diagrams of tested footings under cyclic pullout and compressive loadings are shown in Figures 4 and 5. As expected, footings with greater embedment depths showed higher capacities except S250 under the compressive load (Figure 4 (b)) which might be due to non-uniformity in the soil condition. The failure load is defined as the load which the load-displacement curve reaches a slope of 0.15 mm per kN of applied load according to GCP-18 (GCP 2015). Table 3 indicates the ultimate capacity extracted from the field tests. It can be seen that apart from S250-1500, ratio of pullout failure load to compressive failure load in a loose to medium sand varies between 0.21-0.35 with an average value of 0.28. The same ratio was reported by Mehdizadeh et al. (2018). Comparing Table 3 with the field tests result presented by Mehdizadeh et al. (2018) on the same footings in the same soil but under monotonic pullout and compressive loads does not show any noticeable decrease in the failure load due to cyclic loadings.

Table 3. Ultimate capacity of footings under cyclic pullout and compressive loadings

Footing Type	Pullout Failure Load (kN)	Compressive Failure Load (kN)
S250-1200	9	43
S250-1500	20	40
S400-1200	19	54
S400-1500	34	114

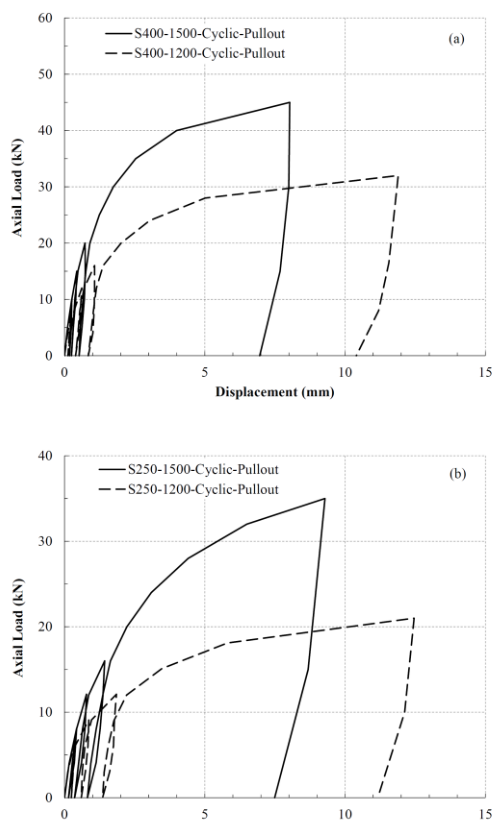

Figure 4. Load-settlement diagram for tested footings under cyclic pullout loadings (a) S400 and (b) S250 with 1200 and 1500 embedment depths

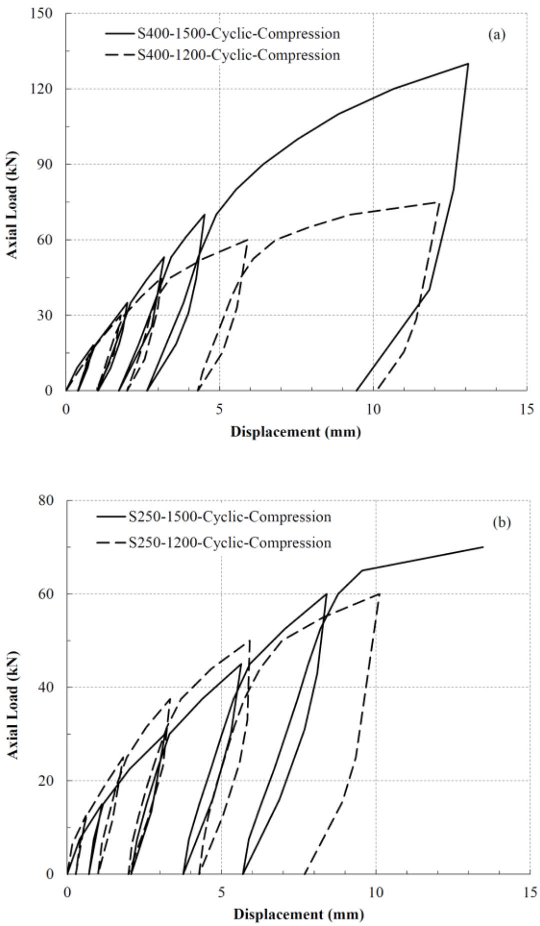

Figure 5. Load-settlement diagram for tested footings under cyclic compressive loadings (a) S400 and (b) S250 with 1200 and 1500 embedment depths

Accumulation of plastic (permanent) deformations of each footing under cyclic compressive and pullout loadings is shown in Figures 6 and 7, respectively. Both elastic and plastic deformations increased by an increase in the applied load. However, if the applied pullout loads are kept below the back-calculated failure loads (suggested in Table 3), elastic and plastic deformations will be less than 1 mm and 4 mm, respectively. Same plastic deformation range but larger elastic deformations (< 3 mm) were observed for footings under compressive loads except for S400-1500 under compressive loads with plastic deformation of 7 mm.

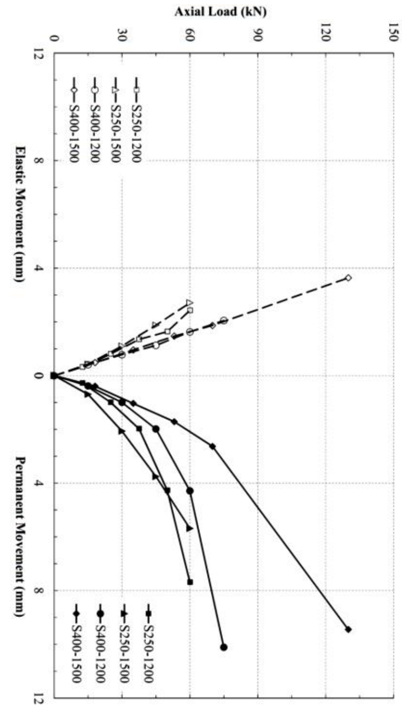

Figure 6. Permanent and elastic displacements vs. applied cyclic compressive loading

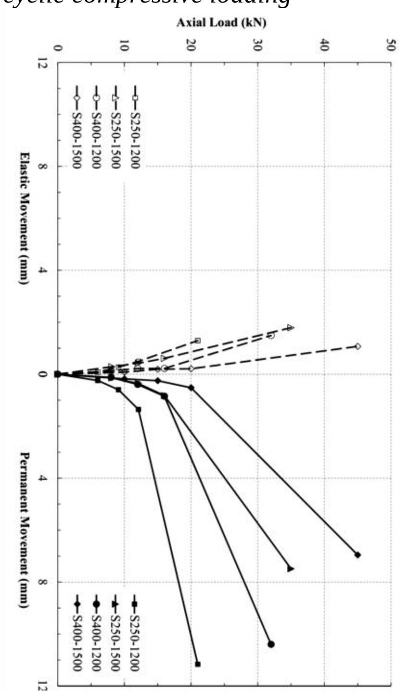

Figure 7. Permanent and elastic displacements vs. applied cyclic pullout loading

To investigate variation of footings stiffness under cyclic loading, two stiffness parameters were defined for unloading (K_u) and reloading (K_r) steps which were the ratio of the applied load over elastic deformation during unloading and induced deformation during reloading, respectively (Figure 8). Figures 9 and 10 show variation of K_u and K_r with applied compressive loads for S250 and S400. It was found that the defined stiffness varied between 20×10^3 to 40×10^3 (kN/m) for all footings under the compressive loads. It is evident that cyclic compressive loading decreased the footing stiffness regardless of embedment depth and the footing configuration. However, this reduction in stiffness was between 5 to 20 percent as long as the applied loads were kept below the back-calculated failure loads (Table 3). Figures 11 and 12 indicate variation of K_u and K_r with applied pullout loads for S250 and S400. Similar to the performance of the footings under compressive loads, the pullout stiffness also decreased under cyclic loadings although it did not show any clear trend. This reduction was found to be as high as 50 to 60 percent for some loading steps. It can also be understood from Figures 9-12 that in contrast with K_u, K_r constantly decreased with cycles of loading which is in agreement with the finding reported by Thomassen et al. (2016). It is believed this reduction in the reloading stiffness is due to development of plastic points in the soil surrounding the minipiles.

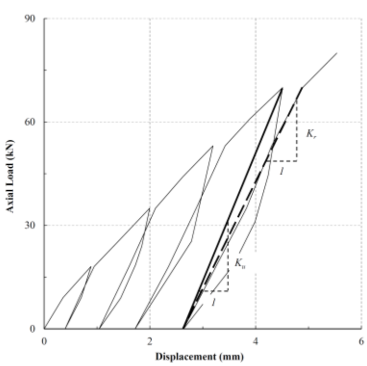

Figure 8. Definition of the footing stiffness during unloading and reloading

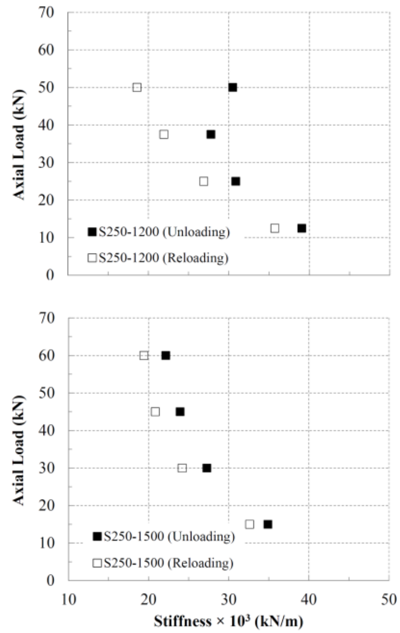

Figure 9. Variation of unloading/reloading stiffness with applied compressive load for S250

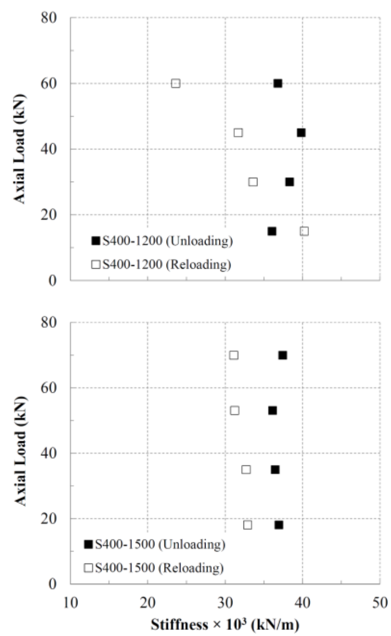

Figure 10. Variation of unloading/reloading stiffness with applied compressive load for S400

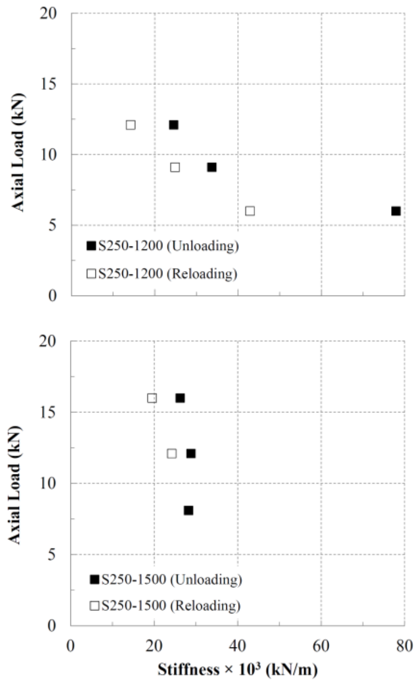

Figure 11. Variation of unloading/reloading stiffness with applied pullout load for S250

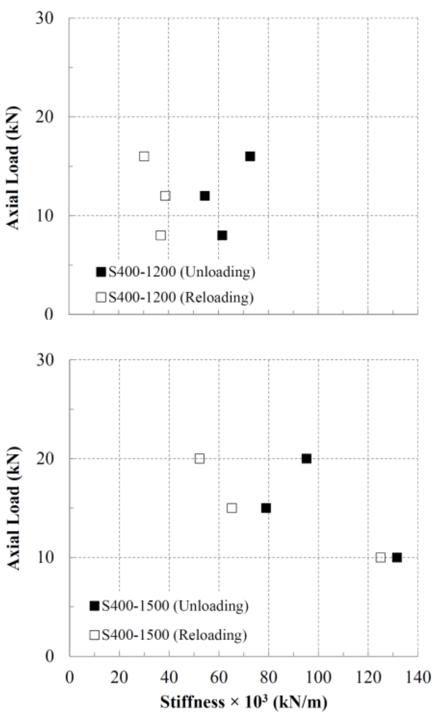

Figure 12. Variation of unloading/reloading stiffness with applied pullout load for S400

5 CONCLUSIONS

Performance of a new driven minipile group footing under cyclic compressive and pullout loading in a non-cohesive soil formation was investigated through field load testing. Tests result in terms of accumulation of plastic deformations and reduction of footing stiffness was discussed. It was understood that accumulation of plastic deformations were always less than 4 mm if the applied load was kept below the ultimate capacity. These permanent deformations fell below 1 mm if the safety factor of 2 was considered for the design load. The footing stiffness decreased gradually under cyclic loading. However, this reduction was found to be normally less than 15 percent if the applied load was kept less than 50 percent of the failure load.

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