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Behaviour of driven battered minipile groups in sand under lateral loading

Comportement des groupes de minipieux battus enfoncés dans le sable sous chargement latéral

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ABSTRACT: Minipiles are generally hollow driven piles, less than 50 mm in diameter and commonly around 2 m in length, without any grouting. Three types of minipile group configuration consisting of individual minipiles battered at 25° with the vertical are investigated in this study to evaluate their lateral load capacities. When the lateral load is applied in the direction of the batte r, they are said to be *positive* battered minipiles, otherwise, *negative*. The minipile groups under study includes a combination of positive and negative battered minipiles as well as minipiles battered in the direction perpendicular to the direction of the transverse load. The geometries are developed to mimic a tree root system, where roots move in different directions to engage a large volume of soil. The behaviour of these systems is investigated using 1g physical modelling, and it is found that the minipile group with the diagonally outward orientation of 25° battered minipiles have the highest lateral resistance. The minipile group with two positive and two negatives battered minipile performs slightly better than the group with one positive, one negative and two outwardly perpendicular battered minipiles highlighting the role of orientation of the system in its performance. In addition, optic fibres are used to record the strain profile along the minipile shafts in the 1g small scale physical model with results indicating higher strain in the leading piles compared to that in the trailing counterpart at the same lateral load.

RÉSUMÉ : Les minipieux sont généralement des pieux battus creux, de moins de 50 mm de diamètre et généralement d'environ 2 m de longueur, sans aucun jointoiement. Trois types de configuration de groupe de minipieux constitués de minipieux individuels battus à 25° avec la verticale sont étudiés dans cette étude pour évaluer leurs capacités de charge latérale. Lorsque la charge latérale est appliquée en direction de la pâte, ils sont dits minipieux battus positifs, sinon négatifs. Les groupes de minipieux étudiés comprennent une combinaison de minipieux battus positifs et négatifs ainsi que des minipieux battus dans le sens perpendiculaire à la direction de la charge transversale. Les géométries sont développées pour imiter un système racinaire d'arbre, où les racines se déplacent dans différentes directions pour engager un grand volume de sol. Le comportement de ces systèmes est étudié à l'aide d'une modélisation physique 1g, et il s'avère que le groupe de minipieux avec l'orientation diagonale vers l'extérieur des minipieux battus à 25° a la résistance latérale la plus élevée. Le groupe de minipieux avec deux minipieux battus positifs et deux négatifs est légèrement plus performant que le groupe avec un minipieux positif, un négatif et deux minipieux battus perpendiculaires vers l'extérieur soulignant le rôle de l'orientation du système dans sa performance. De plus, des fibres optiques sont utilisées pour enregistrer le profil de déformation le long des puits de minipieux dans le modèle physique à petite échelle 1g avec des résultats indiquant une déformation plus élevée dans les pieux avant par rapport à celle de l'homologue arrière à la même charge latérale.

KEYWORDS: pile group, battered, sand, optic fibres.

1 INTRODUCTION

To support the lateral load from bridge foundations and offshore structures, pile foundations are often used in battered configurations and in groups. The lateral capacity of a pile group is influenced by a variety of factors including pile spacing, rigidity and fixity of the pile to the cap. There are several methods like the p-y curve technique (Matlock and Reese 1962), soil pressure distribution (Meyerhof 1995; Prasad and Chari 1999), strain wedge method (Ashour et al. 2020), to predict the load capacity of single piles under lateral loading. Lateral load behaviour of single battered piles have been studied earlier by Meyerhof and Yalcin (1993), Zhang et al. (1999) in the sand and by Rao and Veeresh (1995) in clay, experimentally.

When piles are used in the group, the capacity of the constituent piles reduces compared to their individual capacity due to a shadowing effect (Brown et al. 1988). Over the years, research has been focused on the behaviour of various vertical, battered piles acting in a group, both in sand and clay. Morrison and Reese (1988) and Rollins et al. (1998) performed a full-scale lateral load test on a pile group of nine with a spacing of 3*D* (*D* is the diameter of an individual pile). They observed that the leading piles carry more load than the trailing ones and a similar trend was also reported by Gandhi and Selvam (1997) who tested a wide range of spacing from 3*D* to 12*D* in medium dense sand. These studies suggested that as the spacing increases, the pile group capacity also increases; however, at the same spacing, the introduction of extra piles causes a reduction of group efficiency. McVay et al. (1995) reported a similar trend when pile spacing was increased from 3*D* to 5*D* in medium dense and loose sand. The battered pile groups have been studied by field experimentation (Abu-Farsakh et al. 2011), centrifuge modelling (Zhang et al. 2002) and using finite element modelling (Abu-Farsakh et al. 2018). Abu-Farsakh et al. (2018) reported that among three types of pile groups, battered, mix of vertical and battered and vertical pile group, the battered pile group had the largest lateral resistance.

Minipiles are small piles of a limited length and small diameter that behave similarly to micropiles and are often used to retrofit existing structures or as a new foundation. As battered piles exhibit more lateral load resistance, unique arrangements of battered minipile in the group are studied in this paper. The behaviour of three types of minipile group under lateral loading is assessed by 1g physical modelling. To obtain a better insight into the strain profile along the pile shaft, fibre Bragg grated (FBG) optic fibres were used. The optic fibres are miniature in size, resistant to electromagnetic field and easily manageable when compared to conventional strain instrumentation techniques and have been used widely to obtain strain data from piles (Doherty et al. 2015). In this study, the strain profile along the minipile shaft is reported which was obtained with the aid of instrumentation using optic fibre technology.

2 PHYSICAL MODELLING

The battered minipiles are designated as either positive or negative depending on the loading direction. When the load is applied in the direction of the batter, it is called positively battered and when load is applied opposite to direct of the batter it is called negative battered condition (Fig. 1). In this paper, the lateral resistance of three types of battered minipile group configurations are studied in cohesionless soil. The soil used in this study was uniformly graded dry silica sand and was filled in the tank uniformly to achieve medium dense condition. The minipiles were hollow slender steel pile of external diameter (*D*) of 9.54 mm, length of 360 mm. The three types of minipile group caps are shown in Fig. 2 from the bottom. The guiding sleeves were welded at a centre to centre distance of 60 mm and at a batter angle of 25° with the vertical. The minipiles were driven into the sand through the guiding sleeves and distance from the soil surface to the pile head was 75 mm. As shown in Fig. 2, for Mg1 group, minipiles numbered 1 and 3 (Mg1-1 and Mg1-3) are outwardly battered minipiles perpendicular to the direction of the lateral load. Mg1-4 is negatively battered, and Mg1-2 is positively battered. In Mg2, the minipiles in the leading row (Mg2-1 and Mg2-4) are negatively battered and that in the trailing row are positively battered (Mg2-2 and Mg2-3). The minipile group, Mg3 has all the minipiles battered diagonally outward.

The geometric scale effect was minimised by maintaining a *D* (pile diameter) to d_{50} (mean particle size of the sand) ratio of 25. The boundary effect was controlled by the ratio of *W* (width of the tank) to *D* greater than 50. For the stress effect, since the prototype minipiles are only around 1.6 m which is very small compared to common full-scale piles, the confinement pressure would not be very high at such shallow depths in the field. Hence, assuming a very dense field condition, the relative density was reduced for the model to accommodate the stress-scale effect.

The minipile groups can be categorised as fixed-head as no relative rotation was allowed between the minipile cap and minipile head, however, the pile cap was free to rotate as a whole. The minipiles were secured to the sleeves using grub screws. Force-controlled quick load tests were performed with the aid of an actuator. The test set-up for one minipile group is shown in Fig. 3. One leading and one trailing minipile in every group were instrumented with optic fibres containing 6 arrays of Fibre Bragg grated (FBG) sensors to obtain the strain profiles along the shaft.

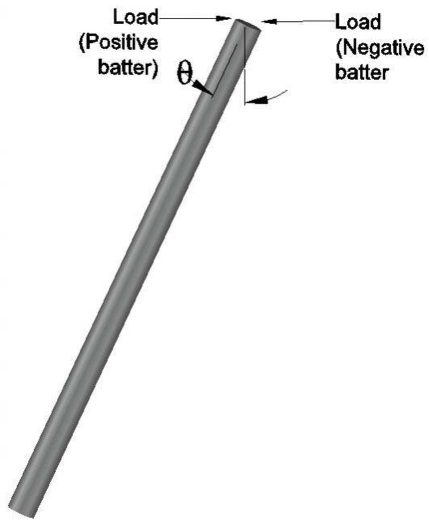

Figure 1. Minipile orientation.

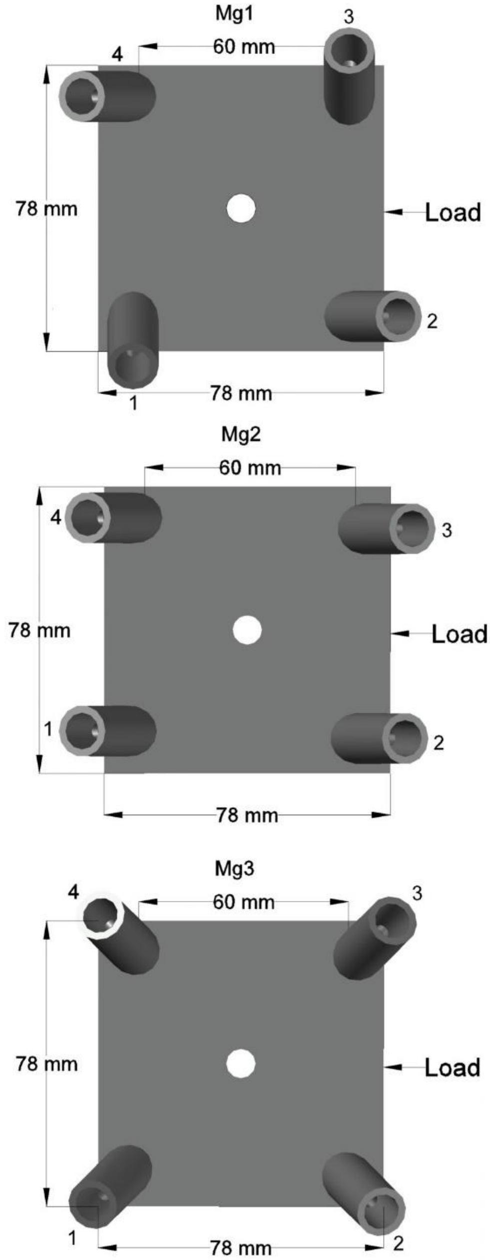

Figure 2. Three types of minipile group cap tested (bottom views).

1.1 *Instrumentation with optic fibre*

The critical soil-structure interaction parameters like soil response and bending moment of a pile can be obtained from the strain profile along the minipile shaft. This is conventionally measured using strain gauges which are adhered along the pile shaft. However, as the length and diameter of the minipiles studied here are only 360 mm and 10 mm respectively, installation of strain gauges would mean the involvement of separate cables for each strain gauge on the already small model pile, adding additional disturbance to the system. Hence, fibre Bragg grated optic fibres were used which enables multiple sensing points along one optic fibre. The optic fibre was adhered to one face of the minipile shaft using cyanoacrylate adhesive by machining 1 mm wide and 0.4 mm deep grooves along the entire length of the minipile. The minipiles were installed in such a way that the instrumented face was pushed against the soil during lateral loading. The spacing and positioning of the FBGs ais shown in Fig. 4.

Unlike strain gauges, optic fibres measure strain or temperature change from the shift of wavelength of the light reflected from the optic fibre. This wavelength shift is recorded using an interrogator at intervals as desired. To find the correlation between the shift of wavelength from the optic fibre and the strain produced, calibration using three-point bending test was performed. The calibration graph as obtained is shown in Fig. 5, where microstrain and shift of wavelength are depicted by *y* and *x* respectively.

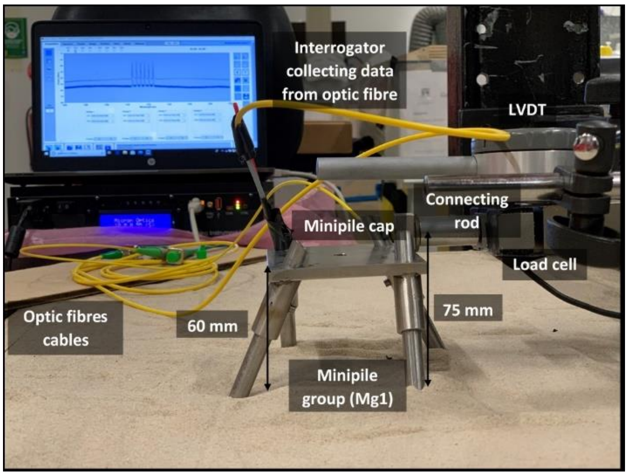

Figure 3. Minipile cap and general instrumentation shown.

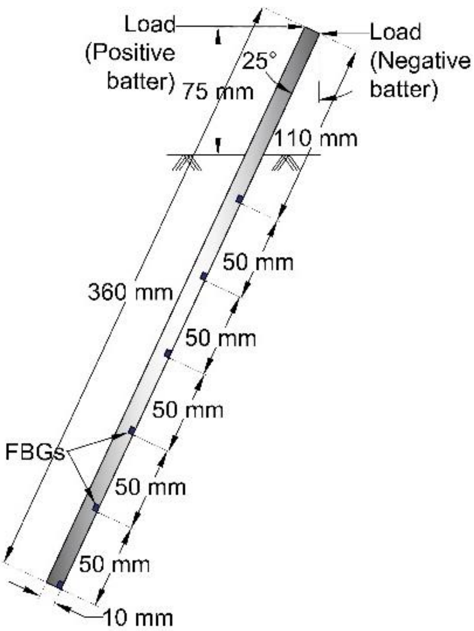

Figure 4. Location of FBGs along the minipile.

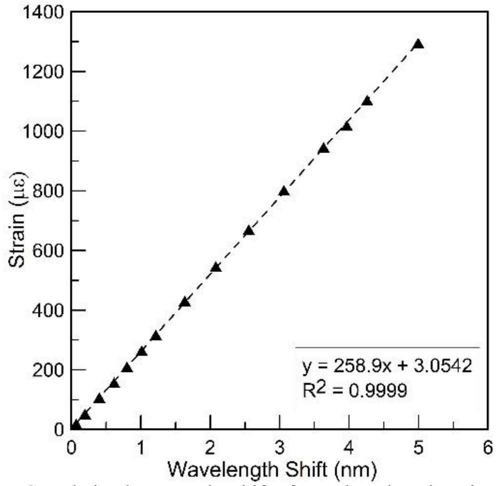

Figure 5. Correlation between the shift of wavelength and strain.

2 RESULTS AND DISCUSSION

2.1 *Force displacement curves*

The lateral resistance versus head displacement is shown in Fig. 6 for Mg1, Mg2 and Mg3. To show the repeatability of the test results, Mg1 test was repeated up to 5 mm displacement and then was terminated as excellent repeatability was observed. Mg1 minipile group's lateral resistance was the least among the three. Although Mg2's lateral resistance was the highest until 3.5 mm displacement, the curve started getting flatter than Mg3 as the force was increased. The single positive battered (load in the direction of the batter) and negative battered (load in the direction opposite to the batter) minipile were also tested individually. It gave an ultimate load (at 20% *D*) of 34 N, 20 N and 12 N for positive, vertical and negative battered minipiles respectively.

When Mg1 and Mg2 are compared, two positively battered minipile in the trailing row for Mg2 contributed to mildly larger lateral resistance than Mg1. Mg1 on the other hand had one perpendicularly battered minipile and one positively battered minipile in the trailing row. The perpendicular battered minipiles in Mg1 acts similar to vertical individual minipile whose capacity is smaller than a single positive battered minipile. The lower capacity of Mg1 and Mg2 in comparison to Mg3 can be attributed to the lower tensile capacity of the trailing battered minipiles in the former.

For Mg3, the arrangement of the minipiles presumably creates a block action where the entire soil block contributes to the higher lateral resistance. At pile spacing of 3*D* to 6*D*, the soil mass within the boundary piles in a pile group is considered to be acting as a block (Patra and Pise 2001). For Mg1 and Mg3, this block action cannot be achieved due to the orientation of individual battered piles, however, for Mg3, block action cannot be eliminated. This conjecture can be further strengthened by obtaining the soil pressure either through instrumentation or numerical modelling. At larger pile spacing such as this (6*D*), the moment arm increases, and the axial force required to prevent the rotation of pile cap decreases, increasing the lateral resistance of the pile group (McVay et al. 1996). As the pile spacing at the head is 6*D* and it increases with increasing depth, the shadowing effect may or may not be ruled out and the minipiles can be assumed to have their total contribution to lateral resistance. The strain profile for the minipile shafts presented in the next section will shed more light about this conjecture.

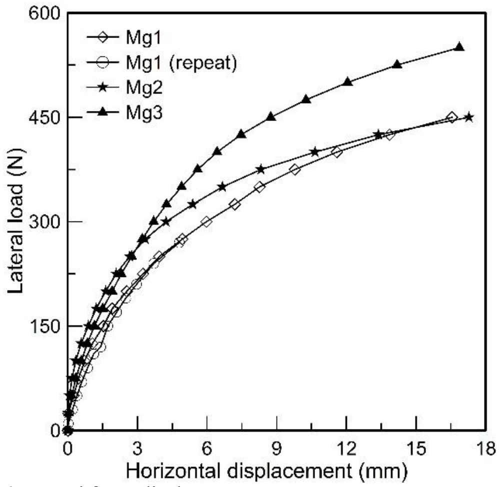

Figure 6. Lateral force-displacement curve.

2.2 *Strain profile*

The strain profiles were measured corresponding to all loading stages for the instrumented minipiles but strains for 450 N load is only presented here for brevity. In Fig. 7a, the strain in the trailing minipile (Mg1-2) is higher than Mg1-1. However, for typical piles in group, leading piles carry higher strain due to shadowing effect. Since, Mg1-1 is battered perpendicular to the loading direction, the minipile carries lower or negligible axial load compared to the minipile battered along the axis of lateral loading. Thus, the total strain observed is also very less than the positively battered minipile in the trailing row. The comparison between the strain profile for the leading negative (Mg2-1) and trailing positive (Mg2-2) minipile is shown in Fig. 7b. The signal from 3rd to 6th FBG of Mg2-2 could not be interpreted due to unexpected noise but it is evident from the figure that the strain sustained by the leading minipile is comparatively higher than its trailing counterpart. Similarly, Fig. 7c demonstrates that strain sustained at 450 N load by the minipiles in Mg3 is lower than Mg1 and Mg2. Also, Mg3-1 carried more strain than Mg3-2 and this can be attributed to two reasons, either due to shadowing effect or negative axial strain in trailing minipiles. When lateral load is subjected to a battered minipile group, the trailing minipiles are in tension which causes tensile strain. The compressive strain in leading row contributes to total strain while tensile reduces the total strain recorded for the trailing minipiles.

When positive and negative battered minipile is individually tested, at the same load, the negative battered minipile sustains a higher strain compared to positive battered minipile at same lateral head displacement. As the spacing at the pile head is 6*D* and it increases further with depth, the shadowing effect could be ruled out (Kim and Yoon 2011). However, more evidence is required to testify this fact. Fig. 8 shows the comparison of the strain profiles of the leading minipile for all three types of group at 2 mm (20% of *D*) displacement. As the force recorded by Mg2 was highest followed by Mg3 and Mg1, the strain profile also shows a similar pattern.

The strain data can also be used to derive p-y curves at different depth which will give the p-multiplier for the instrumented minipiles. Future research is required to interpret the effect of spacing on the capacity of the presented minipile groups.

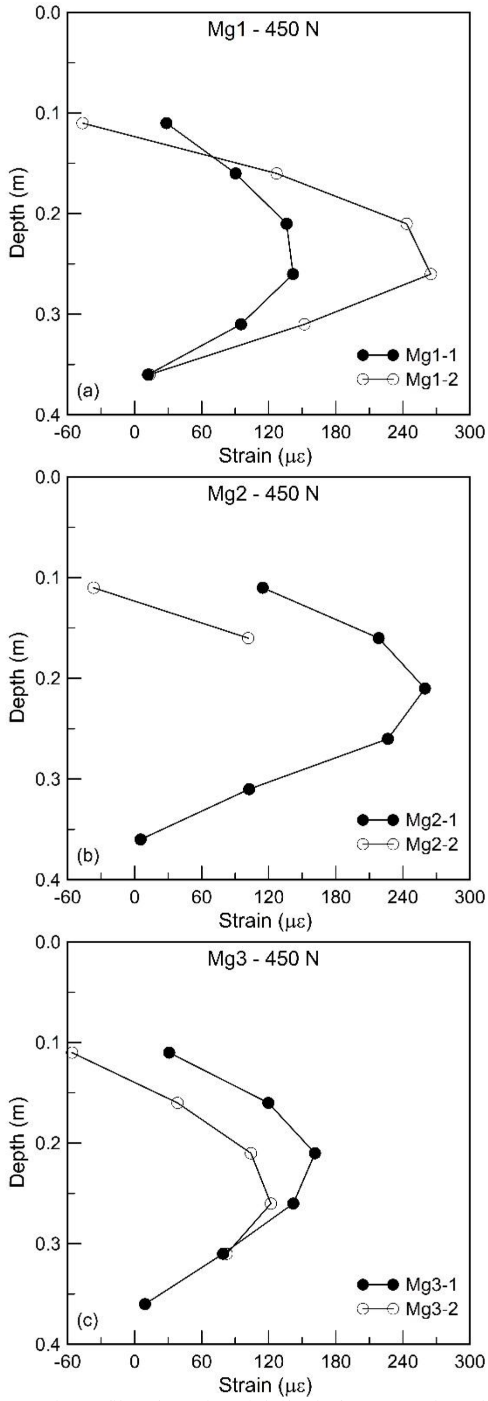

Figure 7. Strain profiles along the minipile shaft at 450 N lateral load.

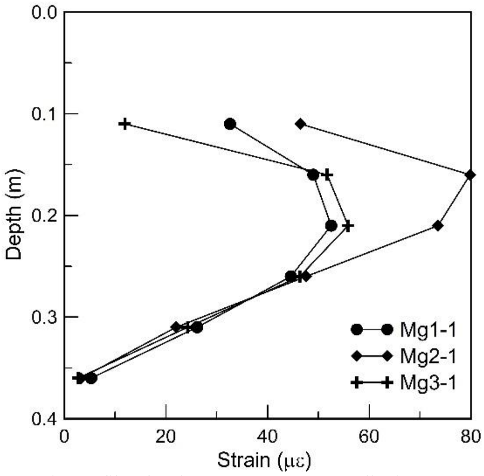

Figure 8. Strain profiles for three groups at 2 mm displacement.

3 CONCLUSIONS

Three different types of minipile groups are tested using 1g physical model to interpret the effect of orientation of battered minipiles at the same pile head spacing of 6*D*. It was found that the lateral resistance of the minipile group is affected by the inclination of the minipiles. Configuration Mg1 gives the lowest lateral resistance, while Mg3 gives the highest lateral resistance at the same horizontal displacement. The involvement of perpendicularly outward 25° battered minipiles was attributed to the lower load-carrying capacity of Mg1 when compared to Mg2.

The strain profile along the minipile shafts for each pile group was recorded using 6 FBGs in an optic fibre cable. The leading minipiles sustained higher strain at the same lateral load which indicates a greater proportion of load was carried by the leading rows. The leading row carried compressive axial strain which could be attributed to increase the strain in leading minipiles. The strain profile could be further used to develop p-y curves for the three types of groups. Further studies need to be carried out with a special focus on soil pressure measurement to identify the effect of pile group spacing and the occurrence of shadowing.

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