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Application of Fibre Bragg Grating in monitoring soil-pile interaction for battered mini driven pile groups

Application du réseau de Bragg à fibre à la surveillance d'interaction sol-pieu pour des groupes constitués de mini-pieux dégradés

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ABSTRACT: Improved design of vertically loaded battered pile groups can benefit various geotechnical applications, such as slope stabilisation, earth retention and bridge abutments. Current design methods rely on model pile load tests, while full-scale field tests and numerical modelling based on field results are limited. Questions still exist whether these design methods are accurate enough in predicting the load capacity and settlement behavior of battered piles. To investigate this problem, a steel footing system, termed as a battered mini driven pile group system has been tested. The system comprises of a steel pile cap with varying number of open-ended steel mini piles installed in a battered condition. This paper reports the soil-pile interaction and group effect of battered mini pile based on field pull-out load tests obtained in a site consisted of medium to dense sand deposits. The strain profile along the length of a single battered mini pile was measured with fibre Bragg grating (FBG) sensors during loading. The FBG measurements show that the measured strain profile has good agreement with lateral soil resistance model proposed in literature. From the quick pile load test results of battered mini pile group, it was found that the the group efficiency factor was greater than unity with current configurations but there is a sign of negative group effect with increasing number of piles, indicating the limitation of current design method.

RÉSUMÉ: Une conception améliorée des groupes de pieux dégradés chargés verticalement peut profiter à diverses applications géotechniques, telles que la stabilisation des pentes, la rétention des sols et les culées de pont. Les méthodes de conception actuelles reposent sur des tests de charge de modèles de pieu, tandis que les tests de terrain à grande échelle ainsi que la modélisation numérique basée sur les résultats de terrain sont limités. Des questions subsistent pour savoir si ces méthodes de conception sont suffisamment précises pour prévoir la capacité de charge et le comportement de tassement des pieux dégradés. Pour étudier ce problème, un système de base en acier, appelé système de groupes constitués de pieux dégradés, a été testé. Le système se compose d'un chapeau de pieu en acier avec un nombre variable de mini-pieux en acier à bouts ouverts installés dans un état dégradé. Cet article présente l'interaction sol-pieu et l'effet de groupe de mini-pieux dégradés basé sur des tests de charge d'arrachement sur le terrain obtenus sur un site constitué de dépôts de sable moyen à dense. Le profil de déformation le long d'un mini-pieu dégradé a été mesuré avec des capteurs à réseau de Bragg à fibres (FBG) pendant la charge. Les mesures FBG montrent que le profil de déformation mesuré concorde bien avec le modèle de résistance latérale au sol proposé dans la littérature. Les résultats du test de charge de pieu rapide du groupe de mini-pieux dégradés ont révélé que le facteur d'efficacité du groupe était supérieur à l'unité avec les configurations actuelles; mais il existe un signe d'effet négatif du groupe avec le nombre croissant de pieux, indiquant le caractère incomplet de la méthode de conception actuelle.

Keywords: pile instrumentation; fibre bragg grating sensors, driven mini piles. battered piles

1 INTRODUCTION

Improved design of vertically loaded battered pile groups can benefit various geotechnical applications, such as slope stabilisation, earth retention and bridge abutment. To investigate the behaviour of a battered mini pile group subjected to vertical pull-out load, this paper utilised a footing system comprised of a steel plate with various numbers of steel hollow mini piles (outer diameter of 42.4 mm and thickness of 2.6 mm) installed in a battered condition. The mini piles were driven at an angle of 25° from vertical through the guiding sleeves of steel plate to the required embedment depths. Most of the literature studied the load response of battered mini pile group with model pile load tests (Tsukada et al., 2006; Sharma et al., 2014; Kyung et al., 2016; Kyung and Lee, 2017). To understand the load-carrying mechanism of a battered mini pile group, the behaviour of a single battered mini pile needs to be first investigated. To the best of authors' knowledge, there is yet a fully instrumented field load test to monitor the behaviour of battered mini piles.

The uplift load-carrying mechanism of a battered mini pile can be considered as two components based on decomposed loads, namely axial and lateral loads as shown in Figure 1 (Mehdizadeh et al., 2016; Kyung and Lee, 2017). In axial condition (Figure 1 (a)), the resistance acting on pile consists of skin friction (P_{fi}). In lateral load (Figure 1 (b)), the dominant

resistance is the lateral soil resistance (P_{hl}) provided by the surrounding soil. The skin friction component in a battered pile is similar to the behaviour of a vertical pile, while the lateral soil resistance has been subject of controversy.

1.1 Lateral soil resistance

Previous researchers have developed different methods to predict lateral soil resistance pressure for pile subjected to lateral load (Broms, 1964; Petrasovits and Award, 1972; Prasad and Chari, 1999). Brom's method can be considered as the most common method to estimate soil resistance, in which the pile is assumed to rotate at its toe and the lateral soil resistance equals to three times the passive pressure. Petrasovits and Award (1972) and Prasad and Chari (1999), on the other hand, suggested that there is a point of rotation above the pile toe. Lin et al. (2014) investigated soil-pile interaction of laterally loaded pile through a fully instrumented experiment. In the experiment, the force acting on pile body can be measured directly. It was reported that the measured force distribution on laterally loaded pile had better agreement with the model suggested by Prasad and Chari (1999). The methods mentioned hereinbefore, produce only the ultimate pressure and significantly different distributions of lateral soil resistance. There is limited research to measure the development of lateral soil resistance as a function of applied

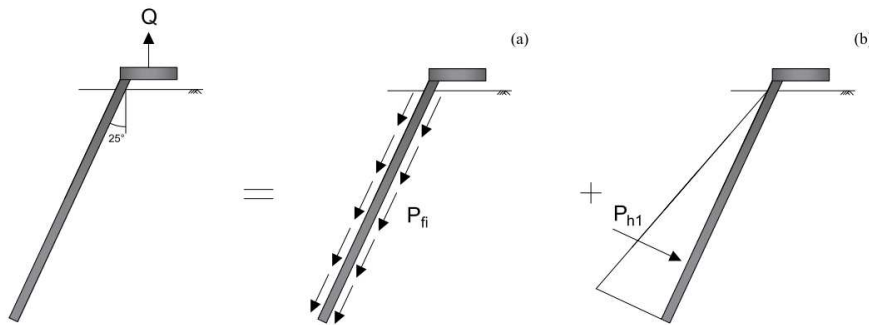


Figure 1. Load-carrying mechanism of a battered mini pile under pull-out vertical load: (a) skin friction resistance; (b) lateral soil resistance (Kyung and Lee, 2017).

load and hence reducing robustness of current designs of battered pile (Lin et al., 2014). Moreover, there is still a lack of field instrumentation to measure the lateral soil resistance pressure acting along pile's shaft.

1.2 Group effect of mini pile group

After determining the load capacity of a single battered mini pile, the current design method suggests that this capacity is multiplied by the number of piles in a battered mini pile group to determine its group capacity. However, previous research showed that there is limitation in this approach, in which the pile group capacity cannot be justified by the capacity of a single pile (Mehdizadeh et al., 2018). When piles are installed in group, the group capacity can be different from the sum of single piles due to interaction between neighbouring piles (Shanker et al., 2006; Sharma et al., 2014). Without correctly characterising the group effect, the group capacity can be underestimated or overestimated. The group effect in pile groups with small-diameter piles such as micropiles have been discussed by various researchers (O'Neill, 1983; Tsukada et al., 2006; Kyung et al., 2016). O'Neill (1983) conducted full-scale load tests in loose and dense sand. The tested piles were driven piles subjected to compression load. It was reported that the group efficiency of pile group in sand was always greater than unity if the piles were not bored or jetted. This contradicts with the model developed by Sayed and Bakeer (1992), who suggested that the group efficiency factor was usually less than unity as the interactions between piles could reduce the pile group's overall ultimate load capacity. Tsukada et al. (2006) indicated that the group efficiency factor could be less than or greater than unity depends on the relative density of sand. It was reported that the mini pile group had group efficiency factor greater than unity in dense sand and the factor was higher when compared to loose and medium dense sand. Kyung et al. (2016) conducted model tests to investigate the group

effect in battered micropile group with different spacing. It was found that the group efficiency was less than unity for all spacing which was consistent with the results in Sayed and Bakeer (1992).

Previous studies showed large discrepancy in determining group efficiency for small-diameter pile group. This is because the efficiency of a pile group can be affected by various factors such as time, soil types, geometry of pile group, pile cap contact and pile driving force (O'Neill, 1983).

In this study, the soil-pile interaction of a battered mini driven pile was monitored by fibre Bragg grating (FBG) sensing technique to investigate the lateral soil resistance acting along pile length when subjected to vertical pull-out load. To investigate the group effect, quick pile load tests were conducted on two mini pile group configurations. Based on the results from tests, the robustness of current design methods for pull-out load capacity of a battered mini pile group was discussed.

2 SITE CONDITIONS

Instrumented field load tests were performed at a test site located at a Melbourne's southern suburb, Fingal in Victoria, Australia. Three Cone Penetration Tests (CPT) were conducted within the test area. Figure 2 shows the results of CPTs. Two CPTs were terminated at a depth of approximately 2.5 m, where a dense layer of silty sand was found. The *in-situ* investigation and test results indicate that the site consisted of organic fill in the top 400 mm underlain by silty sand deposit. The soil profile consists primarily medium dense silty sand and becomes dense deposit from depth of 2 m. No water table was encountered at the site up to 10 m depth. Variation of the soil unit weight and internal friction with depth based on the CPT results are shown in Table 1.

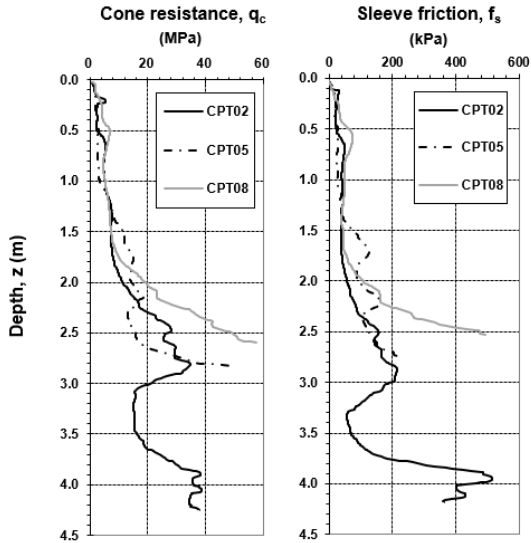


Figure 2. Results of CPTs performed at the test site

Table 1. Soil profile at the test site

Layer number	Depth (m)	γ (kN/m ³) (Mehdizadeh et al., 2018)	ϕ' (°)
1	0-0.5	16.8	35
2	0.5-1	16.3	34
3	1-1.5	16.9	38
4	1.5-2	17.6	37
5	2-3	18.7	40

Note: γ = soil unit weight; ϕ' = internal friction

3 TEST PILES INSTRUMENTATION

The test mini pile is a steel, open-ended pipe pile with an outer diameter of 42.4 mm and a wall thickness of 2.6 mm. Three grooves, namely G1, G2 and G3, with 4 mm wide and 1.5 mm deep were machined along each test pile shaft (Figure 3a) to mount FBG sensors. A groove is required as a two-part adhesive could be applied to cover the groove for harsh environment protection. The grooves were arranged concentrically around the pile's central axis, so the angle between them is 120°. A 200 mm space was left at pile top such that there is enough room for jackhammer for pile driving. A fibre string with a total of six FBG

sensors was embedded in each groove. Locations of the six sensors were 200, 470, 740, 1010, 1280, 1550 mm away from the pile head. In comparison with conventional electric strain gauges, FBG sensors string installation required less installation time as multiple sensors were allowed to be written on a single string. Multiple sensors on one string also mean the number of cables need to be handled were largely reduced, making this approach an extremely efficient strain monitoring technique for small-scaled geotechnical structures.

4 FIELD TEST PROGRAM

The test program aims to assess the soil-pile interaction of battered mini pile and its expected behaviour in a battered mini pile group system. In total, four static pull-out load tests were performed on single battered mini piles and battered mini pile groups. For single pile load tests, the instrumented mini piles were driven outward at an angle of 25° from vertical with a hand-held jackhammer to an embedment depth of 1400 mm. Non-instrumented quick pile load tests were conducted for two configurations of battered mini pile groups. Figure 3b shows the layouts of the battered mini pile groups used in this study. Both pile groups utilised same dimension of steel plate which was 263 mm by 263 mm and same embedment depth of 1500 mm. To study the group effect, pile group with 4 piles (S250-1500-4piles) and 6 piles (S250-1500-6piles) were tested in field. The pull-out load tests were conducted according to FHWA (2005), ASTM-D1143 (2013) and D3689 (2013) with some modifications. To eliminate the impact of organic material on the test result, a 400 mm trench was dug and the test piles were installed at the bottom of the trench. The pile was subject to pull-out load with an incremental load of 0.5 kN until failure occurred. Each incremental load was maintained for 5 mins. Deformation was recorded using two digital indicators mounted on the pile top cap. Failure was defined such that the pile can no longer sustain the applied load and

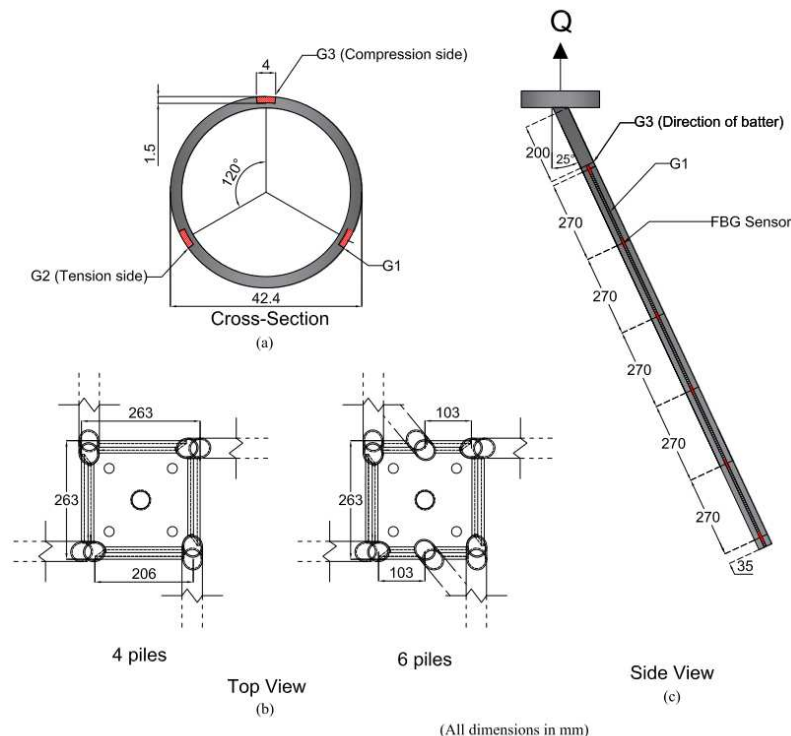


Figure 3. Dimensions of the test mini pile and the layout of the FBG sensors on the test pile: (a) Dimensions of grooves and the cross section of test pile; (b) layout of battered mini driven pile group with 4 and 6 piles; (c) layout of FBG sensors on the test pile (dimensions in mm)

continuous jacking was required. The pile was unloaded to 0 kN at the end of the test and residual settlement recorded. The strain along pile length was recorded by FBG sensors at various loading stages. Unfortunately, due to technical issue, the fiber string in G1 was broken while setting up the test and strains were not recorded.

5 TEST RESULT AND DISCUSSION

5.1 Monitoring strain results and analysis

Strain along G2 represented the tension side, while the strain along G3 represented the compression side. Figure 4a and 4b show the measured strain curves of the grooves along the pile's shaft. All strains were recorded 5 minutes after each loading stage. From Figure 4a and b, It

can be observed that the trends of strain curves in G2 and G3 changed significantly with increasing applied loads. In Figure 4a, the strain along the pile length in G2 has increased to depth of 435 mm (10D below ground surface) and decreased from this point onward. The strains measured in G3 shows similar behaviour until the strain curves reached the point of rotation. Figure 4b illustrates the point of rotation along the pile length has shifted from 330 mm to 890 mm below ground surface. Prasad and Chari (1999) has proposed an equation to calculate the depth of point of rotation when a pile is subjected to ultimate lateral load.

$$a = \frac{[-(0.567L + 2.7e) + (5.307L^2 + 7.29e^2 + 10.541eL)^{0.5}]}{2.1996} \quad (1)$$

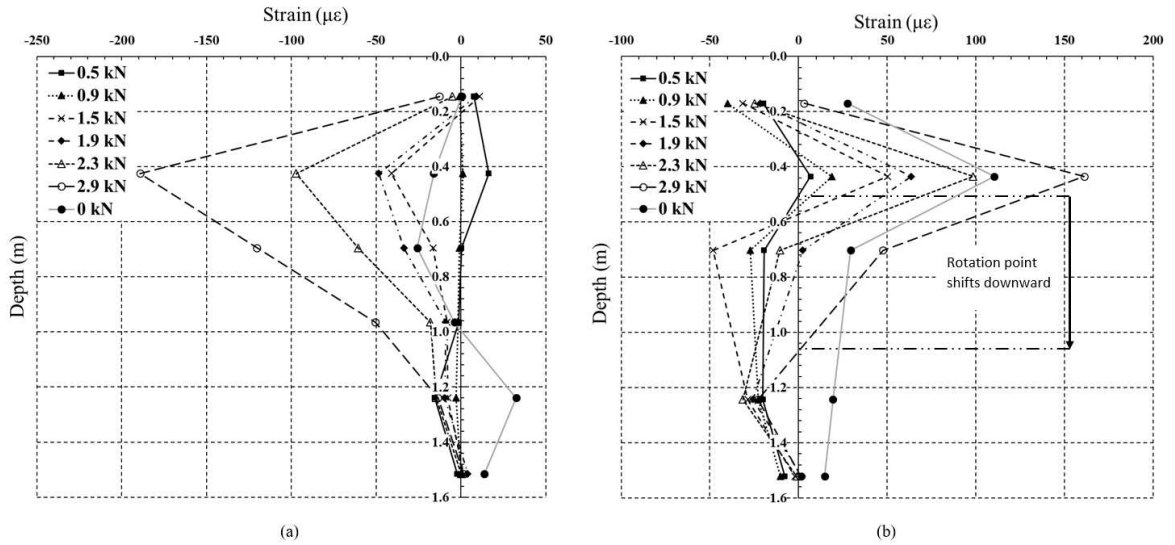


Figure 4. Measured strain curves during the pull-out load stages: (a) strain curves along G2; (b) strain curves along G3.

Where a (m) is depth of point of rotation below ground; L (m) is embedment depth of pile; and e (m) is eccentricity of loading. The measured depth of rotation point was then compared with calculated value. The calculated value was 0.97 mm which shows good agreement with the measured value with a difference of 80 mm, or 5%. This indicates the method proposed by Prasad and Chari (1999) works well in determining the lateral soil resistance for battered mini pile.

5.2 Load-settlement responses

Load-settlement curves of single battered mini pile and battered mini pile group with four and six piles are shown in Figure 5a. The load-settlement curves of the single battered mini piles indicate that there is no further increase of load capacity after the ultimate capacity is reached. For the group battered mini pile groups, it is shown that there were increases of load capacity after yielding. The displacements at the ultimate pull-out capacity is defined as S_{max} , indicated by vertical dashed lines in Figure 5a. The values of S_{max} for battered pile groups were smaller than the values of single battered pile which is

consistent with the results reported by Kyung and Lee (2017). It was suggested that the overlap of resistance zones of mini piles was likely to be occurred in the group due to the interaction of neighbouring piles. This leads to mobilisation of ultimate capacity at smaller displacement.

5.3 Group effect for mini pile group

Group efficiency factor, η_{GMP} , was introduced by Kyung and Lee (2017) to determine the pull-out capacity of a mini pile group:

$$P_{u,GMP} = \eta_{GMP} \sum P_{u,SMP} \quad (2)$$

Where $P_{u,GMP}$ (kN) is load capacity of micropile group, η_{GMP} is group efficiency factor and $P_{u,SMP}$ (kN) is load capacity of single micropile. Kyung and Lee (2017) suggested that η_{GMP} can be calculated with the following equation:

$$\eta_{GMP} = 1 - \frac{1}{N} \sum \{0.045 [\cos^2(3.5\theta)] + 1\} N_{ad} \quad (3)$$

Where N is total number of micropiles in group, θ is battered angle of pile and N_{ad} is

number of adjacent micropiles in group. To determine η_{GMP} for both configurations, S250 with 4 piles and S250 with 6 piles, the field test results in this study were input to Eqs. (2). Table 2 summarises the values of η_{GMP} determined from the pile load test results. According to the results, η_{GMP} is greater than unity, which indicates the pull-out capacity of a mini pile group is greater than the sum of the amount of single mini piles in the group. However, it should be noted that the rate of increase of η_{GMP} decreases with increasing number of piles in the group, which indicates a sign of negative group effect as suggested by previous researches. The theoretical η_{GMP} for battered pile groups with four and six piles installed at an angle of 25° outward were also calculated using Eqs. (3). The η_{GMP} of six piles was plotted against η_{GMP} of four piles to evaluate the negative group effect due to the addition of extra two piles into the system (Figure 5b). Figure 5b shows that the theoretical group effect is consistent with the measured values. From the results, the group effect of additional two piles to a group of four piles is found to be $\eta_{GMP} = 0.88$. The test results of battered mini pile group show that negative group effect exists when extra two pile were added into the system. However, the positive effect of group is larger than the negative effect, which leads to η_{GMP} greater than unity. This shows that the pull-out load capacity could be underestimated if η_{GMP} of a battered mini pile group is assumed to be less than unity. More investigation is required to explain why the current configuration leads to higher load capacity.

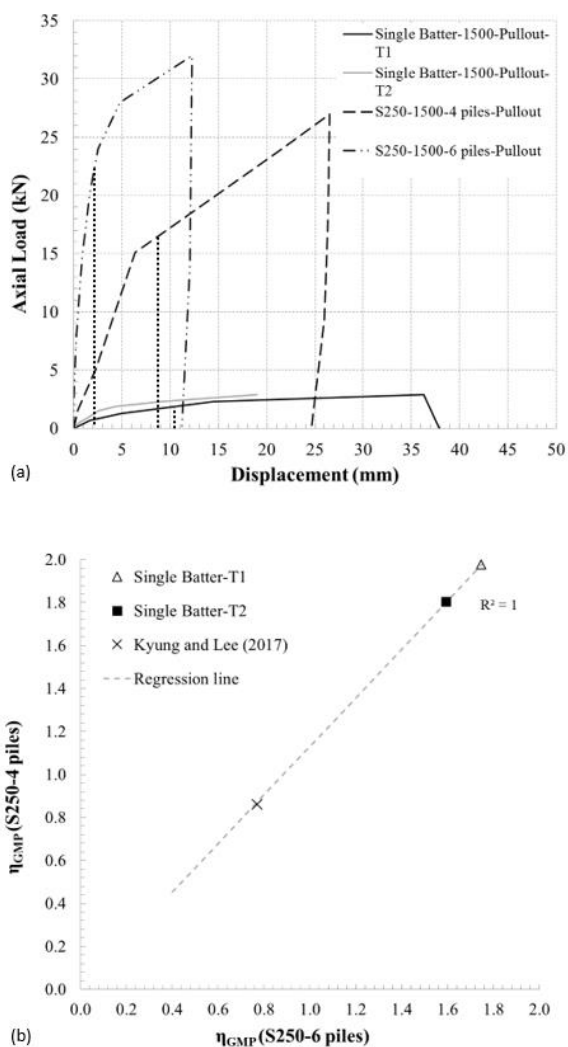


Figure 5. Field test analyses: (a) load-settlement curves of single battered mini piles, battered mini pile groups with four and six piles; (b) Effect of increasing number of piles.

Table 2. Summary of ultimate capacity and group efficiency factor for single and group mini piles.

Configurations	Ultimate Pull-out Capacity (kN)	Total Pile length (m)	Ultimate Pull-out capacity per meter length (kN/m)	Group Efficiency Factor, η_{GMP} (S250-4 piles)	Group Efficiency Factor, η_{GMP} (S250-6 piles)
S250-1500-4 piles	16.6	6	2.8	-	-
S250-1500-6 piles	22	9	2.2	-	-
Single Battered-T1	2.3	1.4	1.6	1.80	1.59
Single Battered-T2	2.1	1.4	1.5	1.98	1.75

6 CONCLUSIONS

In this study, the soil-pile interaction of battered mini pile group was investigated, focusing on the lateral soil resistance acting along pile length and group effect of the system during pull-out load test. For this purpose, a series of quick pile load tests were conducted in a site consisted of medium to dense silty sand deposit. A single steel pipe pile was instrumented with FBG strings to monitor the soil-pile interaction. Two quick pile load tests were conducted on two mini pile group configurations to investigate the group effect of the system. The research outcomes and recommendations are summarised below:

- Along the tension side of the pile, it was found that the strain has increased until it reached certain depth and decreased from that depth onward. Along the compression side, similar behaviour was observed, except there was a rotation point observed.
- The theoretical depth of rotation point was calculated using equation proposed by Prasad and Chari (1999). The measured depth of rotation point matches the calculated depth with a difference of 5%.
- Group efficiency factor was found to be greater than unity with current configurations but there is a sign of negative group effect with increasing number of piles. The results was consistent with the theoretical group effect.
- Instrumented tests on a battered mini group is required to monitor the group behaviour of battered mini piles. New design method for this system is also required as current design can lead to underestimation of load capacity.

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