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# GROUP CAPACITY AND EFFICIENCY OF FULL FRICTION PILES ON VERY SOFT SOIL

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**ABSTRACT:** This study was conducted by loading on full-friction piles in very soft clay. The test piles comprised of square concrete piles of 20 cm x 20 cm, with 11.5 m and 17.5 m long. The pile groups consisted of 2x2 piles and 3x3 piles, with the distance between piles from 3 to 5 times pile diameter. The loading tests were conducted on single piles (2 tests), on individual piles within a group of piles (5 tests), and on a group of piles (4 tests). The results showed that the loading capacity of a single pile, in general, was higher than the capacity of individual pile within a group of piles; and yet, the capacity of individual pile within any group of piles was higher for the pile at the edges of the group than for the pile at the center of the group. Furthermore, since the loading capacity of any group of piles was always less than the capacity of single pile multiplied by the number of piles, the pile group efficiency factor was found to range from about 50% to 70%. Finally, the group of longer piles was found to yield lower efficiency factors than those of shorter piles.

*Keywords: Pile foundation on soft soil, Full- friction piles; Capacity of pile group; Pile-group efficiency.*

## 1. INTRODUCTION

About 10% of the total land area of Indonesia comprises of the land of soft soils, such as those in Sumatra, Kalimantan and inconsiderable part of Papua [1]. These soft soils have the low bearing capacity and very large compressibility so that many problems will appear with the construction of buildings on top of the soils. One of the problems is the potential of a relatively large settlement of friction pile foundation, which is the type of pile foundation when the entire pile lengths are still inside the soft soil layers so that the foundation support is mostly derived from the soil frictional resistances along the pile shafts. In many occasions, the friction pile foundation foundations have to be used when the thickness of soils with soft to medium consistencies is relatively large (> 20 m), when the location of the bearing stratum of hard soil layer is fairly deep, or when the buildings are relatively light to medium in weight. In this situation, building designers mostly prefer to use the friction pile foundation, because this type of foundations has been common to function fairly well, although in some cases rather large settlement is also observed.

The use of friction pile could be made to cause relatively very little settlement if the actual working loads in the pile foundation is less then 1/3 of the ultimate supporting capacity of the piles [2]. However, the frictional resistances of pile foundation in soft soils are generally rather low; so that if the maximum working load is limited to merely 1/3 of the pile supporting capacity, the amount piles needed for the foundation will be higher. It should also be noted that the study of [2] was applied for single model pile only (in laboratory scale model), while in reality pile foundation are always in a group of piles, so that group efficiency factor is to be used, and this means the friction pile capacity is even smaller.

Study on a group of small-scale friction piles had been conducted in the field using 5 (five) model piles to form a group of piles that were inserted inside clayey silt soil [3]. The ultimate capacity of the individual pile was then used to compare with the capacity of the pile group. This test, however, was conducted as small-scale pile test only. A further test of group piles, another study of a laboratory model of pile group had also been conducted [4], and this study obtained the pile group ultimate capacity for 2 types of pile shape, square and circular. The results of this study showed that the ultimate capacity of pile group was higher when: (a) pile cross-sectional area was bigger, (b) the pile depth was deeper, and (c) the number of piles in the group was more, which are naturally expected from tests on pile group.

Since most of the existing studies on a group of friction piles were either on the model pile in the laboratory or on small-scale pile test in the field, there has not been any large-scale test directly on a group of piles in the field ever be attempted. Therefore, the current knowledge of friction pile group capacity and group efficiency is still considered unsatisfactory, validation from real pile test is still needed.

For a group of piles, the formula for pile-group efficiencies is mostly obtained also from the empirical formulas [5-6], which are obtained from testing on either small-scale field test or laboratory scale model of pile groups of end-bearing piles. There has not been any attempt to try large-scale testing on a group of piles directly in the field, due to the limitation of the load that can be used. The question arises on whether the existing formula of pile group efficiency are still applicable also for the friction piles in the group. This is one of the main reasons why this study in this paper was performed. Full-scale pile group testing directly in the field are very much needed and expected.

Until recently, people had never conducted any study on fully friction piles in full-scale test in the field, despite there has been many constructions of buildings on soft soil with foundation consisted of a group of friction piles only. Many buildings in some cities in Sumatra and Kalimantan, Indonesia, are founded mostly of a full-friction group of piles. Yet, no information could be obtained on the behavior of those buildings until now. Likewise, more recent information regarding the behavior of a full-friction group of piles from other places in the world is practically nil. Most of the more current field tests were performed for either only on single friction pile [7-8] or on a group of piles but with the end-bearing type embedded into a firmer soil layer underneath [9]. The test on fully friction group of piles has never been tried until this study.

This study is actually performed to investigate the long-term settlement behavior of full-friction pile in the field. However, while performing this study, the characteristics of the ultimate capacity of a group of piles and the group efficiency are also investigated. This paper concerns only on the ultimate capacity and efficiency of full-friction piles. In this study, field tests had been conducted on concrete pile foundations of square cross-section 20 cm x 20 cm, with depths of 11.5 m and 17.5 m (2 variations of depth), with spacing between piles, 3xd and 5xd spacing. The loading test on the pile was performed on single pile without a group, on each individual pile in a group, and on groups of fully friction piles. The long-term settlement behavior of the full-friction piles will be presented on other paper in the near future.

## 2. SOIL, PILE AND PILE TEST CONFIGURATION

This study was conducted in the city of Banjarmasin, South Kalimantan, where the whole area consists of very thick layers of soft soils. The results of boring test and SPT in the area of study can be described as seen in Fig.1.

The soil layers showed the thickness of very soft soil to the depths of > 22 m, in which the conus resistances (Dutch Cone Penetrometer Test, DCPT) < 10 kg/cm2. The next layer comprises of sandy silt and sand layers with medium density, while the hard bearing layer with SPT > 50 is found at the depth of about 32 m. This soil stratigraphy is almost similar to many of soil layers in other areas of Banjarmasin City, while the thickness of the soil layers may vary slightly (source: Soil Investigation Report by PT Kalimantan Soil Engineering, 2005).

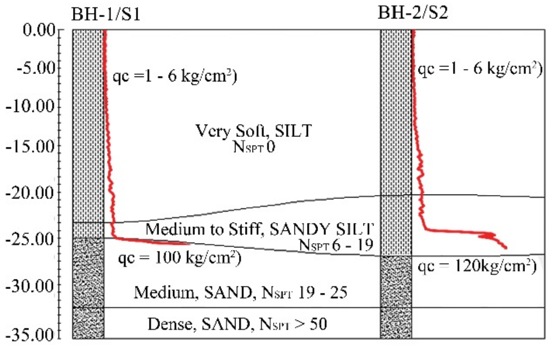


Fig.1. Soil stratigraphy base on N-SPT and CPT

Variation of pile configurations can be described as in Fig.2. The piles were varied in diameters (20 cm x 20 cm square, and 30 cm x 30 cm square cross sections), in lengths (11.5 m and 17.5 m), distances between piles (3x and 5x pile diameter), and numbers of pile within group (1 pile = single separate unit pile, 2x2 piles, and 3x3 piles). All the pile lengths were entirely inside the very soft layer of silt soil.

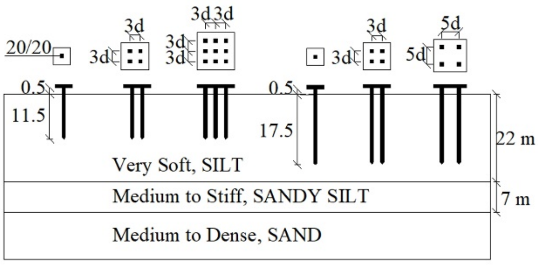


Fig.2. A typical configuration of the test piles, single pile and pile group

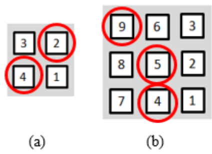


Fig.3. Selected piles for the individual pile testing inside: a) 2x2 pile group; b) 3x3 pile group

Fig.3 shows the layout of individual pile testing performed within a group of piles (indicated with red circles). The individual pile testing was performed prior to conducting the tests on the group before the pile cap was specially formed on the group. The individual pile testing was conducted on 2 selected piles in the group of 2x2 piles, and on 3 selected piles in the group of 3x3 piles. The individual pile tests were performed only on piles with the depth to 11.5 m.

## 3. APPLICATION OF FIELD PILE LOADING TEST

During field loading tests, steel frames were erected on top of the tested piles for placing the loading weight. When testing on the selected individual pile, the frame was placed on the top of the selected pile only; while upon testing on the group of piles, the steel frame was placed on reinforced concrete pile cap, constructed after the tests on individual piles to make the load more uniformly distributed among the piles. The pile caps were positioned to be always at considerable distances above the ground surface. The loading tests were performed at least after 30 days from pile insertion. This measure was to guarantee that all the frictional resistance of the soils surrounding the piles had been 100% mobilized.

The loading on piles was conducted using the quick test method, which meant applying increasingly higher step loading in a relatively short time. Application of loads was performed in 5 to 7 increments of loads, in each increment the load was maintained for 60 to 120 minutes. The loading was terminated when relatively large pile displacement (> 10% pile diameter) was observed under the load in relatively short time.


Fig.4. Field loading tests: a) loading on the single pile and pile group; b) after ultimate load conditions were achieved.

The illustration of field loading tests on the single pile and on pile group can be seen in Fig.4.a and Fig.4.b. Fig.4.a shows one of the loading methods performed before reaching the ultimate load, while the pile is still able to support the load with relatively small displacement only. The condition such as seen in Fig.4.a was performed in several increments of loading, while in every load the pile deformations were continuously monitored. Fig. 4.b shows the condition when the ultimate load has been reached, and failure occurred; or when the pile frame showed very large deformation until the loading frame reached the deformation stopper (it was placed to keep the loading frame to have ample heights at least 50 cm above the ground), so that the pile group can be tested again under the next higher load.

It is perhaps important to mention the condition of the piles during failure, such as in the case of Fig.4.b. It was monitored that the pile displacement vs load for full friction piles was different from tests on one individual pile to the other. Each individual pile loading tests produced a different maximum test result. Therefore, this study shows that individual pile in the group will behave differently to reach its own failure load so that loading a group of the pile will be very dangerous when the load is very near the maximum/failure load. This is because the differential deformation and differential failure load from each individual load may cause severe damages to the structure when the pile group is loaded to near its maximum capacity.

## 4. AXIAL CAPACITY OF FULL FRICTION PILE

### 4.1 Single Pile of Full Friction Pile

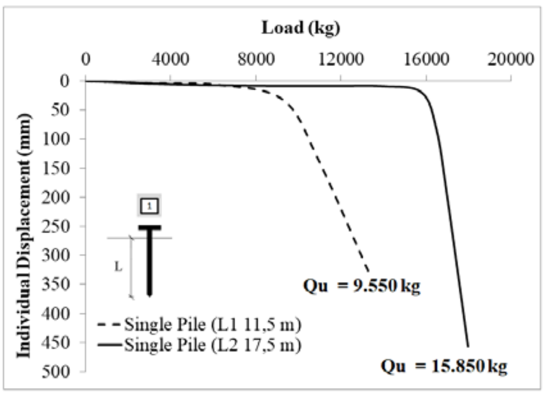


Fig.5. Load-displacement curves of single full friction pile

The axial capacity of full friction pile of a single pile from field loading test is given in Fig.5. The curves in Fig.5 show the correlation between load versus displacement, or well known as P-z curve, of a single pile. During the lower stages of loadings, the condition is still regarded as elastic and the displacement is still very small. However, when the load is approaching the estimated ultimate load, large displacement of pile head will occur in a relatively short time. This condition shows that for fully friction piles, loading of the pile should never be done near the proximity of the predicted ultimate load.

The ultimate axial capacity of the piles in this study was then determined by means of the Tangent method. The full friction pile with 11.5 m embedment length was found to have an ultimate capacity of 9.550 kg, while the pile with 17.5 m embedment length was to yield 15.850 kg ultimate load. As expected, pile length increase will also increase the pile axial loading capacity.

### 4.2 Individual Pile in Group

The results of testing on individual pile inside a pile group are as those given in Fig.6. The individual pile subjected to loading test was part of the 2x2 (total 4 piles in the group); and the individual pile tested were those at the corner, so that every pile was surrounded equally by 3 other piles. The tests on the two piles were conducted simultaneously on the same day, with merely several hours apart.

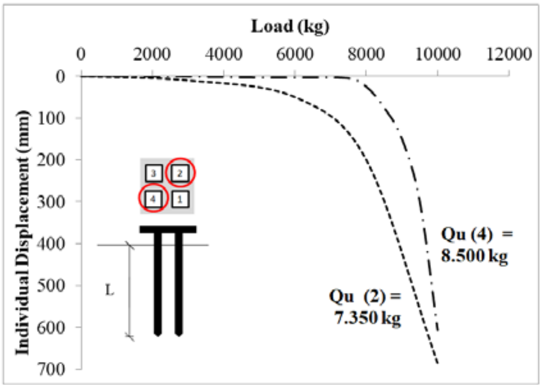


Fig.6. Ultimate capacity of individual pile in group of 2x2 (s = 3d; L = 11.5 m)

From the 2 individual piles tested, the ultimate pile capacities are 7.350 kg and 8.500 kg, and the first pile tested (pile no. 4 in Fig.6) is the one to have the higher loading capacity. This result means that the ultimate capacity of an isolated single pile (as in Fig.5) is higher than the capacity of an individual pile in a group (as in Fig.6), and the reduction of individual pile capacity in the group was about 15% to 25% compared to the single pile capacity. This result also suggests that frictional resistance along the pile shaft may vary with the changes of pile configuration. Furthermore, the variation of the individual pile capacity inside the group is perhaps due to the relative closeness of the testing time between one pile to the other. It is thought that the first pile tested is to have higher capacity, because the movement of one pile inside a group during the pile failure may disturb the surrounding soils so that the soil frictional resistance along the adjacent piles are also affectingly reduced. The capacity of the second pile tested might have been almost equal with that of the first pile, if sufficient time was allocated for testing the second pile after the first (perhaps the time should have been 5 to 7 days apart), so that sufficient time would have occurred for the soil to heal itself completely from the first pile disturbance.

In Fig.7, the capacity of individual pile within a 3x3 group of piles is shown. The positions of the individual pile tested are represented by 3 piles: the middle edge pile (no. 4), the center pile (no. 5), and the corner pile (no. 9). It can be seen from Fig.7 that the ultimate capacities of individual piles in the corner position (pile no. 9) and the middle edge position (pile no. 4) are higher than that of the center position (pile no. 5). It is apparent that the number of piles encircling the tested pile is very much affecting the individual pile capacity. The pile at the edge and corner position have 3 to 5 piles in their surroundings, while the center pile has about 8 piles in its surrounding. Compared to the capacity of a single isolated pile, the individual pile capacity at the edge and corner positions have about 37% to 22% reductions in capacities, while the center position has almost 40% reduction. The middle edge pile no. 4 and the corner pile no. 9 were tested on the same day, which piles no. 4 was the first, while the center pile no. 5 was tested a day before.

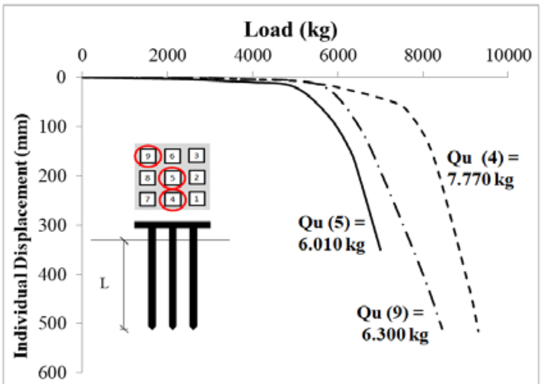


Fig.7. Ultimate capacities of 3 individual piles in group of 3x3 (s = 3d; L = 11.5 m)

The results of individual pile testing in a group of 3x3 piles are found to be consistent with a similar test on friction piles in clayey silt reported [3], in which the individual capacity of the pile at the corner position was higher than that of the center position. Furthermore, Chelis [10] stated that for individual pile inside a group of piles the existence of the surrounding piles would have caused overlapping between the "bulbs of stress influence" surrounding each pile. The more bulbs of stress influence overlapped one another, the more reduction of pile capacity would be.

The knowledge about the difference in individual pile capacity within a group of piles may become important in designing the pile cap if the pile is loaded to almost its capacity. Each of the individual pile within the group must be assumed to behave differently. However, when the working load is limited by Safety Factor, SF, i.e. SF ≤ 2, so that the axial working load on the pile is less than half of the pile capacity, it is found that each of the individual piles will react almost exactly the same in their elastic stages. Therefore, the design of pile caps may follow the existing conventional methods, providing that at least SF = 2 is applied.

### 4.3 Group of Fully Friction Piles

When testing on a group of fully friction piles, one should give more attention to the failure mode when the load is approaching ultimate capacity. In this study, the failure of pile group occurred because certain individual piles had undergone more displacement than the other piles so that the pile group failure occurred due tilting of the loading frame sideway, rather than due to the acceleration of axial displacement when all piles had mobilized their ultimate resistances. It is apparent that in this study the pile cap used was not stiff enough as required, so that when uneven settlement occurred between piles the loading frame tended to follow each individual pile displacement. The settlement at one side of the loading frame tended to be larger than the other side. This condition may have caused uneven distribution of the load so that more rapid failure had occurred. It is recommended that future similar test on a group of piles use more rigid pile cap.

Fig.8 shows the load vs. deformation behavior of the pile group, which is known as the P-z curve, of full friction pile group in the field with a distance between pile 3x pile diameter (s = 3d), and the length of pile embedment is 11.5 m. It shows much larger ultimate capacity obtained from the 3x3 pile group than of the 2x2 pile group, and the amount is not merely 9/4 x the ultimate capacity of the 2x2 pile group, but slightly larger. Perhaps that is to be expected because of the variation of location between the two groups of the pile. However, at smaller load, the P-z curve of both pile groups are almost identical. From this figure, it may be concluded also that for Safety Factor = 3.0 the deformation is very small so that there should be no worry about deformation effect on the structure.

It had been mentioned [11] that there was very little difference in the design of pile foundation, when the design calculation was based on an assumed P-z curve of the pile group and when the design was based on the simple limitation of working load, in which Pworking ≤ Pallowable. Therefore, it is safe to assume that for full friction pile, one doesn't have to worry about pile settlement if the maximum working load on the pile is still less than 1/3 of the individual pile capacity. This statement still holds true also when the long-term settlement behavior of friction pile is included [2]. More detail explanation about this statement will be given in another paper.

From Fig.8, it is also shown that larger pile group will produce a higher loading capacity. However, in each group of the pile, in 2x2 as well as

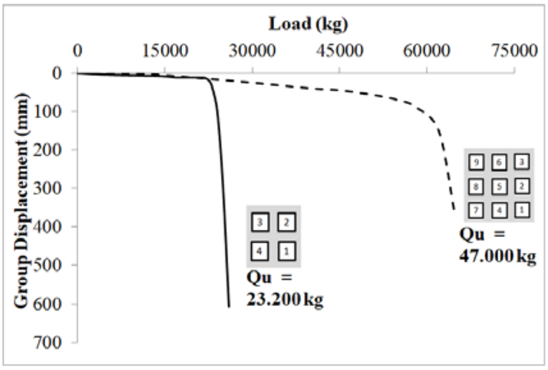


Fig.8. Load versus deformation behavior of pile groups, 2x2 and 3x3; s = 3d; L = 11.5 m.

in 3x3, group pile capacity is always lower than the multiplication of individual pile capacity times number of piles. Therefore, the axial pile group capacity can be assumed as the multiplication of individual pile capacity times the number of piles times a certain efficiency factor. From this study, the amount of efficiency factor for pile group was about 68% for the 2x2 pile group and was about 67% for the 3x3 pile group.

The efficiency factor from this study was found to be almost similar, even if the numbers of piles in the group were not the same. However, the result of this study was not in agreement with the research of Coduto [12], in which it was stated that for pile group of friction pile the efficiency factor could be considered as approaching 1.0 if the distances between piles were larger than 2.5xd (d = pile diameter). This meant the group efficiency factors were applicable only when the pile distances were < 2.5xd. Whereas in this particular study the pile distance is 3xd, and yet the group efficiency factors are still apparent.

Pile loading tests on the pile groups with the depth of pile embedment of 11.5 m and 17.5 m are given in Fig.9. This figure also shows that when the individual pile capacity of 11.5 m pile is 8.500 kg and the individual pile capacity of the 17.5 m pile is 15.850 kg, the efficiency factor for 2x2 pile group of 11.5 m depth is 58% and for 2x2 pile group of 17.5 m depth is 50.8%. This finding of smaller efficiency factor for longer piles is consistent with the assumption that overlapping occurs between the bulbs of stress influence around each pile. Longer piles should cause more overlapping between bulbs of stress influence surrounding the piles so that the reduction factor should be larger. This finding is very logical, but it is entirely new to the existing pile group efficiency formula, which postulates that the pile group efficiency factor depends only on the pile distances and the number of piles inside the group. The length of the pile is never involved, although the stress-influenced bulbs are clearly indicating this assumption. However, further studies are perhaps still needed to validate this finding.

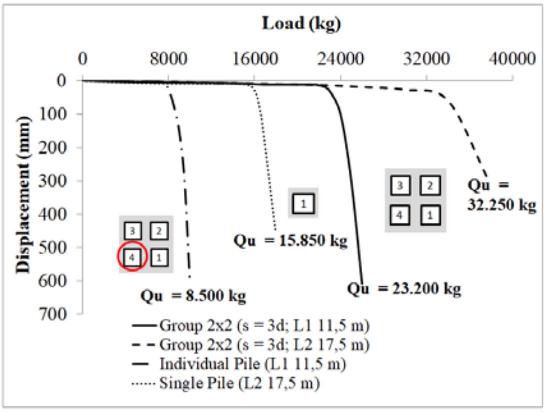


Fig.9. Ultimate capacities of a 2x2 group of piles with variation in pile lengths (L1 = 11.5 m, and L2 = 17.5 m)

From Fig. 9, one can understand that maximum pile deformation at ultimate load is larger for the longer pile. However, their P-z curves are almost identical and show relatively very small deformations during the lower loading.

Fig. 10 shows the P-z curves of two pile groups of 2x2 piles with a similar length of piles, L = 17,5 m, but with different spacing between piles, 3xd and 5xd spacing. The efficiency factor for 2x2 pile group of spacing between piles s = 3d is 50,9% and spacing 5d is 65,8%, correspondingly. As expected, the pile group with larger spacing between piles will yield slightly higher capacity, which is consistent with the pile group efficiency factor. Larger distances between piles will cause less overlapping between the bulbs of stress influence surrounding the piles, hence higher efficiency factor.

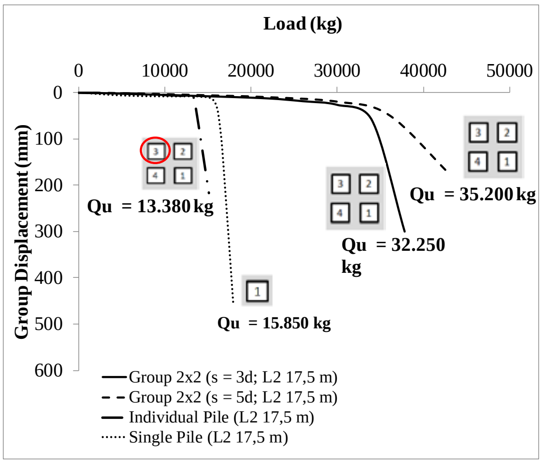


Fig.10 Ultimate capacities of 2x2 group of piles with variation in spacing between piles; s = 3d, and s = 5d (L = 17.5 m).

Before this study, there has never been any real field test conducted on a foundation of pile group. A field test was always performed on the single pile or on an individual pile within a group of piles. The loading capacity of a pile group was always assumed by means of empirical or analytical methods, from which the formulas for efficiency factors of pile group have been suggested. For comparison, the results of efficiency factors can be given in Table 1.

From Table 1, the pile group efficiency factors obtained from this study are much smaller than those given by many other formulas. This phenomenon is thought perhaps because of the soil condition tested in this study is entire of very soft soils, while the empirical formulas from other studies are derived based on a test on better soils of either stiffer clay or sandy soils. For example, the Converse-Labarre formula [5] was the results of testing on sandy soils and the formula of O’Neill [13] was the results of testing on loose sand. Whereas, calculations using the Block Failure Method for floating piles (= friction pile) on cohesive soil as suggested by several authors [14-15], the calculations yield smaller values of efficiency factors for pile spacing of 3d, but almost the same values of efficiency factor for pile spacing of 5d. This discrepancy may appear because the test on a group of piles is very limited. Further validation may still be needed by performing more field tests on pile groups to obtain the more conclusive results. Besides, the efficiency factors of a pile group in this study are also affected by the length of the pile, which was never investigated before. Apparently, the efficiency factor of a group of full-friction piles in soft soil tends to be closer to the formulas given by [14] and [15].

The loading tests on the pile groups of this study produce efficiency factors that are > 50%. This result may be used to conclude that using Safety

Factor ≥ 3.0 against the ultimate load of the individual pile is perhaps adequate to be used in designing pile group allowable capacity. However, since the displacement of a single pile, or of the individual pile in the group, in general, is smaller than the displacement of pile group, perhaps it may be wise to use the P-z curve of the real pile group test in designing the foundation of pile group, especially for the full friction piles. Yet, the real test on a group of full friction piles should not be produced from just short term loading only, because there will be creep settlement involve in it. The authors will discuss the P-z curve for pile group of full friction piles in another paper in a future publication.

## 5. CONCLUSION

The conclusion of this study can be summarized as follows:

a. For a group of full friction piles, the maximum allowable axial load on pile group should be determined using at least Safety factor = 3.0 from the individual pile maximum capacity to obtain a safe design without considering the pile long term settlement.

Tabel 1 Comparison of Pile Group Efficiency Factors from Many Sources

| Lengths, distances between piles, and group configurations | Pile Group Efficiency Factors | | | |
|---|---|---|---|---|
| | L = 11,5 m | | L = 17,5 m | |
| | s = 3x diameter | | s = 3x diameter | s = 5x diameter |
| | 2 x 2 | 3 x 3 | 2 x 2 | 2 x 2 |
| Converse-Labarre (Bolin, 1941) | 0,795 | 0,727 | 0,795 | 0,874 |
| Coduto (1994) | 1,000 | 1,000 | 1,000 | 1,000 |
| Kerisel (1967) | 0,650 | 0,650 | 0,650 | 0,850 |
| O'Neill (1983) | 0,900 | 0,700 | 0,900 | 0,600 |
| Castelli & Maugeri (2002) | 0,812 | 0,747 | 0,812 | 0,764 |
| Terzaghi & Peck (1948) | 0,551 | 0,490 | 0,472 | 0,756 |
| Tomlinson (1994) | 0,421 | 0,360 | 0,361 | 0,577 |
| This study (2018) | 0,682 | 0,672 | 0,509 | 0,658 |

b. Loading on a group of piles will become very critical when approaching the ultimate load capacity because failure occurs due to the differential settlement of each individual pile within the group. Each pile will have different load vs. deformation behavior, so that the loading frame may tilt or distorted, to cause uneven load distribution among the piles and to create accelerated failure. More rigid pile slab perhaps should be considered for a group of full friction pile to assure more uniform displacement.
c. The Efficiency Factors for full friction pile group depend on the pile spacing, a number of piles in the group, and the length of the pile insertion into the soil.
d. The Efficiency Factors of pile groups in this study range between 50% to 70%, which are closer to the formulas based on the Block Failure Method suggested by [14] and [15].
e. Pile group deformation is larger than individual pile deformation so that adequate safety factor should be used. The pile group deformation is larger in pile group with a higher number of piles.
f. It is temporarily assumed that minimum Safety Factor = 3.0 is adequate to be used for full friction pile; however, the use of P-z curve of pile group from real field pile group test should be used, when available, to compare the design results.

## 6. ACKNOWLEDGMENTS

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