Analysis of Geometry Effect on Laterally-loaded Large Diameter Bored Pile Deflection in Soft Soil

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Abstract. A bored pile is one of the foundation type widely used in construction because of its design flexibility. For a laterally-loaded bored pile, additional pile and pile cap play an important role in influencing the lateral capacity. Large diameter bored pile with a 3.5 m diameter then proposed to substitute group piles in order to simplify the construction method aiming the same capacity. This study examines laterally-loaded large diameter bored pile deflection on soft soil as parametric studies with different pile length of 7 m, 14 m, and 21 m. Thick soft soil layer interpreted through soil testing data at Ancol, North Jakarta with the domination of silt. A thorough analysis of this system is modelled using a three-dimensional numerical method, PLAXIS 3D Foundation using push-over analysis that the deflection of laterally-loaded foundation reaches its tolerable deflection according to Indonesian National Standardization (SNI).

1. Introduction

Lateral capacity of bored pile plays important role when it comes to deep foundation in soft soil. Soft soil with cohesive structure contained of soil particle bond which then quantified as shear strength. According to [1] cohesive soil has variation of shear strength based on the direction of principal stress, which then affect soil resistance. The differences in between using group pile and single pile is that the response of group pile affected by nonlinear interaction between pile-soil-pile [2]. Large diameter bored pile then proposed to substitute group pile in order to simplify construction method with the same lateral capacity. There are many studies related to large diameter bored pile under lateral load on cohesion-less soil which tend to gain soil resistance from its cohesion [3-6]. This study aims to examine laterally-loaded large diameter bored pile deflection on soft silt soil in order to comprehend its behavior since there are limited researches available for evaluating large diameter bored pile behavior on soft soil as one of the typical residual soil found in Jakarta.

2. Literature Review

Mono-pile with massive diameter typically used to resist bending moment, also relatively easier constructed [4] compared to group pile. Typical diameter used for offshore structure has slenderness ratio (L/D) at about 5-7 thus influencing pile behavior as rigid piles. Slenderness ratio of soil structure then affecting soil stiffness response for soil interaction with pile increased compared to flexible pile [5]. Laterally-loaded pile performance is predicted with two soil stiffness idealization, constant and linearly proportional to depth [7]. There are many models proposed to analytically predict this inconsistency and variation between models and existing data might be substantial [8]. Force system
for laterally-loaded bored pile is very complex and in three-dimensional space. These forces dominated by passive soil resistance. But, there are pile tip shear resistance, lateral flow, vertical side resistance, and axial resistance component at pile tip also influencing lateral behavior. At shallow depth, soil surrounding single pile might move vertically or laterally [9].

3. Research Methodology

This study conducted with numerical approach using PLAXIS 3D Foundation. Soil parameters selected from N-SPT interpreted through soil testing data at Ancol, North Jakarta and laboratory experiments of five soil sample for various depth taken from deep boring at site. Ground water level defined from field investigation at 1.4 m. Two points chosen at 540 m span with relatively planar elevation and one point located at midpoint. In numerical simulation, soil layers defined using three Borehole1 to simulate each location’s stratification. This study established soil stratification into 4 soil type; silt, silty clay, sandy silt, and sand tabulated in Table 1.

Table 1. Soil stratification.

| Soil Type   | Depth [m] | N-SPT |
|-------------|-----------|-------|
| Silt-1      | 0.00 – 2.20 | 9     |
| Sand        | 2.20 – 12.50 | 5     |
| Silty Clay  | 12.50 – 20.50 | 20    |
| Silt-2      | 20.50 – 28.00 | 60    |
| Sandy Silt  | 28.00 – 36.20 | 24    |
| Silt-3      | 36.20 – 40.50 | 60    |

This study using correlation from N-SPT to soil parameter calculated in PLAXIS such as cohesion, friction angle, stiffness, permeability, unit weight, and Poisson’s ratio. In general, soil differentiated to two constitutive models based on their analysis type. Drained materials are simulated with Mohr Coloumb model while undrained materials are simulated with Soft Soil Creep model. Silt-dominated soft soils are analyzed in undrained condition thus its stiffness parameters defined by Cc, Cs, and Ca. For Soft Soil Creep model, failure behavior is defined by cohesion and friction angle as Mohr Coloumb model does. Other than that, this study using laboratory experiment result on index and engineering properties to verify soil parameter correlation. Table 2 shows parameter used in PLAXIS for each soil type.

Table 2. Soil parameter.

| Soil Type    | Stiffness | Failure Behavior | Drained | E [kN/m²] | v | c [kN/m²] | φ [°] |
|--------------|-----------|------------------|---------|-----------|---|-----------|------|
| Sand         |           |                  |         | 55000     | 0.35 | 11        | 38   |
| Sandy Silt   |           |                  |         | 12000     | 0.27 | 10.5      | 32.53|
| Undrained    |           |                  |         |           |     |           |      |
| Silt-1       | 0.6       |                  | 0.02    | 0.036     | 2.93 | 8.25      |
| Silt-2       | 0.77      |                  | 0.07    | 0.046     | 15.21 | 26.32   |
| Silt-3       | 0.395     |                  | 0.038   | 0.023     | 39.24 | 31.33   |
| Silty Clay   | 0.39      |                  | 0.08    | 0.021     | 12.32 | 17.78   |

As for loading, lateral load applied in pile load test are modelled for validation of pile modelling. While on large diameter bored pile, lateral load applied on 1 m depth and increased until pile reach maximum allowed lateral deflection (push-over analysis). Pile interface is defined surrounding pile

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1 Borehole (in PLAXIS) is defined to determine soil thickness, soil type, and ground water level
model in PLAXIS to simulate interaction between soil and concrete by R-inter value. Calculation steps are divided in 4 phases; initial phase, piling, excavation, and loading.

3.1. Validation
Numerical modelling validated for both soil geometry and pile modelling. Soil geometry validated from its stratification in meshing step compared to actual soil stratification data. For pile modelling validation, pile lateral displacement compared to actual lateral displacement from lateral loading test data. Pile lateral displacement then assessed both for its magnitude and direction as Fig. 1 showed. Pile modelling validation confirmed with such a slight deviation due to modelling process in between model and actual lateral displacement tabulated in Table 3.

| Load Test | PLAXIS |
|-----------|--------|
| 5         | 50     | 2.44   |
| 7.5       | 75     | 4.34   |
| 10        | 100    | 10.54  |

Final Displacement Deviation 1.138%

4. Result and Discussion
Depth effect on bored pile slenderness ratio (L/D) is selected to be 2, 4 and 6 to understand the influence especially through pile deflection. For each pile length, taken 7 m, 14 m, and 21 m, pile lateral capacity at maximum deflection allowed by [10] increase in non-linear function. As Fig. 2 showed, it is known that pile behavior tends to increase head deflection as more load applied. Other than pile length, pile lateral capacity influenced by surrounding soil resistance. Non-linear lateral capacity increase then happens since 7 m-length pile sits on fill material (sand), 14m-length pile sits on silty clay, while 21 m-length pile sits on silt. From this model, it is known that the most increment lateral capacity reach at the 14 m-length piles with 55.26% incremental. Pile deflection significantly increases at 500 kN lateral load for each pile, then after 5 mm deflection each pile capacity differs with gap due to different pile length.
It is known that variation of pile geometry influencing pile deflection along the length. As for 7 m-length piles, deflection tends to be influenced by rigid behavior generating tip displacement for 1.54 mm. In contrary, 14 m and 21 m-length pile deflection at pile head and tip are shifting to different direction indicating influence of soft soil on its tip. This condition resulted into a higher probability of pile rotation since its deflection probably reach point of rotation. Since load-deflection behavior of surrounding soil around the pile is non-linear, response of the pile subjected to lateral load along pile depth is non-linear. Other than that, soil strength around the upper part of pile mobilized and generating load transfer to greater depth. This outcome then developing moment increase more rapidly than the load on the same depth. For soft soil dominated by silt, this model confirmed that thick fill material (6 m layer of sand) can influence the whole pile behavior as the 14 m-length pile sits on silty clay and underlying silt material but generating the most significant lateral capacity increment. The calculated value from numerical modelling agree well with previous behavior in which bored pile bending moment rapidly increase rather than applied lateral load.

Figure 3. Three-dimensional pile deflection at maximum load: (a) L = 7 m; (b) L = 14 m; (c) L = 21 m

To understand pile deflection response against lateral load, this study using three-dimensional model. From Fig. 3, the stiffness of pile is not sufficient to fix the pile head against rotation. Soft soil layer then generating large bending moment at pile tip on opposite direction. As seen above, 7 m-length piles deflect on the same direction while the rest can rotate at some point. This response explains the presence of lateral flow surrounding bored pile as one of the component of soil-pile lateral resistance.

Figure 4. Comparison of maximum moment increment for various pile length
As seen in Fig. 4, it is known for the same load (1000 kN, and 1500 kN) that 7 m-length large diameter bored pile generating the least maximum bending moment amongst all pile length. While 14 m and 21 m-length piles, influenced by its soft soil behavior, generating identical bending moment. Maximum moment occurred at shallow depth for all pile length. This behavior explains lateral load transfer to greater depth. 7-m length pile maximum bending moment occurs at half span (3.67 m), causing lateral tip displacement which then verify its very rigid behavior. 14 m and 21 m-length pile maximum bending moment occurs at one-third span, causing point of rotation of pile which then verify its rigid behavior also started to lessen, now influenced by bending.

5. Conclusion

Analysis of depth effect on laterally-loaded large diameter bored pile deflection is presented using three-dimensional numerical model (PLAXIS). The model is adjusted by comparison to lateral load test. Various pile length is analyzed to understand large diameter bored pile response on form of pile deflection and bending moment. The following conclusions can be drawn:

1. The effect on pile length gradually changing pile influencing behavior. As the pile lengthen, slenderness ratio increases, then large diameter bored pile will response with bending influence.
2. Non-linear behavior for pile capacity occurred since soil layer changes into soft soil at greater depth. The most significant pile capacity increment is achieved at 14 m-length pile.
3. It is known that due to rigid behavior, tip displacement occurred at 7 m-length pile. While for the rest pile length, tip deflection response occurred in opposite direction to pile head deflection. This notes that soil strength around the upper part of pile mobilized and generating load transfer to greater depth.

This study explains behavior of laterally-loaded large diameter bored pile on soft silty soil as it provides a simple representation of pile response in terms of deflection on various pile length. It is proposed to be a thorough analysis on other loading and resistance component in lateral soil-pile system such as the influence of tip shear and axial resistance.

Acknowledgement

The authors wish to gratefully acknowledge the financial support received through the Indexed International Publication Grant for Student Final Project (PITTA) No. PENG-1/UN2.R3.1/PPM.00/2019, which is funded by Universitas Indonesia.

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