Numerical Study Of Spun Pile To Pile Cap Connections In Soft Soil

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Abstract. Numerical study was conducted by SAP software to investigate behavior of two spun piles embedded in soft soil which were connected to pile cap based on Indonesia design code. Push over analysis were performed using SAP software with two different axial loads; 0.1 and 0.4 of $f_{c}$Ag and two different percentages of rebar on concrete infill. To ensure validity of numerical results, model validation was performed against experimental test conducted by other researcher. Horizontal spring was generated by LPILE software to represent soil. The results found that different axial force as 0.1 and 0.4 of $f_{c}$Ag affect the occurrence of moment crack of spun piles by 18% and 39%, respectively. Addition of rebar on concrete infill slightly improve moment crack of spun pile. Both parameters do not affect displacement ductility of pile which defines as ratio of maximum displacement to yield displacement.

1. Introduction
Earthquake is the process of releasing energy in the soil layer that is forwarded to the building. To survive, the building must be able to receive that energy. During large earthquakes, structural damages are allowed with the form of plastic hinges. The concept is known as performance-based design where dissipation of earthquake energy is achieved by forming the plastic hinges. The method has been well implemented on upper structure.

The results of investigation after earthquake in Japan showed that severe damages are also occurred on sub structure, i.e. foundation. The lesson learned is pile foundation should be designed as ductile member at seismic risk level. Several research has been conducted to investigate behavior of pile foundation due to seismic load [6–8, 11, 24, 26]. Based on those research, in the earliest 2010, performance based design has been adopted on sub structure as mentioned in [2,4,5] where yielding of the pile-to-deck connections is permitted. However detail application about the code are not fully understand yet. Until 2017, several research still has been conducting to get deeper understanding how to implement the code [9, 10, 12–14]. The study investigate strength and ductility of pile foundation and also connection detail between pile cap and pile. Connection between pile and pile cap is critical since there is a sudden change of area, stress, and stiffness from pile cap to pile and this part should be able to distribute gravity and earthquake loads from upper to bottom structure.

Based on research conducted, [5] indicates that fix connection between pile to pile-cap can be achieved by two ways which are embedded pile as $1.5-2D$ to pile cap or by providing extended strand or anchor. In Indonesia, the last type is preferred since it is simpler regarding arrangement.
of pile cap reinforcement. Moreover, spun pile is one of the most widely for bridges and wharf foundation due to economic reason in Indonesia. It is circular precast prestressed pile with hollow inside. Special attention should be taken since it has limited areas compared to other piles. To accomplish sufficient embedment length, reinforce concrete is filled into hollow with particular depth. Several studies has been conducted to investigate performance of the pile and its connection to pile cap. A recent experimental and numerical study was carried out by [12–14] based on common practice in China and South Korea.

Wang investigated 6-types of spun pile connections to pile cap in China through experimental test. Numerical study was conducted to study the effect of diameter, number and penetration depth of anchorage to pile cap and the effect of axial forces. It was found that all specimens were fail due to bending and each parameter had different effect to each specimens. [13] investigated behavior of strengthening spun pile to pile cap connections which was called as composite spun pile through a series of test. It was found that the initial rotational stiffness of pile-cap connection was affected by the length of pile-head inserted in footing and the location of longitudinal reinforcing bars. [14] conducted three test of spun pile connections, one was the common connection type in China, and two were strengthened with concrete next to pile cap and by filling steel profile into hollow. The strengthening improved bending capacity thus can avoid a premature fracture failure at the connection.

Research of seismic performance of spun pile in Indonesia has been carried out by [16,17,26]. Experimental study were conducted to investigate bending capacity, ductility and confinement of spun pile produced by one of famous company in Indonesia. It is found that 600mm diameter of spun pile was recommended to be used only in low to medium seismic zone in Indonesia due to low ductility. However, the study ignores connection with pile cap and external confinement provided by soil.

Numerical study was conducted to investigate behavior of two spun piles embedded in soft soil which were connected to pile cap based on Indonesia design code. Push over analysis were performed using SAP software with two different axial load; 0.1 and 0.4 of \( f_c A_g \). The behavior is presented as lateral forces vs lateral displacement curve, displacement ductility and flexural capacity. To ensure validity of the results, numerical model was confirmed by test conducted by [18].

2. Research Methodology

2.1. Validation Model

The study started with validation model to ensure that built model in SAP could represent the real structure. Experimental study conducted by [18] used as reference. The study was the
lateral load test on a spun pile concrete having an outer diameter of 800 mm, a thickness of 120 mm, and a length of 34 m as shown in Figure 2. It was reinforced with 9 mm in diameter of 38 steel wires. Non-linear stress-strain relationships were applied for concrete and steel material according to experimental data. Nominal compressive and tensile strength of pretension concrete was 78.48 MPa and 5.55 MPa, respectively whereas yield strength of steel wire was 1226.25 MPa. After the pile was driven into the ground, the spun pile was filled with concrete with the nominal compressive and tensile strength were 20.6 MPa and 2.84 MPa, respectively. The concrete was reinforced by steel of 22D8 with yield strength of 471 MPa. Pile was modelled as single frame element and connection between piles to pile-cap is modelled as fix restrain. Discrete fiber model in section designer of SAP was used to describe section properties of spun pile.

Figure 2: (a) Chen’s Spun Pile (b) Soil bor log

Figure 3: (a)Section designer (b) Soil bor log

To reduce computational work, plastic hinge was assigned at the maximum moment. SAP
provide three ways to define plastic hinge properties, which are auto hinge, user-hinge default and user hinge manual input. Auto-hinged menu determine moment-curvature based on strain limit refer to Table 10.8 [5] whereas user-hinge defaults calculate based on section designer input. Meanwhile, the hinge was defined as fiber hinge by locating coordinate of prestressed bar and additional bar through user-defined menu. Loss of prestressed was assumed as 25%. If stress ratio of ultimate stress to yield stress of prestressed stand is 0.9, hence ultimate stress is equal to 1362.5MPa. Therefore prestressed force before losses is approximate as 953.75MPa (0.7 × fpu × Aps).

The boring log of soil at test location is shown in Figure 2 (a). As can be seen, the soils are clay near the ground until 3m of depth, fine sand at ground level −3 to −7m and soft clays at −7 to −12m. Location of water is 1m below the ground surface. Soil was modelled as non-liner support link based on p-y curve obtained from LPILE software as presented in Figure 3 (b). The curves are determined based on average N-SPT value with red color in Figure 2 (b). There were 26 springs were located on average N-SPT value with red color in Figure 2 (b). There were 26 springs were located on geometric node shown in Figure 4.

Push over analysis was performed to represent step by step loading stage conducted in the experiment. Numerical analysis with SAP were carried out by three different ways in defining plastic hinges properties. Results were plotted together with the experimental results and presented in Figure 4. User-defined plastic hinge menu is more accurate reveal from its graph that close to experiment. User defined means that plastic hinge properties was determined based on fiber cross section by located thoroughly the ten prestressed bar coordinate. Hence, the software can accurately obtain moment-curvature so that post yielding behavior of the pile close to experiment. As shown in Figure 6 the graph obtained from SAP analysis is only slightly different from the experiment. It can be concluded that the numerical model is valid and can represent the real condition. Hereafter, user defined fiber plastic hinge menu is suggested to be used to define the plastic hinge in numerical study when using SAP software.

2.2. Numerical Study
The study aims to investigate behavior of two spun piles connected pile cap under lateral load. Push over analysis was conducted on group of pile consist of one, two and three piles. The pile length was 20m which consist of 8m and 12m. The 60mm-diameter with concrete strength as 52MPa, the most common pile used for bridge, was chosen. It has 10cm-thick and reinforced by 24D9 of PC bar and 4mm-diameter of spiral wire. The pitch is 50mm at pile end and 100mm at the middle. It was assumed that pile was surrounded by soft clay soil (su = 20kPa) and stand on massive rock. Figure 5 and Table 1 shows pile discrete along its depth. As shown, spun pile
Figure 5: Discrete of Spun Pile

As stated on clausal 12.9.1 of SNI-2487-2013, connection between spun pile to pile caps should be provided by embedment length LD as shown in Figure 5 which refer to equation 1. The length is a function of effective stress of PC bar \( f_{se} \), stress of PC bar at nominal flexural and stand diameter \( (db) \). Based on this equation, the minimum length should be 890mm and to simplify it was taken as 1 meter. Within this section, spun pile was filled by concrete with similar strength as pile cap, 35MPa. Rebar as 1\% and 4\% were varied as reinforcement. There is no prestressed force at this section as an effect of pile cutting. Other section had effective prestressed force as 53.48kN per strand. To represent the dead load from upper structure, vertical force was varied from 0.1 and 0.2 of pile capacity which equal to 160ton and 320ton respectively.

| Depth     | Length (m) | Pitch (mm) | Remarks                                           |
|-----------|------------|------------|---------------------------------------------------|
| SP600-B-L1 | 0.00 to -1.00 | 1          | 50       | With concrete in fill, prestressed force is assumed as zero |
| SP600-B-L2 | -1.00 to -6.20  | 5.2        | 100      | Middle part of upper pile, hollow section, prestressed force |
| SP600-B-L3 | -6.20 to -9.80  | 3.6        | 50       | Connection of two end pile @1.8m; hollow section prestressed force |
| SP600-B-L2 | -9.80 to -18.20 | 8.4        | 100      | Middle part of bottom pile, hollow section, prestressed force |
| SP600-B-L3 | -18.20 to -20.00 | 1.8        | 50       | End of bottom pile, hollow section, prestressed force |
Figure 6: Connection of spun pile to pile cap according to SNI 2843-2013

Figure 7: P-y Curve from LPile

Figure 8: Numerical model of Spun pile

\[ l_d = \left( \frac{f_{se}}{21} \right) l_d + \left( \frac{f_p s - f_{se}}{7} \right) d_b \]  

Figure 8 show numerical model of spun pile. As can be seen, it was modelled as beam column which stand on pin ended with non linier spring element to present soft soil. Spring properties
are based on p – y curve obtained from LPILE software as presented in Figure 7. Link element in SAP is used to model spring located at node according to pile meshing. Constitutive model of PC bar and shear wire were based on tensile test conducted by [26]. Meanwhile, reinforcement bar follow Meander stress-strain curve. According to Meander, concrete was divided by two conditions, unconfined and confined concrete. Concrete surrounded by spiral wire was considered as confine concrete. The study was conducted by varying axial load as zero, 0.1 and 0.2 pile capacity and percentage of steel reinforcement in concrete infill by 1% and 4%.

3. RESULTS

3.1. Moment – Curvature of Spun Pile
As described on Table 1, the 20m length consist of 2-piles, 8m and 12m length and hence three are different cross sections, L1, L2 and L3. Upper part with 1m length next to pile cap has reinforced concrete infill spun pile without prestressed force. The other part is hollow section with prestressed force. Figure 10 11 shows moment-curvature of two different cross section. As can be seen, moment of spun pile with concrete infill is 14.28% higher than those without concrete infill. Since curvature is the slope of the strain distribution line, reinforced concrete infill
increase compressive and tensile stress that lead to higher moment. Section L1 is spun pile with concrete infill (rebar 1%) and it is assumed has inactive prestressed bar due to cutting process. Hence prestressed bar is assumed just as a rebar. Moment curvature of section L1 shown in Figure 10 is similar to circular RC column. The pile is subjected to flexural actions and hence after spalling of concrete cover, moment of spun pile reduces. In this case, the maximum moment occurs just before the concrete cover spalls. Different moment curvature is found on prestressed spun pile as shown in figure b. The pile is under axial and flexural and therefore the curvature is defined from two values: the curvature that initiates crushing and spalling of unconfined concrete cover and the curvature that initiates flexural cracking moment. As shown in the figure, the maximum moment value reach just before crashing of concrete cover and then moment decrease considerably. After confinement takes effect, small amount of improvement of moment occur.

3.2. Effect of Axial Force and percentage of rebar on concrete infill
Distribution of bending moment along the spun pile 2xSP600LD1%Vo (1% of rebar in concrete-fill without axial load) is shown in Figure 12 when first and second plastic hinge form. As shown, the maximum moment occur next to pile cap and at 5 – 6m below ground level around one-third of pile length. Leading pile (pile 2) suffer higher moment than pile 1 and hence the first plastic hinge also occur at this pile at pile head next to pile cap and then it moves downward to the 5 – 6m below. It is found that flexural capacity of spun pile is 433, 44kNm. This value is similar slightly lower than break moment reported by spun pile manufacture which is 450kNm.

Figure 14 shows result of push over analysis of two embedded piles by varying axial forces (Vo, V1 and V2) and percentage of rebar in concrete infill (1% and 4%). The pile is surrounded by soft soil that presented as horizontal spring. The curves show that axial forces reduce capacity
Figure 12: Bending moment distribution along pile when first and second plastic hinge of 2xSP600 LD1% Vo occur

Figure 13: Bending moment distribution along pile when first plastic hinge occur
Figure 14: Comparison of push over curves

of spun pile, meanwhile percentage of rebar in concrete infill slightly improve pile capacity. Since push over analysis include non-linear geometric due to P-delta effect, therefore the presence of axial force as 0.1 to 0.2 lead to secondary moment that accelerate failure mode of the spun piles. Higher forces result smaller pile capacity.

Trend of curve without axial load is different from piles with axial forces. The curves are similar to moment-curvature presented in Figure 11. Behaviour of spun piles is affected by concrete, prestressed bar and mild steel reinforcement inside concrete infill. In this case, pile capacity reduces after concrete cover of spun pile crash and then increase significantly when ratio of mild steel rebar higher. Percentage of mild steel rebar affect pile capacity more when axial forces is higher. As can be seen on specimen with 0.2$F_c.A_g$ of axial forces (V2), 4% of rebar percentage result much higher force-displacement curve than those with 1% of reinforcement. Table 2 show summary of push over analysis results. Presence of axial force decrease moment crack by 18% and 39% on spun pile with reinforcement as 1% and 4%, respectively when it is compared to pile without axial force. Moment crack is defined as moment when first crack occur. Addition of rebar on concrete infill slightly improve Mcack of spun pile which implies on its push over curve presented on Figure 14. Both parameters do not affect displacement ductility of pile which defines as ratio of maximum displacement to yield displacement.

4. CONCLUSION

Numerical study of two spun piles connected to pile cap that embedded in soft soil has been done. Push over analysis has been carried out under gravity load as 0.1 and 0.4$F_c.A_g$. Percentage of reinforcement in concrete infill was varied as 1% and 4%. It is found that axial force decrease moment crack by 18% and 39% on spun pile with reinforcement as 1% and 4%, respectively when it is compared to pile without axial force. Addition of rebar on concrete infill slightly improve Mcack of spun pile. Both parameters do not affect displacement ductility of pile which defines as ratio of maximum displacement to yield displacement.

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Table 2: Summary of Push Over Results

| Percentage of Longitudinal rebar | Ductility | Moment Crack (kN.m) |
|---------------------------------|-----------|---------------------|
| 1%                              | 4%        | 1% 4% 235 273.52 243.48 |
| 4%                              | 2.315     | 2.315 273.52 243.48  |
| Spun Pile without Axial Force (V_o) | 2.174 - 166.48 197.17  | 2.323 - 86.27 78.84  |
| Spun Pile with Axial Force 0.1 * f'c' * Ag (V_1) | 2.174 - 166.48 197.17  | 2.323 - 86.27 78.84  |
| Spun Pile with Axial Force 0.2 * f'c' * Ag (V_2) | 2.174 - 166.48 197.17  | 2.323 - 86.27 78.84  |

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