Numerical study of low confinement spun pile to pile cap connection

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Abstract. The numerical study has been conducted to investigate the behaviour of spun pile – pile cap connection based on the common practice in Indonesia. The piles manufactured in Indonesia have low confinement where the amount of transverse reinforcement is less than 20% than the minimum requirement set by ACI 318-19. The research objectives are to study the parameters that affect the behaviour of that connection. Three parameters investigated are: the connection details, the effect of concrete infill and the amount of transverse reinforcement. The typical connection of spun pile and pile cap in Indonesia is considered adequate and can perform as fixed connection since slip at connection region was not detected in the FE analysis. The embedment length is adequate to develop yield strength of the prestressed wire. By filling the hollow with the concrete it increases the connection strength by 15% whereas the strength improves more than 50% by adding 6D19 reinforced bar. Adequate confinement improves the performance of the connection at peak post-stage that affects ductility.

1 Introduction

The spun pile is a circular hollow precast prestress pile which is commonly used for bridges and ports. The connection between spun pile to pile cap is a critical part since the change of area, stress, and stiffness occurs in this region suddenly. Rigid connection leads to maximum curvature at this section and hence, it should be designed to possess large ductility which is defined as the ability to undergo large deformation in the post elastic range without a significant reduction in strength. It should be able to transfer force induced by an earthquake from the upper and bottom structure and vice versa.

Study of spun pile connections has been conducted by several researchers [1] – [5]. References [1], [2] conducted experimental and numerical study of several connection types that commonly used in China. The study found that the ductility of the connection was in the range of 2.5 to 3.00. The study conducted by reference [4] tried to improve the strength and ductility of the connection. Bang [3] conducted experiment study at strengthening spun pile using the deformed bar (PHC-B) and more shear reinforcement. The study found better energy absorption and ductility with an average ductility was 4.15. A recent study of improved spun pile connection was conducted by Yang [5]. Four specimens with different improvement were tested until failure. Three layers of carbon fiber-reinforced polymer

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(CFRP) was added to one specimen, one by mixing the steel fiber and the last one by adding a deformed bar to the spun pile. The horizontal bearing capacity and energy dissipation performance have no significant improvement. In overall, the ductility of all specimens is below 3.00.

Study of the performance of pile to pile cap connection in Indonesia is less attracted since the design code of the foundation structure is still based on the conventional design concept. One of the concerns of the spun pile in Indonesia is the amount of transverse reinforcement which is below the minimum requirement according to [6]. Study about Indonesia’s spun pile has been performed by references[7]–[9] who conducted an experimental study. The displacement ductility of the pile were in the range of 3.50 – 4.00. Study conducted by Irawan [8] on a spun pile with a volumetric ratio of transverse reinforcement as 0.24% (the minimum requirement is 1.16%) found that the confinement was insufficient to resist the explosion of the pile’s concrete.

The spun pile is constructed with different spiral confinement, closer distance at the pile end to protect the pile during the driving process and larger distance in the middle. Sometimes, the pile should be cut at the middle part because of the pile depth does not coincide with the finished elevation of the cap and hence the confinement of the piles adjacent to connection is auxiliary insufficient. This research aimed to study the behaviour of spun pile connection based on the common practice in Indonesia by assuming that the pile was cut at the middle part. A preliminary FE study has been performed by using the ABAQUS software. Three parameters affected the connection behaviour were investigated. Prior the FE study, a validation model was performed.

2 Research methodology

2.1 Validation of the finite element model

The results of the experimental study performed by Wang [1] was used as a reference to validate the Finite Element (FE) model. This step is very important to ensure that the FE element model could imitate the actual structure. The experiment was conducted on six spun pile connections with varying connection details. Result of CT5 from Wang [1] was chosen since the detail is closed to spun pile-pile cap connection in Indonesia. The spun pile has an outer diameter of 500mm and a wall thickness of 94mm with a total length of 1.92m. The pile has 10 prestressed bar with 9mm of diameter and the prestressed force as 994MPa. The bar was confined by spiral stirrup of A5 with a pitch of 45mm. The spun pile was filled by concrete and 6 anchor bars with 18mm in diameter was embedded to the pile cap to connect the pile and the cap. The compressive strength of the spun pile and concrete infill was 82.1 and 62.8MPa, respectively. A constant vertical load as 500kN was applied with a cyclic horizontal load.

Figure 1a shows the FE model to represent the experiment conducted by Wang [1]. Predefined field menu was chosen to include the initial prestressed as 994MPa. An eight nodes solid element C3D8R was selected for the spun pile and two nodes truss element (T3D2) for prestressed steel and anchor bars. The bars and concrete were assumed as a perfect bond. Hard contact in normal direction and coulomb friction as 0.3 in tangential direction was selected to describe the connection between the spun pile and pile cap. The constitutive law of material was concrete damage plasticity provided by ABAQUS, meanwhile the steel bar was modelled as bilinear with strain hardening as 0.1. Monotonic push over analysis was performed and the results were presented in Figure 1b. As it can be seen, the initial stage of the FE model is very close to the experimental results until the specimen reaches the yield stage. Then, the FE analysis is slightly lower than the experiment during the post yielding
phase. The gap are found after the connection reaches the ultimate strength where the difference is less than 5%. It reveals that the FE is considered valid.

![Image: FE Model for validation](a) FE Model for validation  
![Image: Results of FE analysis](b) Results of FE analysis

Fig. 1. Validation model and the results.

2.2 Parametric study

As mentioned earlier, the research objective is to study the behaviour of spun pile to pile cap connection in term of strength and ductility. Strength is defined as the peak force which reveals from the force-displacement curve as a result of a push over analysis. Meanwhile, ductility in this study is defined as displacement ductility which is determined as a ratio of maximum displacement ($d_{max}$) to yield displacement ($dy$). Definition of yield and ultimate displacement refer to Park [10]. Yield displacement is defined as a secant stiffness at 75% of the ultimate lateral load. The maximum deformation is estimated based on the peak load-displacement relationship.

The study was performed on a typical spun pile produced in Indonesia. It has 450 mm diameter which was reinforced by 10 prestressed wire with a diameter of 7.1mm. The pile is confined by a spiral with a diameter of 4mm with a pitch of 100mm at the middle and 50mm at pile edge. The pile has a wall thickness of 80mm. The concrete compressive strength of spun pile was 52 MPa whereas the pile cap was 30 MPa. The pile is assumed as elevated pile where the connection was above the ground level and hence the soil effect is ignored. Similar to the validation step, the FE model was built by element C3D8R for concrete and T3D2 for steel. The spun pile – pile cap connection has a similar geometric with the experiment conducted by Wang [1]. The wire and concrete material were modelled as bilinear stress-strain curve with strain hardening and concrete damaged plasticity model. The properties of steel reinforcement are presented in Table 1.

| Table 1. Material Properties of the reinforcement. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Diameter (mm)                  | Prestressed wire | Stirrup of the | Reinforcement | Stirrup of the | Pile cap        |
|                                | 10@7.1           | pile (spiral)   | bar (Rebar)   | concrete infill| reinforcement   |
| $F_y$ (MPa)                    | 1275             | 440             | 440            | 240             | D19-150         |
| $F_u$ (MPa)                    | 1420             | 540             | 540            | 370             | 540             |
3 Results and discussions

3.1 The effect of embedment length

A typical connection of spun pile-pile cap in Indonesia is shown in Figure 2a. The spun pile is penetrated with a depth of about 100mm to the pile cap. When the depth of spun pile does not coincide with the ground level, hence the pile should be cut. The cutting process leads to loss of prestressing at the pile end and therefore the capacity of pile decrease since the yield stress of inactive strand cannot be developed. Hence, the wire should be embedded to the pile cap with particular length to develop the strength. Theoretically, the yield strength of the wire at this part is limited to yield strength of mild rebar. It needs at least 12 – 18 in. (305 – 457 mm) embedment length of the inactive strand to achieve that strength according to PCI standards [11]. Refer to the equations proposed by Salmon [12] the embedment length is about 38 inch or 965mm for straight embedment and 535mm for bent strand.

Since it is difficult to avoid damage of the wire during the cutting process, to fill lack of strength, mild rebar are added by filling concrete into the hollow with a depth of about 1000mm. Most of the time, the wires are not embedded, and it is replaced by the rebars as shown in Figure 2. For a parametric study, the whole spun pile was filled with concrete. The variation of the embedment length is one of the parameters investigated. The concrete infilled was reinforced by 6D19mm. The required embedment length of D19 according to SNI 2847-2019 is 337mm. The length is varied from 300mm, 400mm, 500mm and 700mm where 200mm is bend as shown in Figure 2c. Pitch of transverse reinforcement was varied, 50mm and 100mm. The results are shown in Figure 3.

![Figure 2](image_url)

(a) Typical pile to pile cap connection

(b) Embedment length with straight strand (EL_300 – 500)

(c) Embedment length with bend strand (EL_500+200)

**Fig. 2.** Different details of the connection.

As shown in Figure 3, the different embedment length does not have a significant effect on the behaviour of spun pile connection which reveals from force-displacement curve. The effect is slightly obvious when the pitch of the transverse reinforcement is closer, 50mm. In general, after the ultimate strength is achieved, the connection slowly losses its strength. The connection detail which is represented by the embedment length, affect the strength deduction. However, the difference is not significant. This is because the embedment length varied is above the minimum requirement, except 300mm which is a little bit lower than the
requirements. Therefore varying the length until 700mm (EL_500+200) and double embedment of the wire and rebar (EL_wire_500) do not affect the behaviour of the connection. Another explanation is maybe because of inactive prestressed wire at pile end did not considered in the FE model.

![Graph](image1.png)

Fig. 3. The effect of embedment length of 6D19 with a different pitch of transverse reinforcement.

Stress distribution of prestressed wire based on von-misses criteria are shown in Figure 4. As it can be seen, the wire bar can reach its yield strength for all connection types which is indicated that there is no slip between embedment rebar and the pile cap concrete. The embedment length is sufficient since the wire can develop its yield strength. Therefore, the strength of those connections is similar since all specimens have similar failure mode, yielding of the prestressed wire.

![Graph](image2.png)

Fig. 4. Stress distribution of the prestressed wire.

### 3.2 The effect of the concrete infill

To study the contribution of concrete infill and the rebar, three different spun piles are compared, hollow spun pile (SPH), spun pile with concrete (SPF) and spun pile with reinforced concrete (SPD). The study was conducted on two different confinement, pitch 50mm and 100mm. Compressive strength of the concrete infill is 30MPa which is similar to the pile cap. Prestressed wire was embedded to the pile cap with 500mm for SPH and SPD, whereas spun pile with reinforced concrete is connected to pile cap through 6D19 with 500mm of depth.
The results are shown in Figure 5. Compared to the hollow spun pile (SPH), the concrete infill improve the strength of the connection by 15%. Moreover, the improvement reaches 51-54% by adding 6D19. The effect of confinement is not significant at SPH and SPF. It affects the behaviour of the connection during the post peak stage. After connection reaches the maximum condition, the strength drops 9% when enough confinement is available and 13% for less confinement (pitch 100). The difference between pitch 100 and pitch 50 is about 7%. The summary of concrete infill effect is presented in Table 2 in term of strength and ductility. The ductility of all specimen is between 3.07 – 5.27.

![Fig. 5. The effect of concrete infill and longitudinal rebar.](image)

### Table 2. The summary of concrete infill effect to strength and ductility.

<table>
<thead>
<tr>
<th></th>
<th>Hollow spun pile</th>
<th>Spun Pile with concrete infill fc’(^{30})MPa</th>
<th>Spun Pile with reinforced concrete fc’(^{30}) + 6D19</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SPH pitch 50</td>
<td>SPH pitch 100</td>
<td>SPF30 pitch 50</td>
</tr>
<tr>
<td>Pu (kN)</td>
<td>126.35</td>
<td>125.99</td>
<td>144.71</td>
</tr>
<tr>
<td>Py (kN)</td>
<td>99.70</td>
<td>101.50</td>
<td>119.70</td>
</tr>
<tr>
<td>Ductility</td>
<td>5.27</td>
<td>4.54</td>
<td>3.47</td>
</tr>
<tr>
<td>Improvement (%)</td>
<td>-</td>
<td>-</td>
<td>15%</td>
</tr>
</tbody>
</table>

### 3.3 The effect of transverse reinforcements

Transverse reinforcement plays an important role particularly at the connection region to prevent shear failure and to ensure the forming of plastic hinge. It provides confinement to the concrete and prevents buckling of longitudinal rebar. Hence, the amount should meet the requirement. The guideline about the confinement of precast prestressed pile refers to ACI and PCI standards. However, the two standards have a different formulation. According to ACI 318-19 [6], the need for transverse reinforcement depends on the compressive strength of concrete, the yield strength of transverse reinforcement and the ratio of area between concrete core concrete and concrete cover. Meanwhile, PCI standard defines the need similarly but considering the axial load where higher axial load need more confinement to prevent buckling of the longitudinal bar.
The volumetric ratio of spiral transverse reinforcement is determined as a cross section ratio between the spiral rebar to the spun pile. Assuming the axial load as 0.2$f'c'Ag$, the minimum volumetric ratio of spun pile used in this research is 1.42% according to ACI standard [6] and 1.11% according to PCI standard [11]. However, the volumetric ratio provided is 0.27% at pile end (pitch 50mm) and 0.14% in the middle part (pitch is 100mm). The amount is less than the minimum requirement.

Three spun piles with different amount of confinement was compared to study its effect. Transverse reinforcement of the spun pile are d8-50; d4-50; d4-100, which are equal to volumetric ratio of 0.346%, 0.272% and 0.136%, respectively. Comparing with the minimum requirement set by ACI [6], the percentage is 24%, 19% and 10%. The effect is studied on two conditions, spun pile with concrete infill (SPF) and with reinforced concrete (SPD19). The concrete strength is 30MPa. The results are shown in Figure 6 and Table 3. As presented, there is no change of the behaviour when d4 and d8 were used as the transverse reinforcement for spun pile with reinforced bar. However, the effect is noticeable for spun pile with concrete infill (SPF). The use of d8 improves the strength and the behaviour of the connection to some extent. The curve seems more steady with a slightly declining after the maximum strength reached. The amount of reinforcement contributes to the declining strength. Adequate confinement increases the concrete strength then improve the post-peak behaviour. None of the spiral rebars were detected yield. The stress is between 233 – 255MPa which are less than its yield strength as 440MPa.

![Image](https://example.com/image.png)

**Fig. 6.** Load – displacement Curves of different transverse reinforcement.

**Table 3.** The Effect of Transverse Reinforcement to strength & Ductility.

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Spun pile with reinforced concrete 6D19 (SPD)</th>
<th>Spun Pile with concrete infill (SPF)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Pu$ (kN)</td>
<td>$Py$ (kN)</td>
</tr>
<tr>
<td>d8-50</td>
<td>194.298</td>
<td>148.231</td>
</tr>
<tr>
<td>d4-50</td>
<td>194.295</td>
<td>144.715</td>
</tr>
<tr>
<td>d4-100</td>
<td>190.517</td>
<td>144.496</td>
</tr>
<tr>
<td></td>
<td>Ductility</td>
<td></td>
</tr>
<tr>
<td>d8-50</td>
<td>3.67</td>
<td>3.51</td>
</tr>
<tr>
<td>d4-50</td>
<td>3.34</td>
<td>3.47</td>
</tr>
<tr>
<td>d4-100</td>
<td>3.07</td>
<td>3.40</td>
</tr>
</tbody>
</table>
4 Conclusions

The study on the behaviour of low confinement of spun pile to pile cap connections has been conducted through the FE analysis. Three parameters were investigated, which are the connection details, the effect of concrete infill and the effect of confinement. Spun pile to pile cap connection which is typically used in Indonesia can be considered as fix connection as long as the embedment length of the rebar or prestressed wire is adequate to develop the yield strength. Slip failure at the pile cap was not detected in this study. Yield failure of the prestressed wire were detected which it indicated that the embedment length was sufficient. By filling the hollow with the concrete, it increases the connection strength by 15% whereas the strength improves more than 50% by adding 6D19 longitudinal rebar. Different amount of rebar significantly affects the strength of the connection. The higher quantity of rebar, the larger the effect of concrete strength. The contribution of concrete strength is noticeably at post-peak phase. The effect of transverse reinforcement is noticeable for spun pile with concrete infill (SPF). More confinement provided by transverse reinforcement improves the strength and the behaviour of the connection to some extent. Adequate confinement increases the concrete strength then improve the post-peak behaviour.

The research is supported by Indonesia Ministry of Research and Universitas Indonesia through Applied Research, contract number NKB-2897/UN2.RST/HKP.05.00/2020.

References

6. American Concrete Institute (ACI 318-19), Building Code Requirements for Structural Concrete (2019)