The different effect of cyclic loading protocol on spun pile performance

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Abstract. Numerical study to investigate the effect of various loading protocol to seismic performance of spun pile connection has been performed using OpenSees. Six loading protocols adopted in FEMA P440 were applied to three specimens. The study started with validation of FE model, and the model can closely simulate the experiment conducted by another researcher. The loading was presented in the form of a drift ratio, a number of cycles, and the rate of loading. It is found that different types of loading protocols affect seismic performance in terms of stiffness and strength degradation. Among six loading protocols, TP-01, as adopted in ACI 437.1R-07, give moderate results. Significant stiffness degradation was observed on hollow spun pile compare to those with concrete infill. It is found that the presence of concrete infill improves the strength of the spun pile connection by 45%. Increase the strength of concrete infill slightly improve the performance of spun pile.

1. Introduction
Earthquake is the process of releasing energy in the soil layer that is forwarded to the building. The building will survive if it can absorb that energy to survive. To assess the seismic resistance of a structure, several analysis methods are available, and non-linear pushover analysis is one of them. The analysis employs monotonic or cyclic loading; however, cyclic loading is preferred since it results in several seismic performance indicators. Cyclic loading affects the structural seismic response due to fatigue [1]. The nature of the loading protocol affects the seismic indicators in terms of strength and stiffness degradation and also energy dissipation. It leads to various levels of pinching and strength-hardening behavior. Hence, different types of loading protocols have been developed to investigate its effect on seismic structural performance.

Several studies about the effect of loading protocol were carried out by Marder et al. [2], Maison et al. [3], and Uang et al. [4] with different kinds of structural components. Takemura et al. [5] investigated six identical reinforced concrete bridge piers loaded by several types of loading protocol. The different cyclic envelopes were detected, which was affected by the number of cycles, the amplitude of each cycle, and the loading sequence. Maison et al. [3] studied different backbone curves, according to ASCE 41-13 [6]. The ASCE requires an entirely reverse cyclic loading protocol with increasing displacement levels. The similar results were found that the different protocols affect structural performance. Even though ACI 2007 437.1R-07 [7] suggest only one loading protocol, however, it is necessary to include different loading protocols to get a comprehensive result of seismic performance.

As a part of the research of the seismic performance of spun pile connection in Indonesia, experimental and numerical study has been performed. The performance of spun pile – pile cap connection has been a matter of concern following the typical failure modes observed during the Japan earthquake, where most of the cases of damage are close to the top of the pile next to the pile cap. In Indonesia, spun piles are the most common piles used for medium-rise buildings, bridges, and port. However, none of the research has been conducted on connection performance. Recent research...
conducted by Irawan et al. [8] focused on bending capacity, ductility, and confinement effect of the spun pile. The research concluded that the piles could only be used in low to medium seismic zone due to limited displacement ductility. In overseas, several studies have been carried out to study the performance of a spun pile and its connection to the pile cap, such as Wang et al. [11], Zhaosheng et al. [8], and Bang et al. [14] based on the common practice in China and South Korea. A numerical study of the spun pile connection was performed using OpenSees [15], by varying cyclic loading protocol. Six loading protocol adopted in FEMA P440 [1] were assigned to three spun piles with a diameter of 450mm, and the wall thickness is 80mm. The connection between the spun pile and pile cap was assumed as rigid.

2. Research Methodology

2.1. Model validation
To ensure that the finite element model built to represent the actual structure, validation model was carried out based experimental and numerical study conducted by Wang et al. [12]. The experiment was carried out on a spun pile with an outer diameter of 500mm, a thickness of 94mm, and a length of 1.92m. It was reinforced by 9mm in diameter of 10 prestressed bar with an applied prestress of 994MPa. The bar was confined by spiral stirrup of A5@45mm. The spun pile was filled by concrete, and the connection region was reinforced by six anchor bars of 18mm in diameter and hoop stirrup as A6.5@100mm. The compressive strength of the spun pile and concrete infill was 82.1 and 62.8MPa, respectively. Figure 1 shows the specimen’s detail. Table 1 shows the material properties of the specimens. A constant vertical load as 500kN was applied with a cyclic horizontal load. The reverse cyclic lateral load was applied in terms of displacement control based on drift ratio, as shown in Figure 2. The loading continues until $8\Delta y$, which was equal to the displacement of 80mm until the specimens reached severely damaged.

![Figure 1](image1.png)

**Figure 1.** (a) Set-up of Wang’s Experiment (b) The spun pile (c) Loading Protocol [12]

The numerical model was conducted through 2 stages. Firstly, SAP2000 [16] was utilized to build fibre section through menu section designer since the software has better visualization, but it does not support cyclic loading. Secondly, for cyclic loading analysis, the results were exported to OpenSees Navigator through an s2k file. The pile was modelled as a single frame element, and the connection between pile to pile-cap was modelled as a fixed connection. To ensure that both models built by SAP2000 and OpenSees can represent the experiment, the validation was conducted twice. Monotonic push over analysis was carried out on SAP2000 whereas cyclic loading was performed on OpenSees.
Table 1. Wang’s material properties of steel [11]

| Reinforcement                | Diameter (mm) |  $f_y$ (MPa) |  $f_u$ (MPa) |  $E_s$ (MPa) |
|-----------------------------|---------------|--------------|--------------|--------------|
| Prestressed bar             | A9.0          | 1335         | 1484         | 2.06 × 10^5  |
| Stirrup of pile             | A5            | 514          | 605          | 2.06 × 10^5  |
| Anchor bar                  | B18           | 345          | 524          | 2.06 × 10^5  |
| The stirrup of the anchor bar| A6.5          | 363          | 494          | 2.06 × 10^5  |
| Reinforcement of cap        | B18           | 345          | 524          | 2.06 × 10^5  |

Figure 2(a) shows the finite element model employed on SAP2000. Concentrated plastic hinges were employed on several locations of the spun piles. The validation results are shown in Figure 3(a). As can be seen, the load-displacement curves obtained from SAP2000 have a good agreement with the experiment conducted by Wang. The difference is around 5.13%.

Figure 2. Finite element model: (a) SAP2000 with fixed connection; (b) OpenSees Navigator including strain penetration effect; and (c) OpenSees Navigator with fixed connection.

Figure 2(b) and 2(c) show a numerical model built by OpenSees. As shown, the connection between the spun pile and pile cap was modelled in two conditions, fixed restrain and semi-rigid with some degree of rotation by taking into account the strain penetration effect that occurs on connection region. It was modelled as a zero-length element through the BondSP01 material, according to the model proposed by Sritharan [17]. The Concrete01 was chosen for spun pile, and the Concrete02 was used for concrete infill. Stress and strain curve for both concrete was based on Mender’s theory. The Steel02, uniaxial material, was used to represent the prestressed and anchor bars. Initial stress was applied on Steel02 to describe the prestress on the spun pile.

Figure 3(b) shows a comparison of the hysteretic curve due to cyclic loading analysis obtained from OpenSees and Wang’s experimental results. The FE results show a good agreement with the experiments with 6.9% difference. As can be seen, the rigidity of the connection does not significantly affect the behaviour of the spun pile. The curve is slightly lower when strain penetration was considered in the analysis. According to ASCE 41-17 [6], the bond-slip of the pile to pile cap connection can be excluded in the FE model. Hence, on the next numerical study, the connection was assumed fixed against rotation and translation.
2.2. Numerical Study

As mentioned earlier, the study seeks the effect of different loading protocol on spun pile connection behaviour. Another objective is to find out the suitable loading protocol to be applied to the experimental study. Six loading protocols shown in Figure 5 were applied to three spun pile connections. The numerical model represented the experiment where the set-up was similar to Wang’s. A 1.92m length of 450mm-diameter of the spun pile with a wall thickness of 80mm was connected to pile cap. The pile was reinforced by 10@7.1mm PC bar which was confined by spiral wires of d4-100mm. The prestress force applied was 065MPa. Two spun pile were filled by different concrete strength, 35Mpa and 50Mpa strength of reinforced concrete and one was empty as shown in Figure 4. The details are presented in Table 2. Specimens are named according to its specification followed by loading protocol code. For example, SPH-LP1 means hollow spun pile loaded by loading protocol of LP1.

| No | Model | fc' (MPa) | Spun Pile Prestressed Bar | Stirrup | Concrete Infill Anchor Bar | Stirrup | Pile Cap fc' (MPa) |
|----|-------|-----------|---------------------------|---------|----------------------------|---------|-------------------|
| 1. | SPH   | 52        | 10D7.1                    | D4 – 100| -                          | -       | 30                |
| 2. | SP35D19 | 52       | 10D7.1                    | D4 – 100| 35                         | 6D19    | D8 – 75           |
| 3. | SP50D19 | 52       | 10D7.1                    | D4 – 100| 50                         | 6D19    | D8 – 75           |

Figure 3. Model validation results: (a) under monotonic loading with fixed connection; (b) under cyclic loading with different assumptions on its connection region.

Figure 4. Cross section of spun pile (a) hollow section (b) spun pile with concrete infill.

Table 2. List of spun pile specimens
Table 3. Material properties of steel

| Material                  | Diameter (mm) | $E_s$ (MPa) | $f_y$ (MPa) | $f_u$ (MPa) |
|---------------------------|---------------|-------------|-------------|-------------|
| Prestressed Bar           | D7.1          | $2 \times 10^5$ | 1275        | 1420        |
| Stirrup Pile              | D4            | $2 \times 10^5$ | 440         | 540         |
| Reinforcement Bar         | D19           | $2 \times 10^5$ | 440         | 540         |
| Stirrup Reinforcement Bar | D8            | $2 \times 10^5$ | 240         | 370         |

**Figure 5.** Loading protocol types

3. Result and discussion

The different types of loading protocols were applied on three spun pile connections. Push over analysis was performed, and the results are presented on base shear – displacement curves. To get an exact comparison, the hysteretic curves of cyclic loading are presented on its envelope, and it is shown in Figure 6. The effect of loading protocol is summarised in term of strength and stiffness degradation, as shown in Table 4. As can be seen, the envelope obtained from different loading protocol is affected by a number of cycles, the amplitude of each cycle and the loading sequence. The loading effects behaviour of the spun pile beyond its ultimate phase.

Strength degradation is determined based on the hysteretic response by plotting the peak strength of each cycle. The strength of SP35D19 drops earlier due to loading protocol TP-02, at a displacement of 25 mm, meanwhile the others occur at 40 mm. Moreover, strength degradation of SP50D19 was detected on displacement at 30mm due to TP-02 and TP-03 whereas LP 1 and TP-01 occur at 40 mm. It is
observed that LP1 and TP-01 have the closest results to monotonic loading. There is no strength degradation occur on SP50D19 due to LP2 because of strength-hardening behavior that detected until it reaches the third cycle, as shown in Figure 7(a). The opposite result is found on SP35D19 due to TP-04, which has 8 cycles where the maximum drift ratio is on the first cycle as can be seen in Figure 7(b). The protocol leads to massive strength degradation of 90% because the structure immediately achieves its optimal performance.

Figure 6. Comparison of cyclic envelopes of specimens subjected to five different loading protocol.

Table 4. Summary of strength and stiffness degradation due to different loading protocols.

| Specimens       | Strength Degradation (%) | Stiffness Degradation (%) | Specimens       | Strength Degradation (%) | Stiffness Degradation (%) |
|-----------------|--------------------------|---------------------------|-----------------|--------------------------|---------------------------|
| SPH-LP1         | 21.6                     | 90.7                      | SP35D19-TP2     | 17.0                     | 94.7                      |
| SPH-TP1         | 25.5                     | 91.1                      | SP35D19-TP3     | 17.3                     | 92.6                      |
| SPH-TP2         | 22.8                     | 96.8                      | SP35D19-TP4     | 90.0                     | 101.8                     |
| SPH-TP3         | 23.5                     | 95.1                      | SP50D19-LP1     | 15.3                     | 87.1                      |
| SP35D19-LP1     | 15.9                     | 86.9                      | SP50D19-TP1     | 14.9                     | 87.8                      |
| SP35D19-TP2     | 0.0                      | 85.1                      | SP50D19-TP2     | 17.6                     | 94.7                      |
| SP35D19-TP1     | 14.9                     | 87.6                      | SP50D19-TP3     | 17.3                     | 92.6                      |

Reinforced concrete structure experience stiffness degradation as a result of cracking, loss of bond, or interaction with high shear or axial stresses [1]. It can be calculated based on secant stiffness at each cycle of the hysteretic curve. Since TP-02 has 32 cycles, hence it leads to a massive reduction in stiffness. Whereas, the smallest stiffness degradation occurs on LP1 that consist of only 8 cycles. Thus, more cycles result in larger stiffness degradation.
Pinching behavior is characterized by a large reduction in stiffness during reloading after unloading, along with stiffness recovery when the displacement is imposed in the opposite direction. It can be seen from the hysteresis curve of three specimens subjected to loading protocol TP-01, as shown in Figure 8. It shows that more significant stiffness degradation resulted in more severe pinching behavior. Hollow spun pile (SPH) loss its stiffness and strength larger than spun pile with concrete infill. Reinforced concrete inside the spun pile improves the strength by 45% from 102.4kN to 149.4kN. Different concrete infill, 35Mpa and 50Mpa, only slightly affect the strength of the connection.

4. Conclusions
The study of loading protocol selection to the behaviour of spun pile connection has been conducted by utilizing the OpenSees. Validation model was performed to ensure a reliable FE model. The models built by SAP2000 and OpenSees Navigator have close behaviour to the experiment conducted by Wang.
Considering the strain penetration effect that occurs at the connection region is slightly reduced the structural performance compared to a rigid connection. Since the difference is only about 6.9% and hence, fixed restrain was used for the numerical study.

The study found that cyclic loading leads to structural fatigue and therefore, the structural strength is smaller than monotonic loading. Six different types of loading protocols affect structural performance in terms of strength and stiffness degradation. The effect is obvious beyond its ultimate phase. The smallest stiffness degradation occurs on SPH followed by SP35D19 and SP50D19 due to loading protocol LP1, which only has 8 cycles. The percentage is 90.7%, 86.9%, and 87.1% for SPH, SP35D19 and SP50D19, respectively. Thus, the loading protocol with a fewer number of cycles resulted in smaller stiffness degradation. The smallest strength degradation as 14.9% occurs on the SP35D19 and SP50D19 model due to loading protocol TP-01. The protocol LP1 results in the smallest strength degradation as 21.6% on SPH. Among the six-loading protocol, TP-01 results in moderate degradation and therefore, it is adopted by ACI 2007 437.1R-07 as loading protocol to be applied in assessing seismic performance.

Pinching behavior is detected on the hysteretic curve of SPH, hollow spun pile, which indicates a large reduction in stiffness compared to spun pile with concrete infill. Reinforced concrete with 6D19 rebar, which is inside the spun pile improve the strength by 45% from 102.4kN to 149.4kN. Different concrete infill, 35Mpa and 50Mpa, only slightly affect the strength of the connection.

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