NUMERICAL ANALYSIS OF PILE-TO-PILE CAP CONNECTION OF PRECAST PILE AND CAST-IN-PLACE PILE

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ABSTRACT

The pile transfers the loads from the superstructure to deeper and more competent soil layers. It ensures the stability of the structure, making it one of the crucial parts of the foundation of numerous civil engineering structures. The pile cap is typically a reinforced concrete slab that sits on the top of the pile or a group of piles to transfer the vertical loads, moments, and lateral forces from the superstructure to the piles. In practice, the connection between the pile and pile cap offers various options, encompassing differences in embedment lengths, reinforcement detail, and other design variations. This study investigates the pile cap connection of precast pile and cast-in-place pile for different connection details: fixed connection (cast-in-place pile) and hinged connection (precast pile) analytically. The structural performance of both precast and cast-in-place piles heavily depends on an effective pile-to-pile cap connection. At the same time, there have been many studies on the structural behavior and performance of pile-to-pile cap connections. Research specifically focused on the connection details between cast-in-place piles and cast-in-place pile caps is limited. This paper aims to analyze the structural performance of the cast-in-place pile-to-pile cap connection under various static loading conditions using numerical simulation with ABAQUS. Additionally, a comparison is made between the pile-to-pile cap connections of precast piles and cast-in-place piles in terms of their response to vertical loading conditions, failure modes, and overall performance. This study finds significant differences in the load-bearing capacity of each model connection type due to differences in embedment length for precast piles and reinforcement detailing in cast-in-place piles. Moreover, the investigation includes the consideration of the variation in the length of embedment in the precast piles. Furthermore, the influence of different parameters on the behavior of connections is assessed through finite element model analysis.

Keywords: *Cast in place pile, precast pile, pile cap, pile to pile cap connection, FEM.*

1. INTRODUCTION

Pile foundations support heavy loads by using a pile cap, to transfer vertical loads, moments, and lateral forces from the structure to the piles. This ensures even load distribution, preventing structural issues and differential settlement. The pile-to-pile cap connection is a crucial component that influences the foundation system's overall structural performance and behavior. Several methods are used to design the pile-to-pile cap connection in structural design, analysis, and construction. Fixed and hinged connections are two of the most common types among them. These connection types determine the degree of rotational constraints and freedom between the pile and pile cap, impacting the foundation's response to external loads and ensuring stability.

A fixed connection prevents any rotational movement, ensuring a rigid connection between the pile and the pile cap. This type of connection is usually used when the cast-in-place pile is connected to the cast-in-place pile cap to resist the vertical and lateral loads. Especially when lateral loads are applied, a fixed pile-to-pile cap connection is often desired to control deflection (Richards et al., 2011). Studies on prestressed concrete piles (Sheppard, 1983) and steel pipe piles (Silva & Seible, 2001) have represented that reinforcement extended into the pile cap creates a fixed pile-to-pile cap connection. However, the embedment length of the piles can substantially influence the structural behavior of the pile cap. As for the precast pile, the hinged connection allows relative rotation between the precast pile and pile cap while still providing the necessary load-bearing capacity and stability. Harries and Petrou have shown in a study where two precast piles were tested without any reinforcement at the connection with a plain embedment of 0.46m (Harries & Petrou, 2001). This research confirmed that utilizing plain embedment alone sufficed for transferring moments surpassing the flexural capacity of the piles. Harries & Petrou also recommended that the concrete cover of the pile cap should not be considered part of the embedment length. This investigation also concluded that designing plain embedment of a precast, prestressed pile into a cast-in-place pile cap is sufficient for achieving the necessary pile capacity. Upon examining various pile embedment lengths, Harries and Petrou proposed that the width of the pile could be considered as the required embedment length for achieving the flexural capacity of the pile. Finally, this study recommends a minimum absolute embedment length of 12 inches (305mm) (Harries & Petrou, 2001).

In summary, the variations in the connection details between concrete pile-to-pile cap connections lead to different degrees of restraint against the rotation as well as the capacity of the connection. This paper, in particular, emphasizes two connection types for precast piles and cast-in-place piles with cast-in-place pile caps. Furthermore, this study elucidates the performance difference of precast piles for varying depths of plain embedment. Moreover, this paper summarizes the numerical analysis results of the other pile-to-pile cap connections under a variety of loading conditions. In addition, this investigation undertakes a comparative analysis of the numerical simulation test results between the two numerical models of the pile-to-pile cap connection designed and analyzed in ABAQUS.

Table 1: Key findings from relevant research

Study	Methods	Factors contributing to the pile-to-pile cap connection
Harries & Petrou, 2001	An experimental program is executed with two prestressed concrete pile models to illustrate that the plain embedment (without any treatment) of the pile into the pile cap is sufficient to generate the required strength for resisting the load.	• Connection through plain embedment is adequate for transferring moments exceeding the flexural capacity of the piles. • The necessary plain embedment length must be equivalent to the width of the pile, given that this paper focuses on square piles. • The minimum required embedment length should be 12 inches (305 mm).
Richards et al.,	An experimental program is undertaken involving	• Embedding the pile into the pile cap proves more cost-effective than a fixed connection for

2011	four different steel pipe pile models, each featuring varied pile embedment lengths, reinforcement details, and concrete fill within the pile.	moment resistance and fixity. • A minimal embedment length is adequate for generating flexural capacity. • Longer embedment length might be a reliable alternative for replacing shear reinforcing in the pile cap. • In soft soil conditions, fixed connection is preferred when the pile is subjected to lateral loads to prevent deflection. • A fixed connection with extended bars can establish a rigid connection, while a connection relying solely on plain embedment may exhibit comparable performance.
Guo et al., 2017	A comprehensive analytical and experimental investigation is conducted on a full-scale prestressed concrete pile, encompassing three distinct types of connections.	• The pile and pile cap connection point experiences maximum shear forces and bending moments. • The rotational restraint is 0.7 times that of typical connection practices for stationary axial loadings in the case of plain embedment connection. Consequently, the hinged connection proves more effective in minimizing the bending moment at the pile head. • Flexure is identified as the cause of failure for all specimens. • The pile embedment length into the cap notably influences the strength and stiffness of the connection. • An optimal embedment length of 12 inches (300 mm) is recommended.
Xiao, 2003	An experimental program is initiated to assess the moment capacity of four square prestressed concrete piles, despite their shallow embedment.	• Connection with shallow embedment can exhibit considerable resistance to bending moment. • This connection type exhibits sufficient strength to endure both compressive and tensile stresses, as indicated by the cyclic axial loading test. • It is recommended to utilize the yield capacity of the dowel bars as the tensile capacity for the piles.
Xiao et al., 2006	The seismic performance of the steel pile-to-cap connection was experimentally analyzed under cyclic horizontal and vertical loading to measure the tensile, compressive, and moment capacity.	• A shallow embedment of a steel H-shaped pile can establish a pinned connection. • Despite featuring a pinned support condition, the connection is capable of withstanding a significant amount of bending moment. • This capacity of resisting moment might not be desirable at all conditions. Some other forms of failure modes may dominate at the connection point unexpectedly.
M. Teguh et al., 2005	A numerical analysis is conducted to examine the nonlinear behavior of various connection types between prestressed concrete piles and pile caps under seismic loads.	• Between plain embedment and headed embedment, the latter demonstrates better performance in improving seismic performance. • The paper recommends an embedment length ranging from 1.2 to 1.5 times the pile diameter or width to reduce stress development at the connection point and minimize crack formation.
Joen &	A comparative study is	• Of all the connection types, the most preferred is

Park, 1990	undertaken to assess the performance of various connection types under seismic loading.	plain embedment with a roughened pile top. • The second most favored connection is the fixed connection. • The connection designed with dowel bars and epoxy resins has resulted in the formation of wide cracks during failure.
Yang et al., 2020	An experimental and numerical analysis of various connection types subjected to low cycle loading is conducted. The nonlinear behavior of the connection point is evaluated by comparing both numerical and experimental results.	• Damage is caused due to bending while crushing the pile cap at the connection point. • Before failure, a hinge joint is formed between the pile and the pile cap. • Low cycle loading developed an ability to rotate before failure. • This paper recommends considering the formation of resistance to damage due to too little rotation of the pile.
T. Wang et al., 2014	Both experimental and numerical analyses are conducted, considering six different connections from pile to cap.	• Failure is caused by bending in all six specimens. • The rotation capacity varies at the connection point for different types of connections. • To analyze the load vs deformation relationship, numerical analysis through finite element models can be a reliable option. • The influencing factors for stiffness and strength (such as diameter and number of anchored bars, axial load, and embedment length) differ among the various specimens.
M. Teguh et al., 2006	Addresses the current approaches to designing the connection, points out potential alternative methods for the design, and delves into prospective research avenues.	• Plain embedment allows less congestion of reinforcement bars while offering comparable strength. • This paper also suggests a longer embedment length to ensure a more rigid connection. • Highlights the advantages of a fixed connection over a hinged connection.

Several researches have been conducted on the connection design and analysis. Most of them are based on experimental analysis and numerical simulation of similar models to verify the experimental results and measure the nonlinear behavior of the connection. However, studies related to fixed connections with reinforcement bars extended into the pile cap are quite limited. Table 1 represents the key findings of some of the related papers including their suggestions and recommendations. The design recommendations are considered while designing and modifying the numerical models designed in ABAQUS.

2. METHODOLOGY

There are two fundamental approaches in foundation engineering: the structural approach and the geotechnical approach to analyze the structure's performance. The structural approach mainly considers structural parameters like material properties, connection types, boundary conditions, loading system, development of stress, and moment and failure criteria. In the geotechnical approach, the soil parameters, settlement, and foundation system are the focus of analysis. For this analysis, no soil was considered. Instead, this study is based on the structural performance of different connection types.

2.1 Finite Element Method

Two types of materials (i.e. concrete, and steel) are used to design the pile-to-pile cap connection model for the simulation. A pile of 15000mm in length and 450mm in diameter was used for all the models. The clear cover for the pile and pile cap was kept at 50mm for all the models. As for the pile cap, the dimension was 1050mm x 1050mm x 1050mm. 12 #7 bars were added to the pile as main reinforcement. A circular hole was extruded into the pile cap to embed the pile into it. The depth of the extrusion varied in different models. For all the fixed connections in the cast-in-place pile, the depth of extrusion was limited to 150mm. For the precast model, the depth of extrusion depended on the embedment length of the pile. SI (mm) unit was used throughout the simulation in ABAQUS for this analysis.

The material properties were generated using two different MATLAB programs (i.e. ABAQUS CDP Generator, and ABAQUS Steel Generator) to define the concrete and steel. To determine the appropriate structural elements, solid and truss elements were chosen for concrete and steel respectively. A solid continuum 3D hexahedral element of first-order reduced integration (C3D8R) was chosen for the concrete pile, and a continuum 3D tetrahedral quadratic solid element (C3D10) was chosen for the concrete pile cap. For the pile reinforcement, a 2-node line-shaped linear 3D truss element (T3D2) was chosen.

2.1.1 Material Properties

To generate the necessary material properties for concrete and steel in the ABAQUS simulation, certain basic parameters were taken into account. Table 2 refers to some of the fundamental properties that were used both in ABAQUS CDP Generator and ABAQUS CAE software to define concrete and its plasticity, compression behavior, and tensile behavior. Table 3 indicates the steel properties used in the simulation to generate the steel's plastic and elastic behavior in the simulation.

Table 2: Concrete properties

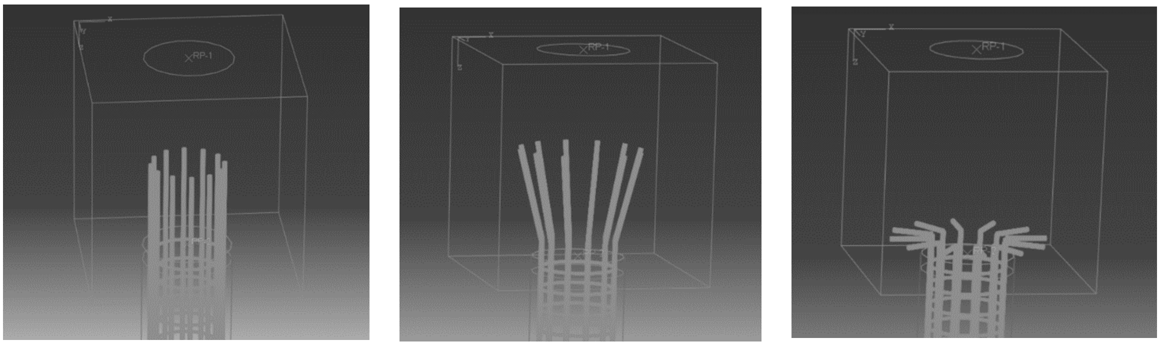
Properties	Value
Mass Density	2.30E-09 tonne/mm3
Young's Modulus	18888.88 MPa
Poisson's Ratio	0.18
Yield Stress	35MPa (5000 psi)
Dilation Angle	35˚
Eccentricity	0.1

Table 3: Steel properties

Property	Value
Mass Density	7.85E-09 tonne/mm3
Yield Stress	210000 MPa
Young's Modulus	0.3
Poisson's Ratio	740MPa

2.3 Model Introduction

In this study, different models were used to compare the structural performance of the fixed connections. Figure 1 indicates the differences between the fixed connections. The pile main bars were extended straight into the pile cap in the fixed connection model 1. In the second model, the pile bars were extended 105˚ inclined into the pile cap to create a fixed connection between the pile and pile cap. For the third model, the pile bars were bent 90˚ to build the connection between the pile and pile cap.



(a) Fixed connection model 1 (pile bar extended straight into the pile cap)

(b) Fixed connection model 2 (pile bar extended 105˚ inclined into the pile cap)

(c) Fixed connection model 3 (pile bar extended 90˚ bent into the pile cap)

Figure 1: Different types of fixed connections

Figure 2 shows the model used to simulate the structural performance with a hinged connection. In this model, the pile is connected to the pile cap with plain embedment without any extended reinforcement from the pile. To simulate the structural performance of the hinged connection, three different models were used with different embedment lengths (i.e. 6 inches, 12 inches, and 18 inches).

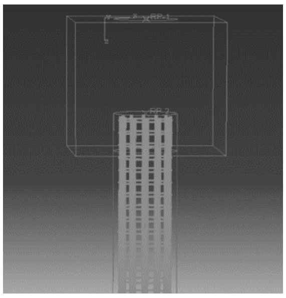


Figure 2: Hinged connection with plain embedment

2.3 Loading and Constraints

This study assumed that the pile and the pile cap had a perfect bond condition. So, the longitudinal slip between the pile and pile cap surface was neglected in this FEA analysis. To establish a solid connection between the pile and the pile cap, surface-to-surface contact was defined between the pile surface and the embedment surface of the pile cap. To define the contact, friction formulation was considered a penalty with a friction coefficient of 0.3 in the tangential direction. Moreover, the contact behavior in the normal direction was defined with hard contact. The Coulomb friction in the tangential direction was used to ensure the pile and pile cap's shear force transfer (X. Wang, 2021). As constraints, tie and embedded region defined the connection between the pile and pile cap. The tie was used to define the connection between the pile's concrete surface to the pile cap's concrete surface. Furthermore, the embedded region was defined to establish the connection between pile and pile caps reinforcement.

In this test, a vertical load is applied on the top of the pile cap to run the simulation and determine the structure's load-bearing capacity. However, no particular magnitude of load was defined. Instead, the pile and pile cap were allowed to translate 30mm in all three directions. The software simulation determined the load required to translate the pile cap to that restricted extent. For a few models, the value of these allowable translations was increased to simulate the extent of their capacity to withstand load. As assumed, the hinged connection with 12inch and 18inch embedment might be able to with much higher load; the allowable translation for these two models was defined as 50mm and 60mm, respectively (X. Wang, 2021). However, the bottom of the pile is fixed and any kind of translation and rotational displacement is restricted.

2.4 Validation of Model

In 2021, Wang conducted a study named 'Research on the vertical bearing capacity of pile foundation under wave scouring.' This study investigated the influence of the wave scouring on the vertical bearing capacity of the pile. For this analysis, the researcher used the finite element software ABAQUS to simulate the load-settlement of the pile, considering the wave-scouring action. A static load of 4000KN was applied on the top of the pile. After simulation, the results were compared to a field test result to verify the model's correction. (X. Wang, 2021)

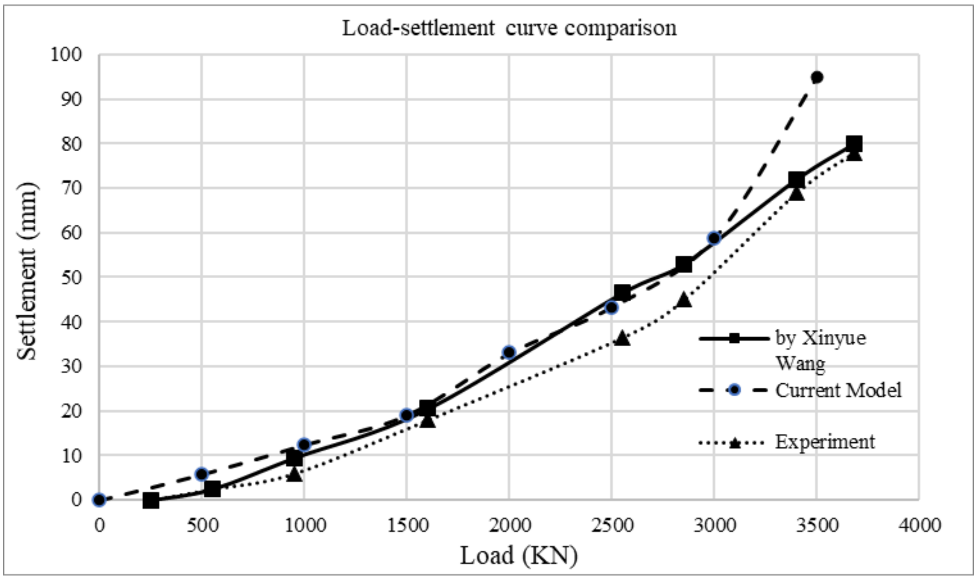


Figure 3; Comparison of the load settlement curve between the field experiment, simulation by (X. Wang, 2021), and current model

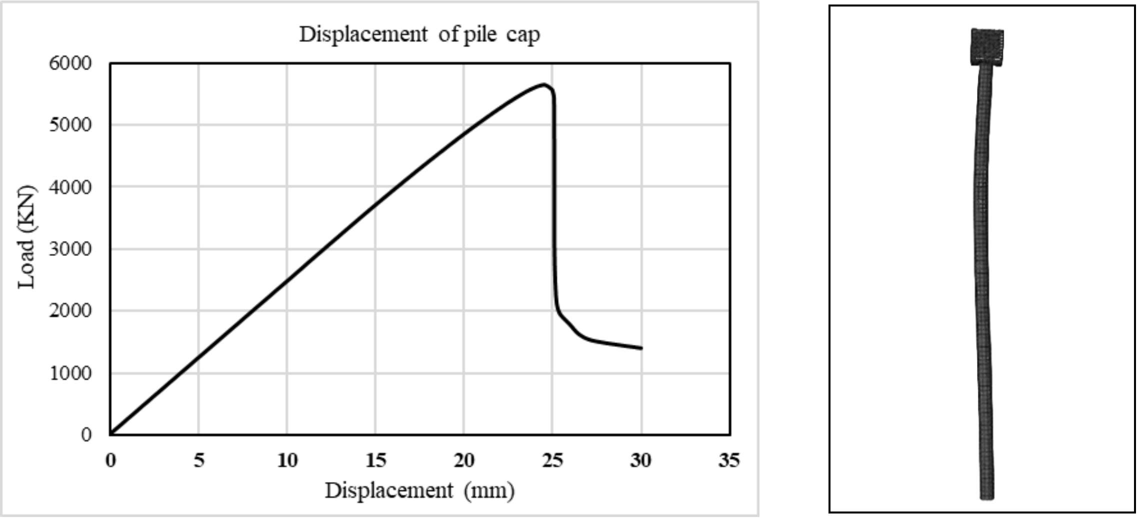
Figure 3 conveys the comparison of the load settlement curve between the field experiment, the simulation by Wang, and the current model done for this particular study. Between these two simulations, there are some fundamental differences. For example, the numerical model by (X. Wang, 2021) does not specify the type of loading used for the simulation. Also, the data related to load and settlement are not precise. So, only the soil properties and maximum loading were considered for the verification process. The simulation results do not match precisely. But they are close, which indicates the correctness of the current models. Since all six models are designed similarly, only one pile and pile cap model simulation was considered adequate.

3 RESULTS & DISCUSSION

The effect of material properties, boundary conditions, constraints, loading, and the differences in the connection details are explored between different fixed and hinged connection models, and hence the analysis is compared.

3.1 Fixed Connection

Figure 4(a) elucidates the load settlement curve of the fixed connection with pile bars extended straight. The load-bearing capacity of the fixed connection with the pile main bar extended straight into the pile cap is 5695KN. The displacement due to this load reaches up to 24.9mm. At this particular load, the pile-to-pile cap connection fails. After this point, the pile body starts to withstand the load, and buckling of the pile starts to occur. Figure 4(b) shows the buckling of the pile due to the failure of the pile-to-pile cap connection. About 1600KN to 1400KN was adequate to cause the rest of the displacement.

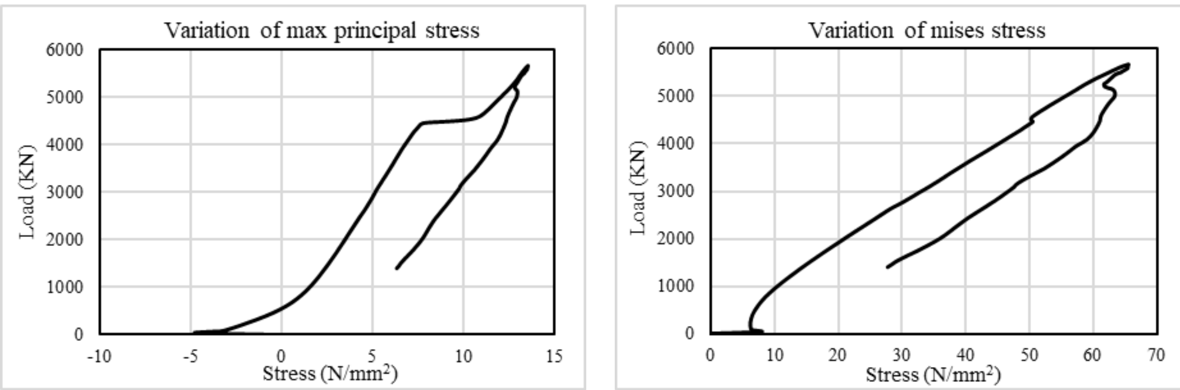


(a) Load displacement curve of fixed connection with pile bars extended straight

(b) Buckling of pile due to failure of pile-to-pile cap connection

Figure 4: Load displacement curve of fixed connection with the straight bar extended into the pile cap

Figure 5(a) shows the development of the max. principal stress at the connection point. Initially, a negative stress of 4.65N/mm^2 was generated right after applying the load of 39KN. As the load increased, the stress started to transform from negative to positive stress. The developed stress at the connection point started to increase as the connection point was withstanding most of the force and transferring it to the rest of the structure. Once the load exceeds the connection point's bearing capacity, the stress increment stops at the pile-to-pile cap connection. While the pile body resists the rest of the load after the failure of the connection, the stress at the connection point also decreases. Here, the maximum stress reaches up to 13.56N/mm^2 with the applied load of 5655KN.



(a) Variation of max principal stress with respect to load

(b) Variation of mises stress with respect tocogg load

Figure 5: Development of stress at the fixed pile-to-pile cap connection point

Figure 5(b) represents the variation of von Mises stress with respect to load at the connection point of the pile and pile cap. After applying about 39KN load on the pile cap, the developed mises stress increases up to 7.98N/mm^2 initially. As the load increases, the rate of the increment of the stress development is not increased linearly. Instead, the increment rate is decreased, and then the stress development is relatively linear until the connection point fails.

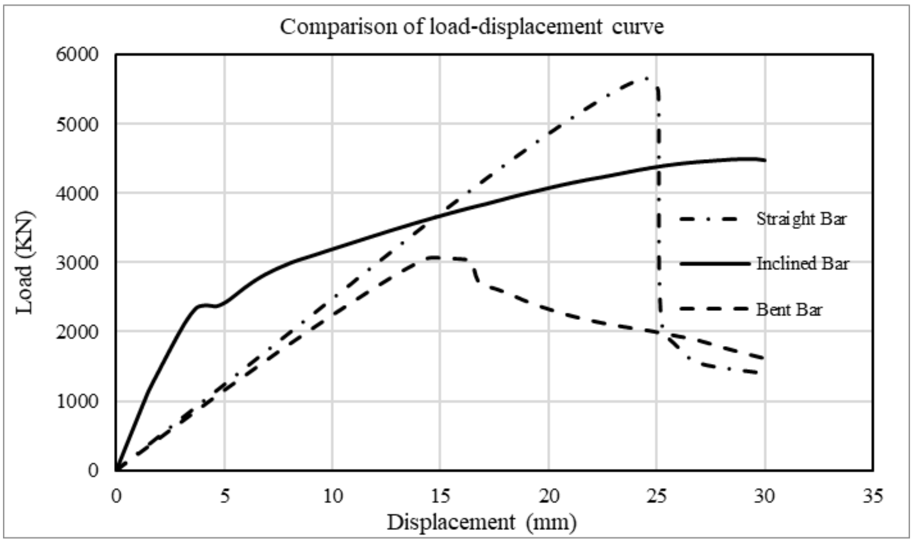


Figure 6: Load displacement curve for different fixed connection

Figure 6 shows the comparison of the load-displacement curve for different types of fixed connections to compare the structural performance of connection types. Among all these three types of fixed connection, the one with the straight bar extended into the pile cap can withstand the most load. Although the inclined bar connection has a relatively lower load-bearing capacity than the previous one, the sustainability of the connection point is quite good, as a significant amount of load is required to cause further displacement after the connection fails. Comparatively, the bent connection has the least strength to withstand vertical load.

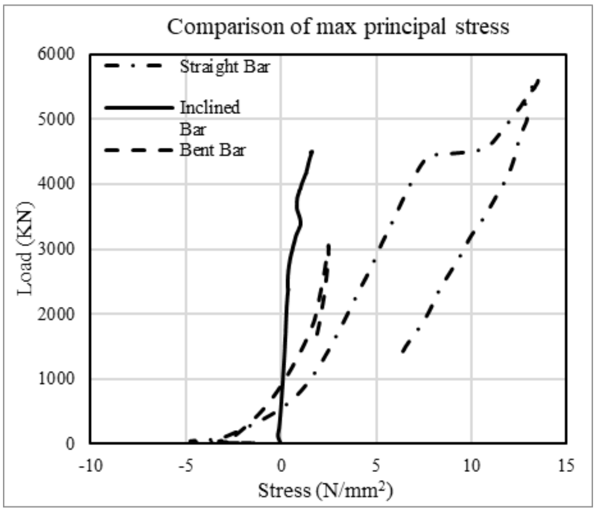


Figure 7: Comparison of max principal stress of different fixed pile-to-pile cap connections

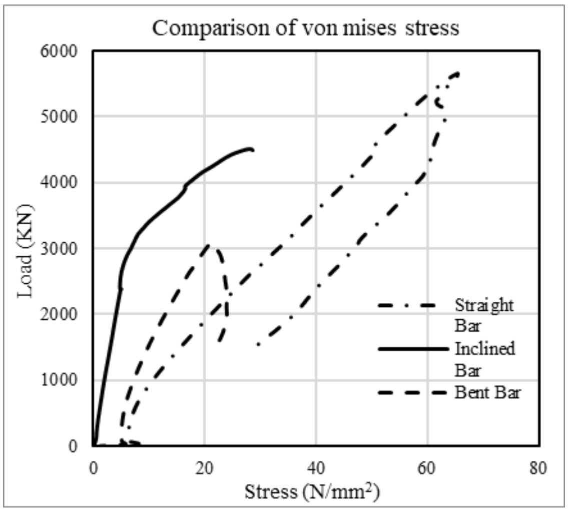


Figure 8: Comparison of von Mises stress of different fixed pile-to-pile cap connections

Figure 7 indicates the comparison of max principal stress with respect to load at the connection point. At the very beginning of the application of load, a negative stress is developed at the connection point. The rate of increment of the stress at this point is quite high. As the rest of the graph shows positive stress, this negative stress generation indicates the formation of tensile stress. When the magnitude of the applied is relatively low at the beginning of the simulation, the load is resisted mostly at the connection point. As a result, negative stress occurs due to uneven distribution of the stress.

Moreover, the rate of increment of the magnitude of the negative max principal stress is quite high. As the magnitude of the load increases, the negative stress is turned into a positive which indicates the formation of compressive stress. And the increment rate starts to reduce at the same time.

The formation of von Mises stress at the connection point follows a similar manner as shown in Figure 8. Although there is no formation of negative stress. However, the simulation indicates that the magnitude of the stress is highly related to the load-bearing capacity. After the failure of the connection point, the increment rate of stress starts to decrease along with the magnitude of the stress.

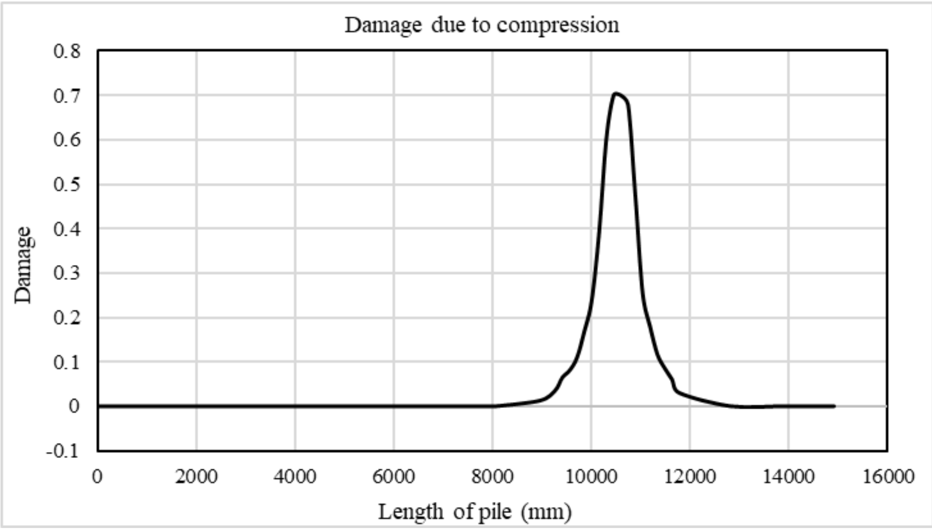


Figure 9: Length of concrete damage on the pile body

Figure 9 represents the location of the concrete damage on the pile body after the formation of buckling. The concrete damage due to compression on the pile body occurs at about 8000mm to 13000mm.

3.2 Hinged Connection

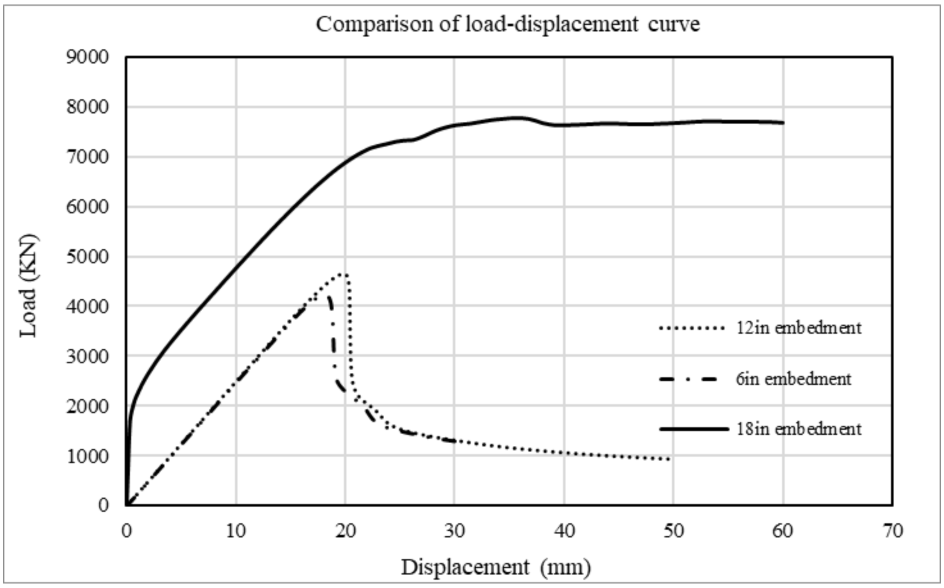


Figure 10: Load-displacement curve for different hinged connection

Figure 10 shows the comparison of the load-displacement curve of different hinged connections. Comparatively, the higher the embedment length is, the more load the connection can resist before failure. Also, with the 18-inch plain embedment connection, the failure mode is quite different. For 6-inch embedment and 12-inch embedment, the load-displacement curve is relatively similar. And the load required to cause further displacement after failure is comparatively low. However, with an 18-inch embedment, a solid connection forms according to the simulation. As a result, the load required to cause further development after the failure is nearly equal to the load-bearing capacity of the connection point.

The magnitude of the max principal stress development at the beginning of the simulation is quite high as well as the increment rate as shown in Figure 11. As the magnitude of the applied load increases, the load is transferred to the pile body from the connection point. However, when the load is transferred to the pile body, the magnitude of the stress decreases because of a more even distribution of load. The mechanism of von Mises stress development is quite similar to the max principal stress development as shown in Figure 12.

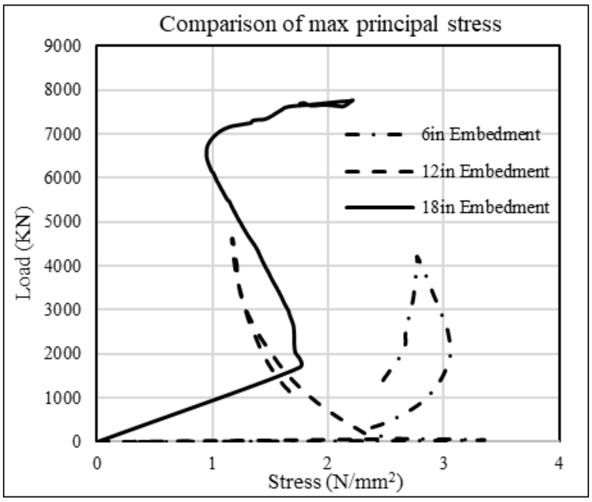


Figure 11: Comparison of max principal stress of different hinged pile-to-pile cap connections

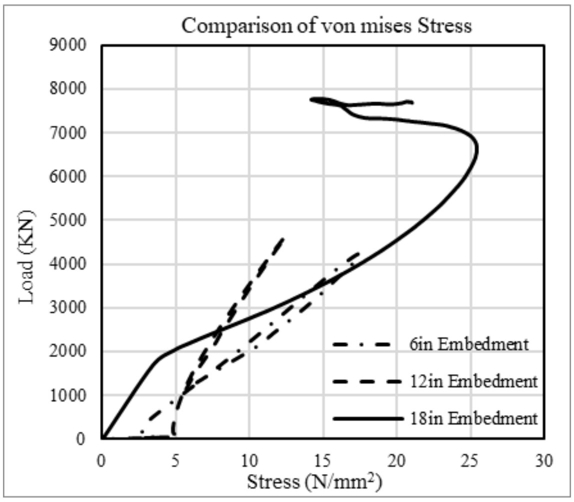


Figure 12: Comparison of von Mises stress of different hinged pile-to-pile cap connections

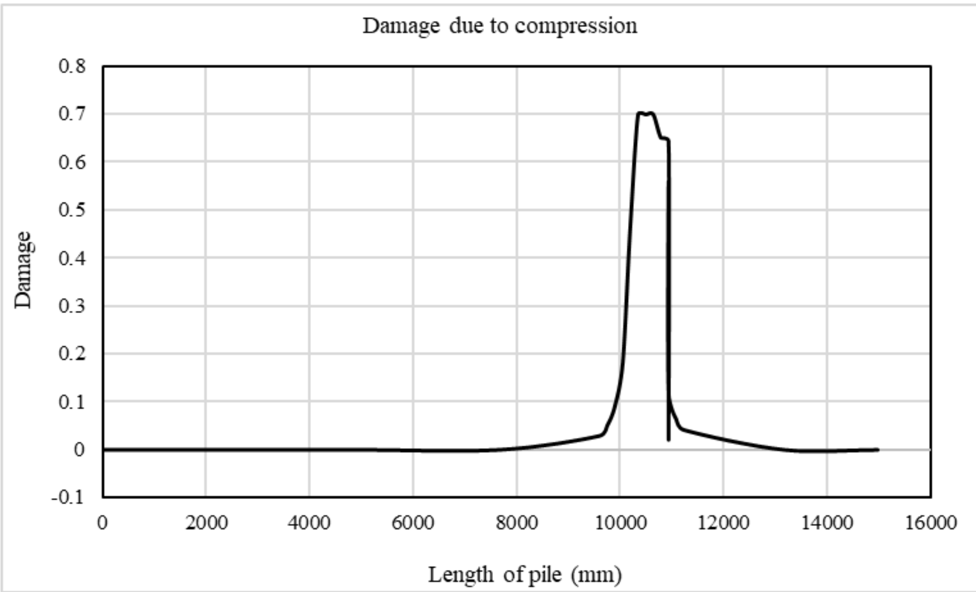


Figure 13: Length of concrete damage on the pile body

When the load is transferred from the connection point to the pile body, a buckling is caused in the pile body due to resisting excessive load with the similar mechanism of the fixed connection models.

The damage occurs at the pile body at a depth of 9600mm to 12235mm from the bottom as shown in Figure 13.

4 CONCLUSION

The following conclusions can be drawn from the analysis:

1. Fixed connections with a straight bar and inclined bar extended into the pile cap are preferred over the 90˚ bent bar extended. The strength of a fixed connection featuring 90˚ bent bars is compromised due to the restricted extended length of the bars.
2. The strength of the hinged connection with plain embedment can be enhanced by increasing the embedment length. Although a minimum 6-inch embedment is required for precast pile connection to the pile cap, maximum stability occurs when the embedment length equals or exceeds the pile diameter.
3. The strength of the pile foundation is predominantly dictated by the strength of the pile-to-pile cap connection before it reaches failure. Initially, stress accumulates at the connection point upon applying a load. Following the connection failure, the load is resisted by the pile's length, with the main bar in the pile experiencing the highest stress.

REFERENCE

Guo, Z., He, W., Bai, X., & Chen, Y. F. (2017). Seismic Performance of Pile-Cap Connections of Prestressed High-Strength Concrete Pile with Different Details. *Structural Engineering International*, *27*(4), 546–557. https://doi.org/10.2749/222137917X14881937845963

Harries, K. A., & Petrou, M. F. (2001). Behavior of Precast, Prestressed Concrete Pile to Cast-in-Place Pile Cap Connections. *PCI Journal*, *46*(4), 82–92. https://doi.org/10.15554/pcij.07012001.82.92

Joen, P. H., & Park, R. (1990). Simulated Seismic Load Tests on Prestressed Concrete Piles and Pile-Pile Cap Connections. *PCI Journal*, *35*(6), 42–61. https://doi.org/10.15554/pcij.11011990.42.61

M. Teguh, Duffield, C., Mendis, P., & G.L. Hutchinson. (2005). *3-D FINITE ELEMENT ANALYSIS OF PILE-TO-PILE CAP CONNECTIONS SUBJECTED TO SEISMIC ACTION*. 14-1-14–17.

M. Teguh, Duffield, C., Mendis, P., & G.L. Hutchinson. (2006). Seismic performance of pile-to-pile cap connections: An investigation of design issues. *Electronic Journal of Structural Engineering*, *6*, 8–18. https://doi.org/10.56748/ejse.654

Richards, P. W., Rollins, K. M., & Stenlund, T. E. (2011). Experimental Testing of Pile-to-Cap Connections for Embedded Pipe Piles. *Journal of Bridge Engineering*, *16*(2), 286–294. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000144

Sheppard, D. A. (1983). Seismic Design of Prestressed Concrete Piling. *PCI Journal*, *28*(2), 20–49. https://doi.org/10.15554/pcij.03011983.20.49

Silva, P. F., & Seible, F. (2001). Seismic Performance Evaluation of Cast-in-Steel-Shell (CISS) Piles. *ACI Structural Journal*, *98*(1). https://doi.org/10.14359/10145

Wang, T., Yang, Z., Zhao, H., & Wang, W. (2014). Seismic Performance of Prestressed High Strength Concrete Pile to Pile Cap Connections. *Advances in Structural Engineering*, *17*(9), 1329–1342. https://doi.org/10.1260/1369-4332.17.9.1329

Wang, X. (2021). Research on Vertical Bearing Capacity of Pile Foundation under Wave Scouring. *Open Journal of Modelling and Simulation*, *09*(02), 124–134. https://doi.org/10.4236/ojmsi.2021.92008

Xiao, Y. (2003). Experimental Studies on Precast Prestressed Concrete Pile to CIP Concrete Pile-Cap Connections. *PCI Journal*, *48*(6), 82–91. https://doi.org/10.15554/pcij.11012003.82.91

Xiao, Y., Wu, H., Yaprak, T. T., Martin, G. R., & Mander, J. B. (2006). Experimental Studies on Seismic Behavior of Steel Pile-to-Pile-Cap Connections. *Journal of Bridge Engineering*, *11*(2), 151–159. https://doi.org/10.1061/(ASCE)1084-0702(2006)11:2(151)

Yang, Z., Li, G., & Nan, B. (2020). Study on Seismic Performance of Improved High-Strength Concrete Pipe-Pile Cap Connection. *Advances in Materials Science and Engineering*, *2020*, 1–22. https://doi.org/10.1155/2020/4326208