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EXPERIMENTAL STUDY ON MOMENT RESISTING MECHANISM AT PILE-PILE CAP INTERFACE #1: Experimental Investigation

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Abstract

After the 2011 Tohoku Earthquake and 2016 Kumamoto Earthquake, some buildings were demolished due to damages to piles that made it difficult to maintain serviceability even though the superstructure did not suffer much damage. It is a new lesson for the Japanese engineering society that buildings can lose their functions even if the superstructure has no or very minor damage.

In the 1980's, Kokusho et al. and Kirihara et al. studied the seismic behavior at the pile-pile cap interface. Their piles were embedded in pile caps as deep as their pile diameter and they showed that the resisting mechanism depends on embedment lengths of the pile. However, recent piles have anchorage reinforcement to enhance the moment capacity with much smaller embedment length. In order to design for bending behavior at the interface, there are some issues to be quantified such as concrete strength enhancement due to the bearing effect of concrete, confining effect from reinforcement in the pile cap, volume of concrete in the pile cap which reacts against bending action and other factors.

This study presents experimental results on five pile cap specimens to examine the ultimate bending moment capacity and failure modes at the pile-pile cap interface. The test parameters included pile embedment length (0.33D, 0.66D, where D is the pile diameter, 400mm), amount of anchorage reinforcement (none, 8-D10), axial-load level (50kN, 400kN), and amount of shear reinforcement in the pile cap (none, 2-D10). Specimens were tested under one-sided cyclic lateral loading. The peak loads were reached at a drift angle of approximately 0.5%, when cracks penetrated the pile cap perpendicular to the loading direction. The test results showed that the bending moment capacity increased with deeper embedment length, more anchorage reinforcement and pile cap shear reinforcement, and larger axial compression load. It was also clear that the moment contribution from the concrete next to the embedded pile was significant due its bearing mechanism, even if the embedment length was as short as 0.33D. This paper provides a detailed description of the experimental program and classifies typical failure mechanisms of pile-pile cap connections for numerical modeling.

Keywords: Foundation structure; Pile - pile cap interface; Embedment length; Moment resisting mechanism

1. Introduction

The main objective of earthquake-resistant design of pile foundations for major earthquakes is to facilitate continuous use of buildings and protect infrastructure. To achieve this objective, there are issues to be addressed regarding the second-level seismic design of pile foundations, including pile caps, for strong earthquakes. Therefore, there is a need to study pile and pile cap response to strong earthquakes.

From the detailed investigation of pile response after the 2016 Kumamoto earthquake and the 2011 Tohoku earthquake, Tamura et al. [1] observed building inclination and tilt resulting from damage to the pile-pile cap connection. These tilts made the continued use of buildings impossible. Even when the super-structure suffers relatively minor damage, it is difficult to locate the damage of pile foundations and repair the pile. In addition, the process of reinforcing and restoring the pile is very expensive and time-consuming. This highlights the need to reconsider the method of designing the connection between pile and pile cap.

It is difficult to quantify the strength, deformation capacity, and bearing mechanism of the pile and pile cap not only because of different pile connection methods and the characteristics of the pile group, but also due to the complex three-dimensional interaction at the connections. Moreover, high-capacity piles have recently been developed due to the enhancement in steel (material) strength and frictional force around the driven ribbed pile. Consequently, the capacity of the pile has also increased. Hence, to adequately transfer higher loads from columns to piles, the capacity of the pile caps should also be increased. For this purpose, the load transfer mechanism in connections between pile and pile cap should be well understood.

This study presents experimental works on pile-pile cap connections to investigate the ultimate moment capacity and failure modes. Kokusho et al. [2] and Kirihara et al. [3] studied the seismic behavior at the pile and pile cap interface with embedment length of *D* or more (where *D* is diameter of the pile). But, more recently piles have anchorage reinforcement to enhance the moment capacity with much smaller embedment length. In order to design for bending behavior at the interface, there are some issues to be quantified such as concrete strength enhancement due to the bearing effect of concrete, confining effect from reinforcement of the pile cap, the volume of concrete in pile cap which reacts against bending action, among other factors. To the authors best knowledge, there are only a few studies on the bending behavior of pile and pile cap interface with embedment length less than *D*. Therefore, this study aims to address this gap. The following sections describe the experiment, test results, and discussions.

2. Experiment Outline

Table1 presents the details of the test specimens. The cross-section and reinforcement details of the specimens are shown in Fig. 1. The test specimen was arranged so that the pile cap was at the bottom and the steel pile at the top, opposite to how they are implemented in the real field. In this test, a 20 mm thick steel tube was used as the pile (intended to remain elastic throughout the testing).

The main test variables are embedment length of the pile, presence/absence of cage reinforcement, anchor reinforcement, and axial load. The embedment length of the pile head is 0.33D for specimens A01, A02, A04, and A19; and 0.67D for B01. Cage reinforcement constituting of vertical and hoop reinforcement was arranged inside the pile cap for A02, A04 and A19 (Fig. 1(c)-(d)). Among these, only specimen A19 had anchor reinforcement (Fig. 1(d)) which is welded to the steel pile. The weld length is 60 mm and the anchor length is 400 mm. In particular, each specimen was tested with the following objectives:

B01: determine the shear strength at the front surface of the pile cap.
A01: evaluate the slipping failure at the back side of the pile cap.
A02: study the influence of the cage reinforcement.
A04: study the influence of axial force.
A19: examine the effect of the anchor reinforcement.

The yield strength of the D10 and D16 reinforcing bars were found to be 338.6 MPa and 334.2 MPa, respectively. The compressive strength of the concrete in the pile cap was found to be 24.8 MPa from material

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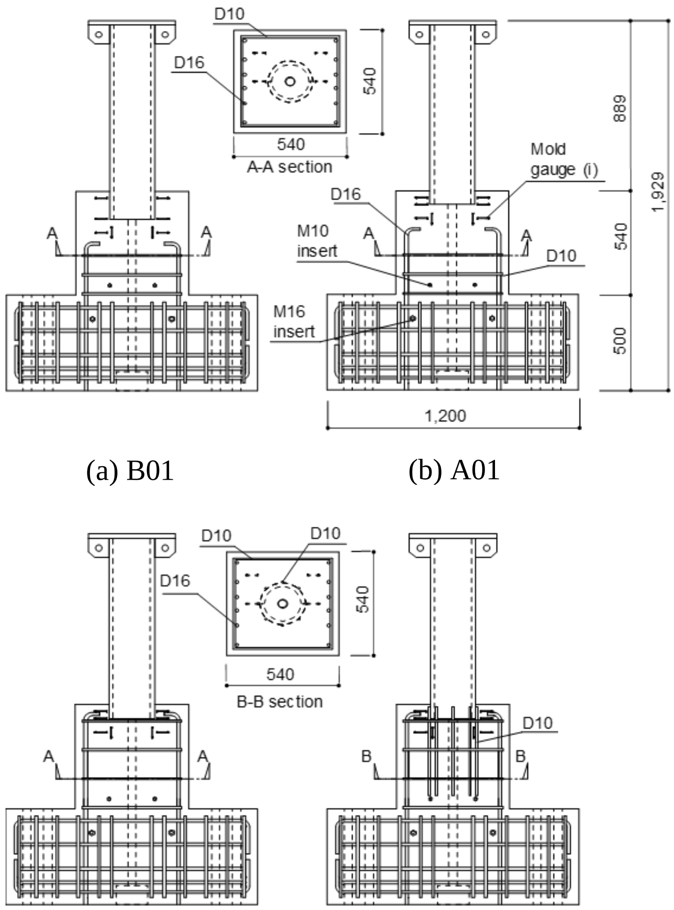
testing. A post-tensioning rod, from the pile top-flange to the base of stub, was utilized to prevent the pile from falling down during the handling process.

Table.1 – the specimen parameters

No.	Embedment length (mm)	Axial force (kN)	Anchor reinforcement	Cage reinforcement	
				Vertical	Hoop
B01	0.67D	50			
A01	0.33D	50			
A02		50		6-D16	2-D10
A04		200		6-D16	2-D10
A19		50	8-D10	6-D16	2-D10

*Diameter:216mm, Pile:steel, Thick:20mm, Pile cap size:2.5D, Concrete strength:30Mpa



(a) B01 (b) A01

(c) A02,A04 (d) A19

Fig.1 – Test specimen details

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All of the specimens were tested in an identical test setup as shown in Fig.2. One-sided cyclic loading in the horizontal direction under constant axial load was carried out. The displacement was controlled by the horizontal hydraulic jack.

The applied loading protocol is depicted in Fig. 3. Two cycles at each drift were applied at drift angles (taken as the ratio of horizontal displacement to height of lateral load application point from the pile cap top surface) 0.125%, 0.25%, 0.50%, 0.75%, 1.00%, 1.50%, 2.00%, 3.00%. Moreover, Teflon™ plate was used at the pile top to prevent out-of-plane displacement of the pile.

The horizontal displacement at the loading point was measured by a displacement gauge attached to the steel frame fixed to the bottom stub, and a target welded to the side surface of the steel pile (Fig. 2).

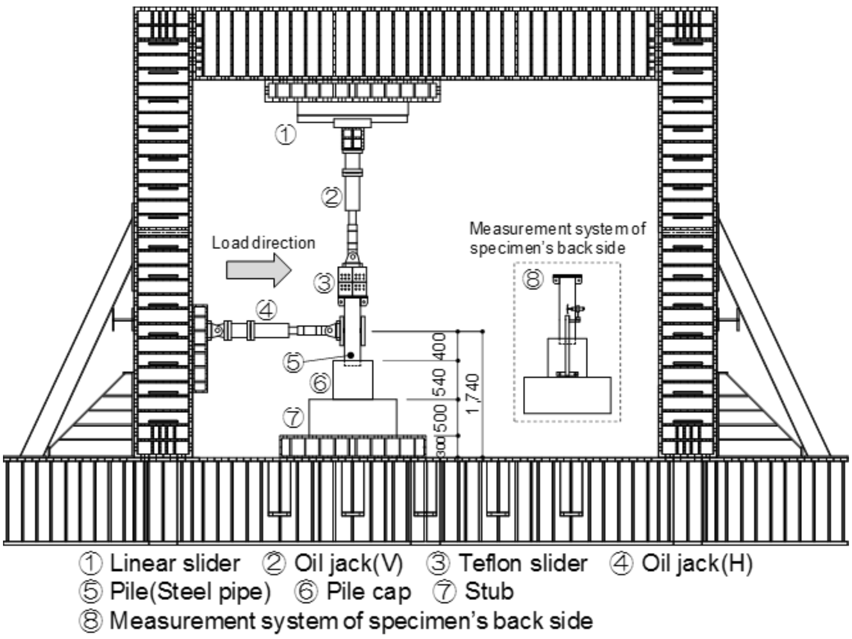

Fig. 2 – the loading system

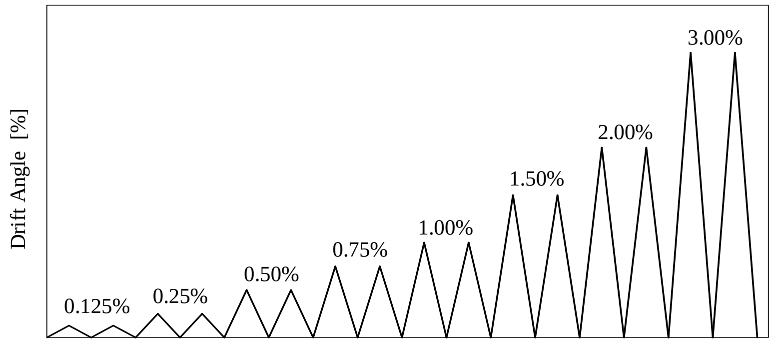

Fig. 3 – Loading protocol

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3. Experimental Results and Discussion

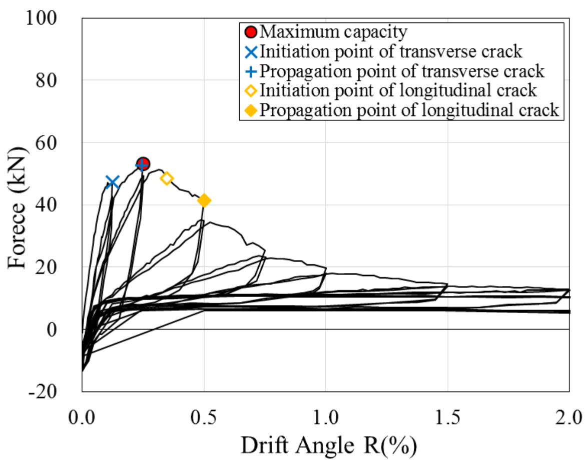
3.1 Load deformation response

Fig. 4 shows the lateral load deformation relationship for the test specimens. Lateral deformation is presented in terms of drift angle (R) taken as ratio of horizontal displacement to height of lateral load application point from pile cap top surface, in percentage. In addition, the occurrence of characteristic events first occurrence of cracks parallel and perpendicular to the loadings, and crack propagation to the sides are also shown in the plot. For specimen B01, which has a 0.67D embedment length, the peak was observed at 0.25% drift. In contrast, the peak was observed at 0.5% drift for specimens A01, A02, A04 and A19, which have an embedment length of 0.33D.

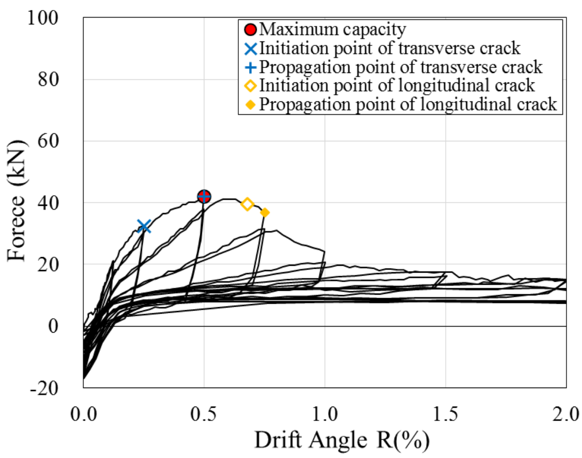
For all the specimens, cracks perpendicular to the loading direction (hereinafter referred to as transverse cracks) appeared before reaching the peak strength. None of the reinforcement yielded before reaching the maximum capacity. For specimens B01, A01, A02, and A04, cracks parallel to the loading direction (hereinafter referred to as longitudinal cracks) appeared after the maximum capacity. For specimen A04, the transverse crack formed and immediately propagated to the sides.

The strongest specimen was A19 which has anchor reinforcement, cage reinforcement, and 0.33D embedment length. The capacity of specimen A02 is higher than that of specimen A01 due to the presence of cage reinforcement. However, the peak of specimen A02 was smaller than that of B01 which has a higher embedment length of 0.67D. This implies that the pile embedment length contributes more to the moment capacity than does the cage reinforcement.

Specimens A02 and A04 had different axial loads while all other parameters were identical. Comparing the force-drift response of these specimens shows that axial (compression) load in the pile increases the moment capacity of the pile to pile-cap connection. Among all the specimens, the capacity of A04 was the second largest due to the higher axial load.



(a) B01



(b) A01

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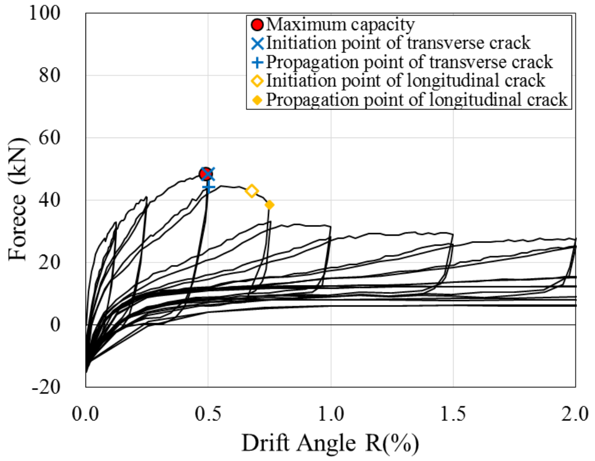
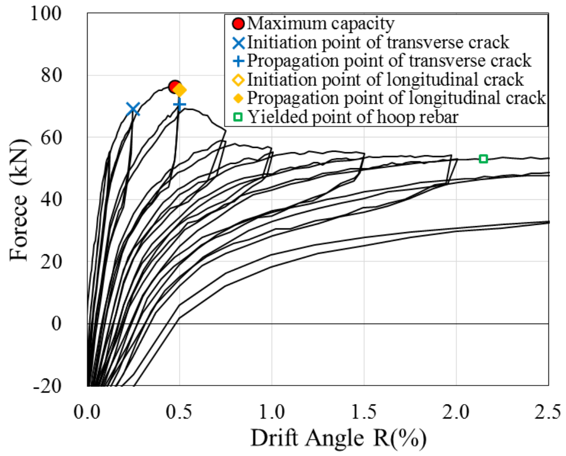
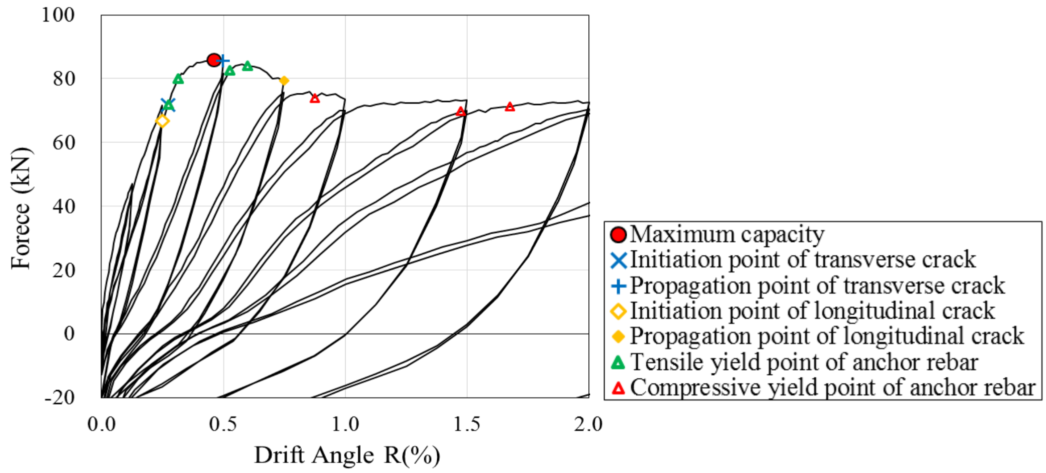


(c) A02



(d) A04



(e)A19

Fig. 4 – Cyclic load-deformation response for the test specimens

3.2 Typical crack pattern of pile caps

Fig. 5 shows cracks observed in the pile cap for the specimens at 3% drift. The definition of type and location of cracks (used in subsequent discussions) is presented in Fig. 5(a).

In specimen B01, transverse cracks occurred first at 0.125% drift and propagated to the left and right sides at 0.25% drift. After that a longitudinal crack formed in region A at 0.35% drift and propagated to the front at 0.5% drift. On further loading, 45° cracks formed in the pile cap as shown in Fig. 5(b). No cracks were observed on the back side of the loading direction. Similar crack patterns were observed in specimens A01, A02, and A04. Based on these observations, failure mode of these specimens is a combination of flexure and shear failure in front of the pile in the loading direction.

For specimen A19, the initial cracks occurred in Region B propagating radially outwards from the pile head at 0.5% drift. On further loading, these cracks propagated to the left and right side at 0.75% drift, and additional cracks were observed at hoop reinforcement locations on the right side (Fig. 5(f)) at 2.0% drift. Based on this observation, the failure mode of this specimen is a combination of bending and shear failure in front of of the pile in the loading direction, and bending failure on the behind the pile.The different failure

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modes of pile-cap bearing with a laterally loaded pile are discussed in the companion paper (Part 2) together with moment capacity formulation corresponding to these failure modes [7].

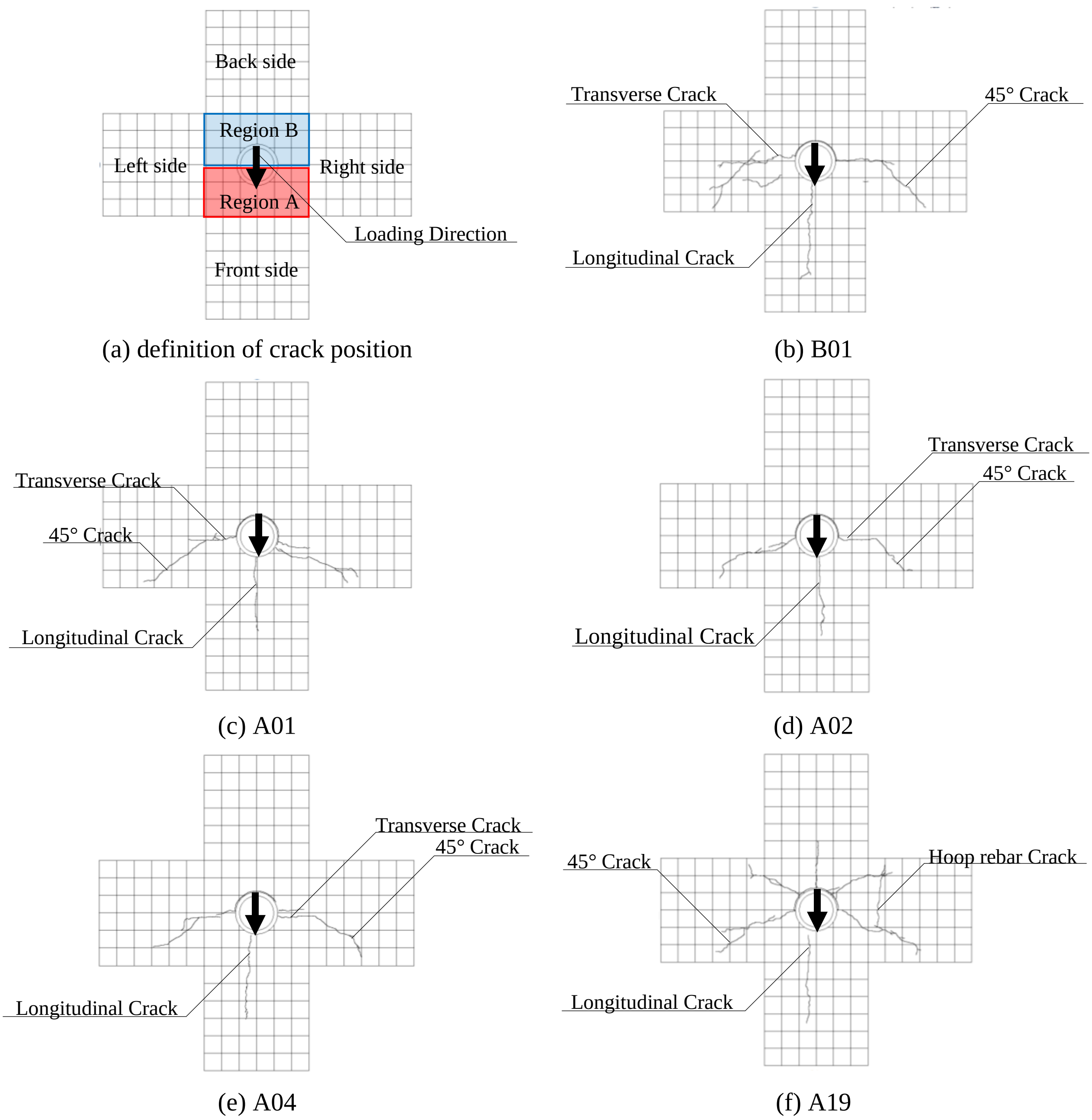

Fig. 5– Cracks observed in the pile cap at 3% drift

3.3 Strain measured in reinforcing bars

3.3.1 Hoop reinforcement strain

Fig. 6 shows the recorded strain values in hoop reinforcement for specimens A04 and A19.

The strain values are larger near the pile cap surface in front of the loading direction. These strain values reduce with increase in distance from the pile cap surface. In contrast, strain in the hoop reinforcements on

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back side of loading is very small. Therefore, it can be inferred that the hoop reinforcements has significant effect on bearing mechanism of the pile in front of the loading direction.

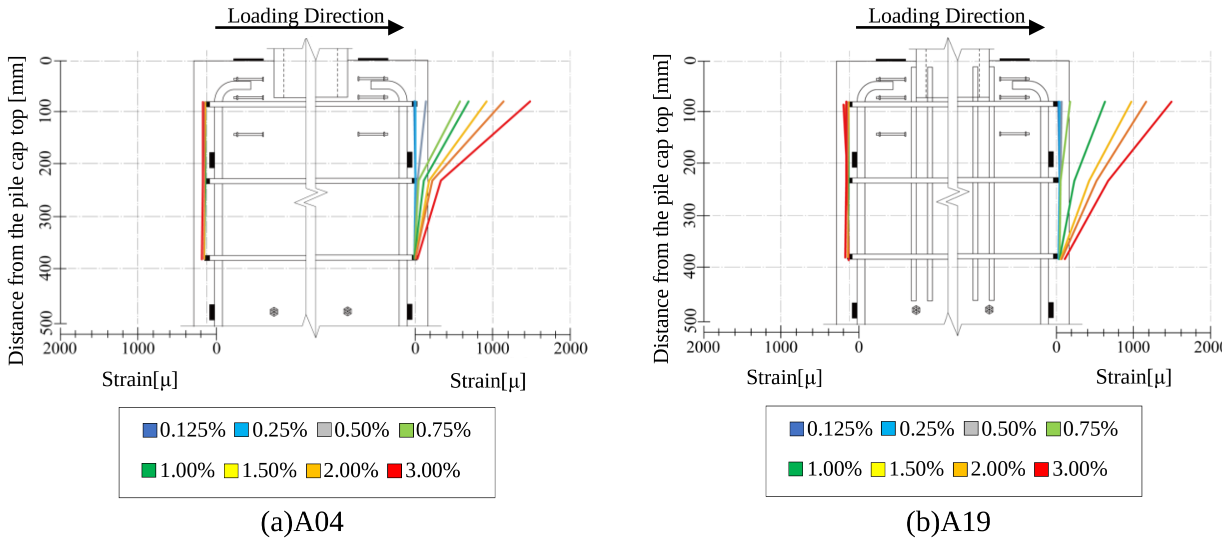

Fig. 6 – Strain in hoop reinforcement measured in the experiment

3.3.2 Vertical reinforcement strain

Fig. 7 shows the recorded strain values in the vertical reinforcement for specimens A04 and A19.

For specimen A04, the strain values were very small in both the front and back sides of the loading direction (Fig. 7(a)). On the other hand, for specimen A19 the strain in vertical reinforcement in the front side of loading direction was higher near the pile surface. The strain in vertical reinforcement in the back side of the loading direction increased with increase in distance from the pile cap surface (Fig. 7(b)).Comparing Fig. 7(a) and 7(b), it can be deduced that the vertical reinforcements contribute to the bearing mechanism, but this effect tends to be small under larger axial loads.

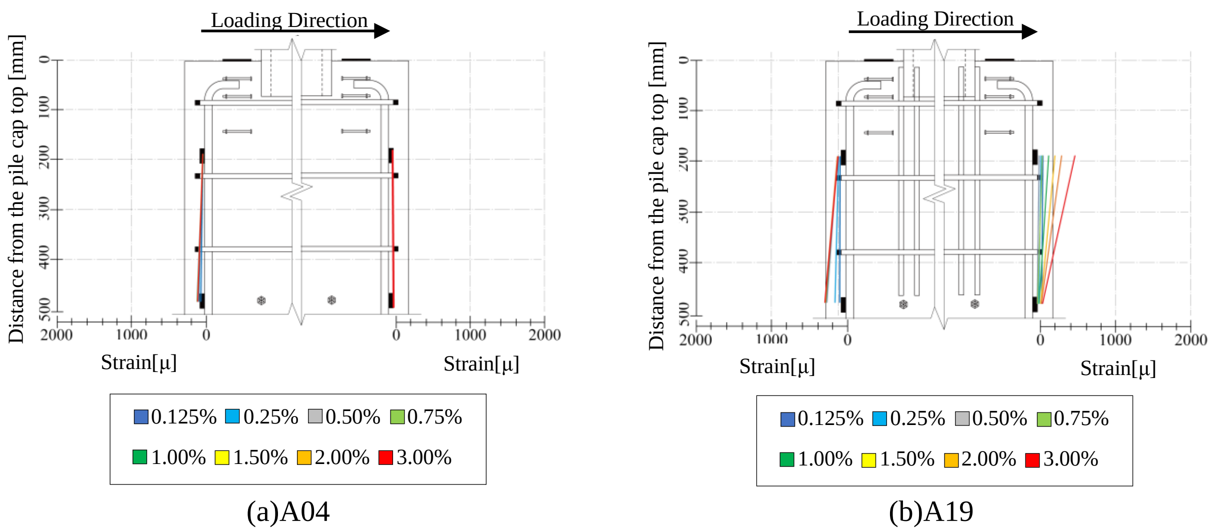

Fig. 7–Vertical reinforcement Strain

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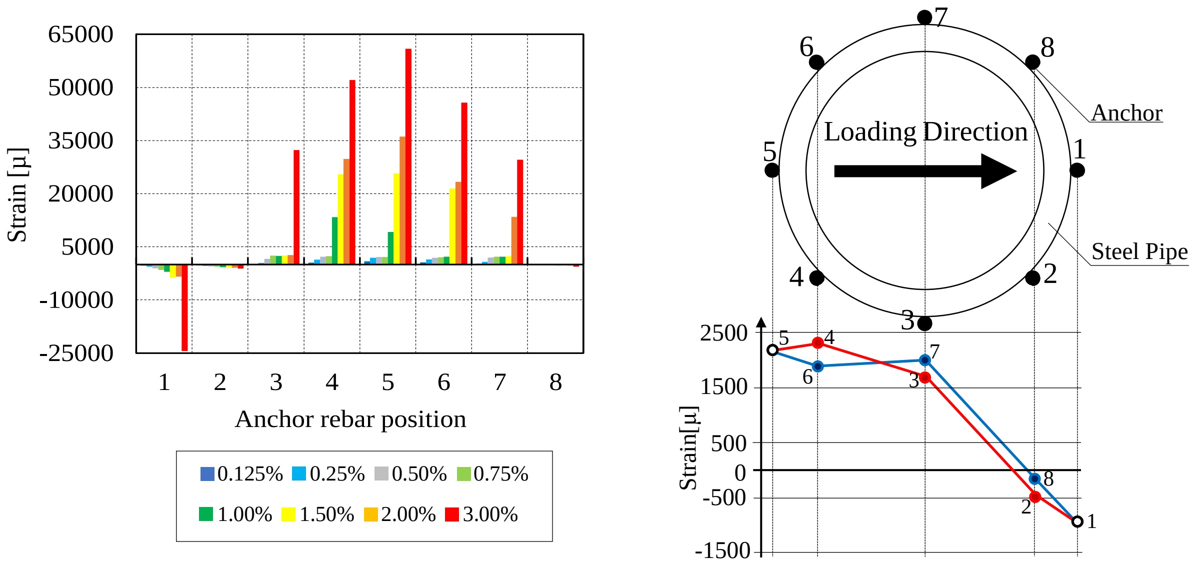
3.3.3 Anchor reinforcement strain

To further investigate the contribution of anchor reinforcements, Fig. 8 shows the measured anchor reinforcement strains around the pile head of specimen A19. The results presented in Fig. 8(a) correspond to the strain measured at drift values (from 0.125% to 3.0%) at anchor reinforcement positions defined in Fig. 8(b).

The results show that the No.5 anchor reinforcement (directly behind the loading direction) reached the maximum value of tensile strain and the No.1 anchor reinforcement (directly in front of the loading direction) reached the maximum value of compressive strain. The anchor reinforcements No. 3, 4, 6, and 7 also reached high tensile strain values. Thus, it can be understood that the anchor reinforcement on the back side of the loading direction have greater contribution on the tensile force of the pile.



(a) anchor reinforcement strain values at different drifts (b) strain values at 0.5% drift

Fig. 8– Strain in anchor reinforcement for specimen A19

3.4 Strain in pile cap concrete

To understand the pile cap concrete response, the concrete strains in the pile cap near the pile head of specimens A04 and A19 are presented in Fig. 9.

The results in Fig. 9(a) and (b) show that the concrete strain in the back side of the loading direction is very small compared to the strain in concrete in front of the loading direction. Thus, for piles with small embedment length, the concrete in the front of loading direction has more influence on the bearing mechanism than that in the back side.

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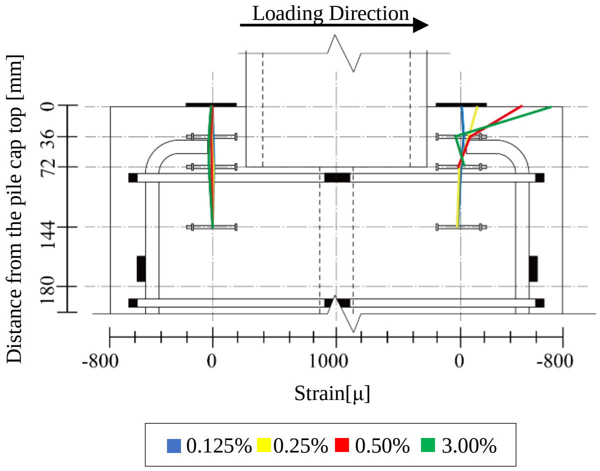
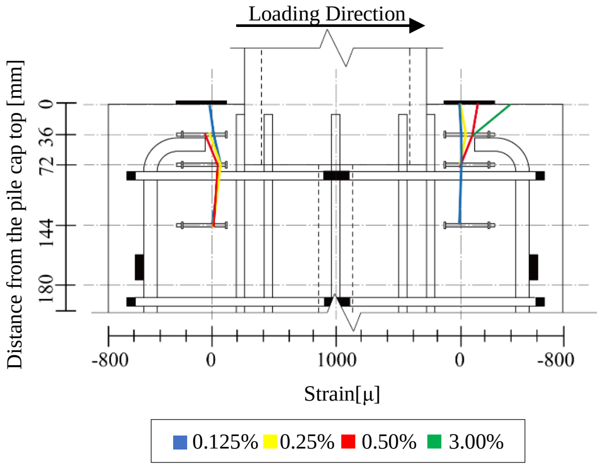


(a)A04



(b)A19

Fig. 9–internal concrete strain

4. Conclusions

This paper presented an experimental study on five pile cap specimens to understand the ultimate bending moment capacity and failure modes at the pile-pile cap interface. The lateral load-deformation relationships, failure modes, and material strain measured in the test were discussed. The findings from this study can be summarized as follows:

・The lateral load capacity of specimens A01 and A02 which have an embedment length of 0.33D were smaller than that of specimen B01 which has an embedment length of 0.67D. However, the capacity of specimens A04 and A19 which have embedment lengths of 0.33D were larger than that of specimen B01 due to the larger axial compressive load and the presence of anchor reinforcement, respectively.

・The failure mode of specimens B01, A01, A02 and A04 was a bending/shear failure in the front side of the loading direction. For specimen A19, the failure mode was bending or shear failure in the front of the loading direction, and bending failure in the back side of the loading direction.

・The hoop reinforcement and the concrete in the front of the loading direction have significant effect on the bearing mechanism. Vertical reinforcements in the front of the loading direction also contributes to the bearing mechanism; however, this contribution tends to be small under the larger axial compression loads. Anchor reinforcement in the back side of the loading direction contributes significantly in the bearing capacity of the pile.

The companion paper [7] uses these experimental observations to discuss moment resisting mechanisms and verify the accuracy of moment capacity equations developed therein.

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