Acta Polytechnica CTU Proceedings **33**:300–308, 2022
https://doi.org/10.14311/APP.2022.33.0300

SUGGESTION OF ULTIMATE STRENGTH FORMULAS OF PARTIAL FRAME PILE CAP COMPOSED OF EXTERIOR COLUMN, FOUNDATION BEAM AND PILE

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Abstract.

Currently, there is no research and few valid experiments of pile caps. And shear failure mechanism of a pile, exterior column and foundation beam and pile caps in RC structure is not resolved yet under bi-lateral loading. Therefore, a performance evaluation method based on mechanical behaviour for pile caps has not been established. First, the fracture type was specified from the experimental results. Secondary, the ultimate strength formula of the pile cap was proposed based on the previous experimental results. It is a theoretical formula based on the truss-arch theory. It was confirmed that this formula can accurately evaluate the ultimate strength of the pile cap.

Keywords: Failure mode, pile-cap, ultimate strength formulas.

1. Introduction

Although the seismic performance of buildings after a large earthquake is ensured under the current seismic standards, measures to ensure continuous use after a large earthquake have not been established. Prevention of building collapse at the time of a major earthquake is secured by current earthquake resistance standards but plans to ensure continued use after the earthquake have not been established. It is necessary to develop a method for conducting performance-oriented seismic design with "Sustainability of buildings after earthquake" as the required [1]. From the viewpoint of continuous usability, it is conceivable that the pile cap will be damaged and deformed in the axial direction will occur and the building will not be able to continue to use due to the inclination of the building. Pile cap is an important structural joint member. Its function is to transfer the stresses occurring on the columns through a group of piles to the ground, taking place the complex stresses under earthquake loading. It is very important to clarify pile cap shear failure mechanism of reinforced concrete (RC) structures. However, shear failure mechanism of a pile, exterior column-beam pile cap in RC structure is not resolved yet under bi-lateral loading. Therefore, in this study, the frame experiment of the pile cap was carried out using two types of hoops arranged in the pile cap as experimental factors. The purpose of this study was to clarify the effect of columns and pile cap hoops on pile caps. We evaluated the pile cap shear strength formula proposed in the previous study [2, 3] and proposed a pile cap shear strength formula based on the truss-arch mechanism.

2. Outline of Test

2.1. Specimens

Fourteen half-scale reinforced concrete pile caps assembled a precast pile, an exterior column and aă-foundation beam, those specimens modelled actual middle-high buildings, were tested. Aăconfiguration of specimens, section dimensions and reinforcement details are shown in Figure 1. Specific properties of specimens are summarized in Table 1. Material characteristics of concrete and steel are listed in Tableă2, respectively.

The constant axial load in compression was applied at the top of the column for all specimens. The depth and width of the column section were 300mm and 300mm, respectively. The depth and width of the foundation beam section were 200mm and 600mm, respectively. The length from the center of the column to the loading point on a beam end was 1500mm. The height from the center of the beam to the supporting point on the top of the column or to the bottom support was 1200mm and 1275mm, respectively. Steel pile (Diameter is 190.7mm, thick is 45mm) was used as a precast pile, the embedment length was 100mm, 8-D19 bars were arranged as anchor dowel bars. The grout was filled into the hollow part of the Steel pile for all specimens. All specimens were designed to form shear failure mechanism.

For the specimen A-7a and A-8, the pile cap hoop ratio (${}_{pc}p_w$) was arranged in 0.22%, the column hoop ratio in pile cap (${}_{c}p_w$) was arranged 0.47 times more than the specimen A-7a. For the specimen A-7b and A-9, the pile cap hoop ratio (${}_{pc}p_w$) was arranged in 0.10%, the column hoop ratio in pile cap (${}_{c}p_w$) was arranged 0.23 times more than the specimen A-7a. For the specimen A-8 and A-9, the column hoop ratio

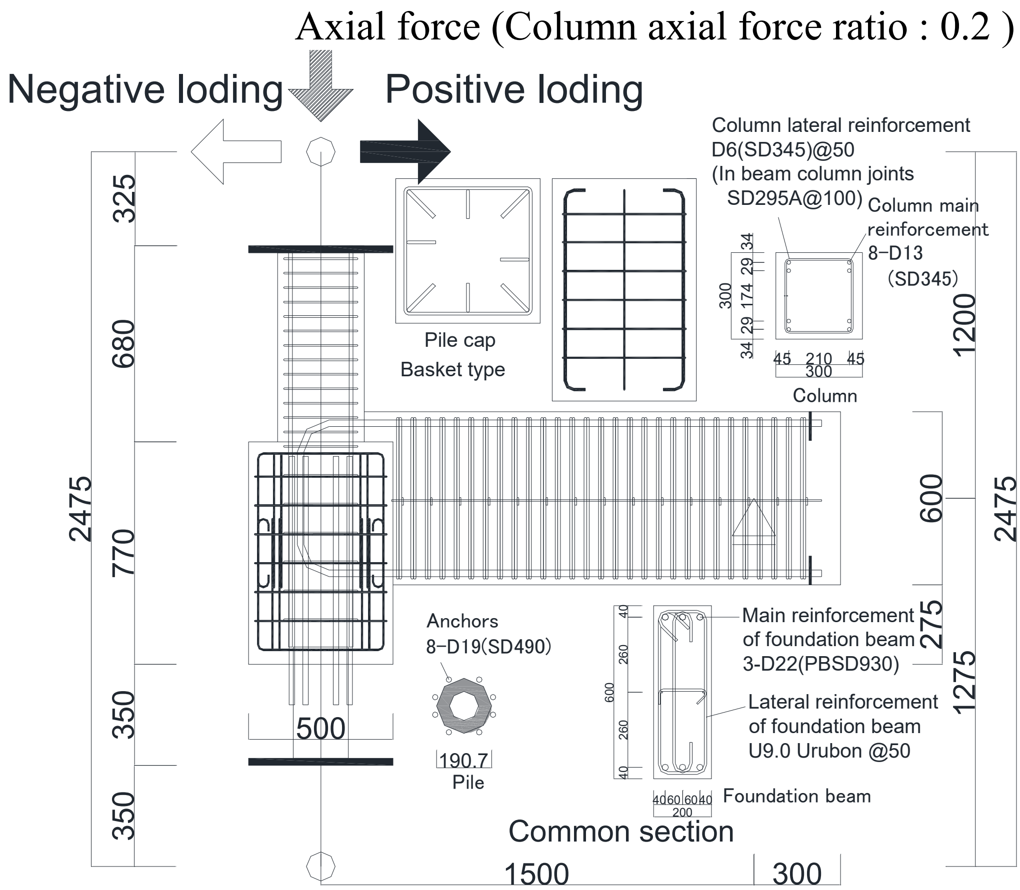


Figure 1. Derails of Specimens.

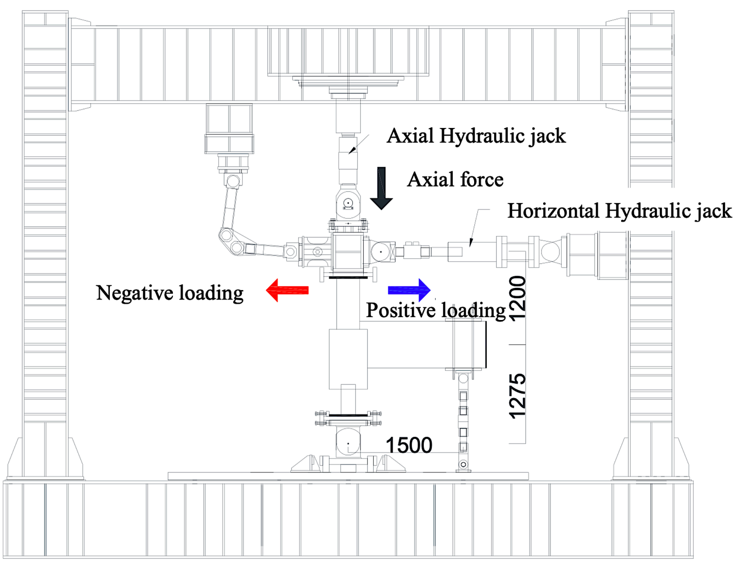


Figure 2. Details of Specimens.

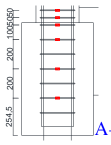
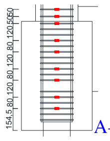
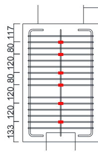
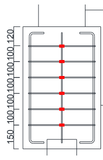
Specimen		A-7a	A-7b	A-8	A-9
Axial force (Axial force ratio : 0.2)		500 kN	514 kN	462 kN	467 kN
Column	Width × Depth	300 mm × 300 mm			
	Main reinforcement	8-D13(SD785)			
	Hoop	D6(SD785)@50			
	Hoop in pile cap	D6(SD295A)@100	D6(SD295A)@50	D6(SD295A)@300	D6(SD295A)@300
	(Hoop amount : cPw[%])	(0.15)	(0.30)	(0.07)	(0.07)
Foundation Beam	Width × Depth	200 mm × 600 mm			
	Main reinforcement	Upper and Bottom 3-D22(PBSD930)			
	Stirrup	U9.0(1275MPa)@50: High-strength shear reinforcement			
	Spacing bar	2-D6(SD295A)			
Pile	Steel pile	S45C φ190.7 t-45mm			
	Anchor bar	8-D19(SD490)			
Pile cap	Width × Depth × Height	500 mm × 500 mm × 770 mm			
	Vertical reinforcement	4-D6(SD295A) 4-D10(SD295A)			
	Hoop	D6(SD295A)@50	D6(SD295A)@100	D6(SD295A)@50	D6(SD295A)@100
	(Hoop amount : pcPw[%])	(0.22)	(0.10)	(0.22)	(0.10)
		 A-7a	 A-7b	 A-8	 A-9

Table 1. Properties of Specimens Details.

in pile cap ($_cp_w$) was arranged in 0.07%.

$$_cp_w = {_ca_w}/(b \times l) \qquad (1)$$

$$_{pc}p_w = {_{pc}a_w}/(b \times l) \qquad (2)$$

Where, b: pile cap width, l: distance between the centers of gravity of the main beams of the foundation beam, $_cp_w$, $_{pc}p_w$: the total of each cross-sectional area of the column and the pile cap hoop arranged in the cross section ($b \times l$).

2.2. Loading Apparatus and Instrumentation

A loading apparatus is shown in Figure 2. The foundation beam end was supported by horizontal roller, while the bottom of pile was supported by a universal joint. The reversed cyclic horizontal load and the constant axial load in compression (an axial load ratio of 0.20 in all specimens) were applied at the top of the column through a tri-directional joint by three oil jacks. The jack orthogonal to a horizontal loading direction prevented an out-of-plane overturn for specimen.

All specimens were controlled by a story drift angle for one loading cycle of 0.25%, two cycle of 0.5%, 1%, 2%, one cycle of 3% respectively, and two cycle of 4%. The story drift angle was defined as a story drift divided by height of the column and pile; 3400mm and 2475mm. Lateral force, column axial load and foundation beam shear forces were measured by load-cells. Story drift, foundation beam and column deflections, and local displacement of a pile cap panel were measured by displacement transducers. Strains of foundation beam bars, column bars and pile cap bars, anchors and hoops were measured by strain gauges.

3. Test results

3.1. Story Shear - Drift Relationship

Relationships between the story shear force and the story drift angle are shown in Figure 4. The story shear force was obtained from moment equilibrium between measured beam shear forces and the horizontal force at a loading point on the top of the column. The pile cap hoop yielded before the story shear force achieved the maximum strength. For specimen A-7a and A-7b, the maximum strength was 1.06 times larger on the positive loading than specimen A-7a, 1.11 times larger on negative loading, respectively. After the maximum strength, the decreasing rate was 17% at positive loading for specimen A-7a, 25% at negative loading for specimen A-7b. When the pile cap hoop is larger than the column hoop, the effect

Specimen	Reinforcing bar	Parts used	Yield stress [N/mm^2]	Yield strain [μ]
A-7a A-7b	D6(SD295A)	Column, Pile cap	451.2	2246
	D6(SD785)*	Column	900.4	6684
	D10(SD295A)	Pile cap	361.0	1989
	D13(SD785)	Column	816.1	5331
	D19(SD490)	Anchor	530.0	3027
	D22(PBSD930/1080)*	Main reinforcement of Foundation beam	999.4	6933
	U9.0(SBPD1275/1420)*	Reinforcing bar of Foundation beam	1319.5	8672
A-8 A-9	D6(SD295A)*	Column, Pile cap	378.7	4079
	D6(SD785)*	Column	928.3	6985
	D10(SD295A)	Pile cap	362.7	1936
	D13(SD785)	Column, Pile cap	900.4	6735
	D16(SD785)*	Column	879.1	6716
	D19(SD490)*	Anchor	543.5	3538
	D22(PBSD930/1080)*	Main reinforcement of Foundation beam	1001.6	6990
	U9.0(SBPD1275/1420)*	Reinforcing bar of Foundation beam	1450.8	8507

Table 2. Material Properties of Steel.

Specimen	Compressive strength [N/mm^2]	Modulus of elasticity [$\times 10^4$ N/mm^2]	Strain at compressive strength [μ]	Split tensile strength [N/mm^2]
A-7a, A-7b	28.4	2.08	2652	2.16
A-8	25.7	2.01	2767	2.21
A-9	26.0	2.02	2755	2.21

Table 3. Material Properties of Concrete.

on the maximum shear strength and the ductility capacity were increased. For specimen A-8 and A-9, the smaller the total hoop mass($_{pc}p_w +_c p_w$) in the pile cap, the lower the maximum shear strength.

3.2. Crack patterns

Crack patterns at the maximum strength are shown in Figure 3. For specimen A-7a and A-8, the pile cap vertical bar and the hoop yielded before the story shear force achieved the maximum strength and the column base was crushed at maximum strength. After the maximum strength, the pile cap shear crack width did not increase so much, and the damage to the column base became larger. The maximum strength was determined by pile cap shear failure, and after the maximum strength, it was judged that the column was destroyed by crushing. For specimen A-7b and A-9, before the maximum shear strength, the pile cap hoop, the vertical bar and the column hoop yielded. Due to the width of the pile cap shear cracks has increased after the maximum shear strength, it was judged that pile cap shear failure was destroyed in these two specimens.

4. Consideration of the pile cap hoops

4.1. Pile cap crack properties

Specimens A-7a and A-7b in which the total hoop amount ($_{pc}p_w +_c p_w$) in the pile cap is almost the same and the ratio of $_{pc}p_w$ and $_cp_w$ are different are compared. Comparing the pile cap cracks at the time of the final failure of the two specimens shown in Figure 3, specimen A-7a, which had many pile cap hoops, had dispersed pile cap shear cracks. On the other hand, the specimen A-7b, which had many column hoops, showed a different characteristic that the cracks did not disperse, and the width of several shear cracks increased. This suggests that, of the two types of hoops, the pile cap hoops arranged on the outside contribute a greater shear force and are more effective in preventing brittle shear failure.

4.2. Strain distribution of pile cap hoop

4.2.1. Pile cap hoop

Figure 5 shows the strain distribution of pile cap hoops for specimens A-8 and Aŋ9. The two specimens have different $_{pc}p_w$, and $_cp_w$ and have the same amount of reinforcement. At the time of positive

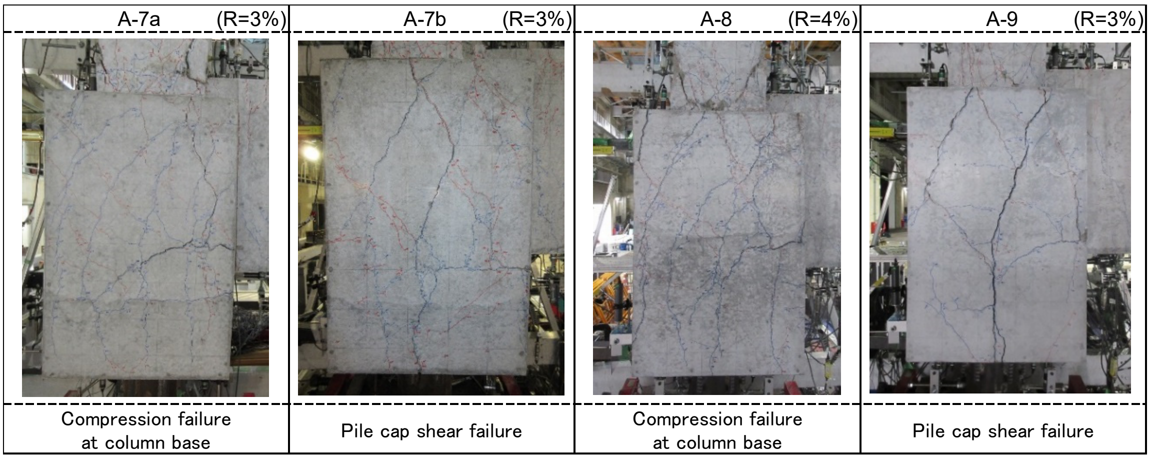


Figure 3. Failure mode at end of test.

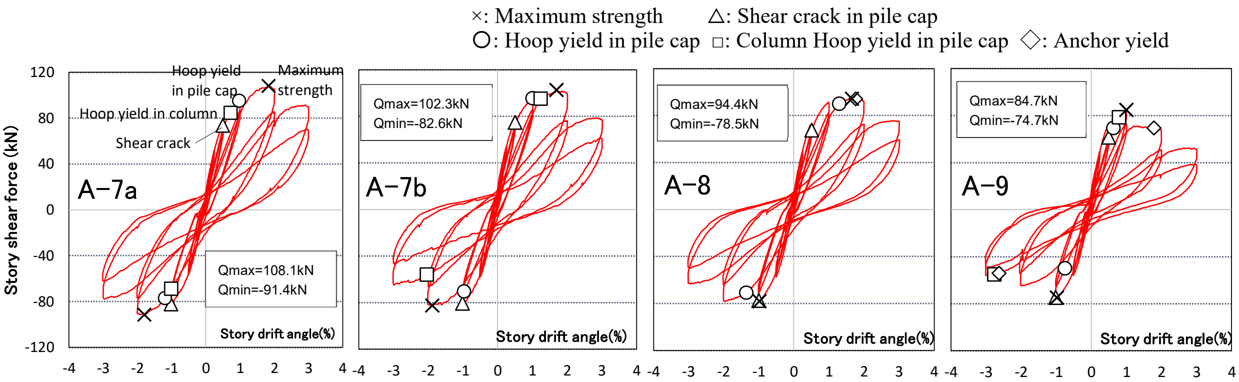


Figure 4. Details of Specimens.

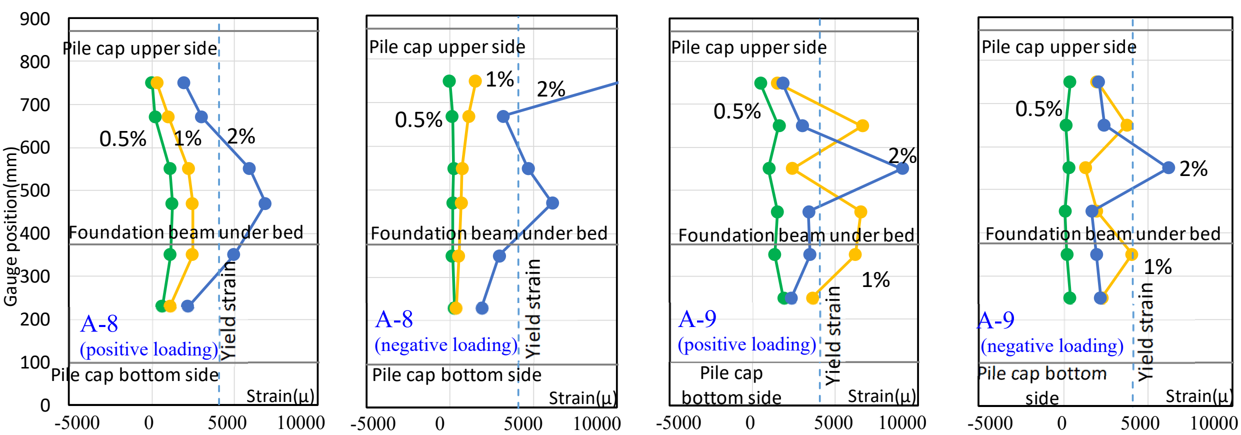


Figure 5. Strain distribution of pile cap hoop.

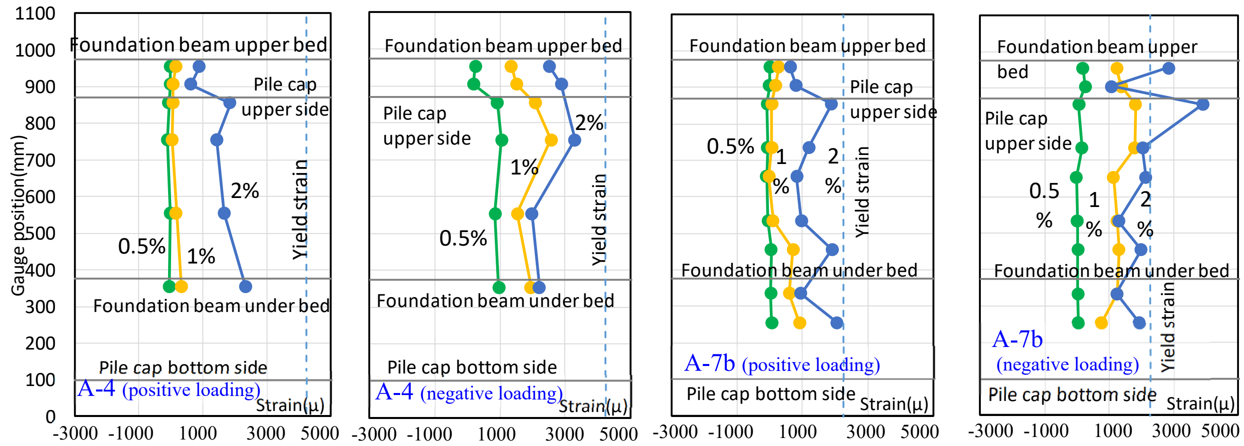


FIGURE 6. Strain distribution of column hoops in pile cap.

loading, the strain at the lower end of the foundation beam was large in both specimens. For specimen A-8, the strain did not reach the yield to $R = 1\%$, but for specimen A-9, the strain had reached the yield to $R = 1\%$. It is considered that the tensile force acting one hoop was dispersed in the specimen A-8 with a large amount of ${}_{pc}p_w$, and the hoop did not yield until R=2%. On the negative loading, the strain amount of specimen A-8 was smaller than that of the positive loading until the maximum shear strength ($R = -1\%$). Also, the strain at the top of the pile cap was larger than that at the bottom of the foundation beam, and the difference depending on the loading direction was observed. In specimen A-9, the strain became smaller as compared to the positive loading. Compared with test specimen A-8, the strain increased up to $R = -1\%$ as in the case of positive loading. As described above, by arranging a large amount of ${}_{pc}p_w$, it is possible to reduce the ratio of a single hoop to the shear force acting on the pile cap.

4.2.2. Column hoop in pile cap

Figure 6 shows the strain distribution of the column hoops in the pile cap of specimen A-7b and specimen A-4. In test specimen A-4, ${}_{c}p_w$ was arranged 0.15%, and ${}_{pc}p_w$ was recombined in the same amount as specimen A-7b. At the time of positive loading, the strain at the lower end of the foundation beam tended to increase as in the pile cap hoops in both specimens, but the column hoops did not yield even at the maximum strength ($R = 2\%$). When the strain values of the two specimens were compared, the strain value of the column hoop was almost unchanged even if ${}_{c}p_w$ was increased. The ratio of the shear force acting on the pile cap differs between the pile cap hoop and the column hoop arranged in the pile cap. It is considered that pile cap hoops contribute more effectively to shear resistance because the tensile force of pile cap hoops decreases with increasing.

4.3. Relationship between the pile cap input shear force and the amount of hoop

Figure 7 shows the relationship between the maximum pile cap input shear force, the amount of pile cap hoop, and the pile cap hoop in the test specimen of this study and specimen A-4. The tensile strength of the main bar of the foundation beam was calculated from the strain at the critical section position of the foundation beam, and the input shear force of the pile cap was calculated by the following equation.

$$V_j = T - Q_c \tag{6}$$

Where, T: tensile force of foundation beam bar, Q_c: story shear force.

When ${}_{c}p_w$ was less than 0.15%, the input shear force increased as ${}_{c}p_w$ increased, but when ${}_{c}p_w$ was more than 0.15%, the input shear force became almost constant. The effect of ${}_{c}p_w$ on pile cap strength was considered to be limited to ${}_{c}p_w \leq 0.15\%$ in this study. Even when ${}_{pc}p_w$ increased, the input shear force showed almost the same value or a tendency to slightly increase. At the time of positive loading, the input shear force generally tends to increase as the total hoop amount in the pile cap increases. However, the relationship between the total hoop amount and the input shear force became constant under negative loading.

4.4. Carrying of the pile cap hoop

Figure 8 shows the ratio of the average stress and the yield stress of the pile cap hoop at the maximum strength in the specimen of this study and specimen A-4. In the case of pile cap hoops, the stress at the maximum shear strength was large in all specimens at positive loading. On the other hand, at the time of negative loading, the stress varies greatly for each specimen. For the column hoops, the stress at positive loading was smaller than that of the pile cap hoops. Furthermore, the carrying stress of the column hoop was almost constant even if ${}_{c}p_w$ was arranged more than 0.15%. This is consistent with the

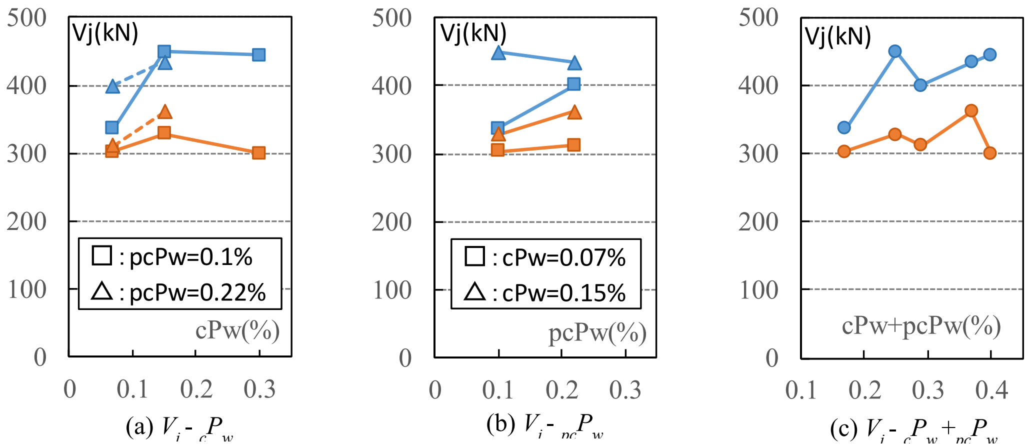


Figure 7. Relationship between maximum input shear force and two kinds of hoop in pile cap.

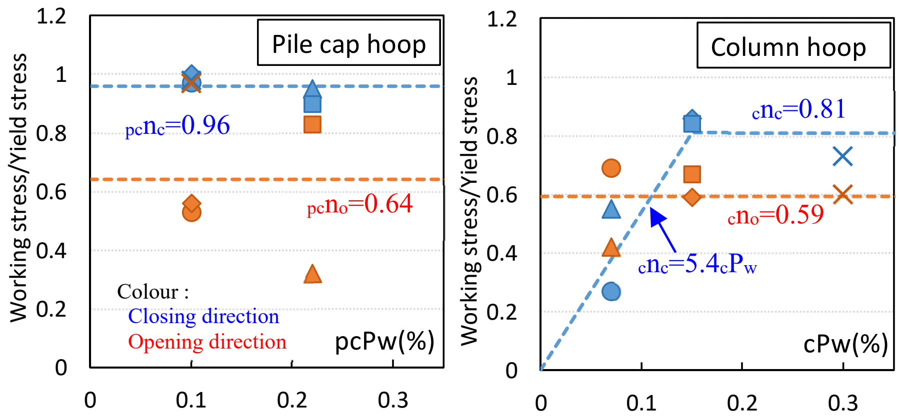


Figure 8. Ratio of the average stress and the yield stress of the pile cap hoop.

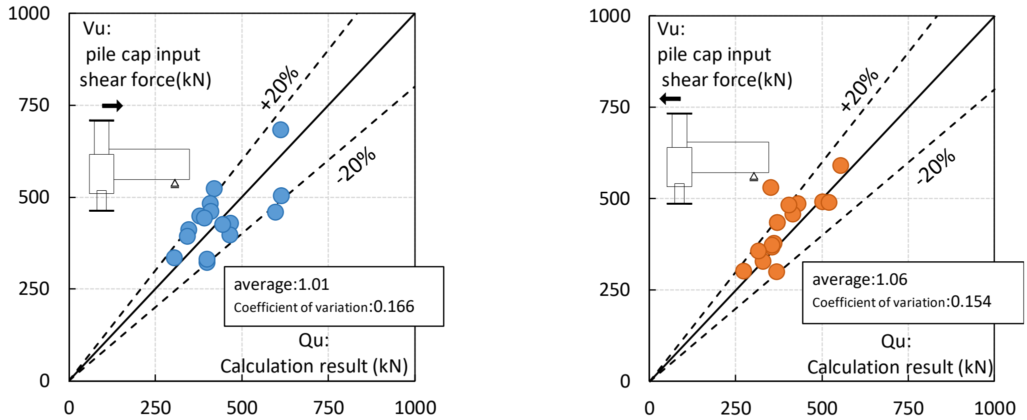
1. when $\nu_0\sigma_B -_c \sigma_t < 0$	V_u is smaller of the follow. $$V_u = \begin{cases} \dfrac{\lambda_c\,\nu_0\,\sigma_B + {}_cn\ {}_cp_{we}\ {}_c\sigma_{wy}}{3}\ {}_cb_e\ {}_cj_e \\ \dfrac{\lambda_c\,\nu_0\,\sigma_B}{2}\ {}_cb_e\ {}_cj_e \end{cases} \quad (3)$$
2. when $\nu_0\sigma_B -_c \sigma_t \geq 0$ and $\nu_0\sigma_B -_c \sigma_t -_{pc} \sigma_t < 0$	$_cV_t = 2\,{}_cn\ {}_cp_{we}\ {}_c\sigma_{wy}\ {}_cb_e\ {}_cj_e$ $_{pc}V_t$ is smaller of the follow. $${}_{pc}V_t = \begin{cases} \dfrac{\lambda_{pc}\,(\nu_0\,\sigma_B -_c \sigma_t) + {}_{pc}n\ {}_{pc}p_{we}\ {}_{pc}\sigma_{wy}}{3}\ {}_{pc}b_e\ {}_{pc}j_e \\ \dfrac{\lambda_{pc}\,(\nu_0\,\sigma_B -_c \sigma_t)}{2}\ {}_{pc}b_e\ {}_{pc}j_e \end{cases} \quad (4)$$ $V_u =_c V_t +_{pc} V_t$
3. when $\nu_0\sigma_B -_c \sigma_t -_{pc} \sigma_t \geq 0$	$_cV_t = 2\,{}_cn\ {}_cp_{we}\ {}_c\sigma_{wy}\ {}_cb_e\ {}_cj_e$ $_{pc}V_t = 2\,{}_{pc}n\ {}_{pc}p_{we}\ {}_{pc}\sigma_{wy}\ {}_{pc}b_e\ {}_{pc}j_e$ $V_a = (\nu_0\sigma_B -_c \sigma_t -_{pc} \sigma_t)\ \dfrac{bx_n}{2}\sin 2\theta \quad (5)$ $V_u =_c V_t +_{pc} V_t + V_a$

Note: $x_n = \frac{D}{4}(1+2\eta)$, $\theta = \tan^{-1}\frac{D-x_n}{L}$, $\nu_0 = 2.3\,\sigma_B^{-0.33}$.
Symbols are explained in the nomenclature.

Table 4. Pile cap shear strength formula based on previous investigation.

Loading direction	Closing	Opening	Closing	Opening
	$_{pc}n_c$	$_{pc}n_o$	$_{c}n_c$	$_{c}n_o$
Carrying ratio	0.96	0.64	5.4 cPw (cPw < 0.15 %) 0.81 (cPw > 0.15 %)	0.59

TABLE 5. Carrying stress coefficient.



(a) opening direction (b) closing direction

FIGURE 9. Relationship between experimental values and proposed calculations.

fact that the input shear force became almost constant in the range of $_cp_w$ over 0.15% in the relationship between V_j and $_cp_w$. Based on the above results, the values obtained by approximately calculating the ratio of the carrying stress applied to the hoops of the pile cap and the column are shown by the broken line in Figure 8. And Table 5 shows the carrying stress coefficient obtained from the Figure 8. Table 4 shows pile cap shear strength formula applied carrying stress coefficient.

The stress of the hoops under positive loading was approximated in the range of $_cp_w < 0.15\%$ so that the proportion of the hoops increased in proportion to the increase of $_cp_w$. In the range of ă$_cp_w \geq$ ă0.15%, based on the fact that the strength did not change even if $_cp_w$ was increased, using the ratio of the material strength of specimen A-7a and the carrying stress of 0.81, the upper limit of $_cp_w \cdot_c \sigma_y$ was set to 0.55 (N/mm^2).

5. 5. Compatibility of pile cap ultimate shear strength formula

The calculation was performed by substituting the coefficients obtained in Table 5. The target specimens were the specimens of this study and the specimens judged to be pile cap shear failure in past experiments [2–4]. Figure 9 shows the comparison between the calculation result by the proposed formula and the experimental value. The input shear force was determined from the value of the strain gauge by defining the position at which the strain of the main bar of the foundation beam was maximum as the critical section. As shown in Figure 9, the experimental / calculated values obtained by the proposed formula were generally within ±20% (dotted line in the Figure), and the average and coefficient of variation were 1.01-1.06 and 15.4-16.6%, respectively. The average (the dashed line in the Figure) and the standard deviation were also considered to be valid as experimental values. However, only the standard type specimen was greatly underestimated on the side where the column-foundation beam opened. The cause is considered to be that the effective reinforcement ratio of the pile cap is extremely low at 0.03%, and the truss mechanism has not been formed. From this experiment, the minimum reinforcement amount is set to 0.07% as the applicable range of the pile cap effective reinforcement ratio.

6. Conclusions

1. Among the reinforcements arranged in the pile cap, the pile cap stirrups contributed more to the shear load. By arranging many pile cap hoops, an increase in pile cap shear crack width was suppressed.
2. It was confirmed that the relationship between the total amount of hoops in the pile cap and the input shear force to the pile cap was different depending on the loading direction.
3. The shear strength formula proposed in the past

was able to be evaluated safely by considering the load ratio of the hoops at the time of pile cap shear failure.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number JP23560679. This experiment was carried out in Structural Lab. at BRI. Authors would like to express their gratitude to JAPAN PILE Co., Ltd. for providing steel piles, Neturen Co., Ltd. and TOKYO TEKKO CO., Ltd. for providing steel bars, we are deeply grateful to them.

List of symbols

${}_{c}b_e$ the truss effective width in column

${}_{c}j_e$ the truss effective depth in column

${}_{c}V_t$ column shear strength in truss mechanism

${}_{pc}p_{we}$ the effective ratio of shear reinforcing bar in the pile cap

${}_{pc}V_t$ pile cap shear strength in truss mechanism

${}_{c}\sigma_t$ column compression stress in truss mechanism

${}_{pc}\sigma_t$ pile cap compression stress in truss mechanism

${}_{c}p_{we}$ the effective ratio of shear reinforcing bar in the column

${}_{c}\sigma_{wy}$ the yield stress in column reinforcing bar

${}_{c}\sigma_{wy}$ truss effective coefficient in column

${}_{pc}\sigma_{wy}$ the yield stress in pile cap reinforcing bar

${}_{pc}b_e$ the truss effective width in pile cap

${}_{pc}j_e$ the truss effective depth in pile cap

b pile cap effective width

D pile cap effective depth

L member length

V_a shear strength in arch mechanism

x_n the neutral axis position in arch mechanism

η axial force ratio

θ the angle of compression strut in the arch mechanism

λ_c the yield stress in column reinforcing bar

λ_{pc} the truss effective coefficient in pile cap

ν_0 effective coefficient of concrete compression stress

σ_a compression stress in arch mechanism

σ_B concrete compression stress

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