EXPERIMENT and RESEARCH on THE BEHAVIOR of PILE CAPS

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ABSTRACT: To study the behavior of thick pile caps, five 1/10 scale models of nine-pile caps with different heights, reinforcement ratios and forms of reinforcement layout were loaded on vertical loads. The experiment results indicated that the failures of all the five models are resulted from punching shear (two-way shear). It was found that the strut-and-tie model is also suitable for the designing of pile caps with nine piles and more rational than the traditional shear design procedures, and the longitudinal reinforcement should be concentrated over the piles to form reinforced tie.

KEYWORDS: pile caps; strut-and-tie model; crack load; failure load

Introduction

As important structural elements, pile foundations are used extensively in civilian constructions and highway bridges. As far as pile cap is concerned, it provided to spread the vertical (and horizontal, under certain circumstances) loads to piles. Usually, such a pile cap is of reinforced concrete and is cast directly on the top of piles. The column or wall from the superstructure erects on the cap. Most of these caps are thick pile caps and behave unlike flexural members. Some experimental researches on the behavior of pile caps have been reported in literatures[1,2,3] both at home and abroad. These reports confirmed that the load-transferring mechanism and failure mode of pile caps conform to the strut-and-tie models. However, much research work has been done on pile caps with no more than six plies. Further researches shall be carried out on design of large-scale pile caps with a group of piles in complicated loads by strut-and-tie models.

Research Significance

1. The pile foundation of nine-pile cap can be divided into middle pile, angle piles and side piles. Under conditions of changing the rigidity of piles, the load distribution form of all kinds of piles can be definitely judged.
2. There is no report on the test of nine-pile cap both at home and abroad. The ultimate bearing capacity of the pile cap has a close relationship with the arrangement of piles.
3. Nine-pile cap has various strut distribution and strut-tie connection forms in the process of validating the calculating criteria of space truss model.

Present Design Methods

Stress distribution in the pile cap is so complicated that nations of the world only make some fundamental regulations for the cap design at present, and they are differ from each other. According to the failure mode and failure mechanism, they can be divided into two kinds. The first kind sees the pile cap as a general flexural component whose bearing capacity of bending, punching and shearing will be calculated according to the designing criterion of concrete structure, but modification must be made to the computing formula of bearing capacity as considering the influence of shear span ratio according to the characters of punching and shearing failure of the cap. The other kind suggests that the pile cap need to be analyzed by the strut-and-tie model according to the spatial suffering force character of thick cap, and it is believed that the load is mainly bore by the truss which composed of concrete and steel bar in the direction of internal stress current in the cap. Design methods for pile cap which given in the listed references[4,5] belong to the first kind, and the references[6,7,8] belong to the second kind. The code[4] is the first criterion which classify the strut-and-tie model into the design of pile cap at home : the critical section of pile cap should be calculated according to the "beam model" when the distance between the center of the outmost piles and the column (pier) face is greater than the height of cap, and when the distance is equal to or smaller than this height. It will be calculated according to the "strut-and-tie model"

Test Program

Specimens for testing are scaled models, since full-scale pile caps would not only be expensive but also unmanageable in available facilities in the laboratory. Considerations about the specimens are listed as following points:

1. Keeping the size of cap within 1200 x 1200mm, so that the base of testing machine could accommodates the specimen.
2. C20 concrete was adopted for casting the cap. Adopt C60 concrete for casting piles and columns in the pre-casting form in order to make sure both piles and columns respectively under and over the cap will not fail before the failure of the cap.
3. Three 150mm standard test cubes were cast for each batch of specimen, amounting to 27 cubes.
4. A universal testing frame was used to apply compressive load onto the columns. Steel plate with 5mm thickness was placed between column and jack to ensure that the column which under stress would act uniformly.
5. It was decided to use three typical series of specimens to cover the range of variables found in Chinese general engineering practice. Five pile caps with nine piles for one column (as shown in Fig. 1) were adopted for the test. These models varied in height of caps, reinforcement ratios and forms of reinforcement layout. An important aim of the test is to study the influence of various heights of caps, steel ratios and forms of longitudinal reinforcement layout.

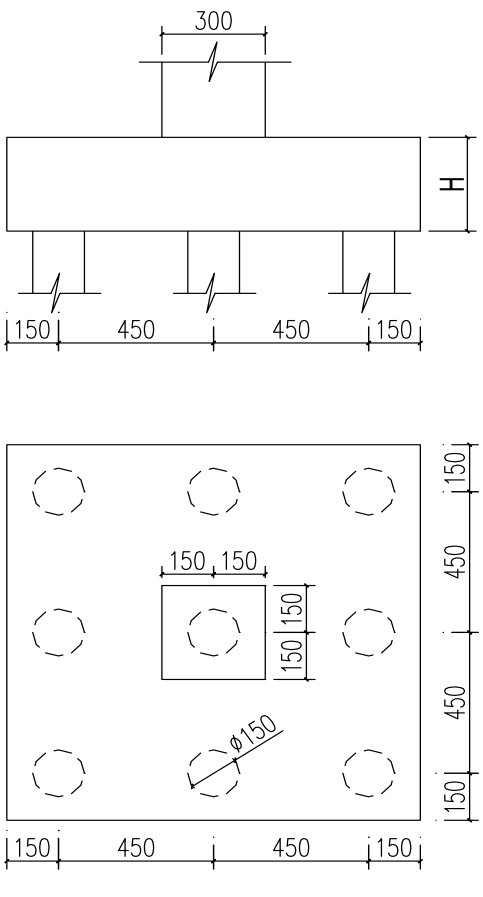


Fig.1 Nine-pile cap details (All dimensions in mm)

Experimental Details, Materials and Testing

Five nine-pile cap specimens with identical plan dimensions were fabricated for the experiment. These specimens will be labeled from S1 to S5. Details of the five pile caps are shown in Table 1. S1 was a plain concrete pile cap, which served to verify the test devices and as preliminary specimen for the following caps. The rest of specimens were designed according to the strut-and-tie model[9,10]. S2 was similar to S3 except for the different layout of reinforcement. S4 and S5 were constructed to test the effects of varied heights and reinforcement ratios on pile cap behavior.

Table 1 Physical dimensions and reinforcement details of specimens

Specimen label	Cap size, mm		Pile diameter, mm	Arrangement of reinforcement	Reinforcement layout
	Plan size	h			
S1	1200 square	360	150	——	Plain specimen
S2	1200 square	360	150	12Φ14 each way	Bunched
S3	1200 square	360	150	6Φ16+5Φ14 each way	Grid
S4	1200 square	300	150	6Φ14+6Φ12 each way	Bunched
S5	1200 square	420	150	6Φ16+6Φ14 each way	Bunched

The Concrete which used for the experiment was premixed C20 concrete. Columns and piles were cast in the same batch and cured for 28 days in the standard curing room. Adopt Φ10 main steel bar and Φ6 round steel bar for piles while adopt Φ16 main steel bar and Φ8 round steel bar for columns.

The total loads applied to the column were measured by the use of oil gauge. Vertical deflections of the pile caps were measured by displacement transducers and dial indicators. Electrical-resistance gages were installed at some special locations along selected reinforcements. Measuring points of hand-held strain gauge were fixed on some sides for measuring average strains of plain concrete with different heights. Piles were supported on steel pedestals, which in turn were supported on rubber pads. Piles with different rigidities could be simulated by varying the rigidities of rubber pads. All electronic measurement data were automatically recorded by computer. The load on the columns was increased by step; the load increment of each step accounts for 10% to 15% of the predicted failure load.

The plain concrete pile cap (S1) was firstly tested to determine the maximal ultimate bearing pressure and failure mode; so that the rest specimens could be tested following the similar testing procedure and the test data could be used for reference for the following tests.

Analysis and The Results of Discussion

A number of observations were made during the tests, and we can make a conclusion that the pile caps are prone to two-way shear, most specifically punching shear. Fig.2 shows the observed crack patterns of the pile caps at failure. The failure load of these specimens was predicted by using some of the aforementioned design methods. Results of the analysis with experimental loads are presented in Table 2.

In the plain concrete pile cap (S1), four major cracks formed at the bottom when the load added to550KN, which traversed immediately to the sides and resulted eventually in abrupt failure. As soon as the load exceeded the tensile capacity of the concrete, the cracks formed simultaneously and failure took place, so that the cracking load is the failure load of S1.

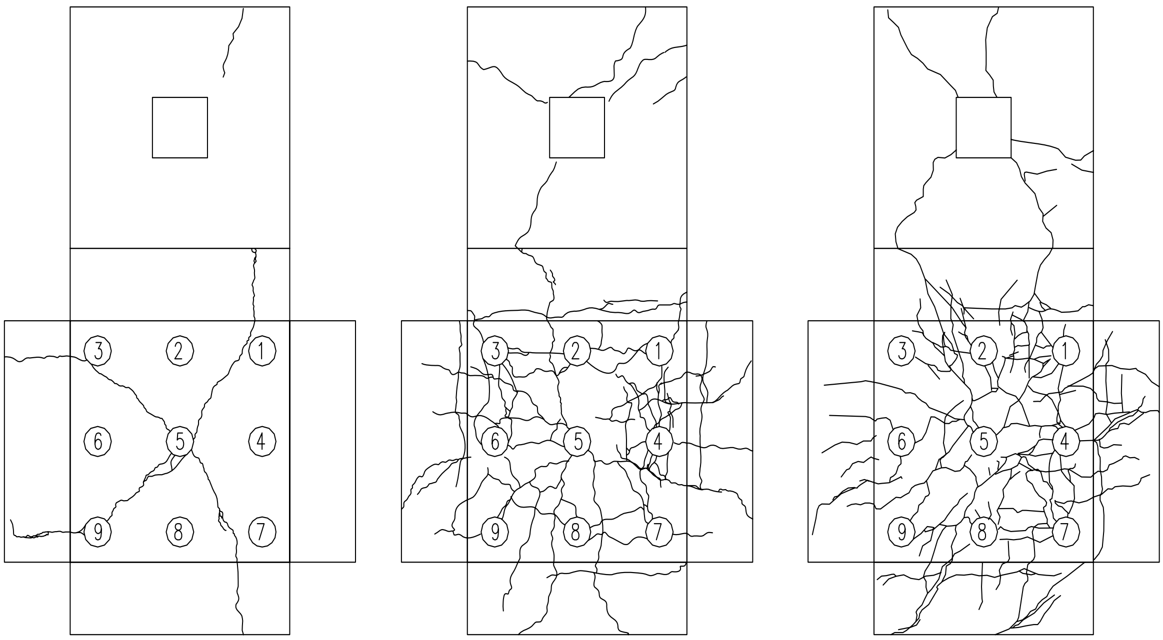
Table 2 Comparison of experimental and predicted failure loads

Cap	Predicted loads, KN				Failure load, KN	Ratio of experimental to predicted loads, KN			
	CDBF[4]	CHBC[6]	ACI[5]	AASHTO[8]		CDBF	CHBC	ACI	AASHTO
S1	——	——	——	——	550	——	——	——	——
S2	1066.5	907.6	1232.7	1935.3	2100	1.969	2.314	1.704	1.085
S3	1066.5	907.6	1232.7	1935.3	1900	1.782	2.093	1.541	0.982
S4	733.5	623.8	842.8	1651.3	1800	2.454	2.886	2.136	1.090
S5	1445.9	1231.2	1605.5	2135.7	3300	2.282	2.680	2.055	1.545

S2, which was designed in accordance with the strut-and-tie model, has the same predicted failure load with S3. The first crack appeared at the bottom of the cap at approximately 700KN and extended to the sides promptly. The strains in the reinforcements suddenly increased as soon as the first crack appeared. At the load of 1200KN, cracks further developed, the largest width of the crack measured 0.2mm. Many new cracks developed around piles before the failure load was approaching; when the total load applied on the column reached the maximal load of 1900KN, a shear failure occurred with a square crack pattern within the inside edges of the peripheral eight piles. Removed concrete along the failure cracks, a punching cone could be found that extended from the column's outside to the inside edges of the piles.

S3 was similar to S2 except for the layout of reinforcements. The ultimate load was 2100KN; an increase of 11% over the S2 value. The first crack was observed at 700KN with the strains of the reinforcements in the relevant locations exhibited a sudden increase. The difference in reinforcement arrangements had hardly any effect on the crack load. The largest crack width measured was 0.2mm when the load was approximately 1300KN. As the load continued to increase, a large number of cracks kept on developing at the bottom and the sides of the pile cap. At the failure load of 2100KN, several primary cracks were found to develop at the top surface which surrounding the column faces. The appearance of the failure zone was similar to the S2 which was a typical punching zone.

The failure processes of S4 and S5 were similar to S2. S5, which was designed with deeper depth and larger amount of reinforcement than S4 failed at a maximum load of 3300KN. The failure load was 83% higher than the S4. The first crack appeared at the bottom of pile cap S5 at the load of 1000KN, 67% higher than the crack load of S4. It is indicated that the increment in thickness of pile cap and reinforcement quantities can effectively improve the crack load and failure load of the cap. Cracks continued to develop at a slow rate with the load increased. The failure load reached in company with many new cracks developed on the vertical faces, bottom and top surface of the cap.



(a) Pile Cap S1 (b) Pile Cap S2 (b) Pile Cap S3

Fig.2 Typical crack patterns of the pile cap specimens

Conclusion

The shear strength of a thick pile cap is considerably estimated using the "beam model". Strut –and-tie models were found to be reasonable for designing thick pile caps, which have been supported by the available test data. The destructive process of the plain specimen indicated that longitudinal reinforcement has a strong influ ence on the shear strength of pile cap. In reinfor cing concrete pile caps, there are some key factors contributed to the bearing capacity, such as span to depth ratio, amount of reinforcement and reinfor cement arrangement. However, the “beam model” doesn’t take the contribution of longitudinal reinforcement of the shear strength into account and is excessively conservative for pile caps.

References:

[1] Sabnis, G.M., and Gogate, A.B. 1984. “**Investigation of thick slab (pile cap) behavior**”. ACI Journal, 81(5): 35-39.

[2] Adeber P, Kuchma D, Collins M P. “**Strut and tie models for the design of pile caps: an experimental study**”. ACI Structural Journal, v87, n1, Jan-Feb, 1990: 81-92.

[3] Adebar P, Zhou Luke. “**Design of deep pile caps by strut-and-tie model**” [J]. ACI Structural Journal, v 93, n 4, Jul-Aug, 1996: 437-448.

[4] GB50007□2002□□□□□□□□□□□[S]

[5] ACI Committee 318, “**Building code requirements for reinforced Concrete (ACI318-02)**,” American Concrete Institute, Detroit, 2002.

[6] JTG D62□2004, □□□□□□□□□□□□□□□□□□□□[S]

[7] Canadian Standards Association. “**CAN3-A23.3-M94 Design of concrete structures for buildings**”. Canadian Standards Association, 1994

[8] Standard specifications for Highway Bridges, “**15th ed., American Association of State Highway and Transportation Officials (AASHTO)**”, Washington, DC, 1992.

[9] Cavers, William, Fenton, Gordon A. “**An evaluation of pile cap design methods in accordance with the Canadian design standard**” [J]. Canadian Journal of Civil Engineering, v31, n1, February, 2004: 109-119.

[10] Adebar Perry. “**Discussion of An evaluation of pile cap design methods in accordance with the Canadian design standard**" [J]. Canadian Journal of Civil Engineering, v31, n6, December, 2004: 1123-112