Ultimate shear strength of pile caps

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Abstract

This paper proposes a design methodology for ultimate shear strength of pile caps subject to various stresses, based on experiments and numerical analyses. First, we determine an evaluation equation for shear strength of pile caps with compressive piles. Second, we clarify the shear resistance mechanism of pile caps with pull-out piles, and confirm to be able to apply the determined evaluation equation to those with pull-out piles by modifying the setting of shear span. The proposed methodology was introduced into the current version of the Japanese Specifications for Highway Bridges (March 2002).

1 INTRODUCTION

Due to the disastrous consequences of earthquakes in past decades, the need for an approach that would unify and simplify design procedures for bridge foundation has been recognized. In the 1995 Hyogo-ken Nanbu Earthquake there was a clear demand from structural engineers for an appraisal of consistent design methodologies that could provide a realistic description of the behavior of pile caps. This paper describes two investigations on the behavior of pile caps.

The first one introduces a newly established design method for ultimate shear strength of pile caps supported by compression piles. Typical pile caps are in the category of deep beams or two-way slabs. This paper reviews extensive research activities on pile caps and establishes a design method to enhance the structural performance of pile caps consisting of deep beams.

The second investigation focuses on damage to pile caps due to the pull-out of piles subjected to a heavily inclined-eccentric load during an earthquake. In former design specifications of bridges in Japan, the structural design method of pile caps with pull-out piles was not well documented. In addition, there have been few studies on the structural evaluation of pile caps with pull-out piles because the occurrence is not common in moderate earthquakes. The Public Works Research Institute (PWRI) therefore conducted experimental studies to investigate the shear-resisting mechanism

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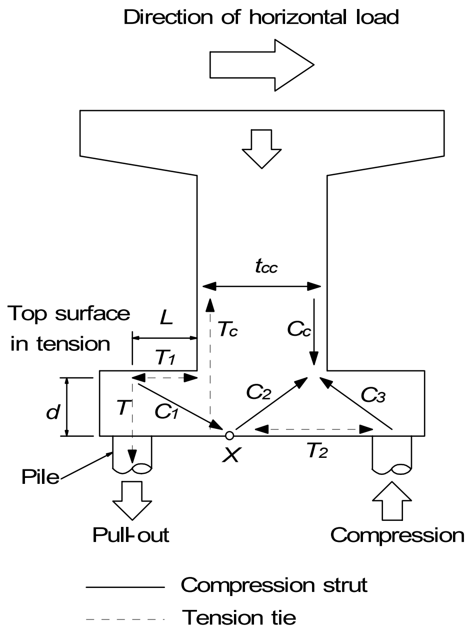


Figure 1 Struts and ties in a pile cap

of pile caps. The experiment included several specimens consisting of columns and pile caps using the parameters of shear span to depth ratio. Load-deformation relationship, strain development, crack pattern and so on were observed in the experiment. In addition, numerical analysis demonstrated the validity of these observations for establishing a design system.

This paper proposes a design methodology for ultimate shear strength of pile caps subject to various stresses, which leads to a more accurate, economical and rational approach for these structural units. The proposed methodology was introduced into the current version of Japanese Specifications for Highway Bridges (March 2002). PWRI has also proposed a design method for the slab effect (punching shear) based on relevant experimental investigations. The detailed discussion is given elsewhere [1, 2].

2 IDENTIFICATION OF LOAD PATHS IN PILE CAPS USING STRUT-AND-TIE MODELS

For deep beams, walls and discontinuous regions of structures, design methods based on strut-and-tie models are frequently utilized to describe load effect and resistance [3]. This relies on the assumption that the design expects convenient load paths to form within structural concrete members that are considered to form struts and ties or various types of truss models.

Figure 1 illustrates the load (stress) paths in a pile cap where solid lines and dotted lines represent compression struts and tension ties, respectively. The right-hand side of Figure 1 explains that the pile reaction is supported by forming a "force triangle" consisting of C_3 (compression) and T_2 (tension).

Many experimental studies have confirmed the applicability of strut-and-tie models for pile caps with compression piles. On the other hand, the force equilibrium is different in the pile cap due to the pull-out pile. It seems that conventional compression strut is not available in this case, which means that point X has to be determined by a complicated and sophisticated load pass. This is the main difference in the design of pile caps in the case of compression and pull-out piles.

3 REVIEW AND RE-EVALUATION OF THE SHEAR DESIGN OF PILE CAPS

3. 1 Existing shear design of pile caps

The design procedure for pile caps documented in the Specifications for Highway Bridges IV; Substructures, Japan [4, 9] includes 1) shear span a to effective depth d ratio, 2) shear strength of concrete contribution and 3) shear resistance due to transverse reinforcement. The shear span to effective depth ratio a/d in pile caps is an important parameter in shear design. The shear strength of a pile cap is the sum of the concrete contribution and resistance of shear reinforcement.

$$S_d = S_{dc} + S_{ds} = c_{dc} S_c + c_{ds} S_s \tag{1}$$

$$S_{dc} = c_{dc} S_c , \quad S_{ds} = c_{ds} S_s \tag{2}$$

where S_d is shear strength as deep beams, S_{dc} is shear resistance carried by concrete in deep beams and S_{ds} is shear resistance carried by transverse reinforcement in deep beams. S_c is shear resistance carried by concrete in ordinary (slender) beams, S_s is shear resistance carried by transverse reinforcement derived from truss analogy, c_{dc} is the modification coefficient of S_c and c_{ds} is the modification coefficient of S_s, both being dependent upon a/d.

In 1996, the design specification introduced a design formula for evaluating shear strength of pile caps. The coefficients c_{dc} and c_{ds} were provided as follows:

$$c_{dc} = \frac{6.3}{1.3 + 0.8(a/d)^2} \tag{3}$$

$$c_{ds} = \frac{a}{2.5d} \tag{4}$$

Both coefficients are valid for beams of a/d less than 2.5. However, these seem to be overly conservative, particularly with respect to Eq. (3). Although the coefficients c_{dc} was determined from the results of numerous experiments on various deep beams, the coefficient was set considerably lower than the average value because of the large scatter in the load test results. The coefficient c_{ds} was given by conservative judgment because only minimal data was available.

Accordingly, the small shear strength of concrete using Eq. (3) requires a considerable amount of transverse shear reinforcement in some cases, so there is a demand to review and modify Eqs. (3) and (4).

3.2 Review of load test results [5, 6]

Existing experimental data on the shear strength of deep beams without shear reinforcement was collected and summarized in Figure 2, in which the parameters are shear span to depth ratio and the ratio of shear strength to ordinary beams, where S_e is the observed shear strength. The figure shows considerable scatter in the data and no explicit increase in shear strength with decrease of a/d. In Figure 2, the dotted line derived from Eq. (3) seems to cover the lower bounds of the shear strength. The most probable shear strength of deep beams was obtained by applying the least mean squares method for data of a/d from 0.4 to 3.0. The result is Eq. (5) shown in Figure 2.

$$c_{dc} = \frac{12.2}{1+(a/d)^2} \qquad (5)$$

The large variation in experimental data is probably due to something other than a/d. Through a review of load test results, as shown in Figure 3, it was found that there is a clear difference in the shear strength of concrete between $b/d = 0.2$ and 0.4, where b is the width and S_{dc} is calculated by Eqs. (2) and (5). Since the width of the pile caps should be larger than their depth, i.e., wide beams or slabs, we can omit the experimental results of the specimens in which b/d is less than 0.4. Figure 4 illustrates that the relation between S_e/S_c and a/d derived from previous load tests in which the results of specimens with small b/d ($b/d < 0.4$) are eliminated gives the best fit coefficient in Eq. (6), as shown by the solid line.

$$c_{dc} = \frac{14.0}{1+(a/d)^2} \qquad (6)$$

As the variation in data could be minimized by eliminating the results of the thin specimens, Eq. (6) exhibits high reliability for shear design of deep beams. A reliability analysis was introduced to re-evaluate the modification coefficient c_{dc} employed in the design provisions. Because design practice requires a safety margin in the shear strength, a reliability index, so called β, was set to 2.0, into which only 2.3% of the data may fall. Eq. (7) is also shown in Figure 4 by the broken line.

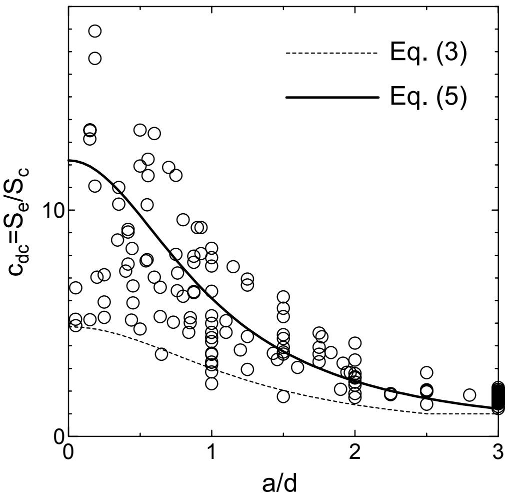


Figure 2 Effect of shear span to depth ratio on shear strength of concrete

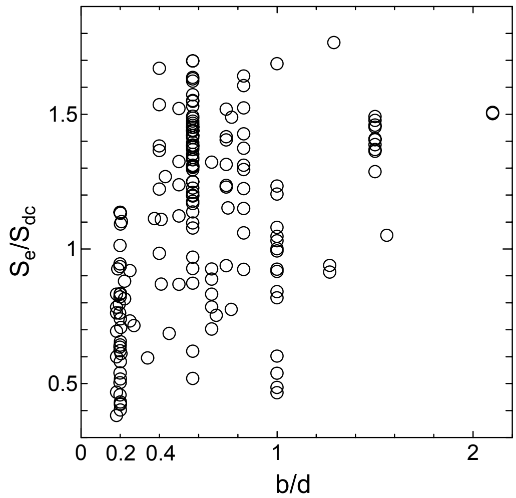


Figure 3 Effect of beam width to depth ratio on shear strength in deep beams

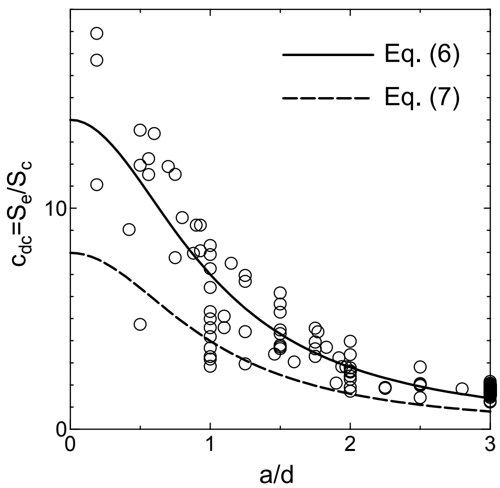


Figure 4 Effect of shear span to depth ratio on shear strength of concrete in the case of $b/d \geq 0.4$

$$c_{dc} = \frac{7.98}{1+(a/d)^2} \tag{7}$$

where c_{dc} derived from Eq. (7) is 30–50% larger than that derived from Eq. (3).

3.3 Effect of transverse reinforcement

In slender beams, transverse reinforcement is effective for increasing both the resistance against diagonal tension after cracking and the strength of concrete compression strut by confinement. In deep beams, however, the angle of compression strut and diagonal cracking increases with the decrease of a/d; in other words, the

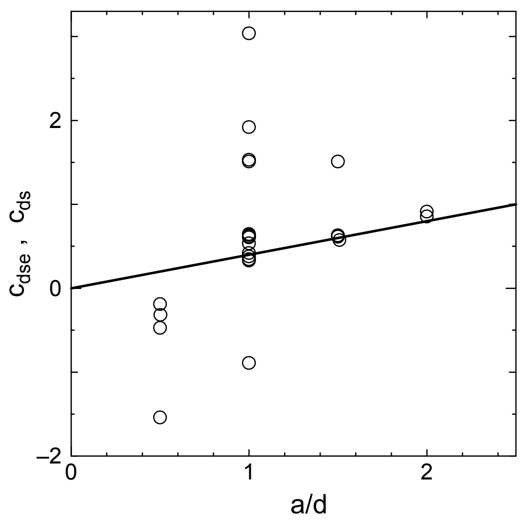


Figure 5 Effect of shear reinforcement on deep beams in the case of $a/d \le 2.5$

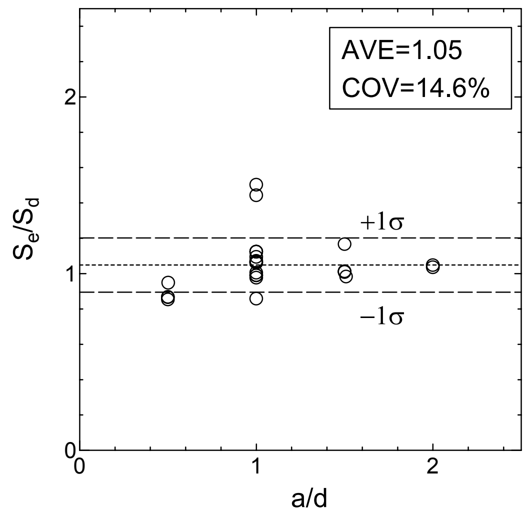


Figure 6 Comparison of observed shear strength S_e and calculated S_d

effect of transverse reinforcement becomes smaller. Although the contribution of transverse reinforcement of deep beam to shear strength was recognized through the experiments, quantitative evaluation on shear reinforcement has not yet been established in the design provisions.

As shown in Figure 5, the shear strength carried by transverse reinforcement depends upon a/d, where all data has b/d of not less than 0.4. In this figure, c_{dse} is derived from the following equation.

$$c_{dse} = \frac{S_e - S_{dc}}{S_s} \tag{8}$$

where c_{dse} is a modification coefficient of the effect of transverse reinforcement on shear strength estimated from experimental results, S_e is observed shear strength, S_{dc} is concrete shear strength calculated by Eqs. (2) and (6) and S_s is calculated shear strength carried by reinforcement by truss analogy. According to Figure 5, the solid line derived from Eq. (4) passes the mean shear strength. In Figure 6, the shear strength S_d calculated by Eqs. (1), (2), (4) and (6) is close to the observed data S_e. These figures clearly demonstrate that Eqs. (4) and (6) give an accurate estimation of the shear strength of deep beams. In comparison with the variation in Figure 5, the variation in Figure 6 is small. The reason is considered to be the small variation of material strength in the reinforcements and the variation of shear strength depends on that of the shear strength carried by concrete. In consideration of the concept of consistent shear capacity of pile caps with and without transverse reinforcement, the current design provision adopts Eqs. (1), (2), (7) and (4).

4 RESEARCH ON THE SHEAR OF PILE CAPS WITH PULL-OUT PILES

4.1 Experimental study [7]

The experimental program, which consists of three test series, involves the investigation of the mechanism and the development of a design method for the shear of pile caps subject to pull-out load.

The parameters in Series A and B tests, which employed two-dimensional models, are shear span to depth ratio. Test Series C adopted complete three-dimensional scale models of a pile cap with a column. The details of the three test series are described below. None of the specimens included shear reinforcement. In these load tests L represents the distance between the face of the pier and the center of the pull-out pile and is commonly used as the shear span in compression piles. On the other hand, in pull-out piles the shear span can be expected to be a little larger than L.

(1) Series A

The scale model involves a column and one half of a pile cap, as shown in Figure 7. The table in the same figure describes the parameters of shear span to depth ratio. The observed behavior is illustrated in Figure 8, where the initiation and propagation of cracks and final diagonal cracking are marked.

(2) Series B

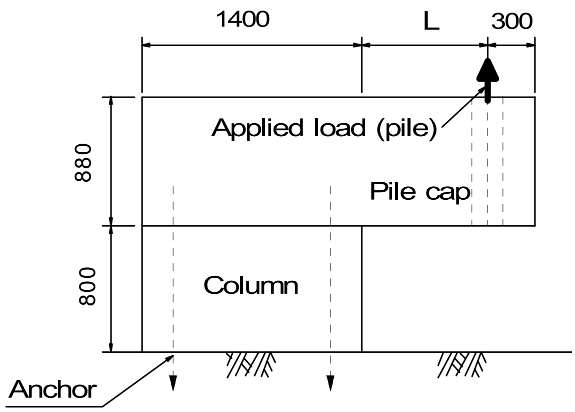
Similar test series, as shown in Figure 9, were conducted to evaluate the effect of shear span to depth ratio on the shear strength of concrete. The cracking behavior up to the point of diagonal shear failure was similar to that in Series A, as shown in Figure 10.

(3) Series C

Different from Series A and B, the Series C test has complete three-dimensional models of a pile cap with a column. The dimensions of the scale models used in this series are shown in Figure 11. The main parameter in Series C is also shear span to depth ratio. The cracks at failure are shown in Figure 12.

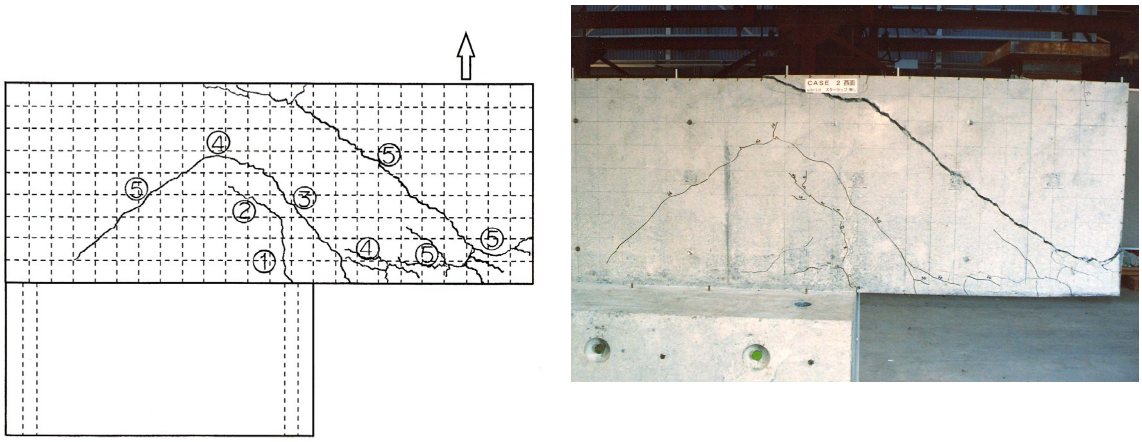
(4) Summary of experimental results

The observed shear capacity is useful data for proposing a design formula for pile caps with pull-out piles (loads). As introduced in Eq. (1), it seems that the modification coefficient c_{dc} for deep beams is applicable in this case by increasing the shear span length to some extent. The increase in shear span is recognized by the load path illustrated on the left-hand side of Figure 1. Figure 1 shows that the length of shear span may be determined by the load path, which depends upon the geometrical condition consisting of effective depth of pile cap d and depth of column t_{cc}. Figure 13 shows that the coefficient of shear strength c_{dc} calculated by Eq. (6) is closely related to a/d where three types of shear span a are compared. The effective depth of the pile caps and the half depth of the columns are not very different (10–20%) in Series A, B and C. Figure 13 gives similar results on the relation between a/d and c_{dc}.



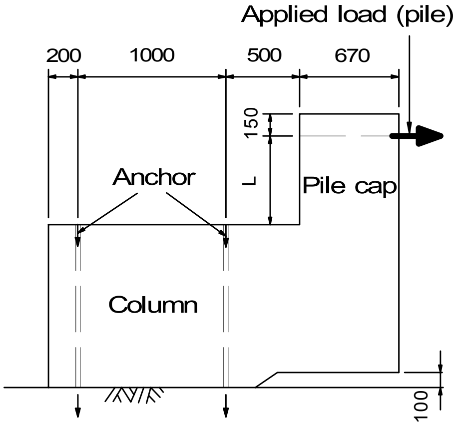
Specimen	A-1	A-2	A-3
Span to depth ratio L/d	0.5	1.0	1.5
Span L (mm)	400	800	1,200
Width b (mm)	600	600	600
Longitudinal rebar	0.83%, f_{sy} =365 N/mm^2		
Concrete strength (N/mm^2)	23.4	24.7	22.6
Maximum load (kN)	1276	737	660

Figure 7 Test specimens and maximum loads in Series A



Crack 1.	Initial crack
Crack 2.	Change in direction of crack
Cracks 3 and 4.	Propagation of crack to column base
Crack 5.	Initiation and propagation of second diagonal crack (failure)

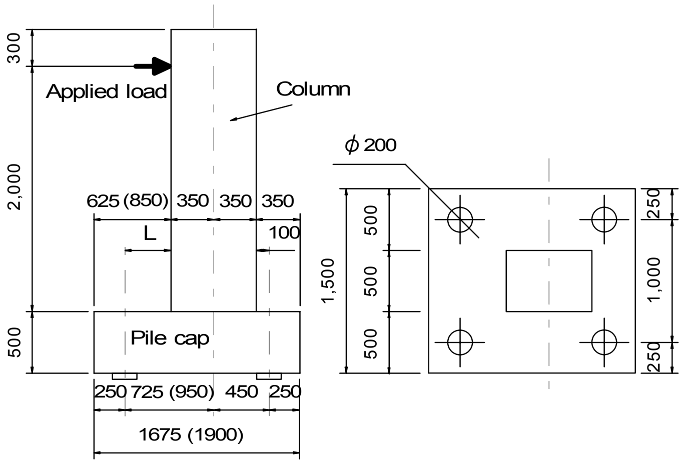
Figure 8 Crack pattern in A-1



Specimen	B-1	B-2	B-3	B-4
Span to depth ratio L/d	1.0	0.5	2.0	2.5
Span L (mm)	600	300	1,200	1,500
Width b (mm)	500	500	500	500
Longitudinal rebar	0.84%, f_{sy} =361 N/mm^2			
Concrete strength (N/mm^2)	23.5	26.0	27.3	27.1
Maximum load (kN)	380	514	249	239

Figure 9　Test specimens and maximum loads in Series B

Figure 10　View of load test in Series B



Specimen	C-1	C-2
Span to depth ratio L/d	0.833	1.33
Span L (mm)	375	600
Width b (mm)	1500	1500
Longitudinal rebar	1.62%, $f_{sy}=375$ N/mm^2	
Foundation type	Four piles	
Concrete strength (N/mm^2)	26.2	29.4
Maximum load (kN)	681	575

Figure 11 Test specimens and maximum loads in Series C

Figure 12 View of load test in Series C

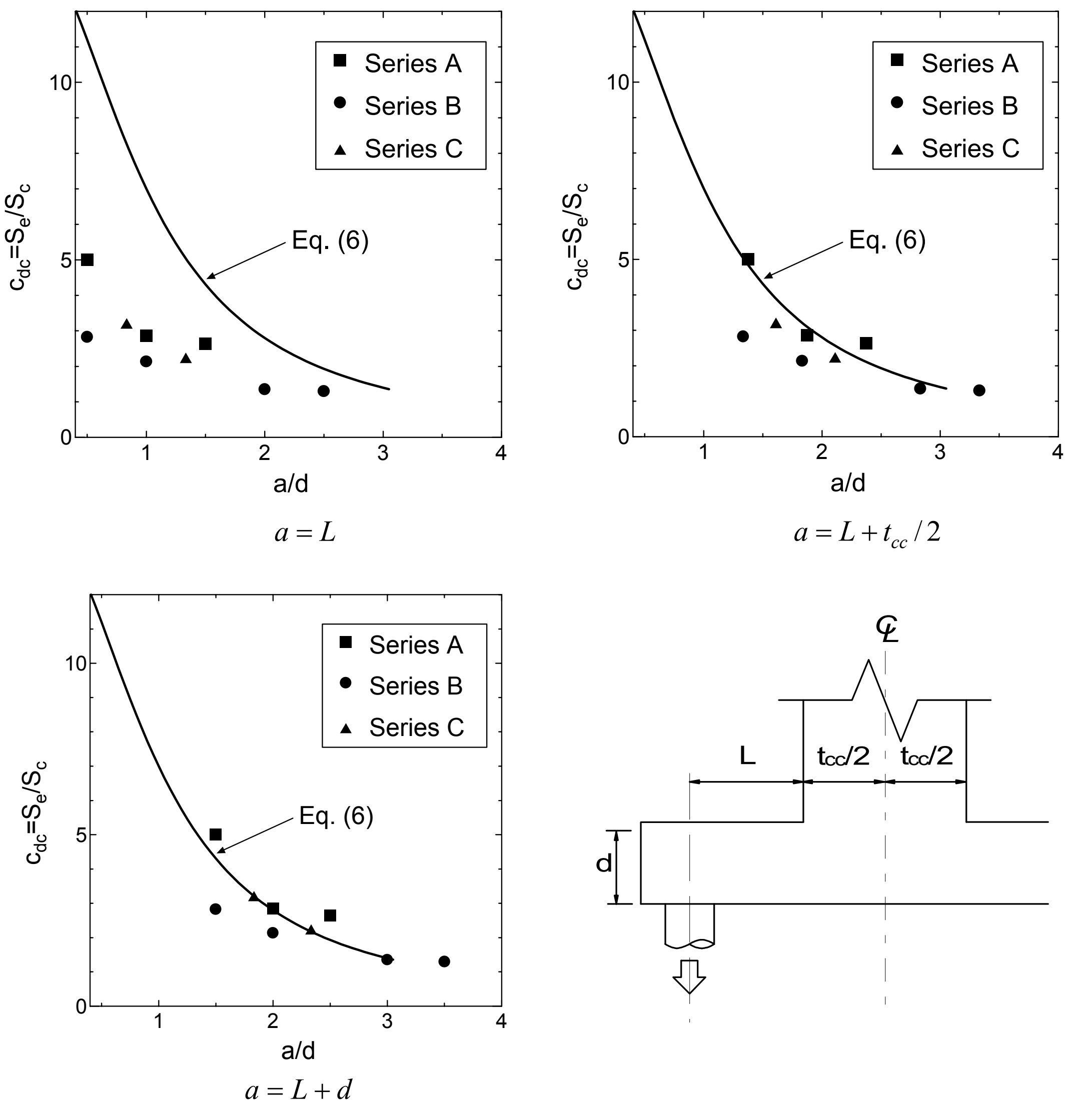


Figure 13 Relation between c_{dc} and a/d for three types of shear span

4.2 Numerical analysis observations [8]

The two-dimensional finite element (FE) models described herein represent the specimens of the experiment. A nonlinear FE analysis was performed for the test specimens of A-2 and C-2.

The load-displacement curves at the loading points are shown in Figure 14. The observed and calculated load-displacement curves are quite similar, indicating that the analysis is capable of describing the load transfer mechanism of the test specimens.

Principal compression stress distributions are shown in Figure 15. On the basis of these figures the compression stress derived from the analysis satisfactorily supports the assumption that the compression strut runs from the pull-out pile to the inside of the column in the case of pull-out piles.

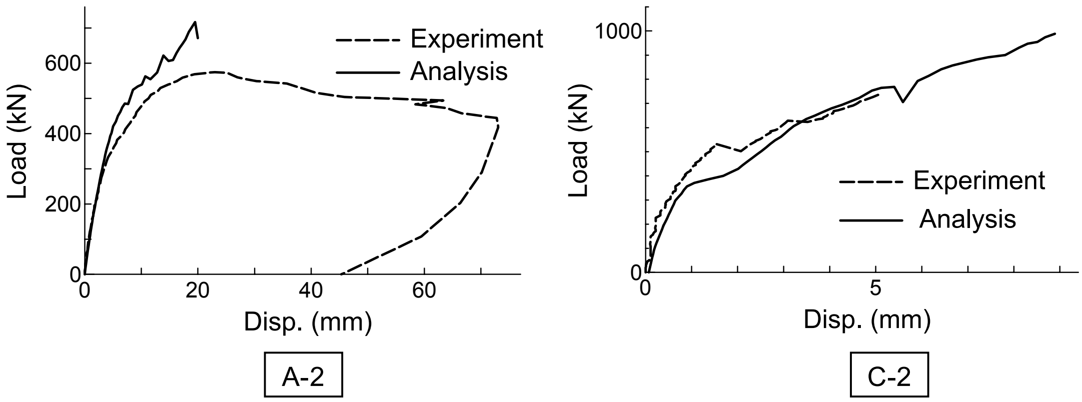


Figure 14   Comparison of measured and calculated load-deformation curves at the loading point

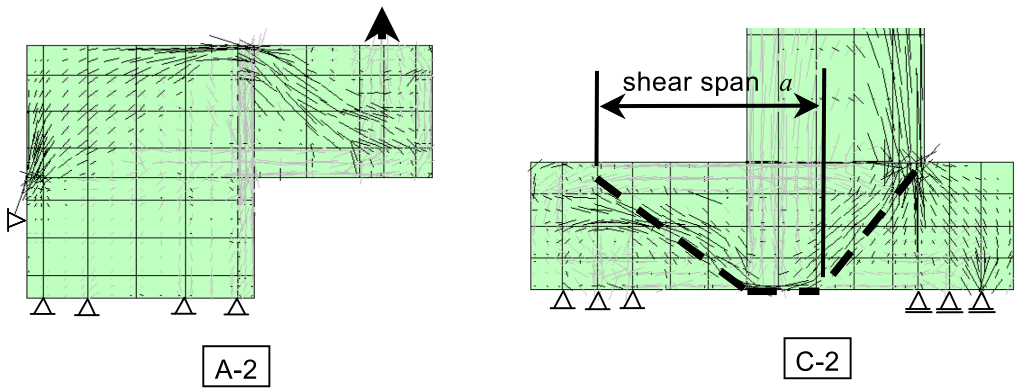


Figure 15   Principal compression stress distribution from FEM

In addition to the above experiments, numerical analysis was conducted for a number of pile caps subject to lateral load on the top of the column in order to evaluate the stress flow and to find an appropriate shear span. The analysis parameters are:

- width of columns,
- effective depth of pile caps, and
- number of rows of piles.

The analysis shows the principal stress in the pile caps in the manner denoted by the thick broken line in Figure 15. As the assumed shear span in Figure 15, a conservative assumption has been made that point X from which the compression strut changes direction as defined in Figure 1 is regarded as the farther point from a couple of the points at which the direction of the stress flow changes near the bottom in the pile cap such that the estimated shear span becomes longer. Consequently Eq. (9) gives the shear span of a pile cap with pull-out piles.

$$a = \min(L + t_{cc}/2,\ L + d) \tag{9}$$

5 CONCLUDING REMARKS

The following extensive investigation shows that a rational design approach has been established for pile caps.

- Re-evaluation of concrete shear strength in deep beams
- Effect of shear reinforcement

Based on the experiments and numerical analyses, the following hypotheses were found to be valid and applicable in the design of pile caps with pull-out piles.

- In the case of pull-out piles, a tied arch appears in the pile cap. However, the flow of compression stress forming the arch has a slightly different angle and runs into the column.
- The above stress flow means that the shear span in the pull-out pile is larger than that in the compression pile.
- The formula for the shear strength of pile caps with compression piles is applicable in cases of pull-out piles by modifying the shear span.

These conclusions were introduced into the current version of the Specifications for Highway Bridges in Japan (March 2002) [9].

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