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Experimental study on the mechanical behavior of bridge concrete pile caps

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Abstract

This paper presents an experimental study on the mechanical behavior of bridge pile caps subjected to lateral loading. Two scaled pile cap specimens with different pile layouts (2×2 and 2×3) were tested to investigate the influence of pile layout on the bearing capacity, crack distribution, strain distribution and load transfer mechanism of the pile cap was explored. Both specimens exhibited bending-dominated failure under increasing lateral displacement. However, specimen SV2×2 developed major bending crack in two directions, whereas specimen SV2×3 exhibited dominant bending cracks only along the width direction with smaller crack widths. The test results indicate that the pile layout significantly affects the stiffness degradation and load transfer mechanism of pile caps under horizontal loading. The maximum lateral load capacities were 255 kN and 314 kN for specimens SV2×2 and SV2×3, respectively. These findings provide experimental evidence for understanding the influence of pile layout on the seismic performance of bridge pile caps.

Keywords: Pile cap, Lateral cyclic loading, Pile layout, Crack distribution, Load transfer mechanism, Experimental study

1. Introduction

In bridge pile foundations, pile caps are essential for transferring loads from the superstructure to the piles. Most studies have focused on pile cap behavior under vertical loads, examining factors such as reinforcement, concrete strength, and size effects [1–6].

However, research on the seismic behavior of pile caps is limited. Existing studies mainly focus on pile-to-pile-cap connections rather than the overall pile cap behavior [7–11]. Field observations indicate that horizontal seismic forces can significantly affect pile caps, causing severe cracking or failure [12], with stress distributions differing from those under vertical loads.

This study addresses this gap by performing quasi-static lateral loading tests on pile caps with two different pile layouts (2×2 and 2×3), aiming to investigate the effects of pile layout on load-displacement behavior, crack propagation, failure modes, and strain distribution.

2. Experimental program

2.1. Specimen details

Two reinforced concrete pile cap specimens, SV2×2 and SV2×3, were designed with 2×2 and 2×3 pile layouts, respectively (Table 1, Figure 1). Both had identical overall dimensions, with a scale ratio of about 1:5. The pier and piles were over-reinforced to ensure failure occurred in the pile cap. Reinforcement details are summarized in Table 2.

Table.1. Dimensions of specimens (unit: mm)

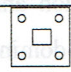
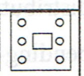
Specimen name	Cap (length×width×height)	Pier (length×width×height)	Pile	
			(diameter×length)	layout
SV2×2	1100×1100×250	350×290×1125	140×275	  SV2×2 SV2×3
SV2×3				

Table.2. Reinforcement details of specimens

(a) Cap

Specimen name	Horizontal reinforcement		Vertical reinforcement
	Top	bottom	
SV2×2	D6@100 mm in two directions	D13@100 mm in two directions	D10 @100 mm in loading direction
SV2×3			

(b) Pier and pile

Specimen name	Pier		Pile	
	longitudinal reinforcement	transverse reinforcement	longitudinal reinforcement	transverse reinforcement
SV2×2	22D19	D10@50mm	8D16 (for one pile)	D6@50mm
SV2×3				

2.2. Material Properties

All components were cast monolithically using ready-mixed concrete. The measured concrete compressive strength was 45.5 MPa, and the elastic modulus was 2.8×10^4 MPa. Reinforcing steel yielded between 372 MPa and 535 MPa (Table 3).

Table.3. Mechanical properties of materials

(a) Concrete

Specimen name	Compressive strength (MPa)	Young's modulus (MPa)
SV2×2, SV2×3	45.5	2.8×10^4

(b) Reinforcing bars

	Yield strain($\mu\varepsilon$)	Yield strength (MPa)	Young's modulus(MPa)
Top bars of cap (D6)	2734	444	1.7×10^5
Bottom bars of cap (D13)	1860	372	2.0×10^5
Vertical bars of cap (D10)	1990	398	2.0×10^5
Longitudinal bars of pier (D19)	2674	535	2.0×10^5
Transverse bars of pier (D10)	1940	388	2.0×10^5
Longitudinal bars of pile (D16)	1980	396	2.0×10^5
Transverse bars of pile (D6)	1890	378	2.0×10^5

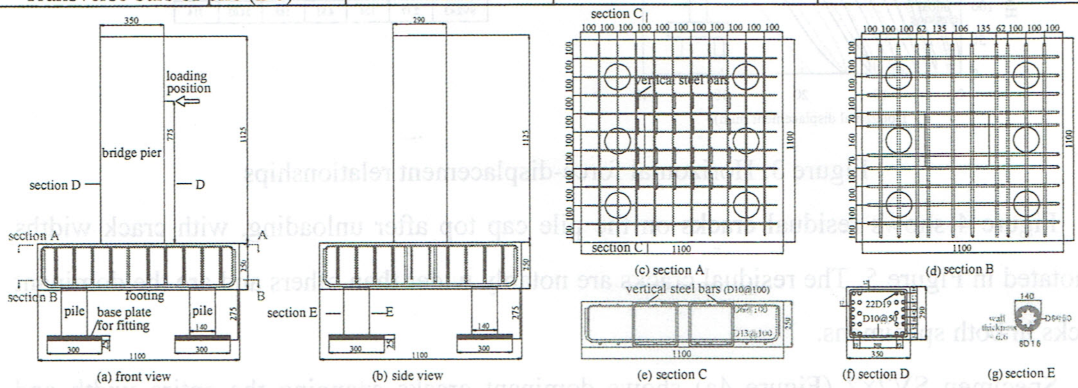
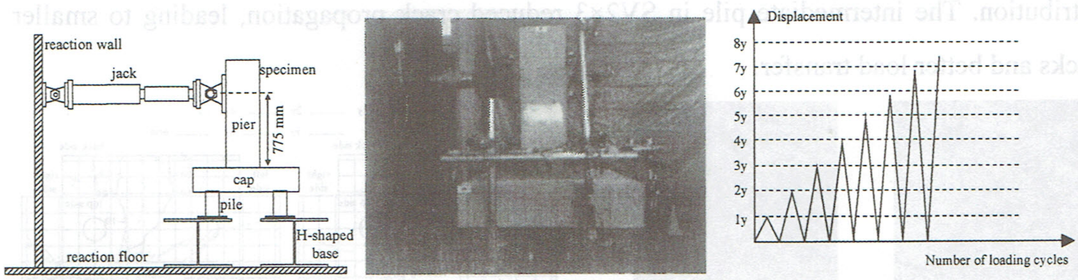


Figure 1. Details of pile cap specimen SV2×3 (unit: mm)

2.3. Experimental Setup and Loading Protocol

Specimens were anchored to a strong floor using an H-shaped steel base. To simulate horizontal seismic action, only lateral displacement loading was applied by a hydraulic jack at the pier head (Figure 2). The tests were displacement-controlled, and the horizontal load, displacement, reinforcement strain, and crack development were recorded.

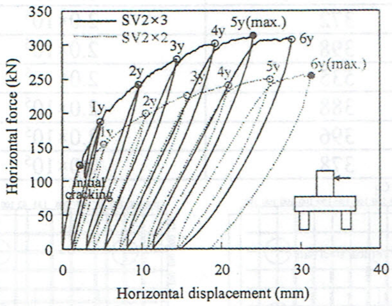


(a)Schematic figure (b)Actual image (SV2×2) (c)Loading protocol

Figure 2. Experimental setup and loading protocol

3. Experimental Results

The horizontal force-displacement responses of specimens SV2×2 and SV2×3 are shown in Figure 3. Before cracking (~125 kN), both specimens exhibited similar stiffness, indicating that the influence of pile layout at this stage was relatively small. After cracking, SV2×2 showed faster stiffness degradation, while SV2×3, with an additional central pile, showed slower stiffness degradation by limiting pile cap damage, exhibited delayed damage and higher peak strength (255 kN vs. 314 kN).



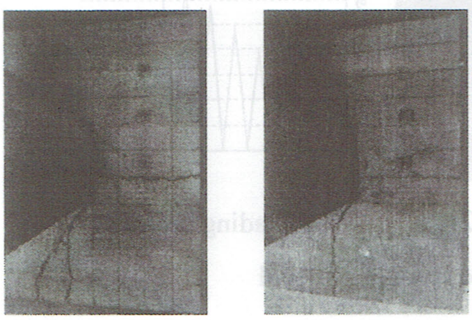
	initial cracking point		initial yielding point (1y)		maximum force point	
	disp. (mm)	force (kN)	disp. (mm)	force (kN)	disp. (mm)	force (kN)
SV2×2	2.63	125	5.22	155	31.33	255
SV2×3	2.17	124	4.81	188	24.03	314

Figure 3. Horizontal force-displacement relationships

Figure 4 shows residual cracks on the pile cap top after unloading, with crack widths annotated in Figure 5. The residual cracks are notably wider than others and are the dominant cracks in both specimens.

Specimen SV2×2 (Figure 4a) shows dominant cracks spanning the entire width and length of the pile cap, while SV2×3 (Figure 4b) exhibits cracks mainly along the width. Both specimens display near-vertical crack propagation from top to side surfaces, with larger crack widths at the top, indicating bending-dominated behavior. Despite different crack patterns, both specimens exhibit similar bending failure modes.

Figures 4 and 5 reveal that cracks in SV2×2 are wider, with maximum widths of 13 mm, compared to 8 mm in SV2×3. This difference shows that pile layout impacts crack size and distribution. The intermediate pile in SV2×3 reduced crack propagation, leading to smaller cracks and better load transfer.



(a) SV2×2 (b) SV2×3

Figure 4. Photographs of residual wide cracks after unloading (the right side)

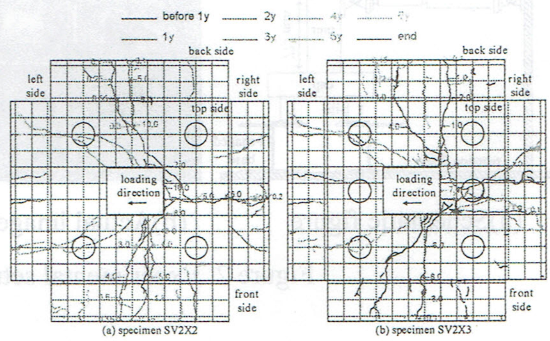


Figure 5. Crack distributions of two pile caps

Figures 6 and 7 show the tensile strain distribution in the pile cap reinforcement for specimens SV2×2 and SV2×3. Strain data were measured at representative points due to symmetry, with arrows indicating strain magnitude and direction. Solid arrows represent upper-side strain, and dashed arrows represent lower-side strain.

Under load, tension develops on the right side of the cap's upper surface and the left side of its lower surface, differing from vertical loading. Strains near dominant cracks on the upper surface are higher, as expected. The strain direction is similar for both specimens, but magnitudes differ.

The maximum strains are 20,511 με in SV2×2 and 3,545 με in SV2×3, corresponding to crack widths. In SV2×2, the strain at the width midpoint (15,924 με) reaches yield, while in SV2×3, the pile restrains crack propagation, affecting the cap's stress distribution and load transfer.

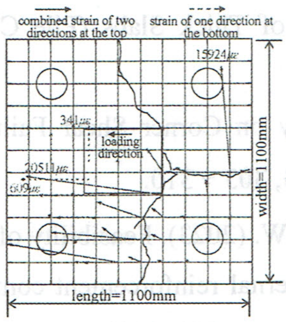


Figure 6. Strain distribution in SV2×2 (horizontal force 186.75 kN)

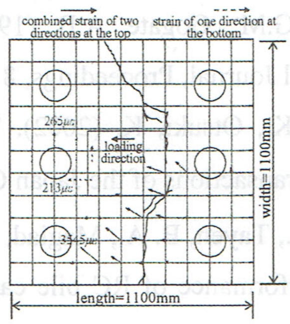


Figure 7. Strain distribution in SV2×3 (horizontal force 187.75 kN)

4. Conclusions

This study investigated the influence of pile layout on the behavior of bridge pile caps under lateral loading. Two pile cap specimens, SV2×2 and SV2×3, were tested, and the key findings are as follows:

1. Pile Layout Effect on Performance: Both specimens exhibited bending-dominated failure, but SV2×3(2×3 layout) showed higher peak strength and slower damage progression compared to SV2×2 (2×2 layout).

2. Crack Distribution and Size: The pile layout significantly influenced crack distribution and size. SV2×2 developed wider cracks (maximum 13 mm) compared to SV2×3 (8 mm). The crack propagation pattern also differed between the two specimens. Thus, the layout affected both the size and distribution of cracks.

3. Strain Distribution: Strain measurements showed greater strain in SV2×2 (20,511 με in the width direction) than in SV2×3 (3,545 με), indicating that pile layout influences strain distribution and deformation under load.

4. Load Transfer Mechanism: SV2×3, with an additional central pile, the load transfer mechanism changes, resulting in significantly improved efficiency, showing higher peak capacity, more uniform load distribution, and effectively suppressing crack propagation.

In conclusion, the layout of piles plays a crucial role in the force-bearing performance, crack distribution and load transfer mechanism of pile caps under lateral loads.

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