

Article | Received 12 March 2026; Revised 2 April 2026; Accepted 7 April 2026; Published 17 September 2026
<https://doi.org/10.55092/phess20260004>

Experimental study and parametric analysis of the vertical bearing capacity of steel hoops under flood–induced wetting conditions

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Abstract: This study investigates the effects of flood–induced wetting on the vertical bearing capacity of steel hoops confining concrete columns. Experimental and theoretical analyses were conducted, including static and dynamic friction tests between steel plates and concrete surfaces, as well as vertical bearing capacity tests of steel hoops under water–layer conditions. The results indicate the following: (1) The friction coefficient showed minimal dependence on vertical pressure under identical conditions, and the vertical bearing capacity of steel hoops increased with higher preload applied by high–strength bolts. (2) For static friction, the coefficient was lowest under dry conditions, moderate under wet conditions, and highest with a water layer on the concrete surface. For dynamic friction, the coefficient was lowest with a water layer on the concrete surface, moderate under dry conditions, and highest under wet conditions. (3) The contact between the steel hoop and concrete column was non–uniform. Under high–strength bolt preload, close contact occurred primarily in the central region and near the wing plates of the steel hoop. Friction under vertical loading was concentrated in these regions, making them prone to local damage in practical engineering applications. (4) In dry conditions, the vertical bearing capacity calculated using either static or dynamic friction coefficients closely matched the experimental results. However, when a water layer existed between the steel hoop and the concrete column, the calculation results based on the dynamic friction coefficient were consistent with experimental values.

Keywords: rainstorm and flood; steel hoop; pretension; bearing capacity.

1. Introduction

With the rapid development of China's social economy, the volume of road traffic has been increasing sharply year by year [1,2]. The single–column pier has the advantages of beautiful appearance and strong adaptability. It is currently the most commonly used pier form [3,4]. In the



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past, the design of single-column pier bridges mainly considered the bearing capacity of the structure, but ignored the anti-overturning stability under eccentric overload [5,6]. Hence, reinforcement designs for single-column pier bridges are requisite. Compared with traditional reinforcement methods, the steel hoop reinforcement of the cap beam has the advantages of simple process, short construction period, and is often used in bridge engineering [7]. In recent years, under the influence of global warming, urban rainstorm and flood disasters have occurred frequently [8], and urban waterlogging has occurred from time to time, causing huge losses to the global natural environment and human life and property. When the bridge pier is submerged or soaked by rainstorm and flood, the bearing capacity of the steel hoop will be adversely affected, posing a great threat to the safe operation of the bridge [9–11].

During flood disasters, the concrete of single-column piers is extremely prone to being soaked. For single-column piers reinforced with steel hoops, the vertical bearing capacity will be affected, which is very unfavorable for the safe operation of bridges. Moreover, there are currently few research documents on this topic. Based on this, this paper first investigates the differences in the static and dynamic friction coefficients between steel and concrete under three conditions: (1) dry state; (2) wet surface of the concrete slab without water seepage; (3) wet concrete slab with a water layer on the surface. Secondly, vertical bearing capacity tests of steel hoops were conducted under the first and third states, clarifying the issue of friction coefficient values when steel hoops are in different states with concrete columns, providing a reference for urban flood disaster research.

2. The working mechanism of steel hoops

The commonly used steel hoop is composed of two semi-circular steel plates joined by high-strength bolts. The corbels can bear heavy loads. The working mechanism of the steel hoop is that the preload applied by the high-strength bolts makes the steel hoop squeeze the concrete column, generating frictional force to resist the vertical pressure above the corbels, as shown in Figure 1.

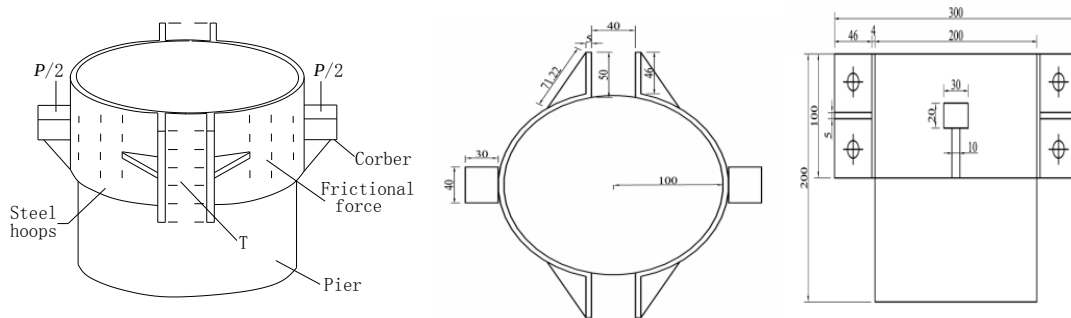


Figure 1. Diagram of the working mechanism of steel hoops.

The bolt torque can be defined as:

$$M0 = kTd \quad (1)$$

Where $M0$ is torque of the bolt, k is torque coefficient, the value is 0.13, T is pre-tightening force, d is the bolt diameter, the value is 12mm.

The vertical load P can be defined as [12]:

$$P = 2\pi\mu T \quad (2)$$

Where P is the vertical load, μ is friction coefficient.

3. The experiment

3.1. The experiment of friction coefficient

It can be known from Equation (2) that the friction coefficient μ has a considerable influence on the vertical bearing capacity of the steel hoops. The friction coefficient encompasses the static friction coefficient and the dynamic friction coefficient. In this paper, the measurements of the two friction coefficients under different states will be conducted.

The static friction coefficient μ_1 . The measurements are carried out by employing an improved TMY friction coefficient tester. The test specimens and testing instruments are shown in Figure 2. In actual engineering, to prevent rusting of the steel hoops, the surface of the steel hoops is usually painted. To be close to the actual engineering situation, the surface of the test steel plate is sprayed with black paint. During the friction coefficient test, the test specimens are divided into three states: (1) dry state (the status during normal construction); (2) the surface of the concrete plate is moist but no water seeps out (the initial time of rainf); (3) the surface of the concrete plate is moist with a water layer (the moment when the flood submerged the steel hoops). The physical pictures of the three states are shown in Figure 2.

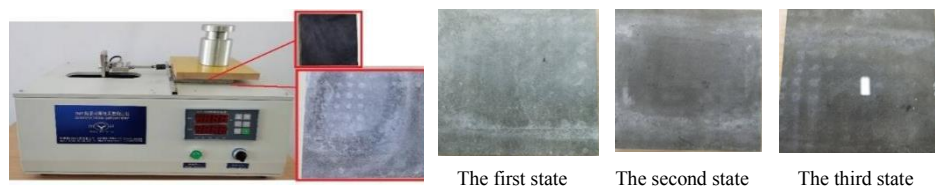


Figure 2. The test specimens and testing instruments of μ_1 .

The test number and detailed material parameters of this test are shown in Table 1. The test steps are as follows:

(1) The static friction coefficient of MCSY1(μ_1)

- Produce concrete slabs 150 mm (length) ×150 mm (width) ×10 mm (height), steel plate 75 mm (length) ×75 mm (width) ×5 mm (height);
- Adhere the steel plate to the center of the bakelite board;
- Place the dry concrete slab at the designated position on the work platform.
- Place the bakelite board on the concrete board and put 1 kg, 2 kg, 3 kg and 4 kg weights respectively on it.
- Measure and record the data.

To reduce errors, the MCSY1 test was conducted with four groups of vertical pressure tests, denoted as MCSY1–1, MCSY1–2, MCSY1–3, and MCSY1–4. For the same vertical pressure, three sets of test specimens were used for testing, denoted as MCSY1–1a, MCSY1–1b, and MCSY1–1c respectively.

(2) The static friction coefficient of MCSY2(μ_1)

Step (1) and Step (2) are the same as mentioned above. After that, immerse the concrete plate in water for 1 minute, take it out, and use a cloth to absorb the surface water. The concrete plate should be moist but without water seeping out on the surface, and then proceed with the subsequent steps.

(3) The static friction coefficient of MCSY3(μ_1)

Step (1) and Step (2) are the same as mentioned above. After that, immerse the concrete slab in water for 1 minute, then take it out. The concrete slab should be moist with a water layer on the surface, and then proceed with the subsequent steps.

Table 1. Test parameters for static friction coefficient.

The test number	Force (N)	State	The test number	Force (N)	State
MCSY1–1a/1b/1c	28	The first state	MCSY2–3a/3b/3c	48	The second state
MCSY1–2a/2b/2c	38	The first state	MCSY2–4a/4b/4c	58	The second state
MCSY1–3a/3b/3c	48	The first state	MCSY3–1a/1b/1c	28	The third state
MCSY1–4a/4b/4c	58	The first state	MCSY3–2a/2b/2c	38	The third state
MCSY2–1a/1b/1c	28	The second state	MCSY3–3a/3b/3c	48	The third state
MCSY2–2a/2b/2c	38	The second state	MCSY3–4a/4b/4c	58	The third state

From the analysis of the static friction coefficient μ_1 in Figure 3, it can be seen that the static friction coefficient μ_1 is the smallest in the dry state, being 0.4552; it is second in the wet state of the concrete slab, at 0.5177; and it is the largest when the concrete slab is wet with a water layer on the surface, reaching 0.5286.

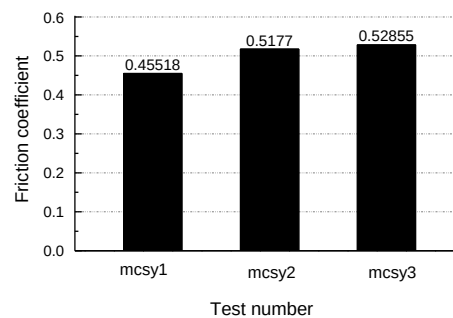


Figure 3. The static friction coefficients of three states.

The dynamic friction coefficient μ_2 . The test specimens and testing instruments are shown in Figure 4. The physical pictures of the three states are shown in Figure 4. MCSY4 represents the first state; MCSY5 represents the second state; MCSY6 represents the third state. The experimental procedures are the same as those mentioned above.

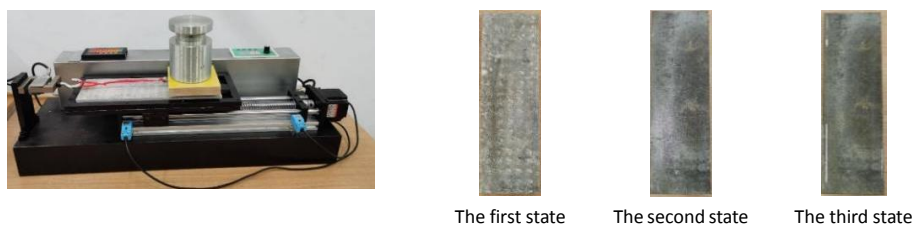


Figure 4. The test specimens and testing instruments of μ_2 .

From the analysis of the dynamic friction coefficient μ_2 in Figure 5, it can be seen that the dynamic friction coefficient μ_2 is the smallest when the concrete slab is wet with a water layer on the surface, being 0.3391; it is second in the dry state, being 0.4058; it is the largest in the wet state of the concrete slab without a water layer on the surface, reaching 0.4366.

Analysis of the data in Table 2 reveals that under the same conditions, the dynamic friction coefficient μ_2 is always smaller than the static friction coefficient μ_1 . The difference is the greatest when the concrete slab is moist and has a water layer on its surface. The reason for this is that water displaces the air between the two surfaces, and atmospheric pressure makes it difficult to separate them. The reason of the coefficient of dynamic friction decrease significantly for state 3 is the lubricating effect of the water layer, which reduces the frictional force when the concrete slab and the steel plate slide at a constant speed.

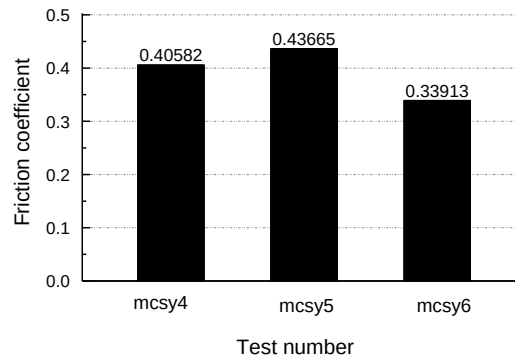


Figure 5. The dynamic friction coefficients of three states.

Table 2. Summary table of friction coefficients.

State	μ_1	μ_2
Dry state	0.4552	0.4058
Moist without a water layer	0.5177	0.4367
Moist with a water layer	0.5286	0.3391

3.2. Vertical load-bearing capacity test of steel hoops

The vertical bearing capacity test of the steel hoops was conducted using the WHY-3000 pressure testing machine in this paper. Analysis of the data in Table 2 reveals that when calculating the vertical bearing capacity according to theoretical Formula (2), the vertical bearing capacity is the smallest in the dry state when the friction coefficient is taken as the static friction coefficient μ_1 ; and when the friction coefficient is taken as the dynamic friction coefficient μ_2 , the vertical bearing capacity is the smallest when the concrete slab is moist and has a water layer on its surface. When conducting the vertical bearing capacity tests in this paper, two states were selected, and a total of four groups of tests were carried out, denoted as Z1, Z2, Z3, and Z4. The detailed test setup parameters are shown in Table 3. To achieve loading, a loading support was specially fabricated. During the test loading, the test component was inverted and placed on the press testing machine, as shown in Figure 6. The preload force is applied by a torque wrench and calculated by Formula (1).

Table 3. Test parameters for the vertical bearing capacity of steel hoops.

Test number	concrete column $D \times H/\text{mm}$	Steel hoops $D \times H \times t/\text{mm}$	Preload	State
Z1	200 × 200	200 × 100 × 5	10 kN	Dry
Z2	200 × 200	200 × 100 × 5	15 kN	Dry
Z3	200 × 200	200 × 100 × 5	10 kN	Moist with a water layer
Z4	200 × 200	200 × 100 × 5	15 kN	Moist with a water layer



Figure 6. Test loading diagram.

4. The experiment results and analysis

4.1. The experiment phenomenon

The images of the steel hoops and the concrete column were extracted as shown in Figure 7. In actual engineering, the steel hoops and the concrete column are not in uniform contact. Under the pre-tightening force of high-strength bolts, the middle area of the steel hoop and the area close to the flange plate are in close contact with the concrete column. Under the vertical force, it is mainly this part that rubs against the concrete column. In actual engineering, this area is prone to damage.

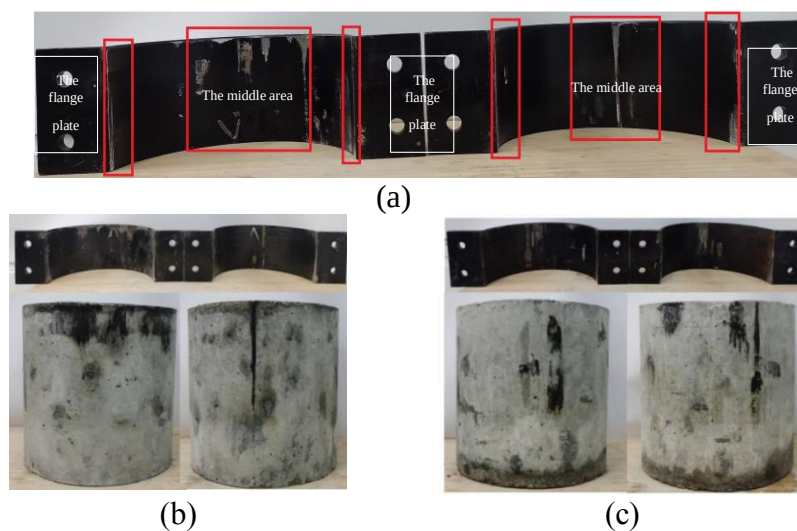


Figure 7. The experiment phenomenon. **(a)** Steel hoops area division; **(b)** Z2; **(c)** Z4.

4.2. Result analysis

Analysis of the data in Figure 8 reveals that in the initial stage, as the vertical force increases, the displacement changes very little, thus its curve rises rapidly at the beginning. Once the peak is reached, the vertical force starts to decrease and the displacement increases rapidly, causing the steel hoop to begin to slide quickly. The vertical bearing capacity of the steel hoop is calculated through theoretical Formula (2). The theoretical calculation value one is obtained by using the static friction coefficient μ_1 , and the theoretical calculation value two is obtained by using the dynamic friction coefficient μ_2 . Analysis of the data in the figure shows that when the concrete column is in a dry state, the vertical bearing capacity of the steel hoop is between the results calculated by the two algorithms; when there is a water layer between the steel hoop and the concrete column, the vertical bearing capacity

of the steel hoop is also between the results calculated by the two algorithms, but it is closer to theoretical value two (calculated using the dynamic friction coefficient μ_2).

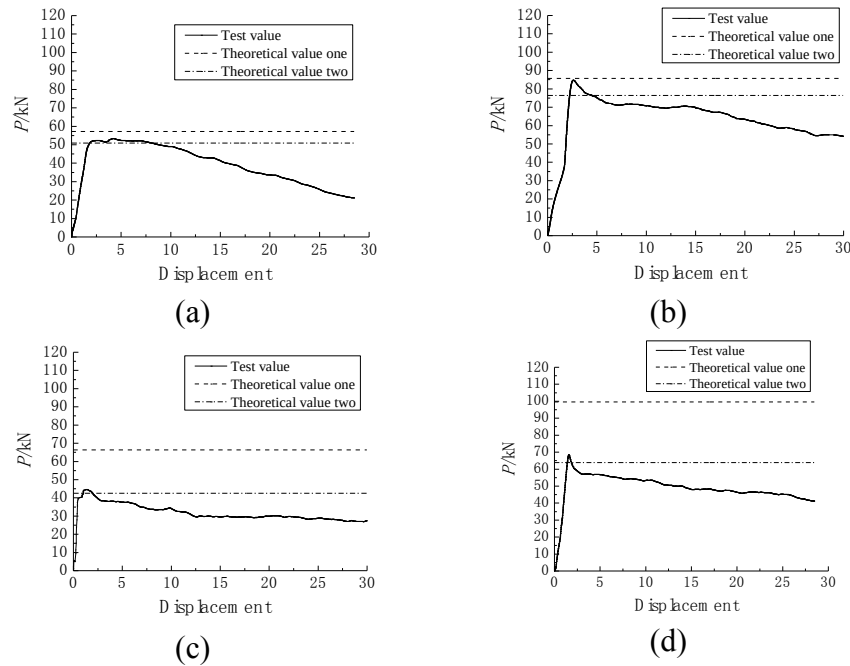


Figure 8. Comparison curve of theoretical value and experimental value. (a) Z1; (b) Z2; (c) Z3; (d) Z4.

The bearing capacity is summarized in Figure 9. The greater the preload of high-strength bolts, the greater the vertical bearing capacity. When the bolt preload T is the same, the ratio of the vertical bearing capacity between Z3 and Z1 conditions is 0.85, and the ratio between Z4 and Z2 conditions is 0.81. This is due to the lubricating effect of water, which significantly reduces the vertical bearing capacity.

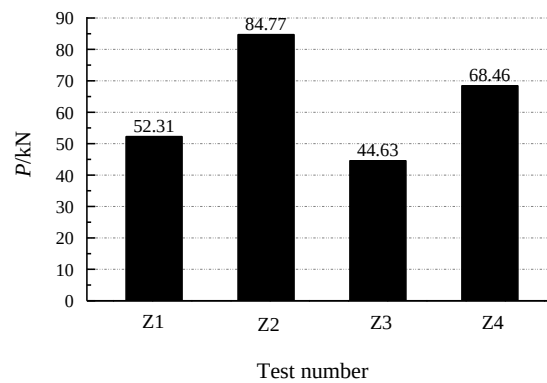


Figure 9. Comparison chart of vertical bearing capacity of steel hoops.

To quantitatively analyze the difference between the experimental values and theoretical values, the results are summarized in Table 4. Analyzing the data in the table, it can be seen that when the concrete column is in a dry state, for Z1, the relative error of the steel hoop bearing capacity calculated using the static friction coefficient μ_1 is 9.3%, and the relative error calculated using the dynamic friction coefficient μ_2 is -2.6%; for Z2, the relative error of the steel hoop bearing capacity calculated using the static friction coefficient μ_1 is 1.2%, and the relative error calculated using the dynamic friction coefficient μ_2 is -7.2%. Therefore, in the dry state, the calculated results of the steel hoop bearing

capacity formula $P = 2\pi\mu T$ using both the static and dynamic friction coefficients are close to the experimental values. The steel hoop bearing capacity calculated using the static friction coefficient is slightly larger, while that calculated using the dynamic friction coefficient is slightly smaller.

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When there is a water layer between the concrete column and the steel hoop, the relative error of the steel hoop bearing capacity calculated by Z3 using the static friction coefficient is 48.8%, and the relative error calculated using the dynamic friction coefficient is -4.6%; the relative error of the steel hoop bearing capacity calculated by Z4 using the static friction coefficient is 45.5%, and the relative error calculated using the dynamic friction coefficient is -6.7%. Therefore, in this state, the friction coefficient μ in the steel hoop bearing capacity formula $P = 2\pi\mu T$ should be calculated using the dynamic friction coefficient.

Table 4. Error table of theoretical and experimental values.

Test number	Experimental values P/kN	Theoretical values one P_1/kN	Relative error $(P_1 - P) / P$	Theoretical values two P_2/kN	Relative error $(P_2 - P) / P$
Z1	52.31	57.17	9.3%	50.97	-2.6%
Z2	84.77	85.76	1.2%	76.45	-7.2%
Z3	44.63	66.39	48.8%	42.59	-4.6%
Z4	68.46	99.5	45.5%	63.89	-6.7%

5. Conclusion

In this paper, load-bearing capacity tests of steel hoops in the different state were carried out, the friction parameters were analyzed, and the following conclusions were obtained:

(1) The larger the preload exerted by the high-strength bolts, the greater the vertical bearing capacity of the steel hoop.

(2) The static friction coefficient between steel plates and concrete slabs is the smallest in a dry state, followed by a moist state, and the largest when there is a water layer on the surface of the concrete slab. The dynamic friction coefficient between steel plates and concrete slabs is the smallest when there is a water layer on the surface of the concrete slab, followed by a dry state, and the largest in a moist state.

(3) The steel hoop and the concrete column are not in uniform contact. Under the preload of high-strength bolts, the central area of the steel hoop and the area close to the flange are in tight contact with the concrete column. Under vertical force, it is mainly this part that rubs against the concrete column. In actual engineering, this area is prone to damage.

(4) In the formula for the bearing capacity of steel hoops under the dry state, the calculation results of the friction coefficient μ using the static friction coefficient and the dynamic friction coefficient are both close to the test values. The bearing capacity of the steel hoop calculated using the static friction coefficient is marginally greater, while that calculated using the dynamic friction coefficient is marginally smaller. When a water layer exists between the concrete column and the steel hoop, it is suggested that the dynamic friction coefficient μ_2 be adopted for calculating the bearing capacity of the steel hoops.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used generative AI tools only to improve language and readability. The authors take full responsibility for the content of the manuscript.

Acknowledgments

The work was supported in part by Henan Province Science and Technology Project 262102240020 and Henan Province Key R&D Special Project 2025 (No.251111321900).

Authors' contribution

Conceptualization, Guotao Dou; methodology, Feng Wang; software, Shuai Li; validation, Feng Wang, Liang Xu and Tie Li; formal analysis, Shuai Li; investigation, Feng Wang; resources, Liang Xu; data curation, Shuai Li; writing—original draft preparation, Shuai Li; writing—review and editing, Guotao Dou; supervision, Liang Xu; project administration, Tie Li; funding acquisition, Guotao Dou. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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