A Preliminary Investigation on Scour Mitigation at Bridge Piers Using Combined Riprap and Sacrificial Piles

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ABSTRACT

To mitigate scour around bridge piers, a united system of riprap and sacrificial piles are involved. Both riprap and sacrificial piles can be designed as effective scour countermeasures. However, both of them have their own deficiencies when utilized in practice. To make full use of these methods, a proper arrangement should be proposed. In this study, flume tests have been carried out to investigate the scour characteristics and feasibil-ity of combined riprap and sacrificial piles. The scour mitigation using riprap is effected by parameters such as riprap size, thickness and lateral extent, while it is effected by parameters such as pile spacing, pile arrange-ment, and pile diameter when using sacrificial piles. The results indicate that when the combined counter-measures are installed properly, more than 55 percent and 74 percent of scour depth can be reduced compared with using only riprap and sacrificial piles respectively. The mechanism and design advice are addressed after analyzing the results. Further investigations are still needed to extent the conclusions towards practical pro-jects.

Key words: *Bridge Scour, Countermeasures, Sacrificial Piles, Riprap*

1. Introduction

Scour is an important factor that plays a central role in almost all underwater obstructions, since it is the dominant reason for failure of these structures. The interaction between the coming water and the bridge foundations leads to the formation of spiral flow that causes large changes in the channel geomorphology. Development and expansion of scour holes will result in a pit under the foundation, which undermines the integrity of soil-structure system and will lead to buckling failure of the bridge piers and even the collapse of the bridge (Hughes *et al*, 2007; Liang *et al.*, 2015a). For the purpose of scour mitigation, various countermeasures have been proposed during the past decades. These methods can be divided into two categories, i.e., passive countermeasures, and active countermeasures (Chiew, 1992; Wang *et al.*, 2017). Passive scour countermeasures mitigate scour by providing a physical barrier, such as riprap, gabions, blocks, etc., which can dramatically improve the nominate resistance of bed materials. On the other hand, active scour counter-measures are designed to decrease the strength of the downward flow and the horseshoe vortex to re-duce the nominal load of the flow field.

Riprap, which is typically placed on the surface of the channel bed, is widely used in practice due to its convenience and low cost. Initial studies on its behavior of reducing scour around a pier have been carried out by (Melville and Coleman, 2000; Lim and Chiew, 2001;

Lauchlan and Melville, 2001; Lagasse, 2007). However, the use of riprap can only provide limited enhancement of the nominate resistance. When the flood is coming, stones might be instable to withstand high approaching stream velocities and buoyant forces and might be eroded or submerged. Chiew (1995) carried out a subsequent study of the causes of riprap failure under clear water conditions and proposed three typical modes, namely riprap shear failure, winnowing failure, and edge failure.

Sacrificial piles are non-service piles placed in the upstream of a bridge foundation, which aims to protect service piles from local scour. Meanwhile, it also protects a bridge against a ship collision and there-fore functions a multi-hazard countermeasure for bridge piers (Svensson, 2009). Laboratory studies were conducted to investigate the effect of sacrificial piles on scour depth (Melville and Hadfield, 1999; Haque *et al*., 2007), and several positive countermeasures, including sacrificial piles have been evaluated (Tafarojnoruz *et al*., 2012; Liang *et al.*, 2015b). It is economical for long time usage and does not require changes in bridge pier designs. However, more experiments and field data are needed to determine the geometric parameters and con-figurations of these piles that achieve the maximum extent of scour protection.

To make full use of active and passive protections, a united system of riprap and sacrificial piles are proposed in this study. Totally, five experimental tests were carried out to investigate the efficiency of scour mitigation using combined riprap and sacrificial piles. In conjunction with laboratory experiments, advanced computational simulations were conducted to further extend the laboratory observations. The scour and sedimentation sour model in FLOW-3D were also used to simulate the performance of sacrificial piles. Finally, advice on the design of combined countermeasures is addressed.

2. Experimental setup

2.1. Experimental facility

The present experiments were conducted in a flume at the Laboratory of Hydraulic and Harbor Engineering in Tongji University, Shanghai. As shown in **Fig.1**, the flume is 50 m in length, 0.8 m in width and 1.2 m in height. It is equipped with glass side-walls and a sand basin in the middle, which is 1 m in depth from the horizon and 0.65 m in width. The facility is computer controlled, with the capability to generate constant currents with specified inflow velocity. An Acoustic Doppler Velocimetry (ADV) was used to monitor the flow velocity in front of the testing area. Detailed description of the flume can be found in previous study (Liang *et al.*, 2016).

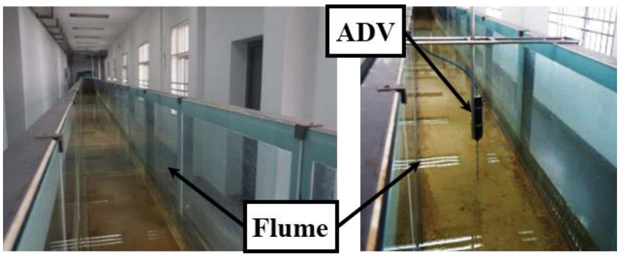


Fig. 1 Experimental facilities: test flume and ADV

2.2. Models and materials of the experiment

Cylinders made of aluminum alloy with the diameter of 0.03 m were used as the pier models, while the sacrificial model piles were made of the same materials with the diameter of 0.01 m. The embedded length of these models is 20 mm. Only one kind of fine sand, whose median particle size is 0.15 mm, with a bulk density of 1.99 g/cm^3 was used in the experiments. Particles used as the riprap model were carefully selected according to the instructions as follows: 1. the specific gravity should be larger than 1.0; 2. coarse elements with irregular shapes are preferred; 3. the particle size should accord with the scale of pier models. After the comparison of schemes, smashed brick, whose specific density is 2.0, with median particle sizes of 2.0 mm to 4.2 mm was utilized as the riprap model. **Fig. 2** shows the photos of models and materials mentioned above.

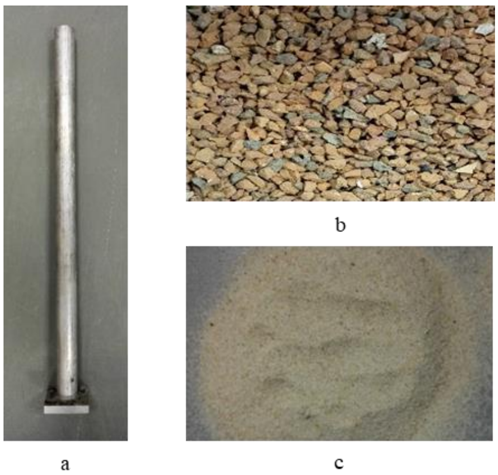


Fig. 2 Photos of: (a) pier model (b) sand (c) riprap model

The hydraulic parameters were set to ensure that the development of scour process can be observed comprehensively. The water depth, *h*, was set at 25 cm for each run. Under this condition, the threshold velocity u_c for the sediments was determined by the equation provided by Dou (1999). The critical flow velocity was calculated as 22.5 cm/s, which ensures erosion to happen. This was set as the inflow stream velocity.

2.3. Experimental method and procedure

Experiments were conducted on four different types of test arrangements, namely riprap, sacrificial piles, and combined riprap & sacrificial piles single pile with two different configurations. Be-sides, scour around a single pier model was carried out as the control group to evaluate the scour mitigation efficiency of these countermeasures. Details of the tests together with the model arrangements are given in **Table 1**. The following experimental procedures were designed and followed: (1) the pier model and sacrificial pile, sediments, and ADV were placed according to the arrangements in the middle of testing area; (2) water was slowly applied from the bottom to saturate the sediment and set at 20 cm; (3) the incoming flow velocity of 25 cm/s was applied to initialize the scour process; (4) the scour depth was measured when the streambed become stable; (5) once the sandpit was leveled after each experiment, the flume was filled very slowly to keep the sand-bed undisturbed; (6) then the experiments were rearranged and steps 1~5 were repeated.

In order to assess the performance of sacrificial piles, the scour depths of piles with and without countermeasure were examined. The scour depth reduction at equilibrium conditions are calculated by

$$R = \frac{y_p - y_c}{y_p} 100\% \qquad (1)$$

where y_p is the maximum scour depth of piles only, and y_c is the maximum scour depth of piles with protections.

A uniform scale is not proper for the flume test. According to the experimental condition, the horizontal scale, λ_L, and vertical scale, λ_H, were determined as 100. The particle scale for riprap, λ_d, is calculated to be 60.6 by the equation (Dou 2003)

$$\lambda_d = \frac{{\lambda_V}^2}{{\lambda_{C0}}^2 \times \lambda_{\gamma_S - \gamma}} \qquad (2)$$

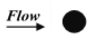
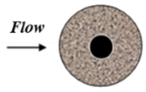
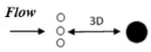
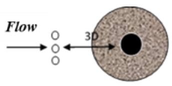
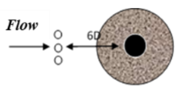
where λ_V is the velocity scale, equals to 10.0; λ_{C0} is the relative scale, equals to 1.0; and $\lambda_{(\gamma S-\gamma)}$ is the material scale, equals to 1.65; γ_S is the unit weight of riprap and γ is the unit weight of water

3. Results and analysis

3.1. Single pier without countermeasures

Fig. 3 shows the scour around the model without protection. Scour depths at different locations around the model were measured and listed in **Table 2** (range means the distance from the pier to the measured point). Scour mechanism and its dynamic process were elaborated in previous study, and the test in this study is a control group to investigate the scour reduction using various methods (Liang *et al*., 2016).

Table 1. Details of the tests and model arrangements

Protection	Arrangements	Riprap Range	Distance between Piles and Pier
No		-	-
Riprap		2D	-
Sacrificial Piles		-	3D
Combined Sacrificial Piles and Riprap I		2D	3D
Combined Sacrificial Piles and Riprap II		2D	6D

a b

Fig. 3 Photos of model protected by riprap (a) before scour; (b) after scour

Table 2. Experimental results for a single pier

Range	Scour Depth (cm)			
(cm)	Upstream	Left	Downstream	Right
0	3.8	3.5	2.8	3.4
0.5	3.7	3.2	2.8	3.1
1	3.6	2.8	2.6	3.0
1.5	3.4	2.6	2.5	2.7
2	3.2	2.3	2.3	2.5
2.5	2.6	1.9	2.1	2.4
3	2.1	1.8	2.0	2.1

3.2. Utilization of riprap and sacrificial piles alone

Fig. 4 (a) and **(b)** present the channel geomorphology around the model protected by riprap pre- and post- scour. Scour depths at different locations around the model were measured and listed in **Table 3**. The previous study shows that the riprap behaves best when it covers the range of two to four times the diameter of pier model. The use of riprap can improve the erosion resistance of sediments and eliminate the scour depth around the structure. However, the riprap will be out of service when it collapses due to radical flow. Bed sediments may be mixed with the riprap as well, which makes it hard to repair the riprap layers.

Scour around the pier model with sacrificial piles can be found in **Fig. 5 (a)** and **(b)**, while the measured scour depths are listed in **Table 4**. The distance between boundaries of service pier and sacrificial piles were set as three times the diameter of pier model. Unlike riprap, the sacrificial piles are hard to be destroyed even under a catastrophic flood. However, the scour mitigation is susceptive to the channel evolution, which may lead to the change of flow direction.

a b

Fig. 4 Photos of model protected by riprap (a) before scour; (b) after scour

a b

Fig. 5 Photos of model protected by sacrificial piles (a) before and (b) after scour.

Table 3. Experimental results for a pier with riprap

Range	Scour Depth (cm)			
(cm)	Upstream	Left	Downstream	Right
0	1.7	1.5	1	1.3
0.5	1.5	1.3	0.7	1
1	1.2	0.9	0.5	0.8
1.5	1	0.7	0.4	0.5
2	0.5	0.5	0.2	0.4
2.5	0.3	0.2	0.2	0.2
3	0	0	0.1	0

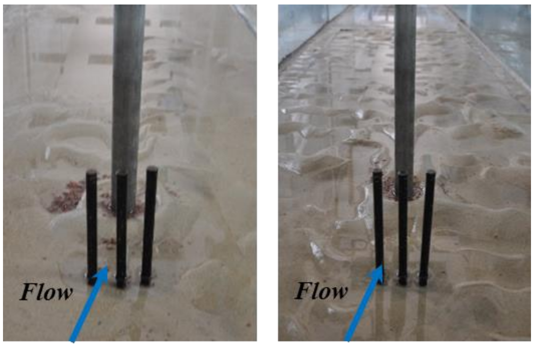
Table 4. Experimental results for a pier with sacrificial piles

Range	Scour Depth (cm)			
(cm)	Upstream	Left	Downstream	Right
0	2.7	2.3	1.7	2.3
0.5	2.4	2.1	1.5	2.1
1	2.3	2	1.3	1.9
1.5	2.1	1.6	1.2	1.7
2	1.8	1.3	1.0	1.4
2.5	1.5	1.1	0.8	1.1
3	1.3	0.9	0.4	1

3.3. Combined riprap and sacrificial piles

Flume tests on combined riprap and sacrificial piles were carried out, and **Fig. 6** shows the results of this countermeasure system with various spacing between the pier and sacrificial piles. Different from using sacrificial piles or riprap only, the combined method can provide stable and long-term protection. The reduction of scour depth at upstream, downstream and side boundaries can be found in **Table 5**.

Observation shows the interaction among structures and particles. The flow decelerates at the upstream of the sacrificial piles causing a protection area downstream. Riprap, as well as the pier, are well protected so that the scour was significantly diminished. For live-bed conditions, sediments winnowed upstream will deposit around the scour area so that the riprap is covered. When the spacing is three time the service pier, the reduction of scour depth was 86.8% (Case I) and 78.9 % (Case II), which provides a much better protection than using riprap (55.3%) or sacrificial piles (28.9%) alone. The arrangement of sacrificial piles has significant influence on the scour mitigation. With the increase of the distance between piles and the service pier, its influence drops. While the distance cannot be too short due to the arrangement of riprap, the recommended distance is determined to be three time the diameter of service pier.



a b

Fig. 6 Photos of model protected by combined system with spacing between the service pier and sacrificial piles of: (a) three times the diameter; (b) six times the diameter.

Table 5. Experimental results for a pier with combined riprap and sacrificial piles

Case	Results (cm)	Upstream	Left	Downstream	Right
I	Scour Depth	0.5	0.4	0.2	0.3
	Scour Range	1.0	1.4	1.8	1.3
II	Scour Depth	0.8	0.6	0.4	0.5
	Scour Range	4.8	2.8	3.8	3.1

4. Numerical simulation

4.1. Introduction of the numerical model

Investigations on scour phenomenon using numerical methodology are meaningful. Firstly, flume tests have their own limitation due to the small-scaled models and the similarity criteria. Ataie-Ashtiani & Beheshti (2006) suggested that the size of the models should not exceed 12% of the total flow section, while Whitehouse (1998) suggested that the ratio of a flume width to a model width should be greater than 6. The limited model scale makes the experimental simulations on large structures extremely difficult. Secondly, details of the scour process together with the key parameters are hard to be captured during a flume test. Results are usually vulnerable to experimental conditions, including unstable flow velocity, sediments arrangement, and other instruments placed near the testing area. At last, the flume tests are time and labor consuming. Testers need to concentrate on operating facilities and taking care of the key parameters. With the advancement in computational models, it has been increasingly realized that computational models provide an important tool to complement and extend the observations from experiments, as outlined in the Strategic Plan by the FHWA Hydraulic Research Laboratory. Numerical simulation features advantages in providing more comprehensive data, cost effective, and efficiency in sensitivity analyses, etc. (Zhao *et al.*, 2010; Li and Tao, 2015; Wang *et al*., 2016).

A three-dimensional numerical model is developed for simulating local scour around the bridge pier with and without various countermeasures. The two-equation model (k-ε model) is used for modeling the turbulence. The governing equations for the turbulent flow are the unsteady incompressible Reynolds-Averaged Navier-Stokes (RANS) equations. The geometrical and hydraulic parameters of the simulation model are developed similar to the experiments. A model of piles with the diameter of 3 m and sacrificial piles with the diameter of 1 m in five arrangements (as shown in **Table 1**) were built. Sediment with the same parameter in experiments was used as a bed material in the simulation.

The boundary conditions were carefully defined to simulate the experimental flow conditions accurately. For all the runs, the boundary conditions were set the same and the parameters were similar to those in the experiments. The upstream boundary was specified with a constant inflow velocity of 3 m/s and water depth of 10 m, while outflow was applied to the downstream boundary. The sidewalls as well as the channel top were defined to be symmetry to describe the free surface of the flow area. The bottom was set to the wall condition. The initial flow heights and flow velocity were also defined based on the data from the experiments. Once these conditions were established, the model would be ready to be applied to each scenario. A total of five simulation runs were carried out, similar as the experiments with or without sacrificial piles. As an example, computational mesh for a single pier is shown in **Fig. 7**.

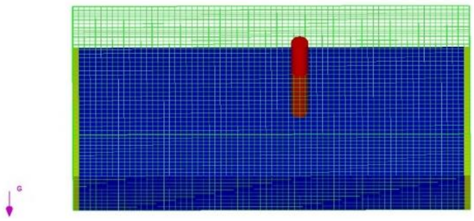


Fig. 7 Computational mesh for scour around a single pier.

4.2. Free surface flow simulation

Free surface flow around a single pier was simulated first. **Fig. 8** presents the side view of computed streamlines and the flow structure. When the flow comes around the pier, it is altered and separated. Downflow and vortex generated by the flow-structure interaction will erode the sediments, which transport downstream. The unbalanced flow velocity is the reason for the change of flow structure. The result agrees well with the measured scour depth.

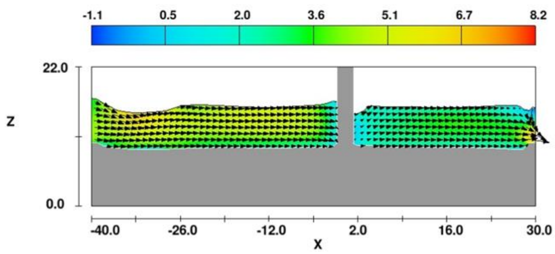
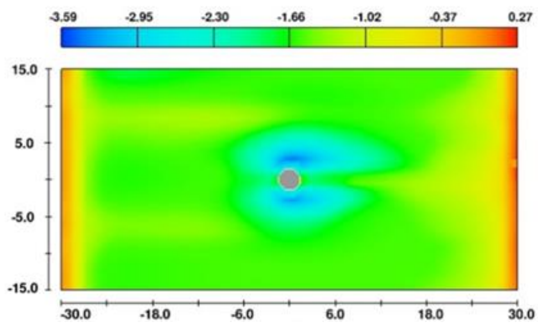


Fig. 8 Computed streamlines and structure profile of a single pier from the side view (Unit: m/s).

4.3. Results for numerical simulations

The results of computational simulations were analyzed to investigate the effects of combined riprap and sacrificial piles. The simulated scour development (the scour depth and the bed elevation) of the single pier was used as the control group. **Fig. 9** shows the bed elevation around the bridge pier for all the five cases.

For a single pier (**Fig. 9a**), scour starts from both sides and results in a symmetry scour hole. Scour occurs severely on both sides. Without any protections, the single pier will be eroded radically and reach its equilibrium with the maximum scour depth of 3.6 m. The bridge will be in danger. When the bed sediments are enhanced with riprap (**Fig. 9b**), the scour depth around the pier becomes slighter with a reduction of approximately 75%. The maximum scour depth in this case is shown around the edge of riprap layers. In practice, the existence of these small scour holes will lead to the rolling failure of riprap element, which may erode the riprap as well. When the sacrificial piles are installed (**Fig. 9c**), flow power around the pier is significantly reduced and the sand from upstream starts to deposit at the downstream boundary. The maximum scour depth appears around both sides of the sacrificial pile groups, while slight scour occurs at the service pier. Using combined riprap and sacrificial piles can reduce the scour depth from the aspects of both flow and sediments **(Fig. 9d**). The deposit sand provides fill up to the fine elements in riprap area, which could also improve the effects of riprap. The maximum scour depth is obviously reduced to 0.22 m, and it keeps away from the service area. All the results and comparisons are given in **Table 6**. The scour reduction simulated by numerical methods usually exaggerate the effect of countermeasures. The reason can be explained that the flow condition in numerical models is constant, while the flow during the experiments is changing. Numerical results are hard to provide the complex interaction between particles and models.



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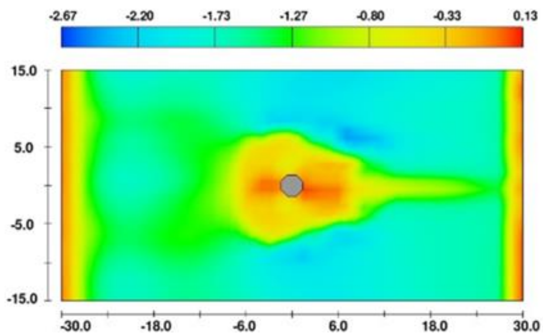

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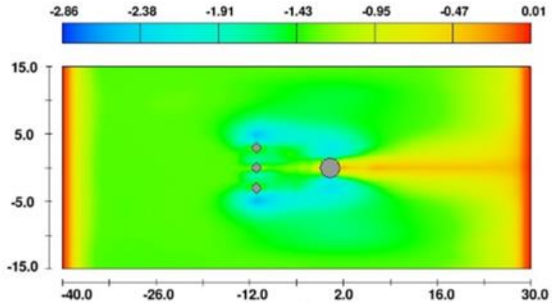

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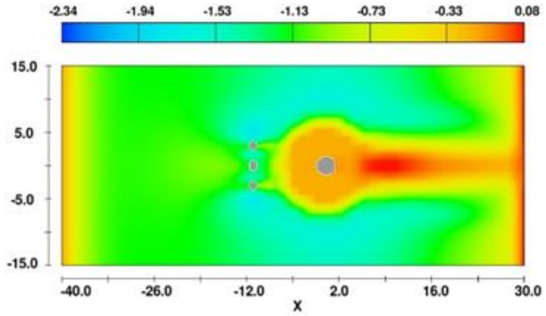

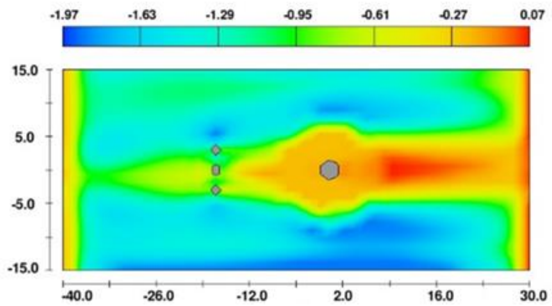

d

Fig. 9 Numerical results for scour around a pier with different countermeasures: (a) no protection; (b) riprap; (c) sacrificial piles; (d) combined riprap and sacrificial piles. (Unit: m).

Table 6. Comparisons between various countermeasures

Experimental Results	No	Riprap	Sacrificial Pile	Combined I	Combined II
Scour Depth (cm)	3.8	1.7	2.7	0.5	0.8
Reduction (%)	—	55.3	28.9	86.8	78.9
Numerical Results	No	Riprap	Sacrificial Pile	Combined I	Combined II
Scour Depth (cm)	3.6	0.9	2.08	0.22	0.49
Reduction (%)	—	75	42.2	93.4	86.4

5. Concluding remarks

Both experimental and numerical investigations of using sacrificial piles as a local scour countermeasure around the pile group foundation have been carried out. In total, five arrangements were carried out by experimental and numerical methods respectively. The scour process was observed and mechanism of countermeasure was analyzed according to the results. The following conclusions are drawn,

(1) The existence of combined riprap and sacrificial piles can alleviate the local scour around underwater foundations obviously. The percentage of diminution varies with the location of piles, while the downstream boundary benefits most among all the positions. Sacrificial piles with the distance of three times the diameter of service pier behave best among these arrangements (up to 86.8% according to experiments, while up to 93.4% according to numerical simulations).

(2) The installed piles also effect the interaction between the riprap and the service pier. The stability of the riprap layer could be significantly increased, while the protection provided by sacrificial piles be-comes smaller when the pile spacing is large.

(3) The FLOW-3D can be used as a good method to explore the scour around piers and their countermeasures in an economic and easy way. Because of the complication of scour problems, the effect of every parameter should be analyzed in further details.

(4) The results of experiments and simulations are not totally the same. The reasons can be divided into two categories: a. the different flow condition and foundation-soil model generated are not the same; b. the method of data collecting is not the same. The results provided by both experimental and numerical methods should be compared and improved by each other to make it more reasonable.

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