Study on Local Scour Protection Countermeasures of Bridge Pier

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Abstract. The scouring effect is a crucial factor affecting the stability of the bridge foundation. Many engineering methods have been developed to reduce the impact of local scour on bridge structures. Among the commonly used protection methods, each method has its limitations and advantages. In this paper, passive method, active method and combination method are used to describe the effects of riprap, collars, slot, sacrificial pile, and vanes methods on the erosion protection effect. The overall judgment of each method is made through the analysis of the factors that may affect the efficiency of protection and the possible shortcomings in the use of protection methods. Then, the inference of device size is derived by combining the various scenarios of the method, so as to help the protection efficiency of the protection method reach the optimal state. Finally, the future development trend and application prospect of the protection method were prospected.

Keywords: Local scour, countermeasures, active method, passive method.

1. Introduction

Scour effect is a crucial factor affecting the safety of Bridges. In China, Yi et al. studied 160 accidents that occurred between 2000 to 2014 and found that 30% of bridge accident reasons were scour [1].

Scour is an inevitable phenomenon which exists if the pier is in the current with a certain velocity. The water flow has a pressure gradient in the flow process, so that when the water flow hits the pier, the water flow will stagnate and generate a downward pressure gradient. Then, the water flow will rush into the scour hole to form a horseshoe vortex. Although the water flow on the side of the impacted pier will lose part of the pressure, it will maintain the original flow direction, passing through both sides of the pier and forming a secondary vortex. Finally, a wake vortex will be generated behind the pier due to the horizontal force of pressure. These three vortices work together to erode the riverbed near the pier's foundation.

Different countermeasures have been designed for many kinds of bridges. According to these ideas, the methods are mainly divided into passive and active methods. The passive method prevents the bridge foundation structure from being affected by this effect by increasing the soil strength in the area where the vortex can erode. The active method is to prevent by reducing the force of the water flow. In this paper, the protection methods are discussed in the form of passive method, active method, and combination method.

2. Passive Method

2.1. Riprap

T Riprap increases the strength of the riverbed near the foundation by replacing the soil near the bridge pier with heavier and larger stones, thereby strengthening the bearing capacity of the riverbed near the foundation to the vortex and reducing the maximum scour depth. This method has easy-to-understand principles and mature application technology, so it is the most used passive method.

There are four common failure types in riprap: shear failure, destabilized failure, edge failure and winnowing failure, among which winnowing failure has the most significant impact on the stability of riprap. Even though the riprap layer keeps intact, this failure method can lead to a scouring effect and completely fail the riprap. The winnowing failure could be caused by a large weight and size gap between the stones used in the riprap and the original soil in the lower part of the riprap layer. This reason will lead to the soil being washed away in the lower layer, but the riprap stones remain in place; the loss of the original soil will cause a scouring effect. This failure can be eliminated using the method of increasing the thickness of the riprap, which prevents water flow from affecting the soil below the riprap layer. At the same time, this method can also directly increase the strength of the riprap layer to reduce the maximum scour depth [2].

The riprap will significantly increase the protection efficiency with its skew angle (less than 20 degrees), but the aspect ratio will not [3]. Maximum scour depth occurs mainly around the bridge piles, so the change of the aspect ratio of the riprap will not affect the state around the bridge pile but only the strength of the riverbed farther away from the bridge pile. Thus, the aspect ratio change only affects the scour depth in the area where the riverbed strength is changed, but not the maximum scour depth. The increase of skew angle can directly increase the thickness of the riprap layer where the maximum scour depth occurs, directly reducing the scour depth.

Another advantage of riprap is that it can repair itself [2]. Because riprap uses heavier and larger stones, even if some of the top rocks fail due to the shear force generated by the current, nearby stones will quickly fill their positions and rebalance.

3. Active Method

3.1. Collars

Collars separate the downward flow by blocking the downward pressure gradient of the flow, preventing the main flow from directly impacting the riverbed and reducing the erosion ability of the horseshoe vortex on the riverbed. Collars are a relatively economical and effective way to drastically reduce the scour hole depth with just one disc [4]. This approach is influenced by several factors, each of which has an empirical value in engineering over the years of research.

The height from the free bed surface to the collars is a crucial factor affecting the efficiency of the collars. In the stage when the position of the collars is higher than the riverbed, the lower the height, the smaller the depth of scour hole, and the better the protective effect of the collars [5]. However, when the height of the collars is lower than the riverbed, the efficiency will increase slightly too. The soil on the upper layer will become part of the scour hole, thus affecting the structural stability of the pier. Therefore, the optimal placement height of the collars is parallel to or slightly lower than the riverbed height [6].

The width W of the collars also affects the efficiency of the protection. Moncada studied the cases when W/D=2 and W/D=3, respectively [7]. According to Fig. 1, although when the position of the collar is significantly lower than the riverbed height, the efficiencies of the two cases are similar. When the collar position is significantly higher than the riverbed, the efficiency of the sample with W/D=2 exceeds that of the sample with W/D=3. However, the efficiency of collars with W/D=3 is much higher than that of W/D=2 in the conventional placement height (the height is on the riverbed plane, or the difference is not large). Some argue that efficiency will continue to increase if the diameter of the collars increases [4]. However, when the collars are too large, the economics of the method will be weakened, and the collars themselves also require additional structures to support them. So, W/D=3 is the most efficient width of the collars [3].

For rectangular piles, the angle between the long sides of the rectangle and the water flow also affects the efficiency of the collars. According to Zarrati et al., the research efficiency decreases with increasing declination angle [6]. Therefore, most of the long sides of the piles are parallel to the direction of the water flow to achieve maximum protection efficiency.

The encircling angle of collars also significantly affects the protection efficiency. Wang et al. studied the protection efficiency of the collar method in the case of 180 degrees, 270 degrees and 360 degrees, respectively [5]. Among them, it is found that the protection strength of 360-degree collars is much greater than that of 270-degree, and 270-degree is much greater than 180-degree. Although using semi-enclosed collars can improve the economy of the method, there is a large gap between the efficiencies, so semi-enclosed collars are not used in actual construction. The collars protection method is used in the case of single piles and pier groups. When collars connect the space between pile groups, the protection efficiency will be the highest [4].

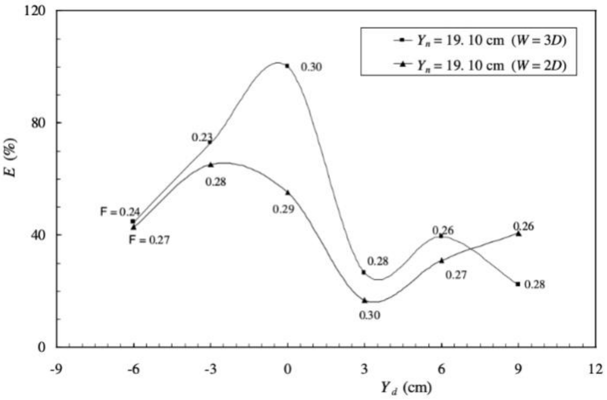

Figure 1. Efficiency E versus Yd was reached with collars of different diameters [7].

3.2. Slot

The slot is to limit the generation and intensity of the horseshoe vortex by diverting the partial down flow, thereby weakening the scour effect. This method also applies to control the long-term and short-term of bridge piers [8].

The length of the slot is a crucial factor affecting efficiency. It is worth noting that any slot length can provide protection efficiency within the riverbed range and water level range. According to the data supplied by Grimaldi et al., when the sinking depth of the slot divided by the approach flow depth is 1/6, 1/3, and 1/2, respectively, the maximum scour depth is reduced by 30%, 69% and 70% [8]. The protection efficiency of the slot will increase with the length, but the growth rate will gradually decrease. In addition, Moncada proposed that the position of the slot also affects the conservation efficiency [7]. When the slot extends from the horizontal plane to the riverbed, the conservation efficiency ranges from 48% to 85%. And when the slot is extended from the riverbed to the water level, the protection efficiency is 60% to 88%.

The width of the slot also affects the protection efficiency. When the width is one-fourth the diameter of the pile, the maximum scour depth is reduced by 20%, and when the width is one-half, the maximum scours depth is reduced by 30% [9]. The protection efficiency also increases with the width, but as the width of the slot increases, the maximum support strength of the bridge pile will also decrease, so a balance between the two needs to be achieved.

3.3. Sacrificial Pile

The strength of the scouring effect is mainly determined by the magnitude of the water flow. Therefore, the sacrificial pile reduces the flow directly impacting the bridge pier by using the sacrificial pile in front of the bridge pier, reducing the scouring effect. The experiment and data simulation results show that the method is quite economical, and the highest protection efficiency can reach 50% [10].

Again, this approach is affected by many factors. The arrangement of sacrificial piles is one of the most critical factors. According to Fig. 2 and Table 1, the maximum front scour depth occurs in the S-4 arrangement, while the minimum front scours depth appears in the S-5 and S-8 structures. The protection efficiency of the sacrificial pile group is higher than the single sacrificial pile. The maximum scour depth occurred in structure S-8, while the minimum scours depth occurred in structure S-9. It can be inferred that in the case of sacrificial pile groups, the protection efficiency will also be affected according to the arrangement. The distance between the sacrificial pile and the bridge pile is also a critical factor affecting the protection efficiency of the sacrificial pile. In S-2, S-3, and S-4, the distance between the bridge pile and the sacrifice pile is four times, five times, and six times the diameter of the bridge pile. According to Table 1, the data shows that the maximum scours depth increases in turn, and the protection efficiency of the sacrificial pile decreases in turn [11]. Therefore, the closer the bridge pile is to the sacrificial pile, the higher the protection efficiency. However, if the distance is too close, the maximum scour depth produced by the sacrificial pile will affect the foundation of the bridge pile, thereby reducing the protection efficiency.

The application of a sacrificial pile has a time effect. This effect causes the maximum scour depth and equilibrium to be reached in less time. In the study of Shahkarami, the maximum scour depth was reached at 70 min without sacrificial piles. After adding sacrificial piles, the maximum scour depth was achieved only at 40 min [12].

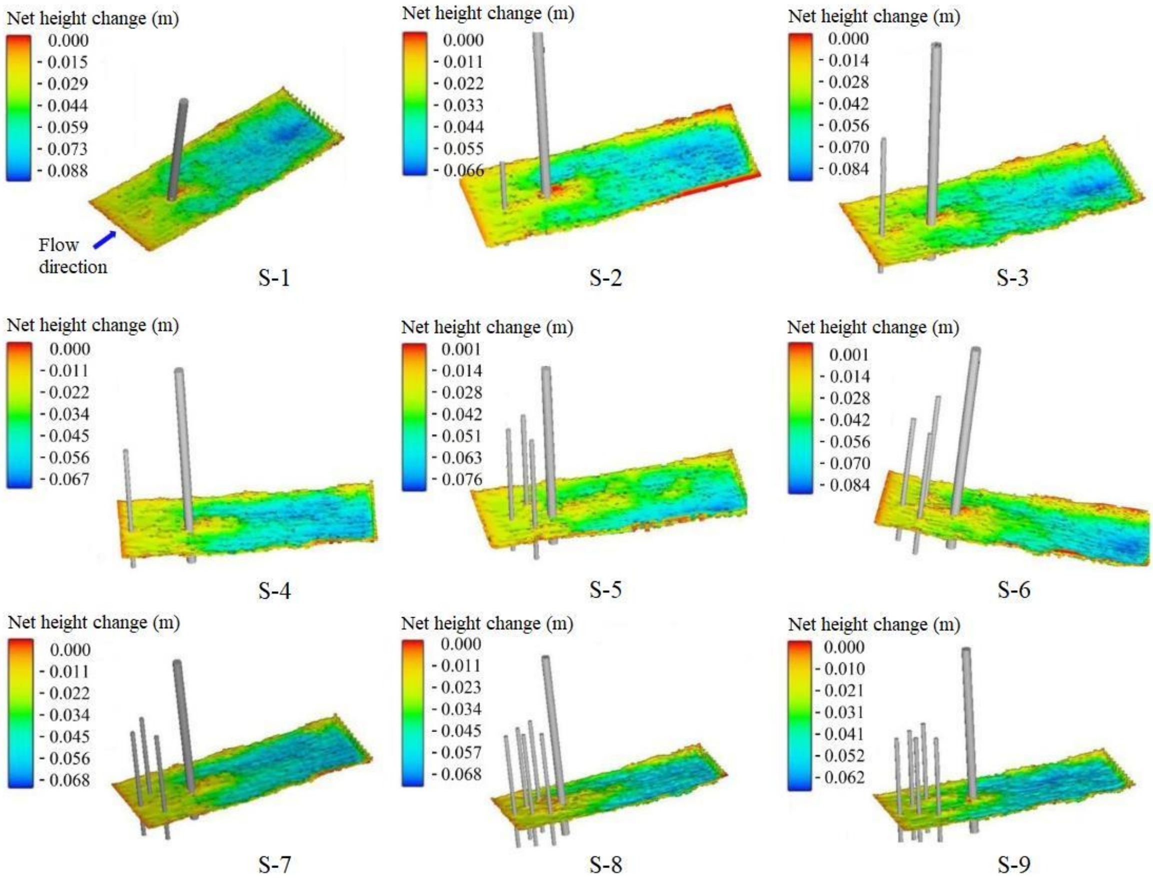

Figure 2. Simulation results (packed sediment height net change) after the steady-state [11]

Table 1. Scour depth in different scenarios [11]

	S-1	**S-2**	**S-3**	**S-4**	**S-5**	**S-6**	**S-7**	**S-8**	**S-9**
In front of the pier	42.6	23.8	29.4	32.3	19.6	20.6	21.4	19.6	20.9
In the back of the pier	17.9	12.6	12.7	12.7	11.4	11.5	11.6	11.3	11.5
On the sides	44	32	38	42	30	41	44	21	23

The direction of water flow and the angle between the line connecting the sacrificial pile and the bridge pile also significantly affect the protection efficiency of the sacrificial pile. When the angle between these two exceeds 20 degrees, the maximum scours depth near the bridge piles with the sacrificial piles will be like those without the sacrificial piles. When the angle is less than 20 degrees, maximum scour depth decreases with decreasing angle [13]. This could be caused by the maximum scour depth on the side of the bridge pile facing the direction of water flow. If the angle is too large, the sacrificial pile will not be able to reduce the flow that contributes to the scour depth, resulting in the protection efficiency of the sacrificial pile approaching 0.

3.4. Submerged Vanes

Installing the Submerged vanes creates a secondary circulation of the water flow at a distance behind the vanes. This circulation weakens water flow before the bridge pile, reducing the maximum scour efficiency [14].

The angle used by the vanes, the distance from the bridge piles, and the distance between the vanes are these three factors that affect the protection efficiency, but the relationship between them and the maximum scour depth is not a linear relationship of a single element. Therefore, three factors affect each other and determine the maximum scour depth together. According to the experimental results of Ghorbani and Kells, the maximum scours depth occurs at moderate angles (18.5 degrees) closer to the bridge piles (0.8 times the radius of the bridge piles) and farther between the vanes (0.5 times the bridge distances) [15]. Pile radius, the maximum scours depth is 1.5 times that without submerged vanes. This may be because the secondary circulation generated by vanes appears near the bridge piles, and the secondary circulation helps the formation of scour holes. In Fig. 3, where vanes height is the distance between vanes; d is the distance from vanes to the bridge pile, and D is the diameter of the bridge pile; Y_c is the scour depth; and Y_n is the scour depth without submerged vanes.

According to Fig. 3, the highest protection efficiency occurs at low angles (8.5 degrees), medium and long distances (1.75 times the radius of the pile), and the distance between vanes is zero. This may cause by the secondary circulation that occurs directly in front of the bridge piles, and there is no flow through the vanes, thus significantly reducing the flow to the bridge piles. In comprehensive Fig. 3, the data in each of the three variables interact with each other and determine the position of the secondary loop. If the secondary circulation is in front of the bridge pile, vanes can increase the protection efficiency. When the secondary circulation and the bridge pile position overlap, the existence of vanes will increase the maximum scour depth. When the secondary circulation is in the bridge pile, at the rear, the presence of vanes will hardly affect the protection efficiency.

The aspect ratio of the vanes board is also a key factor affecting the protection efficiency. When the value of the length ratio is less than 1, vanes mainly rely on the influence of the upstream water flow to reduce the maximum scour height. When the value is greater than 1, the vanes largely depend on the plate to block the water flow, thereby transferring the scour effect from the bridge pile to the front of the plate [16]. Found that if the aspect ratio is greater than one vane offers more significant potential for scour protection efficiency than in another situation.

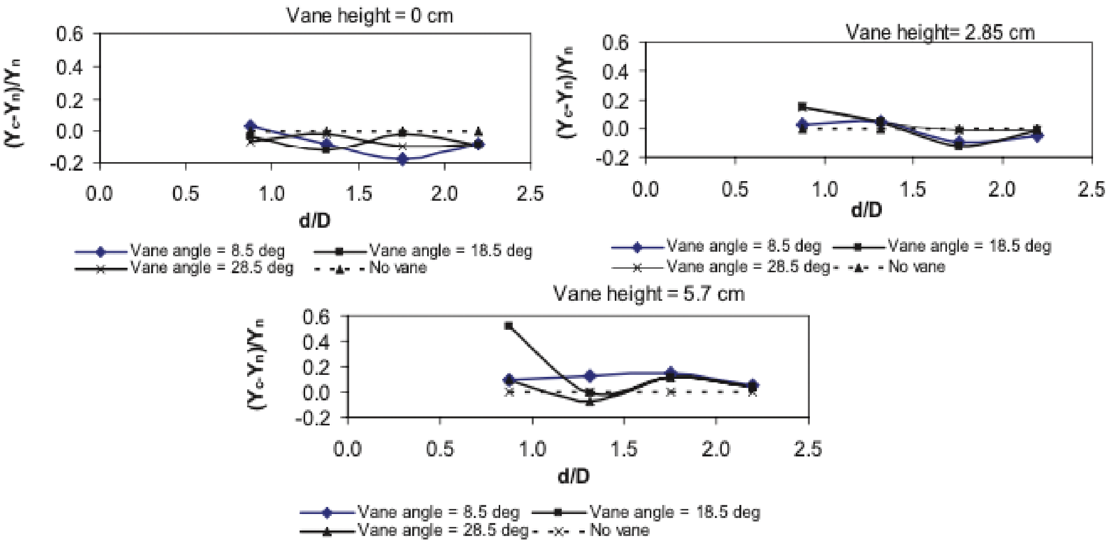

Figure 3. Effect of vane angle on scour depth for vane heights of 0.0D, 0.25D, and 0.5D [16]

4. Combination of Countermeasures

4.1. Collars and Slot

The combined use of collars and slots can reduce the maximum scour depth and even eliminate the impact of scouring effects upstream of the pile [3, 7]. This effect has exceeded the maximum protection efficiency of the two methods used alone. This may be because the two methods adopt different ideas to reduce the maximum scour depth. Collars are mainly responsible for reducing downflow, while slots are primarily responsible for reducing direct flow. Therefore, the two do not interfere with each other but work together.

4.2. Collars and Riprap

When collars and riprap are used together, they will affect each other. Although the increase in the diameter of the collars and the increase in the skew angle can improve the protection efficiency, the magnitude of the drop is much smaller than if only one method were used to change it [2]. This may cause by the two working together on downflow and interfering with each other.

5. Conclusion

In this paper, several methods of influencing the scour effect and their limitations are studied. Their characteristics are summarized as follows:

(1) The impact aspects related to riprap have been studied quite comprehensively, including the winnowing failure, size of stone and thickness of riprap. However, more advanced technologies are needed to help its practical application because of its complex and high-cost construction process.

(2) Collars and slots also have mature researches. The influence factors are mainly studied, and the other factors are hard to affect the maximum scour depth. There is a risk of failure when faced with a sudden increase in water flow, so more detailed calculations are needed to prevent this phenomenon.

(3) Sacrificial pile has been widely used in practice because of its excellent economy. Although most of the relevant researches have been completed, some aspects require more attention, such as the arrangement of many sacrificial stakes.

(4) There are many unknown influencing factors for submerged vanes, so more experiments are needed to study the most efficient application arrangements and limitations of this method. Therefore, this method is far from practical application.

(5) The combination of methods has a good application prospect, but there are also many immature places. In future research, it is necessary to find out how these methods affect each other.

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