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Combination of Riprap and Submerged Vane as an Abutment Scour Countermeasure

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Abstract: Scour is one of the main causes of hydraulic structural failures. The present experimental study examines the use of riprap, submerged vanes, and a combination of these for scour reduction around vertical walls and spill-through abutments under clear-water conditions. Specifically, the influence of placing riprap stones with different apron shapes (geometry) and/or a group of submerged vanes of constant height and length on abutment scour was examined. The main aim is to propose the optimum apron geometry and placement of submerged vanes to (1) reduce edge failure at vertical walls and spill-through abutments; and (2) prevent shear failure at the spill-through abutment (no shear failure is observed around the vertical wall abutment). The results show that using ripraps for scour protection is more effective than submerged vanes. However, the highest reduction in scour depth was achieved when a combination of riprap and submerged vanes was used together. This arrangement can reduce the maximum clear-water scour depth by up to 54% and 39% with vertical walls and spill-through abutments, respectively. Furthermore, selecting appropriate apron scale ratios reduces the required riprap volume by up to 46% and 31% for the vertical wall and spill-through abutment, respectively. In addition, the installation of vanes increased the riprap stability and reduced edge failure in both abutments tested. Finally, using riprap aprons with proper scales ratios at the downstream side of the spill-through abutment also prevents shear failure in this zone.

Keywords: scour countermeasure; vertical wall abutment; spill-through abutment; riprap; submerged vanes

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1. Introduction

Local scour around bridge foundations has caused bridge failure, leading to financial, time and even human losses worldwide [1–4]. To reduce such occurrences, researchers worldwide have investigated bridge scour using various approaches. To understand the mechanism of bridge scour, it is essential to study the flow pattern around the bridge foundation, and the related scour mechanism, which is highly complex. The main factors influencing the abutment scour mechanism are downflow, primary vortex and wake vortices [5,6]. After the flow hits abutment face, a downward flow or downflow develops because of the formation of a pressure gradient. The downflow first excavates a groove around the abutment wall, which in turn expands to form a helical flow (primary vortex) that can effectively entrain and transport sediment particles around the abutment. The flow separation at the outer edge of the abutment creates wake vortices that can lift the bed material like a cyclone in this zone to be transported downstream [7].

Several recent studies [8–12] have investigated different types of scour countermeasures to reduce local scour around bridge foundations. Local scour countermeasures can generally be divided into two categories [13], namely (a) armoring, and (b) flow-altering countermeasures. The former includes installing heavy elements such as riprap stones, gabions, cable-tied blocks, reno-mattresses, grout bags, etc. Flow-altering countermeasures, however, include the installation of submerged vanes, collars, sacrificial piles, spur dikes, and slots [14–17].

Many researchers [18–23] have studied riprap protection at bridge foundations. It is considered an environmentally friendly protection technique because it provides suitable conditions for aquatic organisms to thrive [24]. The permeable media through the particles allows native vegetation to take root and allows the survival of other organisms, helping to restore the stream's natural conditions. Many rock structures providing possible stream restoration with environmental benefits have been proposed and investigated by researchers such as Bhuiyan et al. [25] and Pagliara et al. [26]. From a scouring perspective, riprap stones should be designed to withstand the local shear stresses that form at the abutment. According to Chiew [9–27]; and Melville et al. [20], riprap layer failures around bridge foundations include shear, winnowing, edge and bed-form undermining failures. Shear failure, which occurs when turbulent flow erodes and moves riprap stones around bridge foundations, can be mitigated by using an appropriate riprap size. Winnowing failure is a consequence of the removal of finer materials (uplifting parent materials) through the riprap stones. Its occurrence can be prevented by using synthetic or granular filters. Edge failure occurs when a depression at the border of the sediments and riprap stones propagates and causes riprap stones to slide and fall into the hole. This can be reduced by providing a suitably designed apron. Bed-form undermining is the result of passing bed features (dunes and anti-dunes) around bridge foundations. This failure will bury riprap stones within sediments and can be prevented by placing the riprap below the level of the dune trough [18].

Flow-altering countermeasures exist in the form of in-stream structures, such as W-weirs, U-weirs, J-hook vanes and submerged vanes, the latter of which is not expensive to build [28]. The appropriate design of these structures prevents bank erosion, local scour, and channel degradation and improves grade control [8,18].

In addition to the above-mentioned structures, submerged vanes also have a broad range of applications for the reason that they can modify the local flow field, diverting the incoming flow from directly impinging on bridge piers or abutments and protecting river bend scour. Baltazar et al. [29] used submerged vanes to change flow pattern in a lateral diversion under live bed conditions. The authors reported that the amount of sediment entering to diversion reduced up to 26% when vanes were in place. Vanes prohibit the diversion vortex induced in the main channel by creating tip vortices and modifying velocity flied. Bahrami Yarahmadi et al. [30] used triangular vanes in a 900-flume bend. They concluded that triangular vane reduced bed shear stress near the outer bank, and at the position of 0.8 times of vane length in the downstream, vanes have the best performance in producing secondary flow. Bahrami Yarahmadi and Shafai Bejestan [31] applied triangular vanes in a flume bend. They reported that a single vane reduces average velocity near the outer bank and increases the number of vanes, resulting in the thalweg being pushed from the outer bank towards the channel midway. They reported that the best vanes performance was achieved when the lateral spacing is five times the vanes' length. With regard to bridge foundation, submerged vanes change the magnitude and direction of shear stress upstream of the pier or abutment. One of the first studies on the use of submerged vanes as a pier-scour countermeasure was carried out by Odgaard and Wang [32] and claimed that submerged vanes push the sediment bed toward pier. Later, Lauchlan [33] used vanes to reduce scour around bridge pier and stated that applying vanes resulted in a 34% scour depth reduction. Ghorbani and Kells [14] used vanes as pier scour countermeasures. Ghorbani and Kells [14] concluded that for vanes height other than zero (vanes height measured from sand bed), scour depth increases and maximum scour depth (87%) was achieved when two vanes with the angle of 18.50 were attached to the pier. By using vanes, Johnson et al. [15] used vanes as an abutment scour countermeasure. They reported that vanes reduce velocities and shear stress in the vicinity of foundation and if abutment is within the area affected by vanes, the scour depth will be decreased greatly. They stated that maximum flow control will be achieved when the angle of attack is between 25 and 300, and two structures instead of one improve vanes' performance which resulted in a 96% scour depth reduction around the bridge abutment. Shafai Bejestan et al. [34] used vanes to reduce local scour around a vertical wall abutment. They concluded that vanes reduce velocity and shear stress at the abutment nose and push this area toward the middle channel. The authors utilized different vanes angles and positions and stated that the best performance was achieved when vanes are attached to an abutment at an angle of 400.

In an attempt to overcome the shortages of each method and enhance scour countermeasure techniques, many researchers have applied a combination of different methods to reduce scour depth significantly. Zarrati et al. [35] experimented with the combination of riprap and collar to mitigate local scour around pier groups. They observed that incorporating tow methods resulted in 50% and 60% scour reduction in front and rear piers, respectively; however, using collar independently reduced scour depth by 25% and 30% for front and rear piers. Garg et al. [36] employed sleeve, collar and submerged vanes to protect a bridge pier against local scour. They reported that the combination of these techniques is more effective than using them individually, so that incorporating vanes with collar and vanes with sleeves reduces scour depth by 86% and 70%, respectively, in comparison with applying vanes, collar and sleeves which resulted in 57%, 78% and 39%. In another laboratory experiment conducted by Biswas and Barbhuiya [37], riprap and submerged vanes were used to mitigate river bend scour. They observed that, in a permanent river, it is not possible to mitigate scour, either with riprap or submerged vanes individually; however, bend protection can be attained if a combination of two techniques is applied. Zolghadr et al. [38] performed a laboratory examination to evaluate the effect of riprap and Six Pillar Concrete (SPC) elements separately and in combination on scour around a bridge abutment in different Froude Numbers under clear water conditions. They stated that average scour reductions using SPC elements and riprap alone were 83% and 30%, respectively; however, the highest reduction was achieved when both scour countermeasures were applied, which was 91%. In addition, they reported that the combination of the two techniques removed edge failure thoroughly.

Many researchers have independently used riprap and submerged vanes to reduce scour at bridge foundations. However, to the best of the authors' knowledge, incorporating these two methods has not been investigated at the vertical wall and spill-though abutments. Incorporating both riprap and vanes together may provide a more effective abutment-scour countermeasure because combining them can overcome the weakness of using each method individually. Some potential advantages include riprap stability enhancement and edge failure protection.

Moreover, very few studies have investigated the volume of riprap needed, although it is an important consideration for engineers to determine the cost-effectiveness of an apron design. An appropriate riprap configuration leads to a reduction in riprap volume and cost [39]. Consequently, the present study aims to examine not only the depth of scouring but also riprap failure and volume. In summary, the main objective of this research is to explore the effect of riprap and submerged vanes (singly or in combination) on scour reduction around vertical walls and spill-through abutments in clear-water conditions. The effect of the different geometry of riprap was evaluated on scour depth, edge failure and volume of riprap. Furthermore, shear failure that occurs at spill-through abutment is discussed as well.

2. Materials and Methods

The present experiments were conducted in a hydraulic laboratory the of water engineering department at Shiraz University, Iran. Tests were performed in a flume with 16 m length, 1.2 m width and 0.4 m depth. The abutment model was placed in a recess that was 2.5 m long, 1.2 m wide, and 0.2 m deep, filled with uniformly distributed sediment. The characteristics of the sediment used in this study were: median grain size, $d_{50} = 0.78$ mm for which 50% by weight is finer [40]; geometric standard deviation, $\sigma_g = \sqrt{\frac{d_{84.1}}{d_{15.9}}} = 1.28$ which satisfies uniformity of sediment [41], in which 84.1% and 15.9% of the particles are finer by weight, and specific gravity = 2.63. Based on Raudkivi [42], median grain size was selected to prevent ripple forming ($d_{50} > 0.7$ mm) and the effect of sediment size on scour depth was omitted from consideration in this study since $\frac{L}{d_{50}} > 50$ [1], where L is the abutment length. A rock-filled box was installed at the flume entrance to eliminate the effect of large circulations induced at the flume entrance. The distance between the flume entrance and the sediment recess (test section) was 8.5 m to ensure the formation of a fully developed flow. Two concrete false floors were placed at the upstream and downstream ends of the sediment recess to prevent the leaching of particles, and a layer of the same sediment was glued on the concrete false floors so that a uniform bed roughness existed along the flume. A circulatory flume system was used to introduce the necessary flow for the tests. Three pumps (each with a capacity of 120 L/s) were used to circulate water from a large underground reservoir to the head tank to ensure a constant head. The flow discharge was adjusted using a butterfly valve, and the resulting flow rate was measured with an electronic flow meter installed along the pipe. The flow depth was regulated by using a hand-operated tailgate located at the downstream end of the flume. The scheme of the flume and related facilities are shown in Figure 1.

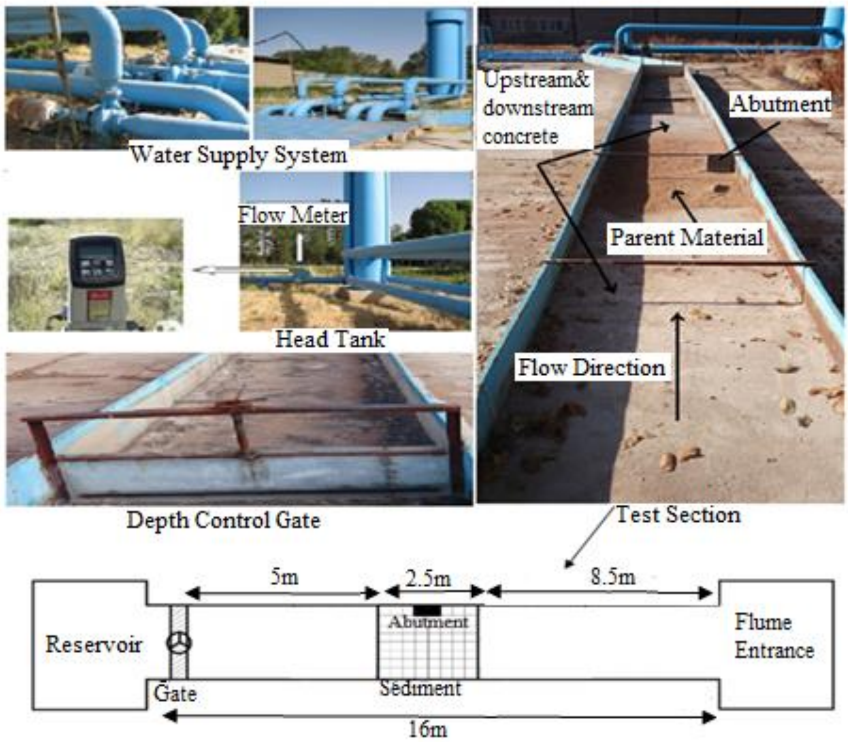

Figure 1. The scheme of test section, instrument and plan view of sediment recess.

Figure 2 shows the two types of abutment examined in this study: (1) vertical wall with three different dimensions; and (2) spill-through abutment. The length of the vertical wall abutments (L) used in the study were 15, 25 and 35 cm with a width of 10 cm. The length of the spill-through abutment (L) was 35 cm; its top width = 10 cm, top length (L') = 20 cm and side slope = 1:1 ($H : V$).

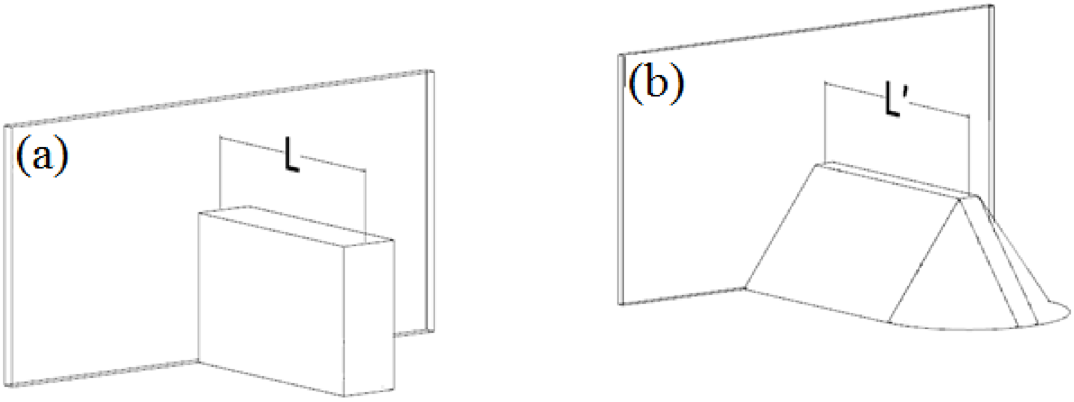

Figure 2. Schematic illustration of the abutments: (**a**) Vertical wall; (**b**) Spill-through.

Riprap stones in the form of fine gravel with median grain size $D_{R50} = 7$ mm were used in this study. The riprap stones were selected based on the study of Chiew [9]. Similar scale ratios of riprap stones also were used by Cardoso et al. [21] for abutment countermeasures ($D_{R50} = 7$ mm and $d_{50} = 0.96$ mm) and Zarrati et al. [35] for pier countermeasure ($D_{R50} = 5$ mm and $d_{50} = 0.95$ mm) in their studies. The scale ratios of the apron (a_R, b_R and t, see Figure 3 for the definition of these scale ratios), which are selected according to Melville and Coleman [1] and Cardoso et al.'s [21] recommendations, are shown in Table 1.

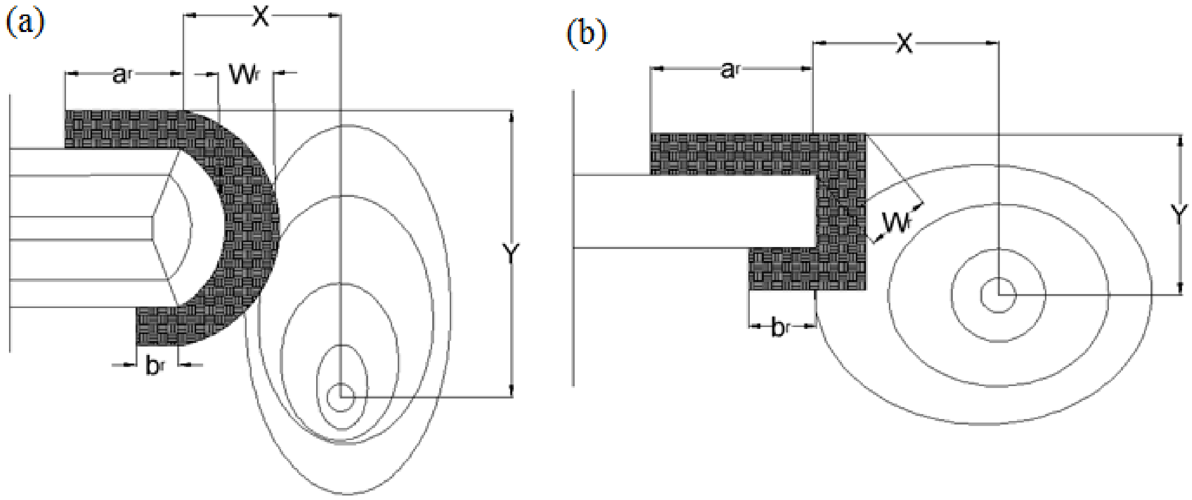

Figure 3. Scale ratios of the riprap apron and position of the maximum scour depth at the (**a**) spill-through abutment; (**b**) vertical-wall abutment.

Table 1. Characteristics of riprap stones.

Type of Abutment	L (cm)	Riprap				
		a_R(cm) =min{L,2y}	b_R(cm) =3D_{R50}	t(cm) =3D_{R50}	w_R(cm)	
					Formula	Value
Vertical wall	15	15	2	2	$w_R = 0.75y\left(L^+\right)^{0.55}$	11
	25	25	2	2	$w_R = 0.5y\left[2K\left(L^+\right)^{0.5}\right]^{1.35}$	26
	35	30	2	2	$w_R = 0.5y\left[2K\left(L^+\right)^{0.5}\right]^{1.35}$	33
Spill-through	35	20	2	2	$w_R = 2y$	28

Note: K is the abutment shape factor = 1 for vertical wall abutment. $L^+ = \frac{L}{y}$ in which y is flow depth. w_R is the apron width. a_R and b_R, respectively, are the upstream and downstream lengths of the apron; and t is the apron thickness.

The apron width (w_R) in the spill-through abutment was selected according to Richardson and Davis's [43] recommendation. For vertical wall abutments with 25 and 35 cm lengths, Melville et al.'s [20] relation was applied; for the length of 15 cm, the Cardoso et al. formula [21] was used (Table 1). A granular filter with median particle size = 1.8 mm and the same scale ratios of the riprap layer was used to prevent winnowing failure. The filter was selected according to Terzaghi's criteria. To install the filter and riprap layers, the volume of the bed material that was the same as that of the apron was first carefully removed, before it was backfilled with the filter and riprap stones to the same level as the initial bed.

The location of the maximum scour depth was also recorded, as shown in Figure 3, in which X and Y are the coordinates of the maximum scour depth locations, respectively. The scale ratios were measured from the abutment toe; these locations are similar to that presented in Cardoso et al. [21].

The parameters that are involved in defining the geometrical layout of submerged vanes are shown in Table 2. The values were selected based on the findings of Johnson et al. [15] and Fathi and Zomorodian [44]. The geometrical layout of the vanes is shown in Figure 4.

Table 2. Parameters of geometrical layout of vanes.

Parameter	Value	
	L_{V15}	L_{V25}, L_{V35}, L_{S35}
Length of vanes (L_S)	$4H_S = 22.5$ cm	22.5 cm
Height of vanes (H_S)	$0.4y = 5.6$ cm	5.6 cm
Angle of vanes relative to flow direction (α)	30°	30°
Distance of vanes from the abutment (P)	$\frac{B}{3.2}$	$\frac{B}{3.2}$
Number of vanes in a row (M)	1	2
Number of rows of vane (N)	1	1
Position of first vane relative to the edge of the abutment (d_V)	$\frac{L}{3}$	$\frac{L}{3}$
Lateral spacing of the vanes (e)	$2H_S < e = 12$ cm $< 3H_S$	$2H_S < e = 12$ cm $< 3H_S$

Note: B is channel width, and y is flow depth. The subscripts V and S represent vertical wall and spill-through, respectively, and 15, 25 and 35 are the abutment lengths in cm.

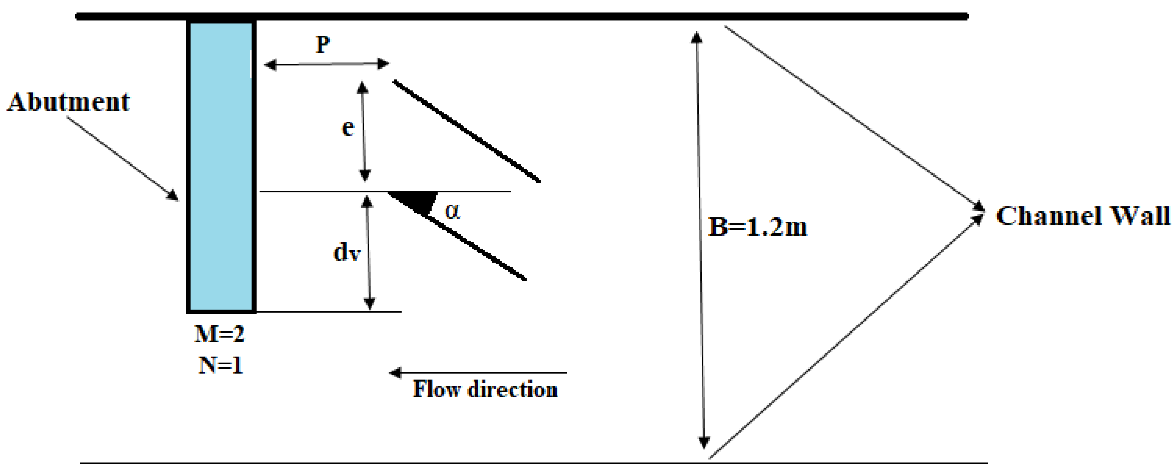

Figure 4. Plan view of channel and arrangement of vanes.

Laboratory Experiments

In Table 2, the angle of attack (α), number of vanes in a row (M), length (L_S) and the height of the vanes (H_S), and the distance of the vane from the abutment (P) are found to have the most dominant effect on the performance of vanes. This is inasmuch as vanes produce horizontal circulations that modify the flow pattern. In submerged vanes, the vortex sheet separation occurs at their top edges, creating a vortex that affects the vertical pressure distribution and, hence, a lift force. The strength of the horizontal circulations depends on the lift force. If the angle of attack is high, for example, the vortex formed and the lift force induced will correspondingly be high [8,45]. Moreover, Odgaard and Wang [8] stated that a vane affects a distance approximately twice its height in the transverse direction. Thus, increasing the number of vanes in a row (M) produces more circulations and a large lateral extent, thereby effecting a superior outcome.

The strength of the vortex circulations induced by vanes decays as they move downstream for the reason of viscous diffusions and bed resistance [8]. Van Zwol [45] reported that the circulations persist within a distance that is twice the vane's length. Accordingly, vanes should be installed at an appropriate distance from the abutment (P) to reduce flow velocity within the area between the vanes and the abutment.

The maximum scour depth occurs at the threshold condition for bed sediment entrainment, ($\frac{V}{V_c} = 1$) where V = mean approach velocity and V_c = critical velocity [46]. Accordingly, all laboratory experiments were conducted near the threshold condition in this study. The critical velocity was computed using the customary mean velocity logarithmic law [9] for a rough bed with the roughness height = $2d_{50}$ as follows:

$$\frac{V_c}{u_{*c}} = 5.75log\frac{y}{2d_{50}} + 6 \quad (1)$$

$$R_e = \frac{V\,y}{\nu} \rightarrow R_e = \frac{0.33 \times 0.14}{10^{-6}} = 46200 \quad (2)$$

In the hydraulic rough turbulent area, the Reynolds Number was 46,200 which confirms using customary mean velocity logarithmic law. In Equation (1), the critical shear velocity, u_{*c}, was calculated from Shield's Diagram. Consequently, the critical shear and mean velocities were determined to be 0.0192 m/s and 0.33 m/s, respectively. The value of flow discharge, flow depth and mean velocity were calculated as 0.045 m^3/s, 0.14 m and 0.27 m/s, respectively.

To determine the test duration needed in the study, a preliminary test that lasted 24 h was first performed, and the temporal evolution of the scour at the location of the eventual maximum scour was plotted. After 6 h, it was found that the rate of change of the scour depth was not significant. In other words, after 6 h, 90 percent of the 24 h scour depth had occurred [47]. Consequently, the test period used in this study is 6 h. In general, reaching equilibrium scour depth is really time-consuming [48]. Long-duration experiments are needed to develop a true equilibrium scour depth [49]. A 96 h duration was reported by Kothyari et al. [50], stating that such a period is required to develop a near-equilibrium scour hole at bridge piers under clear-water conditions [51]. However, since the current study aims to compare how different arrangements of the countermeasures affect abutment scour reduction, the duration used in the study was shortened. Similar studies with shorter experiments dealing with scouring can be found in the literature with 4 h duration or less [16,52].

After the completion of each experiment, the bed topography around the abutments was measured in a 2 cm × 2 cm grid using a laser displacement meter with 1 mm accuracy. The displacement meter, which was capable of moving in both streamwise and lateral directions, was placed on a platform.

Four types of experiments were conducted: (I) abutments without protection (baseline experiments); (II) abutments with riprap apron; (III) abutments with submerged vane; and (IV) abutments with the combination of riprap and submerged vanes. To evaluate the effect of the scour countermeasures, the maximum scour depths measured in the main tests (Types II, III and IV) are compared with that in the baseline test (Type I). Figure 5 shows the location of the maximum scour depth in the baseline experiments for both abutment types.

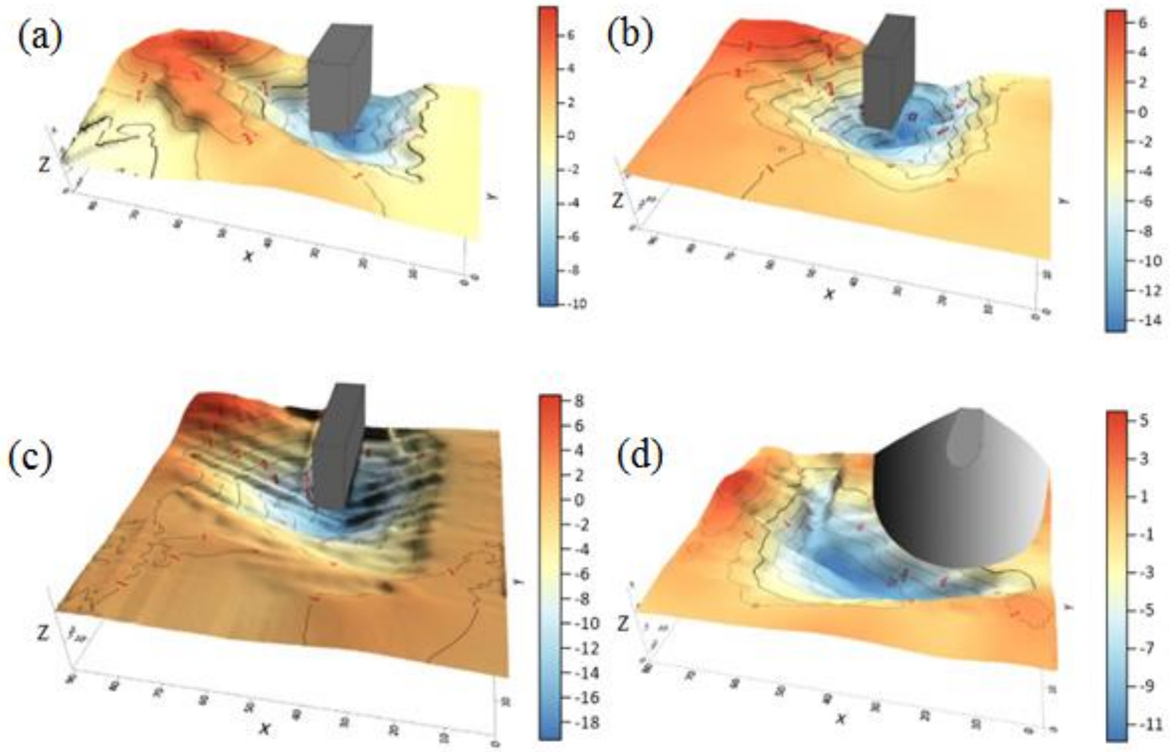

Figure 5. Location of the maximum scour depth at vertical wall and spill-through abutments. (**a**) L_{V15}; (**b**) L_{V25}; (**c**) L_{V35}; (**d**) L_{S35} (Flow from right to left).

In the experiments, two riprap failure modes were observed: edge and shear failure. The former appeared in both abutment shapes; however, it was minor with the vertical wall abutments. Hence, the discussion of edge failure is devoted to spill-through abutments. The latter was witnessed only at the downstream side of the spill-through abutment. To prevent shear failure at the spill-though abutment, larger stones were needed. Consequently, a riprap layer (R_{15}) with a diameter = 15 mm, width = 15 cm and the same thickness of D_{R50} was installed at the downstream side of the spill-through abutment to prevent shear failure.

3. Results and Discussion

3.1. Application of Submerged Vanes and Riprap Individually

In essence, vanes act as a kind of flow-altering countermeasure tool, whereas riprap stones create an armor layer to shelter the finer underlying parent materials from erosion (armoring countermeasure). Tests T_2 and T_3 (Table 3) show the effectiveness of using submerged vanes and riprap placement independently on scour reductions, respectively, as an illustration. As shown in Table 3, the use of a riprap layer (T_3) on scour reduction is more effective than that of submerged vanes (T_2), for two reasons. First, in the case of submerged vanes installations, due to the presence of the scour hole around abutments, the edge of the scour hole produces flow separation to create a curved flow that triggers the formation of the primary vortex, which is one of the dominant factors in scour mechanisms. Second, using ripraps increases the distance between the unprotected materials and the abutment such that the highest turbulence intensity no longer affects the scouring process as long as the location with this intensity is now covered with larger rocks [53,54]. As a result, the reduced flow circulations and disturbances farther away from the abutment are already subsumed into the main flow before encroaching onto the bed material. Thus, using riprap resulted in shallower scour depths compared to using submerged vanes alone. In addition, observations in Test T_3 showed that the riprap layer displaced the maximum scour depth from the abutment toe to the middle of the channel. However, in the submerged vane Test, T_2, the maximum scour depth location remained in the vicinity of the abutment toe. In this case, riprap layers not only reduced the scour more effectively, but also pushed the maximum scour depth location away from the abutment. Relocating the scour hole farther away from the abutment is a key factor in preventing bridge failure [20] (see Figure 6a,b).

Table 3. Summary of results.

Tests Number	Abutment Type	Scour Countermeasures	X (cm)	Y (cm)	Q (cm)	d_S(cm)	d_s/L	Scour Reduction Compared to Baseline Tests (%)
T_1	L_{V25}	–	–	–	0.045	15.2	0.608	–
T_2	L_{V25}	S	–	–	0.045	10	0.4	34.21
T_3	L_{V25}	R	65	24	0.045	9.4	0.376	38.75
T_4	L_{V25}	SR	50	30	0.045	8.9	0.356	41.45
T_5	L_{S35}	–	–	–	0.045	11.8	0.337	–
T_6	L_{S35}	S	–	–	0.045	8.2	0.234	30.5
T_7	L_{S35}	SR	95	26	0.045	7.5	0.214	36.44
T_8	L_{S35}	R_{15}, R	80	22	0.045	7.8	0.223	33.89
T_9	L_{S35}	S, R_{15}, R	98	29	0.045	7.2	0.206	38.98
T_{10}	L_{V35}	–	–	–	0.045	17.8	0.508	–
T_{11}	L_{V35}	S	–	–	0.045	16.1	0.460	9.55
T_{12}	L_{V35}	R	60	40	0.045	13.2	0.377	25.84
T_{13}	L_{V35}	SR	62	35	0.045	12.1	0.346	32.02
T_{14}	L_{V15}	–	–	–	0.045	10.1	0.673	–
T_{15}	L_{V15}	S	–	–	0.045	8.7	0.580	13.86
T_{16}	L_{V15}	R	36	24	0.045	8.3	0.553	17.82
T_{17}	L_{V15}	SR	22	21	0.045	5.5	0.360	54.45

Note: S, R, R_{15} and S, R represent submerged vanes, riprap with a median diameter of 7 mm, and riprap with a diameter of 15 mm, a combination of submerged vane and riprap stones, respectively. Scour countermeasures refer to the device used to reduce scour. The subscripts V and S represent vertical wall and spill-through abutments, respectively, and 15, 25 and 35 are abutment lengths in cm.

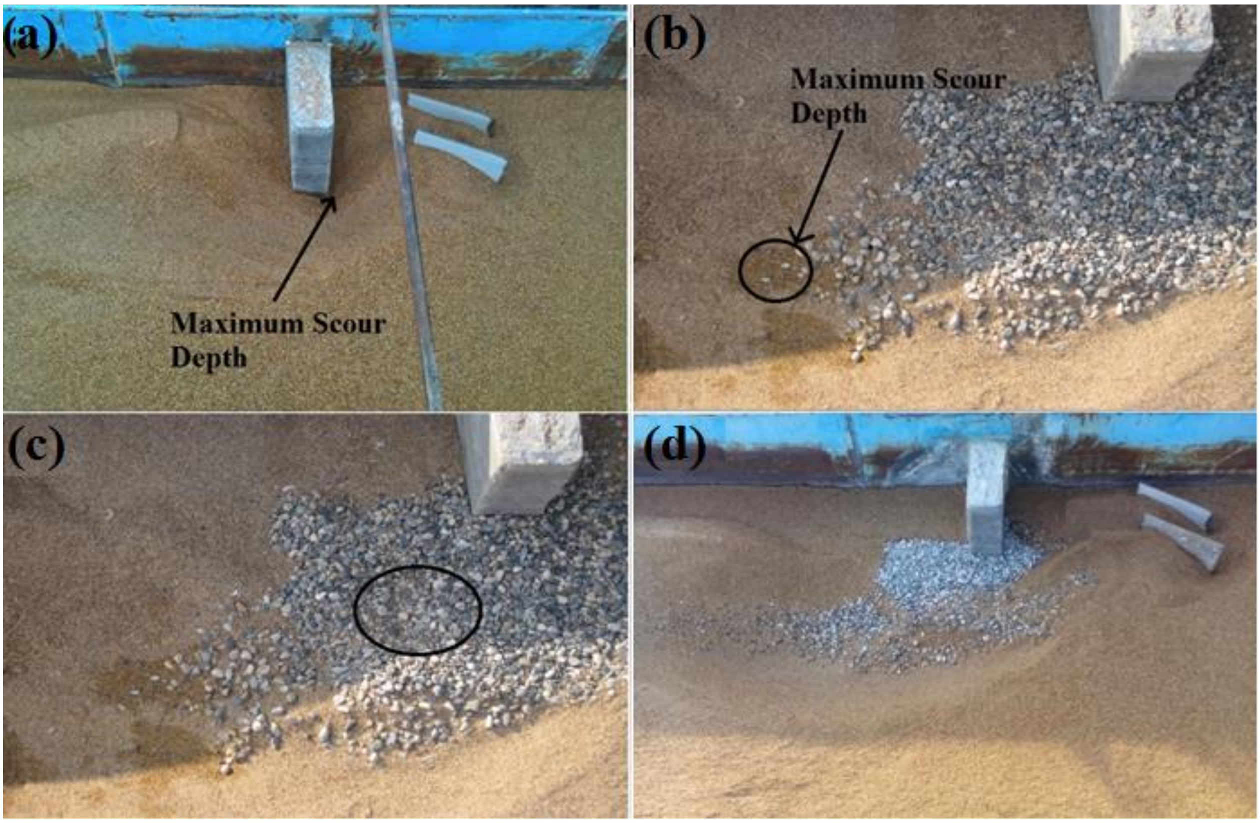

Figure 6. Maximum scour depth location and erosion of riprap stones around L_{V25} in case of submerged vane and riprap. (**a**) T_2; (**b**) T_3; (**c**) T_3; (**d**) T_4 (flow from right to left).

3.2. Combination of Submerged Vanes and Riprap

Although using submerged vanes and riprap stones as abutment scour countermeasures provides positive results, causing definitive scour depth reductions, if they are used together, one could surmise that their combined effects will be even more significant. Consequently, this study examines whether using these methods together can lead to an improved scour countermeasure method, and if so, by how much? Table 3 (T_4) shows the experimental results obtained by using a combination of submerged vanes and riprap, clearly revealing that fewer riprap stones are displaced compared to T_3 (see Figure 6c,d). This is due to the reduction of the local shear stresses and turbulence around the abutment for the presence of the submerged vanes [15,34]. In summary, the experimental data show that using both these methods together can reduce the maximum scour depth by 41% more than that using individual methods separately (compare T_4 to T_3 and T_2 in Table 3).

For the other abutments (L_{V35}, L_{V15} and L_{S35}), similar results to that of the L_{V25} abutment types were obtained when submerged vanes and riprap were used together, although with different percentages of scour reduction. The reason probably is due to the differences in the length and shape of the abutments. In summary, although the effect of riprap on scour reduction is superior to that of submerged vanes, the latter can enhance riprap stability due to their ability to modify the local flow field. The present data show that the highest reduction in scour depth for all the abutments tested occurs when these two methods are used together (Table 3, Tests T_4, T_9, T_{13} and T_{17}).

3.3. Geometry and Scale Ratios of Riprap Apron

Without the armoring layer, maximum scour depth happens at the downstream end of the spill-through abutment (Figure 7a) and with the presence of the apron layer, the edge failure occurs at this zone. To reduce edge failure, apron geometry plays an important role [13]. Since Richardson and Davis [43] have provided a well-known and widely used formula to determine (w_R), a test was performed based on their design (Test T_{18} in Table 4). Test T_{18} is the baseline test to examine the effectiveness of other riprap scale ratios. Despite their recommendation, Cardoso et al. [21] reported that designs using the method proposed by Richardson and Davis [43] are overly conservative. In order to design an apron to achieve optimum cost-effectiveness, its width and thickness are decreased, according to Table 4. The results of four additional tests based on different scale ratios and apron geometry at the spill-through abutment are shown in Table 4. Furthermore, the riprap volume reduction percentages of all of the tests as compared to the baseline test also are shown.

Tests T_{19} to T_{22}, with different apron widths and thicknesses, were conducted to obtain an apron configuration without compromising its effectiveness in this study. In Test T_{19}, the width of the apron was 25 cm (Figure 7b, Geometry I), 11% shorter than that of the baseline Test, T_{18}. The experimental results revealed the presence of edge failure at the apron. Observation clearly shows how a depression is first formed at the interface of the riprap stones and original bed sediments, which is the onset of "edge failure". With time, the depression propagates, causing the riprap stones to slide into it. If this hole becomes excessively large, a total disintegration of the apron may occur [9]. Edge failure and the extent of riprap coverage are closely related; if there is a sufficient supply of riprap stones, this problem may be mitigated. Under this condition, the riprap stones that slide into the scour hole can re-armor the hole to prevent further erosion and total disintegration [9,55,56]. Accordingly, to overcome the observed edge failure, the apron was changed from a circular to a square shape (see T_{20} in Figure 7c, Geometry II), with the aim of enhancing the riprap stones' stability here (compare T_{20} to T_{19}). This observation, which shows a distinct improvement, is consistent with the result of Simarro et al. [13], who reported that the apron geometry of Figure 7c is superior to that of Figure 7b.

Table 4. Results of different geometry and scale ratios of apron at spill-through abutment.

Tests Number	w_R (cm)	w_R/L	a_r (cm)	b_r(cm)	X (cm)	Y (cm)	Shape of Apron	d_s/L	Changes in Scour Depth (%)	Volume of Riprap (cm^3)	Riprap Volume Reduction (%)
T_{18}	28	0.8	20	2	73	25	Geometry I	0.268	_	7393	_
T_{19}	25	0.714	20	2	70	27	Geometry I	0.277	+3	6353	14
T_{20}	25	0.714	20	2	80	25	Geometry II	0.234	−12.7	7228	2.2
T_{21}	20	0.571	20	2	60	23	Geometry II	0.240	−10.6	5439	26.4
T_{22}	25	0.714	20	2	74	30	Geometry II	0.234	−12.7	5006	32.3

Note: The positive and negative signs in Column 9 indicate an increase and decrease in scour depth compared to T_{18}, respectively.

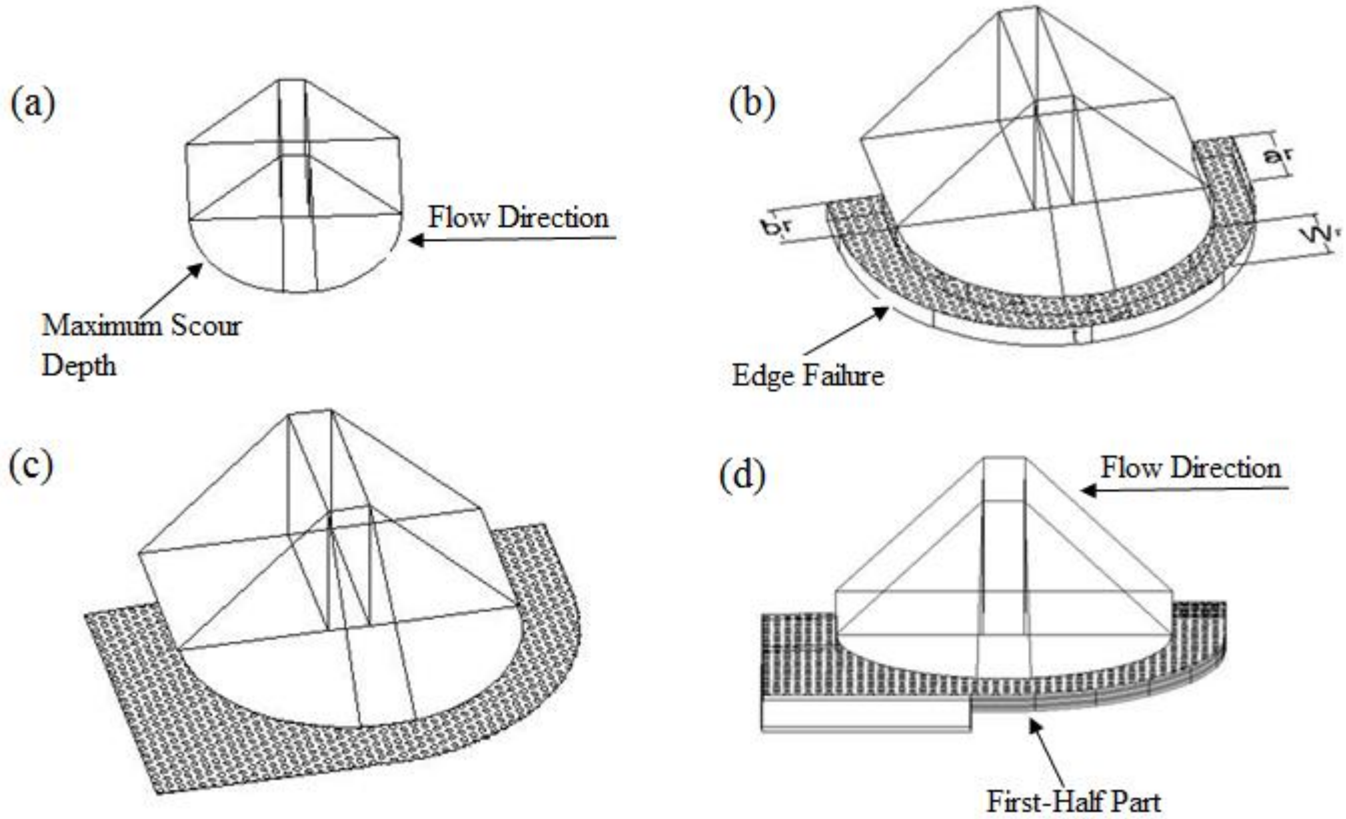

Figure 7. Geometry of riprap particle in spill-through abutment: (**a**) location of maximum scour depth (**b**) Geometry I, T_{19}; (**c**) Geometry II, T_{20}; (**d**) shape of apron with $1.5D_{R50}$, T_{22}. (flow from right to left).

In Test T_{21}, the apron width was further decreased to 20 cm to test the over-conservatism of the method of Richardson and Davies [43]. With this change, the result shows that the location of the maximum scour depth has migrated closer to the abutment toe ($X = 60$ cm and $Y = 23$ cm) because the scour hole position is dependent on apron width [20]. However, edge failure, which occurs at the downstream end of the abutment as shown in Figure 7b, is more prominent when compared to that in Test T_{20}. Hence, the apron width was reverted to 25 cm. However, since scouring and the dislodgement of riprap stones (edge failure) did not occur at the upstream end of the riprap apron, the apron thickness at this location was decreased by $1.5D_{R50}$ in Test T_{22} to reduce the volume of the riprap layer needed (Figure 7d). With this change, the result shows that reducing the thickness of the riprap layer has no effect on edge failure and the resulting scour depth, i.e., it did not exacerbate edge failure. The results also show that edge failure and scour depth were reduced in Test T_{22} compared with Test T_{19} by 12.7%. In addition, the volume of the riprap layer in Test T_{22} is reduced by 32% in comparison to the baseline Test T_{18}.

Similar to the spill-through abutment, the riprap volume is also reduced by decreasing its thickness at the vertical wall abutment so that the apron thickness at the upstream end is reduced by $1.5D_{R50}$ for each vertical wall abutment, and the riprap volume is reduced significantly (see Figure 8). The Figure shows that, despite the significant reduction of the riprap volume in all the abutments (Classes 1 and 2), the scour depth did not increase. Apart from edge failure (Tests T_{18} to T_{22}), which is reflected by the erosion of riprap stones at the downstream end of the spill-through abutment, shear failure is also is observed. To address this problem, an appropriate size of the riprap layer was proposed; an issue that will be discussed in the following section. As mentioned earlier, shear failure was not observed at the vertical wall abutment.

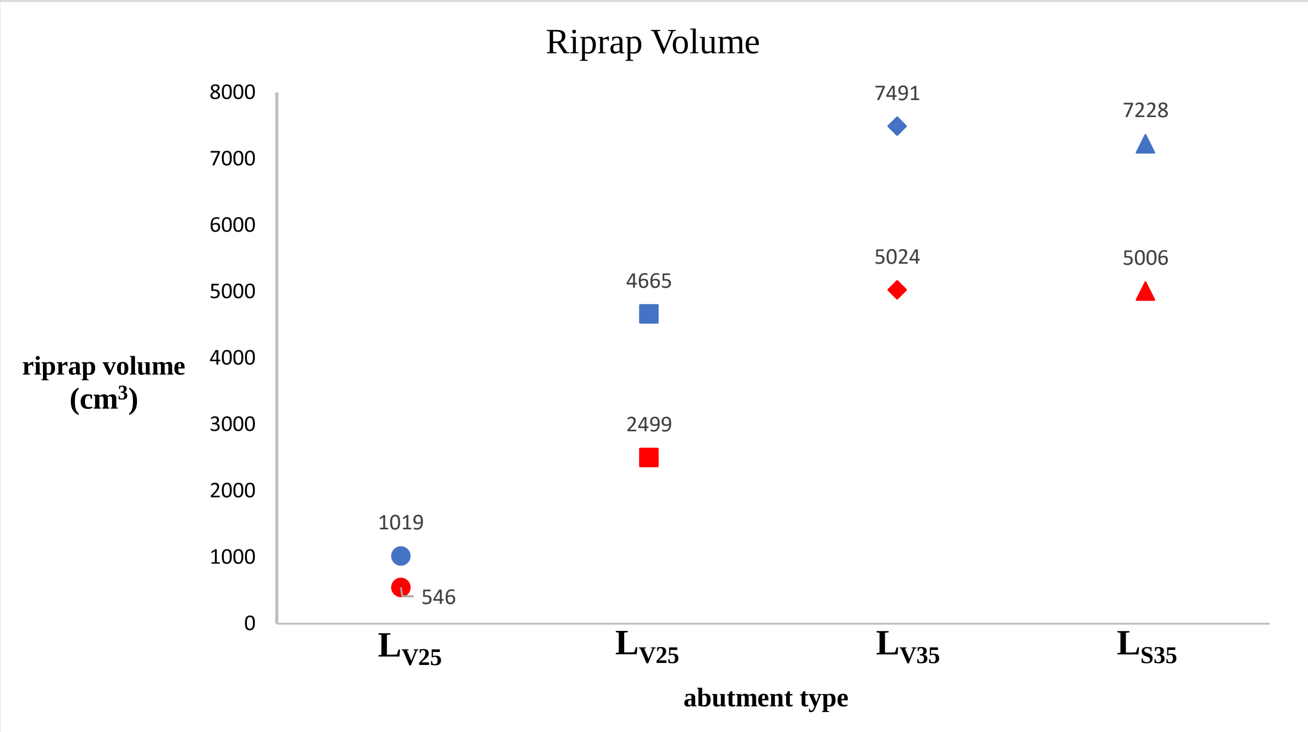

Figure 8. Volume of riprap layer around abutments. Blue symbols represent riprap with $t = 3D_{R50}$ and red symbols represent $t = 1.5D_{R50}$.

3.4. Shear Failure Prevention at Spill-Through Abutment

Shear failure occurs when the riprap stones are not heavy enough to withstand the turbulent flow field [5,13]. In Tests T_{18} to T_{22}, riprap stones at the downstream end of the spill-through abutment were eroded in both geometries I and II (see Figures 7 and 9a) because flow separation has caused an upward flow (wake vortices) that entrains the bed sediments [57]. In addition, the roughness difference between the course riprap and fine bed sediments creates a vulnerable point where the finer materials are eroded. These combine to create a depression (hole) at the interface of the apron and bed sediments. As this scour hole enlarges, riprap stones start sliding and rolling into it (edge failure), as was reported by Chiew [9]. With time, the scour depth continues to grow until the shear stress and turbulence fluctuations around the abutment can no longer erode the parent materials [53]. It should be noted that in the area around the abutment, the shear stress and vortices are higher than those of the approach flow (10 and 1.5 times, respectively, [57]). As a result, reducing the strength of the downflow and primary vortex at the upstream side of the abutment can reduce the strength of wake vortices and edge failure to enhance riprap stability. To achieve this, using submerged vanes is an appropriate alternative. They produce vortices (horizontal circulations) that move downstream with the main flow, augmenting the shear stresses. In addition, vanes reduce velocity within the area between themselves and the abutment, resulting in the formation of a lower pressure gradient and downflow [34,53]. Consequently, the flow separation correspondingly becomes weaker.

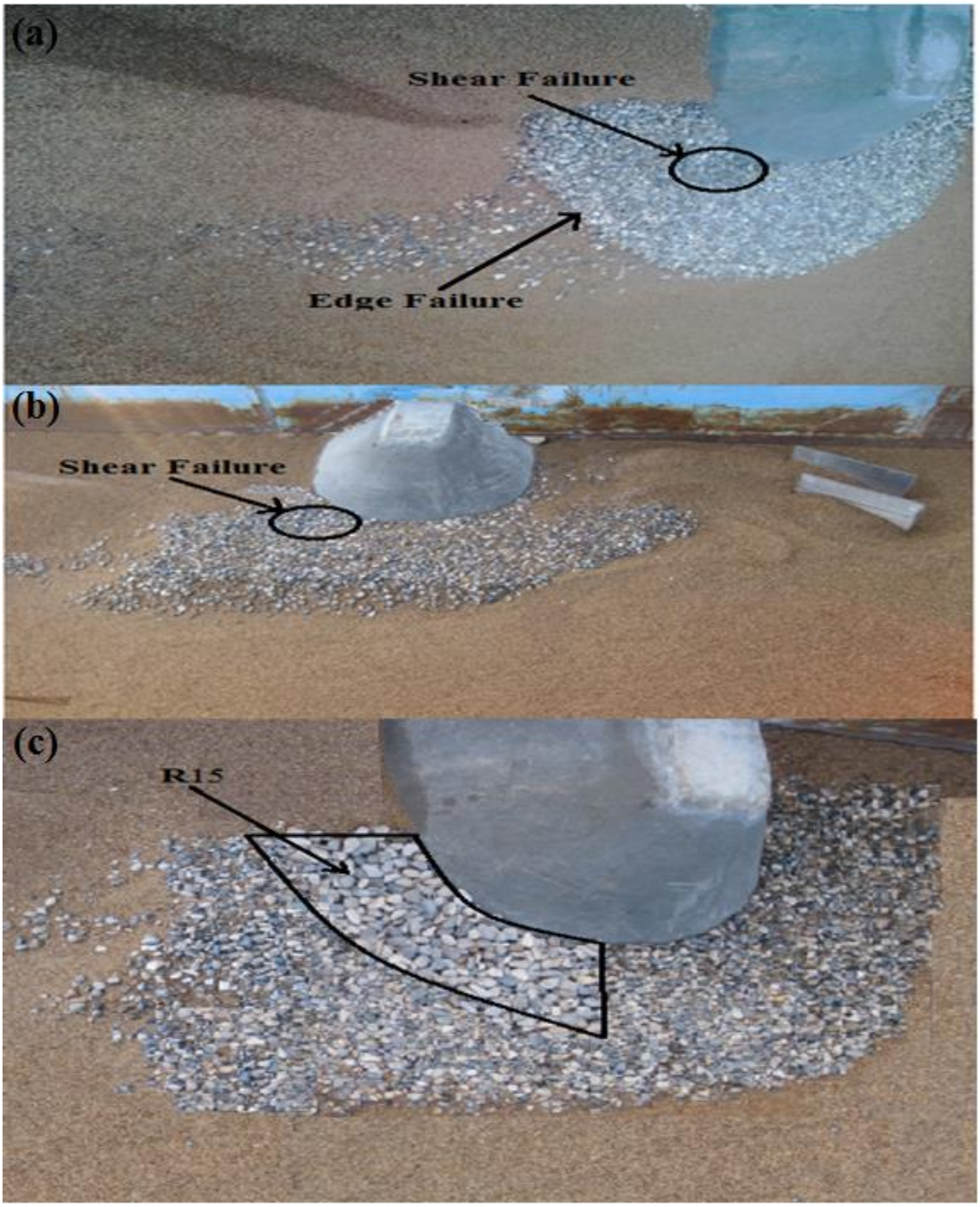

Figure 9. (**a**) T_{19}: shear and edge failure; (**b**) T_7: effect of vane on shear failure; (**c**) T_8: use of R_{15} to arrest shear failure (flow from right to left).

If the placement of vanes still cannot prevent such failures (Figure 9b), installing another riprap layer may be needed. In this study, a riprap layer (R_{15}) with diameter = 15 mm, thickness = $3D_{R50}$ and width = 15 cm was placed around the abutment (Figure 9c). The aim is to use larger riprap stones to arrest shear failure. Test T_8 (Table 3) shows that using R_{15}, the riprap layer is left intact, and shear failure is prevented (Figure 9c). One may infer from these two tests that vanes and riprap size offer different remedial actions in abutment scour countermeasures. The engineer must understand the purpose of their design when using different scour countermeasure approaches.

4. Conclusions

In this study, both armoring (riprap) and flow-altering (submerged vanes) scour countermeasures were investigated individually and together around vertical walls and spill-through abutments. The maximum scour depth and location, armor layer failure, volume and scale rations are discussed in detail.

The following conclusions are drawn from the study:

1. Installing a riprap layer reduces the maximum scour depth by up to 39% and 34% in vertical wall and spill-through abutments, respectively.
2. Submerged vanes reduce the maximum scour depth by up to 34% and 30% in vertical walls and spill-through abutments, respectively. This shows that the effect of riprap on scour reduction is more than that of submerged vanes.
3. The largest decrease in scour depth is achieved through a combination of riprap and submerged vanes. These reductions were 54% and 39% in vertical walls and spill-through abutments, respectively.
4. By installing a riprap layer, the location of the maximum scour depth is relocated away from the abutment toe while it remains close to it by using submerged vanes alone.
5. Applications of submerged vanes enhance riprap stability and reduce edge failure. With vanes, fewer riprap stones are eroded by the flow.
6. A square-shaped riprap layer at the downstream end of spill-through abutments is more effective in promoting riprap stone stability and reducing-edge failure than circular-shaped riprap layers.
7. Using submerged vanes is not an effective way to prevent riprap shear failure at the downstream side of spill-through abutments. Utilizing a larger riprap layer (R_{15}) is needed.
8. By decreasing the thickness of the riprap layer proposed by Cardoso et al. (2010) in the upstream half of the apron, the volume of the riprap layer needed is reduced up to 46% without affecting the riprap efficacy.

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Nomenclature

The following symbols are used in this paper:

a_R	Upstream apron width
B	Channel width
b_R	Downstream apron width
D_{R50}	Median diameter of riprap apron
d_s	Scour depth
d_V	Distance of first vane relative to the edge of the abutment
d_{50}	Median size of sediment bed
e	Lateral spacing of the vanes
H_S	Vane height
K	Abutment shape factor
L	Length of abutment

L'	Top length of spill-through abutment
L_S	Vane length
M	Number of vanes in a row
N	Number of rows of vane
P	Distance of vanes from the abutment
Q	Flow rate
R	Riprap
R_{15}	Riprap with diameter of 15 mm
S	Submerged vane
t	Thickness of riprap layer
u_{*c}	Critical shear velocity
V	Mean velocity
V_c	Critical velocity
w_R	Width of the apron
X	Position of maximum scour depth along the flow direction
Y	Position of maximum scour depth transverse to the flow direction
y	Flow depth
α	Vane angle (degree) corresponding to flow direction
σ_g	Sediment gradation

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