Scour Protection around Bridge Piers Using Tetrahedron Frames

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ABSTRACT

Armoring countermeasure such as riprap stones has been extensively used as a means to protect bridge piers against scour. In this study, an innovative armoring device in the form of tetrahedron frames is tested for its effectiveness as a pier-scour countermeasure. Although the device has previously been used as a protection method against bank and beach erosion, it has not been tested as a pier-scour countermeasure. This study aims to investigate the mechanism of using tetrahedron frames as a pier-scour countermeasure, and to explore its effectiveness. Experimental data show that the frame can effectively protect the foundation of bridge piers against scour. The equilibrium scour depth first increases almost linearly with velocity, then decreases at velocities just above the threshold for bed sediment entrainment until a minimum is reached at about 1.1 times the threshold velocity. The presence of the frames significantly dissipates the energy associated with the downflow and horseshoes vortex. Two-dimensional tests without bridge piers were also conducted and the results show that edge failure, which often occurs at the interface of a riprap stone layer and the finer bed material, does not occur at the periphery of the tetrahedron-frame layer. This observation is confirmed by 3D-tests conducted with a bridge pier.

I. INTRODUCTION

The formation of scour holes around bridge piers is common in rivers and canals. Bridge damages at a river crossing often can be attributed to scouring at its foundations [1]. The protection of the foundation of bridge piers is important since there is an important relationship between bridge failure and scour at bridge foundations.

There are many armoring devices such as riprap, cabled-tied blocks, Reno mattresses, gabion mattresses, concrete-filled mats and bags, concrete apron, dolos, tetrapods, etc. Despite using riprap, which is the most commonly used countermeasure to protect pier foundation against scour, failures still occur. Based on published studies [1~3], there are five failure mechanisms associated with riprap protection: shear failure, winnowing failure, edge failure, bedform-induced failure and bed-degradation induced failure. Each of these failure mechanisms plays a role in causing the eventual demise of the riprap layer.

As a new scour countermeasure, tetrahedron frames was first used to protect riverbank against erosion. It can change a scouring state to a deposition state near dikes or river bank slopes through a change in the velocity distribution resulting in a reduction in local velocity [4]. Knowledge on how a tetrahedron frame affects bridge pier scour is very limited. A thorough understanding of the mechanism of tetrahedron frame protection around bridge piers is necessary before engineers can adopt this method as a pier-scour protection device. The aim of the study is to investigate the mechanism associated with using tetrahedron frames as a pier-scour countermeasure, and to explore its effectiveness.

II. EXPERIMENTS SETUP AND PROCEDURE

Cohesionless uniform bed material with a median particle size of 0.40 mm and a specific gravity, S_s, of 2.65 was used in this study. The geometric standard deviation of the bed material was 1.35. Figure 1 shows the particle size distribution of the sediment.

The specific gravity of the tetrahedron frame was 2.45, and the cross-section of rods making up the frame is 1.7 mm × 1.7 mm with a length = 17 mm. Figure 2 shows the sketch of a single tetrahedron frame and the photograph of two tetrahedron frames stacked on top of each other.

The Shields diagram was used to calculate the critical shear velocity, u_{*c}, of the bed sediment, which is 0.01486 m/s. The corresponding critical mean flow velocity, U_c, was determined using (1), which is similar to the formula given in Chiew [2]

$$\frac{U_c}{u_{*c}} = 5.75\log(\frac{y_0}{1.3d_{50}}) + 6 \quad (1)$$

Two adjustable flumes with dimensions = 6 m length, 0.176 m width and 0.2 m depth (Flume1) and 16 m length, 0.6 m width and 0.6 m depth, (Flume2), respectively, were used in this study. Flume 1 has a feed system while Flume 2 is a sediment- recirculating type flume. For both flumes, water stored in a downstream water tank was recycled using a centrifugal pump, through a PVC pipe into the stilling basin at the upstream end of the flumes. A settling tank at the downstream end of Flume 2 collects the sediment into a steep-sided hopper over the sediment recirculation pump intake. A separate constant speed pump is used to recirculate the sediment, which is collected before the water reaches the water tank. An adjustable weir is located at the downstream end of the settling tank; it acts as a water level controller and prevents sediment particles from entering the main pump intake. The flow rate was monitored using an electromagnetic flow meter, and regulated using the combination of a butterfly valve and a speed inverter.

In Flume 2, there is a 1-m-long recess in which sediment was placed to reduce the amount of bed sediment needed for the test. A cylindrical pier, which was made from a 70-mm-diameter clear Perspex tube, was located at the centre of sediment recess. A bed, consisting of 7-cm thick sediment that has the same property as the sediment particles in the recess, was placed along the bed of the flume,

Figure 3 shows how the Tetrahedron frames were placed around the pier. The extent of a tetrahedron frame layer was defined by its cover, C, which is the border length of the square. The placement cover, C/D, used in this study is 5.

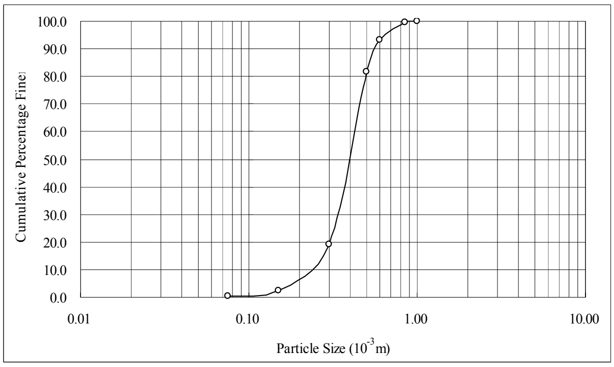

Figure 1. Particle size distribution of sediment

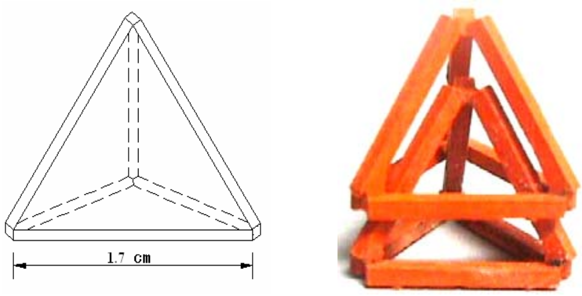

Figure 2. Sketch of tetrahedron frames

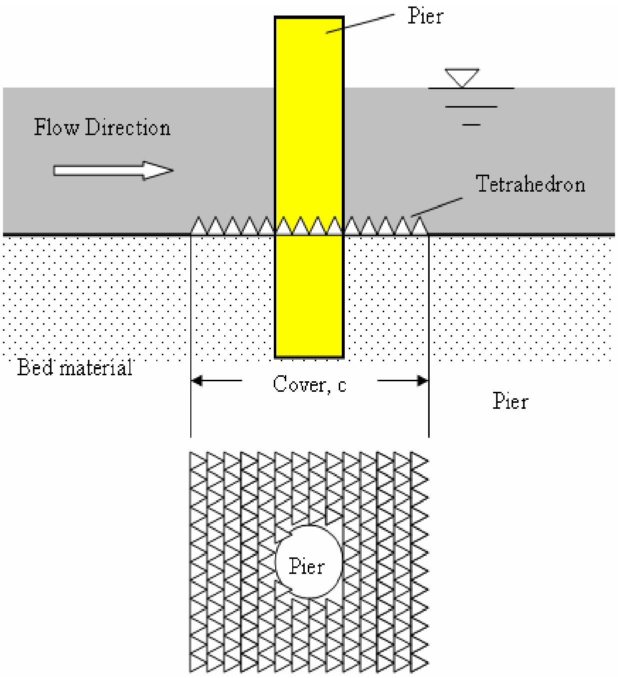

Figure 3. Definition sketch of placement of frames

Before starting the experiments, the bed sediments were well compacted to prevent any presence of air voids which will cause settlement when water was introduced. The next step in the procedure was to level the sediment bed before the tetrahedron frames were carefully placed around the pier. After preparation of the tetrahedron frame layer, the flume was slowly filled with water in order to avoid any undesirable disturbance on the sediment bed. Once the desired flow depth was reached, the flow was slowly increased to its predetermined rate. The stability of the tetrahedron frame layer was observed and development of the scour hole monitored. Two types of tests were conducted. The first was a 2-dimensional test (without pier) conducted in Flume 1. The undisturbed approach flow depth was set at 50 mm. The objective of the tests was to examine whether edge failure will occur with the tetrahedron frame protection. A clear-water condition was used in the test because the flume did not allow for sediment recirculation. The second test was conducted in Flume 2 with a pier surrounded by tetrahedron frames, similar to that shown in Fig. 3. The undisturbed approach flow depth was set at 250 mm. The test aimed to investigate the mechanisms associated with using tetrahedron frames as a pier-scour countermeasure, and to explore its effectiveness. The scour depths were measured using a periscope. The near equilibrium criteria used was that proposed by Melville and Chiew [5], i.e., that the tests were stopped when the change in scour depth did not exceed $0.05D$ (5% of the pier diameter) during a 24-hour period.

III. Bed Erosion with Tetrahedron Frame Protection without Pier

Earlier studies have shown that riprap protection is subjected to a number of failure mechanisms that can destabilize the stones and lead to a complete disintegration of the protective armor. The failure mechanisms under clear-water conditions are shear failure, winnowing failure and edge failure. It is expected that shear failure will also occur with tetrahedron frames when the shear velocity exceeds the critical shear velocity for the entrainment of tetrahedron frames.

Edge failure, as documented in Chiew [2], occurs at the periphery of the coarse riprap stones and fine bed sediment interface. He attributed it to the high shear stress experienced by the finer sediment particles as water flow from the coarse to the fine bed boundary. The downstream finer sediment particles are entrained by the flow because of their lower critical shear stress. When this happens, a local depression, which exposes the larger riprap stones, will form. The stones at the edge will roll or slide into the depression. Chiew stated that such erosion takes place at low velocity ratio where shear and winnowing erosion are normally absent, and constitutes the first sign of failure of the riprap layer. Edge failure hastens the eventual demise of the riprap layer as it enhances either winnowing or shear failure. The former leads to embedment while the latter enhances disintegration of the riprap layer.

A series of tests were conducted without a bridge pier in Flume 1 to eliminate the complex 3D flow field associated with bridge pier scour. Its aim was to examine whether winnowing failure and edge failure will occur with tetrahedron frames protection. Figure 4 shows the layout of the tetrahedron frame layer, which spans the full width of the flume during the test. The purpose of such a layout is to exclude sidewall effects and to ensure a 2D failure behavior. For the tests, the sediment used was 0.4 mm, the approach flow depth = 50 mm and the velocity ratio < 1. The length of the tetrahedron frame layer along the flow direction is 400 mm. It may be inferred from the velocity ratios used in the study that any movement of the sediment is not directly due to the flow velocity.

Observations showed that sediment was scoured at the upstream section of the tetrahedron frame layer and then settled further downstream (see Fig. 5). Tang et al. [4] showed that when flow passes through the frames, different types of vortices are generated and turbulent intensity increase around the rods of the frames due to disturbances induced by the rods. All these cause the scour to form at the upstream section of the tetrahedron frames. The velocity behind a single frame is re-distributed and velocity near the bottom is reduced, causing sediment deposition. The pattern of sediment erosion and deposition observed in this study supports the description by Tang et al. [4].

Scour also occurs at the location downstream of the tetrahedron frame layer. The flow velocity at this location can be sub-divided into two parts: vertical velocity, V_0, which is sensitive to the scour depth and horizontal velocity, U_0, which is sensitive to the position of the scour hole (see Fig. 6). The maximum scour depth, d_{se2}, downstream of the tetrahedron frames layer is highly sensitive to U/U_c. Figure 7 shows that the maximum scour depth increases almost linearly with velocity ratios under clear-water conditions. Obviously, the larger the velocity, the larger the momentum of the flow impinging on the bed is. Figure 8 shows that the position at which the maximum scour depth is located is also related to the velocity ratio.

During the tests, troughs (see Fig. 4) were observed to form downstream of the tetrahedron frames. When water flows over the tetrahedron layer, a large portion of it passes through the tetrahedron frames before impinging onto the bed downstream, thereby causing erosion. A smaller portion impinges on the rods of the tetrahedron frame causing vortex formation within the frame. The former causes sediment erosion resulting in the formation of the trough. The latter, however, causes a reduction of velocity; this resulted in no-erosion in certain locations downstream of the tetrahedron frame layer, as is shown in Fig. 4.

In summary, a tetrahedron frame layer can avoid edge failure for the following reasons:

1. When the water flows through the tetrahedron frames, the velocity can be significantly reduced; and
2. Due to the disturbance induced by the rods, different types of vortices are generated and the velocity is re-distributed. The flat portion and trough that form downstream of the tetrahedron frame layer is an indication of the velocity distribution.

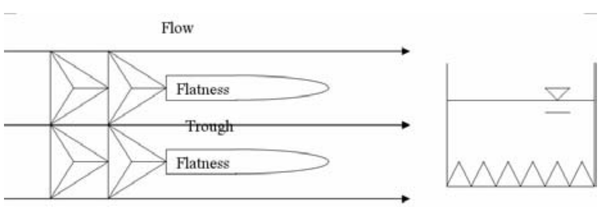

Figure 4. Sketch of trough downstream of frames

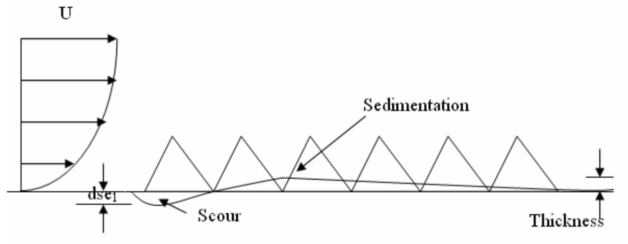

Figure 5. Sketch of the scour and sedimentation within frame layer

Figure 6. Sketch of the flatness and scour hole formed downstream of the tetrahedron frame layer

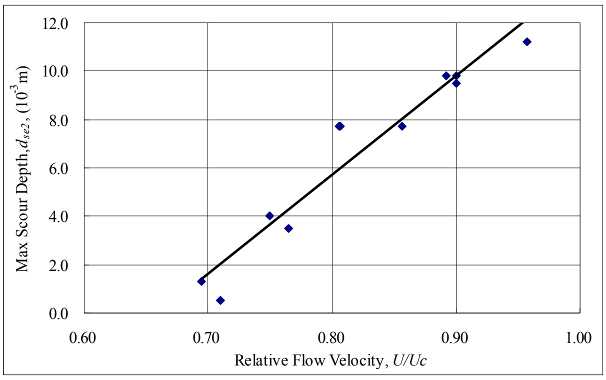

Figure 7. Maximum scour depths (d_{se2}) downstream of tetrahedron layer as a function of flow velocity ratio

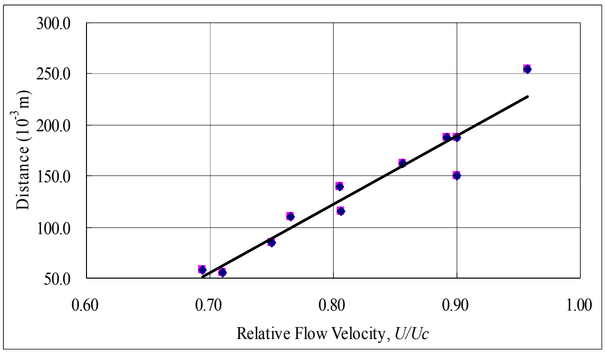

Figure 8. The distance between maximum scour position and end of tetrahedron frame layer as a function of flow velocity ratio

IV. SCOUR AT BRIDGE PIERS WITH TETRAHEDRON FRAME PROTECTION

During the test, the number of tetrahedron frame layers was 1 and 2 (see Fig. 2). The undisturbed approach flow depth = 250mm, with pier diameter D and median sediment size d_{50} = 70 mm and 0.4 mm, respectively. Based on previous studies on local scour at bridge piers [6-7], the equilibrium scour depth becomes independent on the depth of flow relative to pier-width, y_0/D, and the pier width relative to sediment median size, D/d_{50}, when they are larger than 3 and 50, respectively. This effect can also be applied to the present study. Since the flow shallowness and sediment coarseness are negligible, the present study aims to investigate the relationship between equilibrium scour depth and the flow intensity.

Under live-bed conditions, the maximum pier-scour depth occurs when the trough of a bed feature is at the pier. At this juncture, the scour depth includes not only scour due to the pier but also that due to bed form. As a result, it is more pertinent to present scour depth as a temporal rather than the absolute value. To this end, the temporal mean scour depth is obtained from

$$d_{av} = \frac{\sum_{i=1}^{N} d_{si}}{N} \quad (2)$$

where N= 100, measured at intervals of 1 minutes.

Scour depth and width

Early experimental studies on scour around a cylindrical bridge pier have shown that the relative equilibrium scour depth is highly sensitive to the undisturbed approach mean flow velocity, U. Tests were conducted in this study to examine the effect of U/U_c on the formation of the equilibrium scour depth around a bridge pier with the protection of tetrahedron frame layer. Table 1 contains the experimental results obtained in this study. Figure 9 shows how U/U_c affects the relative equilibrium scour depth, d_{av}/D. The experimental data show that d_{av}/D increases almost linearly with the velocity ratio under clear-water conditions. The maximum dimensionless equilibrium scour depth approximately occurs when the relative flow velocity is unity, which corresponds to the critical condition for bed material entrainment.

In live-bed scour, the data show decreasing sour depth until a local minimum is reached, after which the scour depth increase again. This trend is similar to that of local scour at bridge piers without countermeasures [6-7].

The shape of d_{av}/D versus U/U_c curve is related to the bed features translating past the scour hole. When the approach velocity exceeds the critical velocity of the bed sediment, general sediment movement begins and causes a new equilibrium between scour hole development and sediment supply from upstream. For this reason, the shape of d_{av}/D versus U/U_c curve is no longer linear under live-bed conditions. Due to the complement of sediment from upstream, the scour depth decreases after the approach velocity exceeds critical velocity until a local minimum is reached. When the relative flow velocity increases further, the scour depth increases from the minimum depth to larger depths. The data of one tetrahedron frame layer show that the scour depth increasing quickly when the relative flow velocity is larger than 1.3. Actually some of the tetrahedron frames were washed away because their critical velocity was exceeded. When the relative flow velocity reached 1.5, the tetrahedron frame layer was almost totally destroyed due to shear failure such that the scour depth is almost equal to that without any countermeasure. A curve following the trend of the data if the frames were intact is superimposed with a broken line in Fig. 9; this shows the possible trend of the scour depth when the velocity is larger than 1.3. More studies are needed to substantiate this hypothesis.

Figure 10 shows the effect of velocity ratio on the relative equilibrium scour width, L/D, where L is the distance between the nose of the pier and the un-scoured point along the flow direction. The curve has a similar trend as that of scour depth under clear-water condition.

Effect of tetrahedron frame protection

The data of the present study, along with those collected by Chiew [6] and Ettema [8] are plotted in Figs. 9 and 10. The data of Chiew and Ettema were used because their tests were conducted with tests conducted using median grain size = 0.24 and 0.38 mm, respectively; $y_0/D \geq 3$ and $D/d_{50} \geq 50$. Tests conducted in this study have the same general condition.

TABLE 1. SUMMARY OF EXPERIMENTAL RESULTS IN FLUME 2

Test Number	Layer Number	U (m/s)	U/U_c	u_*/u_{*c}	Time (hour)	d_{se} (mm)	d_{se}/D	L/D
A1	0	0.189	0.593		56	52	0.743	1.143
A2	0	0.259	0.815		50	117	1.671	2.571
B1	1	0.275	0.866	1.001	42	59	0.843	1.193
B2	1	0.223	0.702	0.759	71	48.5	0.693	1.043
B3	1	0.166	0.522	0.518	24	9	0.129	0.129
B4	1	0.187	0.588	0.547	46	22	0.314	0.571
B5	1	0.192	0.603	0.601	48	25.5	0.364	0.643
B6	1	0.250	0.787	0.897	63	59.5	0.850	1.143
B7	1	0.237	0.746	0.833	70	51	0.729	1.029
B8	1	0.207	0.651	0.654	94	40	0.571	0.786
C1	2	0.248	0.780	0.881	114	46	0.657	0.929
C2	2	0.167	0.524	0.527	40	8.5	0.121	0.286
C3	2	0.185	0.581	0.578	15	11	0.157	0.314
C4	2	0.209	0.656	0.643	31.5	25	0.357	0.517
C5	2	0.226	0.711	0.777	30	34.5	0.493	0.729
C6	2	0.236	0.742	0.830	25	38	0.543	0.771
C7	2	0.265	0.834	0.939	27	48	0.686	0.929
C8	2	0.285	0.896	1.023	23	53	0.757	1.000
D1	1	0.309	0.969		34	58	0.829	1.143
D2	1	0.338	1.063		36	56	0.800	
D3	1	0.320	1.005		30	55	0.786	
D4	1	0.372	1.168		20	58	0.829	
D5	1	0.404	1.269		28	63	0.905	
D6	1	0.430	1.350		22	78	1.116	
D7	1	0.461	1.449		48	101	1.443	

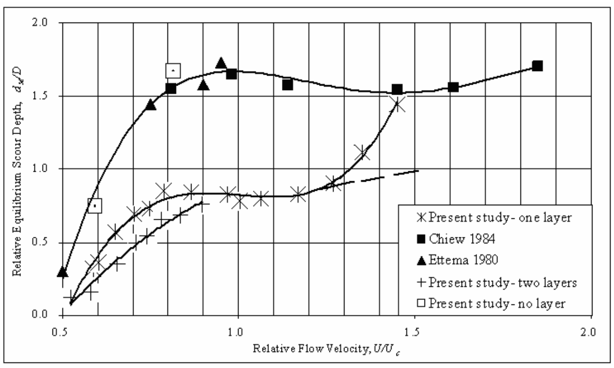

Figure 9. Effects of flow velocity ratio on relative equilibrium scour depth

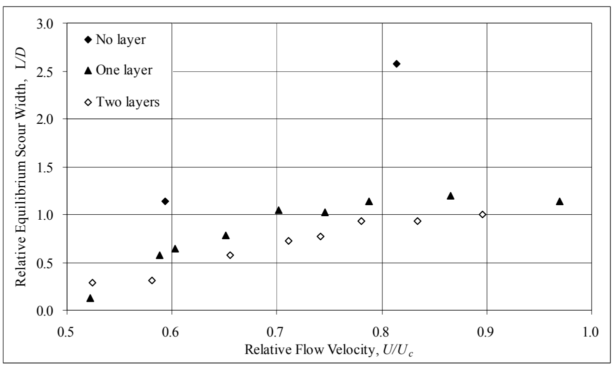

Figure 10. Effects of flow velocity ratio on relative equilibrium scour width

Compared with the experiment data obtained from published studies, the following inferences are drawn:

1. The relative scour depth decreases significantly when tetrahedron frames protection is placed around a pier. When only one layer of tetrahedron frame is placed, the relative equilibrium scour depth is almost half of that without any countermeasures. The relative scour depth associated with two layers is marginally smaller than that with one layer;
2. The tetrahedron frames increases the critical velocity needed for the initiation for scour hole development. This is due to a reduction of the near-bed velocity;
3. The minimum scour depth is reached at a lower flow velocity ratio when compared to that without placement of the tetrahedron frames. Under live-bed conditions, the minimum scour depth occurs at $U/U_c \approx 1.1$ while that without any countermeasure at approximately 1.5; and
4. The relative equilibrium scour width reduces significantly with tetrahedron frames protection. The frames reduce the velocity near the bottom effectively and prevent the scour hole from becoming wider.

Mechanism of tetrahedron frame protection at bridge piers

The two primary mechanisms that cause scour at bridge piers without any countermeasure are downflow and horseshoes vortex. Erosion by the downflow is due to the momentum of a stream of fluid impinging onto the bed at the base of the pier. The stream of fluid acts somewhat like a vertical jet in eroding the bed material, causing the scour hole to deepen. At a certain depth the downflow attains peak strength and thereafter, it gradually decreases as the scour hole deepens. Ettema [8] stated that the downflow velocity reaches its maximum when the scour depth ratio is between 0.8 and 1. The relative scour depth of the present study when the tetrahedron frame layers were intact was all less than 1. This is because the presence of the tetrahedron frame has, to a certain extent, prevented the sediment from erosion by the downflow. Tang et al. [4, 9], conducted a series of experiments on the resistance characteristic of tetrahedron frames and concluded that the velocity can be significantly reduced when water flows over a layer of tetrahedron frame. They stated that "when frames are placed in water, turbulent intensity is enlarged and turbulence energy is dissipated". After the downflow has interacted with the tetrahedron frame, its momentum has been dissipated and significantly weakened before impinging onto the sediment bed. This resulted in reduced erosion.

When a hole around a bridge pier is excavated by the downflow, the horseshoe vortex develops and enhances bed erosion together with the downflow. In the presence of the tetrahedron frames, the energy of the horseshoe vortex is also dissipated, resulting in the formation of a smaller scour hole compared to that without the scour countermeasure.

V. CONCLUSIONS

Based on results from the experiments conducted in the study, the following conclusions are drawn:

1. The scour depth with tetrahedron frame protection at bridge piers increases almost linearly with flow velocity ratio under clear-water conditions, and reaches a peak at the critical conditions of sediment entrainment. Under live-bed conditions, the data show decreasing scour depths above the threshold condition until a local minimum is reached, after which the scour depth increases again, but at a decreasing rate.
2. The tetrahedron frame layer has a positive effect in protecting the pier foundation against scour. It can dissipate the energy of the downflow and horseshoe vortex, thus reducing the pier-scour depth when compared to that without any countermeasure. When one tetrahedron frame layer was placed, the relative equilibrium scour depth is almost half of that without any countermeasures. Two layers provide a marginal improvement.
3. Results conducted in 2-dimensional tests with a tetrahedron frame layer show that it can prevent edge failure. This observation is substantiated by tests conducted with a bridge pier. In the upstream end of the tetrahedron frame layer, erosion occurs but downstream of it, sediment deposition takes place, preventing the formation of edge failure.

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