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Experimental Investigation of the Influence of Grain Size Distribution and Sediment Disposition on Local Scour Around Bridge Pier

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Abstract: Scour around bridge piers due to flooding is the leading cause of bridge failure. Numerous numerical and experimental studies have investigated local scour under various sediment properties, pier geometries, and hydraulic conditions. In this paper, we present the results of an experimental study on the influence of sediment grain-size distribution and disposition on local scour around a circular bridge pier. The study aims to qualitatively evaluate how various factors, particularly grain size distribution and sediment disposition, affect local scour in open-channel flow. Four factors were tested: flow rate, channel slope, grain size distribution, and sediment disposition. Results show that both sediment properties and their arrangement significantly impact the maximum scour depth. While channel slope also affects local scour, its influence is less pronounced than that of flow rate. The most significant changes in scour volume are attributed to sediment disposition in the channel. These findings highlight the critical role of sediment composition and arrangement in bridge pier scour mitigation and provide valuable insights for riverbed protection and hydraulic structure design.

Keywords: Scour; Bridge pier; Sediment; Grain size distribution; Sediment disposition.

1. Introduction

Many accidents involving hydraulic structures result from local or general bed erosion in rivers [1-3]. Scour around bridge piers due to flooding is the most common cause of bridge failure [4-7]. Researchers have conducted numerous numerical and experimental studies to investigate local scour under various sediment properties, pier geometries, and hydraulic conditions [8-11].

The variation of local scour depth with flow intensity is well-documented in laboratory experiments [12-19]. Under clear water conditions, scour depth in uniform sediment increases almost linearly with velocity, reaching a maximum at the threshold velocity [20]. Chabert and Engeldinger [11] analyzed the relationship between maximum scour and the ratio of pier diameter to grain diameter. Liang et al. [21] found that scour scale is influenced by flow conditions, pier types, and sediment properties. Yao et al. [22] and Lu et al. [23] demonstrated that scour depth varies significantly with pier shape and their arrangement. Raudkivi and Ettema [13] showed that non-uniform grain size distributions reduce local scour under lower flow rates. However, when flow rates exceed the critical velocity, scour depth increases and can reach up to 2.3 times the pier diameter. They also noted that for smaller sediment coarseness ratios, larger individual grains impede erosion by dissipating the downstream flow's energy within the porous bed.

Recent studies have explored the influence of grain size distribution on scour processes. Chibana et al. [24] examined the role of grain size distribution and pier aspect ratio in scouring mechanisms, highlighting the importance of sediment grading and pier geometry in understanding sediment sorting and scour formation around bridge piers. Takezaki and Watanabe [25] experimentally evaluated the effect of grain size distribution of bed materials on pier destabilization due to local scour.

These findings underscore the complex interplay between hydraulic conditions, sediment characteristics, and pier configurations in influencing local scour phenomena. Understanding these interactions is crucial for developing effective design and mitigation strategies to ensure the safety and longevity of bridge structures.

In the present study, an experimental approach was used to examine the effects of grain size distribution and its spatial disposition in the channel bed on local scour around a circular bridge pier. Unlike previous research, which mainly focused on uniform sediment distributions or single-size grains, this study investigates how varying grain sizes, and their arrangement influence scour mechanisms, providing a more comprehensive understanding of real-world riverbed conditions.

2. Materials and methods

2.1 Experimental facilities

The experiments were carried out in a 7 m long and 0.075 m wide rectangular flume. The flume has a 5 m long sediment recess in the working section (Figure 1). A 1.5 cm diameter steel cylinder was fixed to the bottom of the channel to simulate a real bridge pier in a river. It was placed 3.5 m downstream from the flume entrance.

The flow characteristics were steady to avoid any disturbance of the scouring process. The flow remained subcritical, as the Froude number was less than one in all experiments. The critical velocity for sediment transport was never reached in any of the conducted tests.

The study was carried out to investigate the general behavior of scour around the pier. The runs were performed by varying channel slope, flow rate, grain size distribution, and sediment disposition. These parameters are summarized in Table 1.

Two grain size distributions were tested: Sediment 1, with a uniform particle size distribution (Cu = 1.64, d_{50} = 0.80 mm). Sediment 2, with a non-uniform particle size distribution (Cu = 4.86, d_{50} = 0.44 mm).

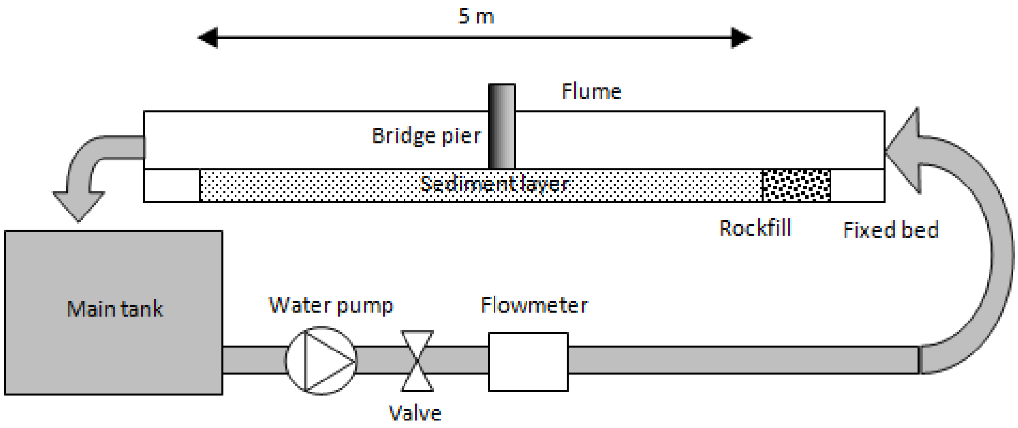

Figure 1. Sketch of the experimental set up.

A granulometric study from sieve analysis was used to determine grain size distribution and sediment properties. The sediment samples were classified as uniform or non-uniform according to the Hazen criterion ($Cu = d_{60}/d_{10}$), where d_{60} and d_{10} are characteristic diameters obtained from the particle size curve. A uniform distribution is defined by Cu < 3, while a non-uniform distribution is defined by Cu > 3.

Two sediment dispositions were tested: Disposition A, represented by a single layer of 4 cm height. Disposition B, represented by two layers of 2 cm each, with finer particles on top.

In order to establish a classification of the factors influencing local scour around a circular bridge pier, we established an experimental protocol consisting of three test cases. The first case by fixing the sediment disposition and varying the slope, the grain size and the flow rate. The second case by fixing the slope and varying the sediment disposition and the flow rate. The third case by fixing the grain size and varying the slope, the sediment disposition and the flow rate.

All experiments were conducted in clear water conditions.

Table 1. Experimental parameters.

Channel slope (%)	Flow rate (m^3/h)	d_{50} (mm)	Grain size distribution (-)	Sediment disposition (-)
0.25	1.6	0.80	Uniform	A: 1 layer
0.50	2.0	0.44	Non – uniform	B: 2 layers
0.50	2.5	0.44	Non – uniform	B: 2 layers
0.50	3.0	0.44	Non – uniform	B: 2 layers

2.2 Experimental process

The following procedure was used for each experimental run. First, the channel slope was adjusted directly on the test bench. Then, the sediment bed was fully wetted before starting the flow. The pump was turned on, allowing water to flow into the channel until the required water depth was reached. The stopwatch was started as soon as the water reached the bridge pier. To measure the maximum scour depth, a graduated scale was placed on the pier.

Additionally, a second ruler was positioned on the external side of the channel to measure lateral scour depth if erosion extended to the flume edges.

Since scour develops rapidly, measurements were taken every minute, with an additional reading after the first 30 seconds of the experiment. At the completion of each test, the pump was shut down gradually to allow the flume to drain slowly, preventing any disturbance to the scour topography.

To determine the scour volume, depth measurements were recorded at seven locations around the pier (Figure 2).

As listed in Table 2, a total of 16 experiments were conducted for different flow conditions, grain size distribution and sediment arrangement.

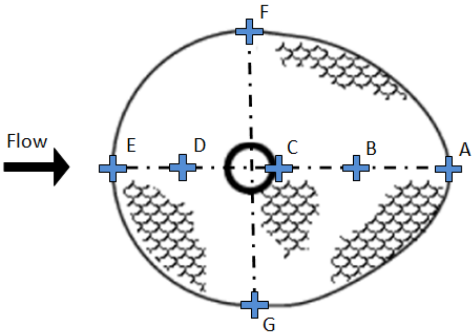

Figure 2. Measured locations around the pier.

Table 2. Experimental values of scour depth according to different grain size distribution and sediment disposition.

Run	Q (m^3/h)	Slope (%)	d_{50} (mm)	Cu (-)	Scour depth (cm)
1	1.6	0.25	0.80	1.64	1.7
2	2.0	0.25	0.80	1.64	2.0
3	2.5	0.25	0.80	1.64	2.0
4	3.0	0.25	0.80	1.64	2.1
5	1.6	0.50	0.80	1.64	1.8
6	2.0	0.50	0.80	1.64	2.0
7	2.5	0.50	0.80	1.64	2.0
8	3.0	0.50	0.80	1.64	2.2
9	1.6	0.25	0.44	4.86	0.7
10	2.0	0.25	0.44	4.86	0.8
11	2.5	0.25	0.44	4.86	0.7
12	3.0	0.25	0.44	4.86	0.8
13	1.6	0.50	0.44	4.86	0.7
14	2.0	0.50	0.44	4.86	0.6
15	2.5	0.50	0.44	4.86	1.0
16	3.0	0.50	0.44	4.86	1.1

3. Results and discussions

3.1 Influencing factors

Figures 3 to 10 illustrate the influence of channel slope, grain size distribution, flow rate, and sediment disposition on scour. However, the degree of influence varies between these factors.

Figures 3 and 4 indicate that an increase in flow rate has a significant impact on the maximum scour depth. In contrast, while an increase in channel slope also affects scour depth, its influence is less pronounced compared to flow rate and grain size distribution.

The final scour volume is influenced by multiple factors. A twofold increase in channel slope results in only half the evolution compared to a twofold increase in flow discharge. Additionally, while the sediment grain size distribution has a notable effect, its impact is slightly less significant than that of flow rate. However, the most significant changes in scour volume are due to sediment disposition, as illustrated in Figures 9 and 10.

These findings align with previous research, particularly the studies conducted by Chabert and Engeldinger [23]. The comparative influence of these factors is summarized in Table 3, where they are ranked based on their impact on scour volume and maximum scour depth.

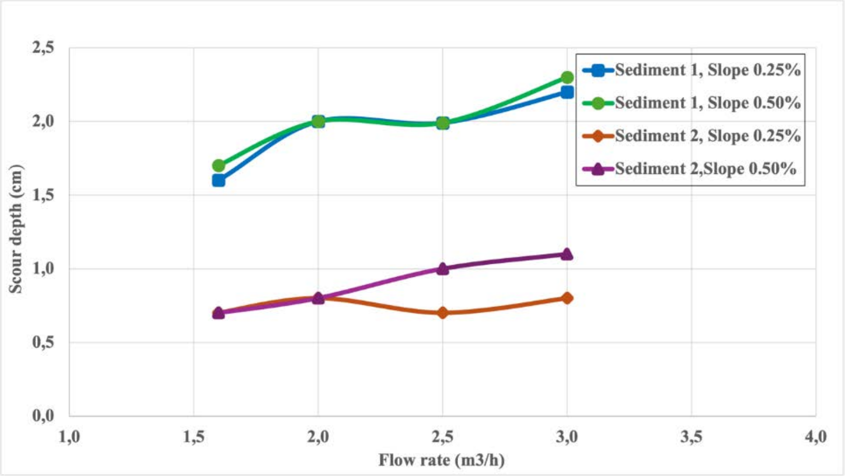

Figure 3. Scour depth evolution within flow rate in disposition A for sediment 1, and sediment 2 for two channel slopes.

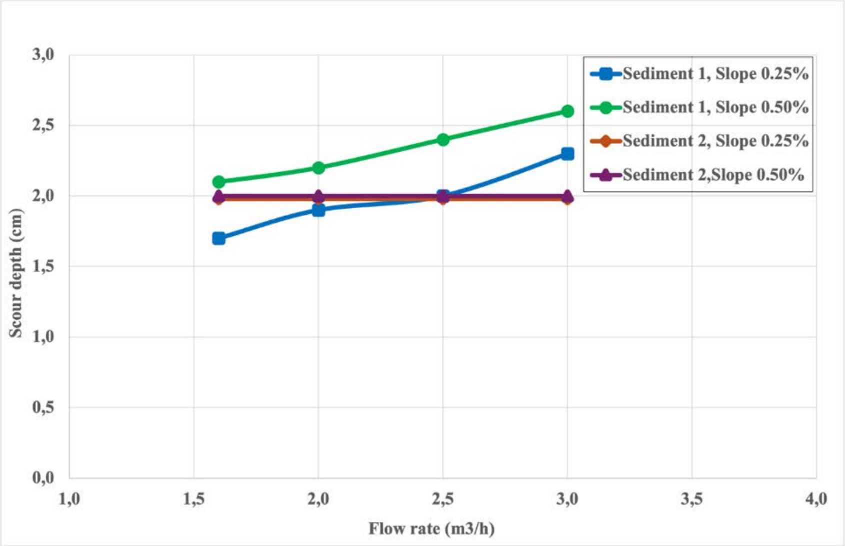

Figure 4. Scour depth evolution within flow rate in disposition B for sediment 1, and sediment 2 for two channel slopes.

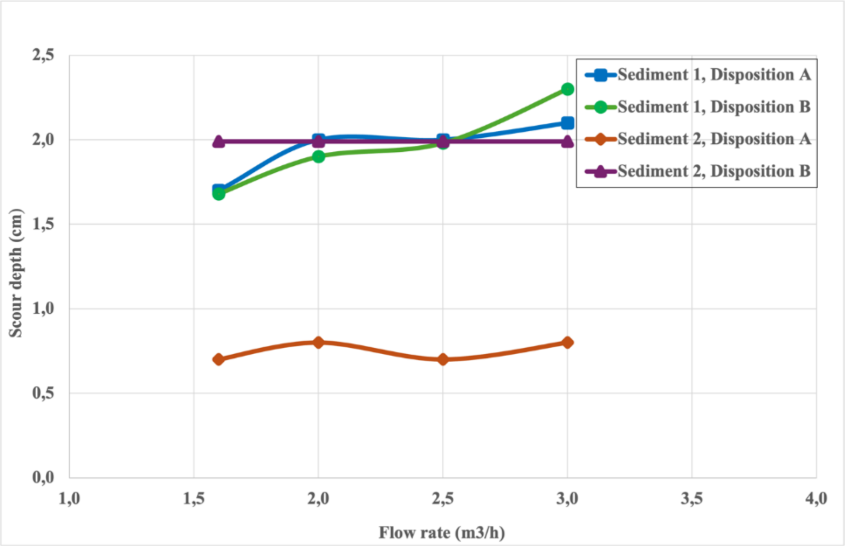

Figure 5. Scour depth evolution within flow rate for a 0.25% channel slope for sediment 1, and sediment 2 in disposition A, and disposition B.

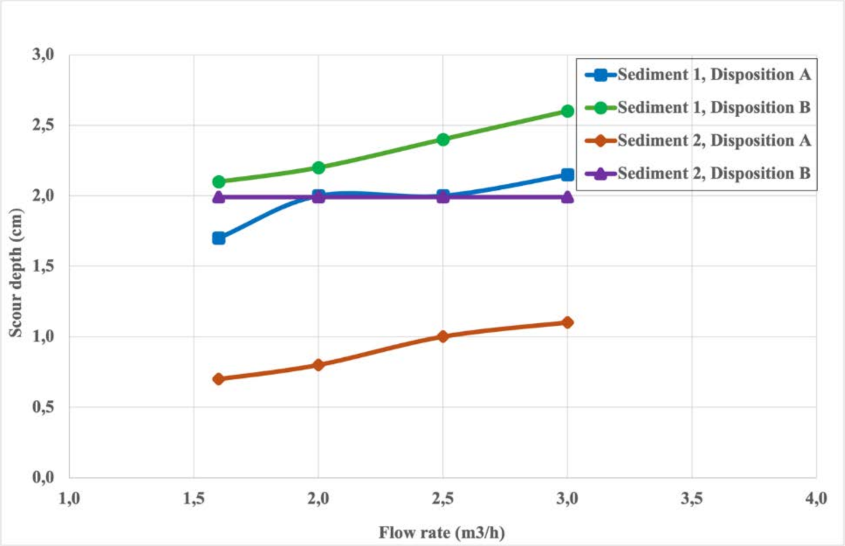

Figure 6. Scour depth evolution within flow rate for a 0.5% channel slope for sediment 1, and sediment 2 in disposition A, and disposition B.

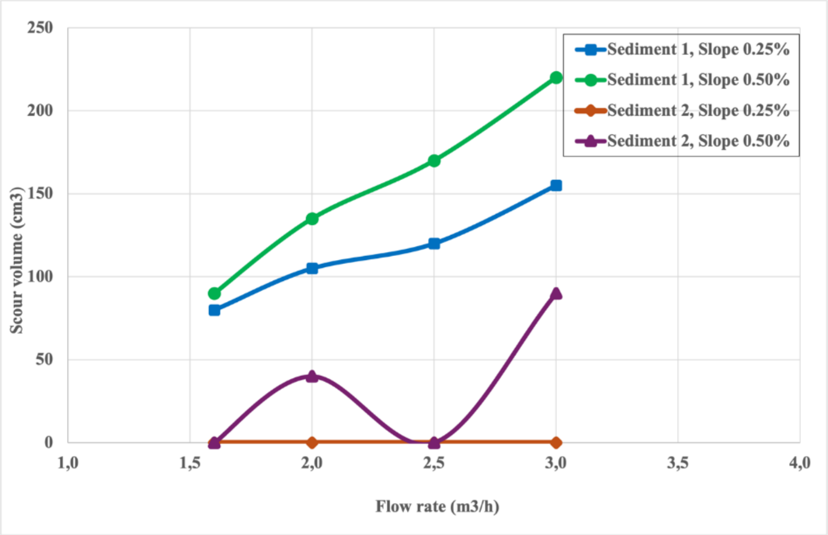

Figure 7. Scour volume evolution within flow rate in disposition A for sediment 1, and sediment 2 for two channel slopes.

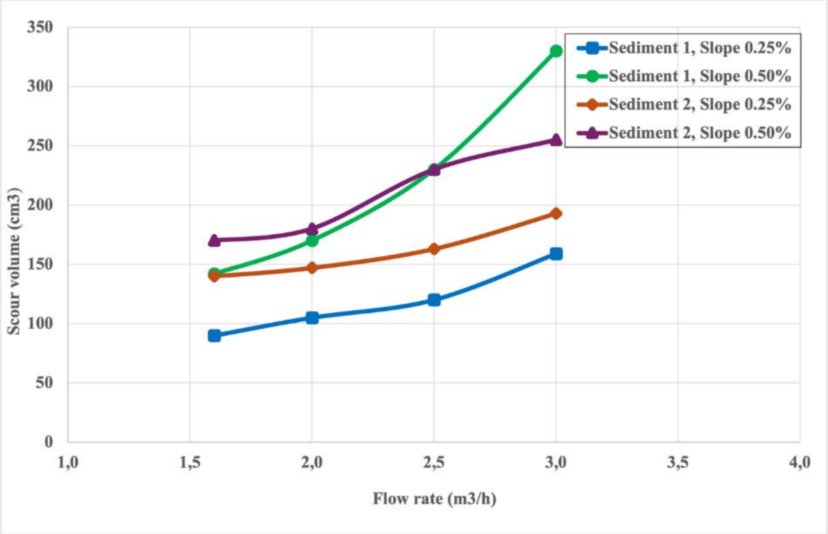

Figure 8. Scour volume evolution within flow rate in disposition B for sediment 1, and sediment 2 for two channel slopes.

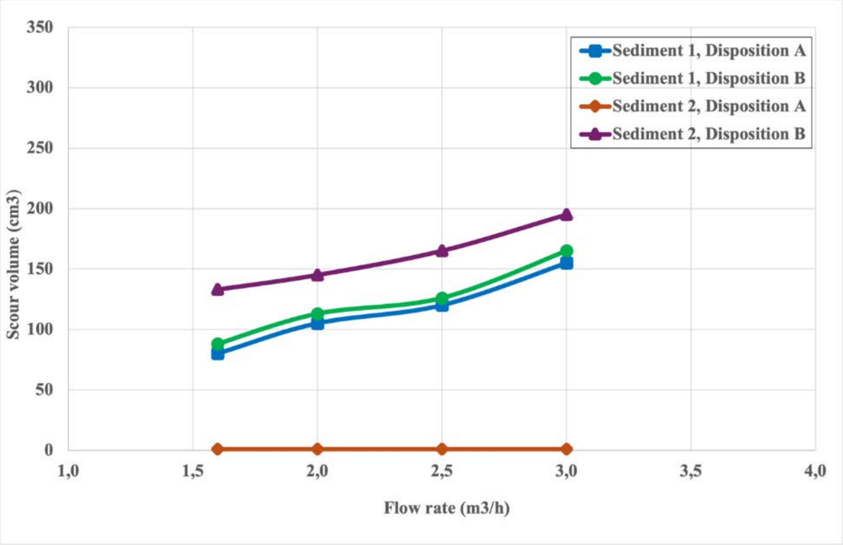

Figure 9. Scour volume evolution within flow rate for a 0.25% channel slope for sediment 1, and sediment 2 in disposition A, and disposition B.

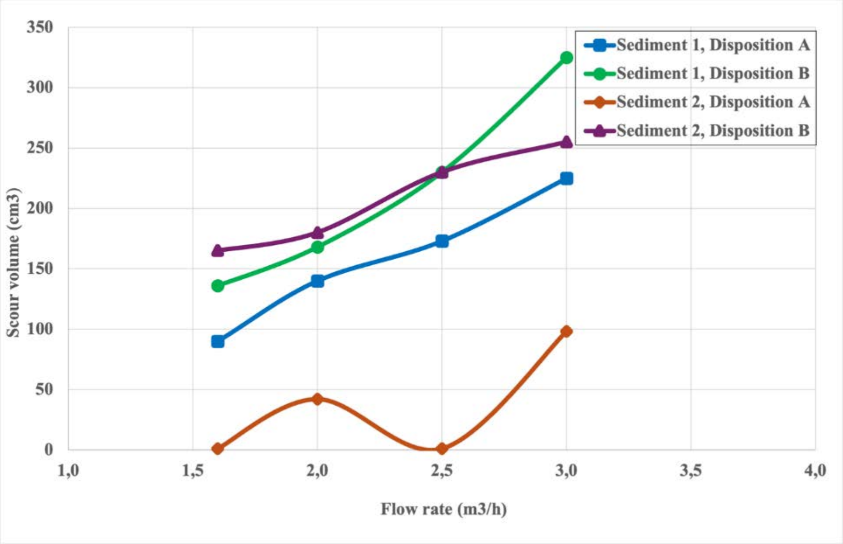

Figure10. Scour volume evolution within flow rate for 0.5% channel slope for sediment 1, and sediment 2 in disposition A, and disposition B.

Table 3. Importance of the factor’s influence.

Factors	Growth	Scour height augmentation (%)	Volume augmentation (%)
Channel slope (%)	x 2	+ 14	+ 34
Flow rate Q (m^3/h)	x 2	+ 29	+ 66
Uniformity Coefficient Cu (-)	x 3	- 61	- 57
Sediment disposition	…	+ 79	+ 79

3.2 Effect of grain size distribution

Figure 4 further highlights that for Sediment 2, maximum scour depth is limited to 2 cm whatever the channel slope, at which point the scour volume increases more significantly for Sediment 1. Figure 5 clearly shows the influence of the arrangement of sediment 2 in the channel independently of the channel slope and the flow rate. This behavior suggests a vertical limitation of scour, controlled by both grain size distribution and sediment disposition.

For Disposition A, the scour volume with Sediment 2 is very small and difficult to quantify accurately (Figure 7). However, based on collected measurements, it is at least half the scour volume observed with Sediment 1. For Disposition B, Figure 8 illustrates an interesting trend: initially, Sediment 2 undergoes more scour than Sediment 1, but this trend reverses when the flow rate exceeds 2.5 m³/h and the channel slope reaches 0.5%.

In terms of temporal evolution, scour depth for Sediment 1 reach its maximum after eight minutes (Figure 11). Whereas for sediment 2 the maximum stabilizes within one minute (Figure 12). Additionally, Sediment 1 exhibits a significantly greater maximum scour depth than Sediment 2, with an average increase of 143% across all experiments. In this case, it can be noted that the grain size distribution of sediment 1 is more favorable to erosion than that of sediment 2 under the same hydraulic conditions.

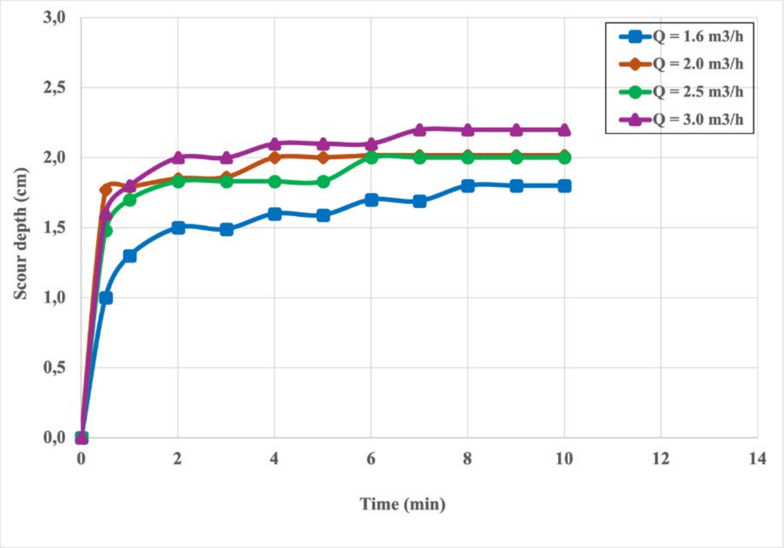

Figure 11. Temporal development of local scour depth in the case of disposition A for sediment 1at 0.25% channel slope.

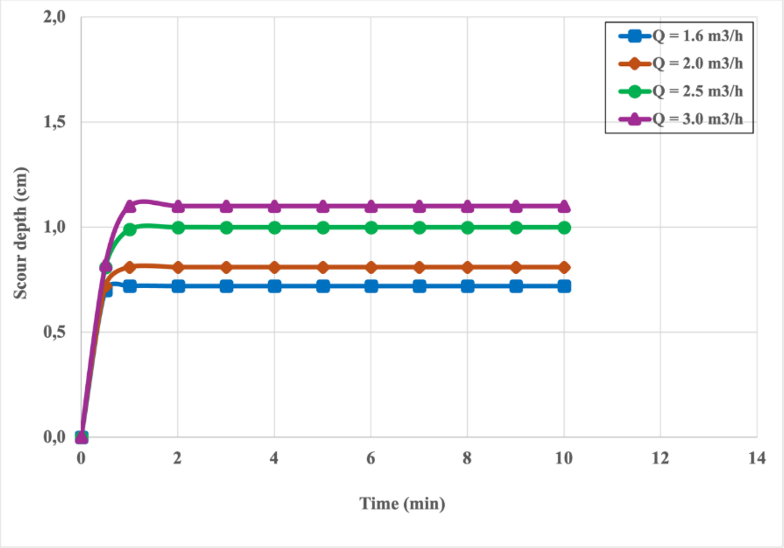

Figure 12. Temporal development of local scour depth in the case of disposition A for sediment 2 at 0.25% channel slope.

3.3 Effect of sediment disposition

A comparison of Figures 11 to 16 reveals that sediment disposition does not influence the time required for the maximum scour depth to develop, which remains 8 minutes in all cases. The maximum scour depth ranges between 1.7 cm and 2.6 cm, which represents an average increase of 9 % for Disposition B compared to Disposition A, though this difference is not highly significant.

For Sediment 2 arranged in two layers (Disposition B), the temporal evolution of scour remains unchanged, with the maximum scour depth reached in approximately one minute. Figure 18 highlights a critical threshold at 2 cm depth, which is three times greater than in Disposition A (Figure 17). This depth corresponds to the second layer of coarse grains, indicating that the coarse material resists further scouring.

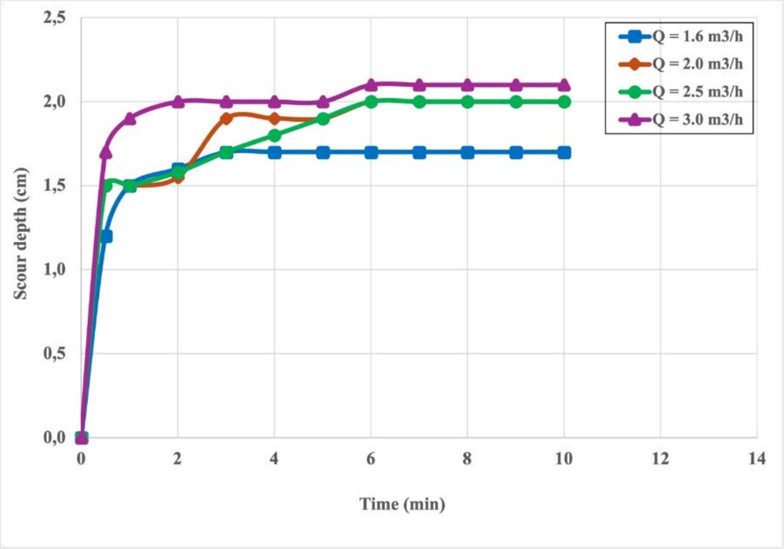

Figure 13. Temporal development of local scour depth in the case of disposition A for sediment 1 at 0.5% channel slope.

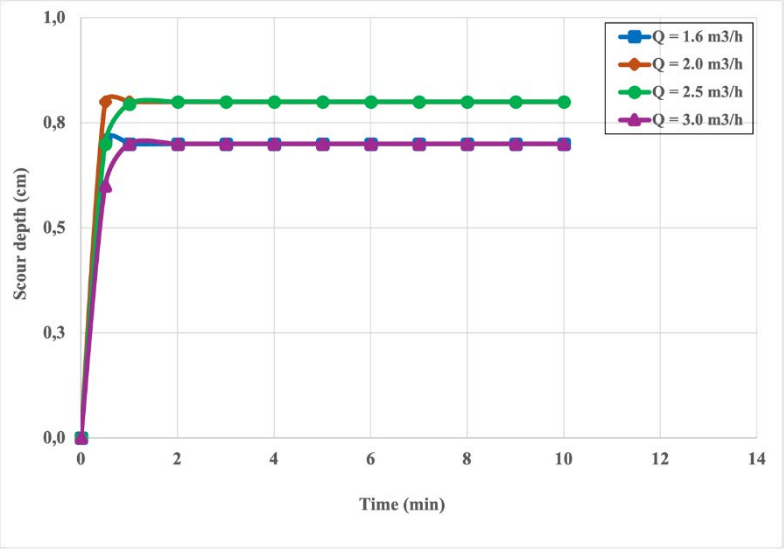

Figure 14. Temporal development of local scour depth in the case of disposition A for sediment 2 at 0.5% channel slope.

For Sediment 1, scour volume increases only when the channel slope reaches 0.5%, at which point the scour volume in Disposition B is 1.5 times larger than in Disposition A (Figure 19).

Conversely, for Sediment 2, the scour hole volume is generally 2.5 to 4 times greater in Disposition B (Figure 20), highlighting its high sensitivity to sediment arrangement. This behavior is directly linked to the grain size distribution, as Sediment 2 has a much wider distribution. When divided into two layers, a fine-grained upper layer is highly susceptible to erosion, while the coarser lower layer is more resistant.

As illustrated in Figures 15 to 20, the effect of sediment disposition varies significantly based on grain size distribution. Therefore, it is impossible to study sediment disposition independently without also considering grain size distribution.

Throughout the experimental analysis, a consistent pattern emerged: coarse grains can limit the scouring process by accumulating inside the scour hole.

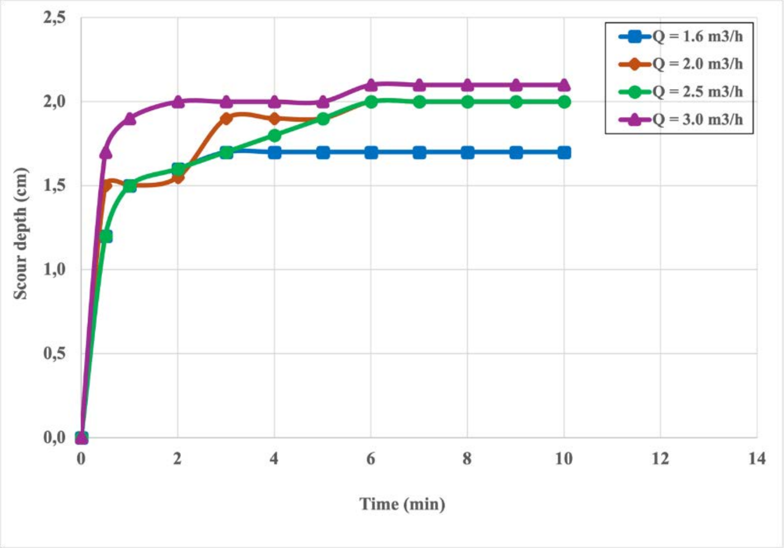

Figure 15. Temporal development of local scour at 0.25% channel slope for sediment 1 in disposition A.

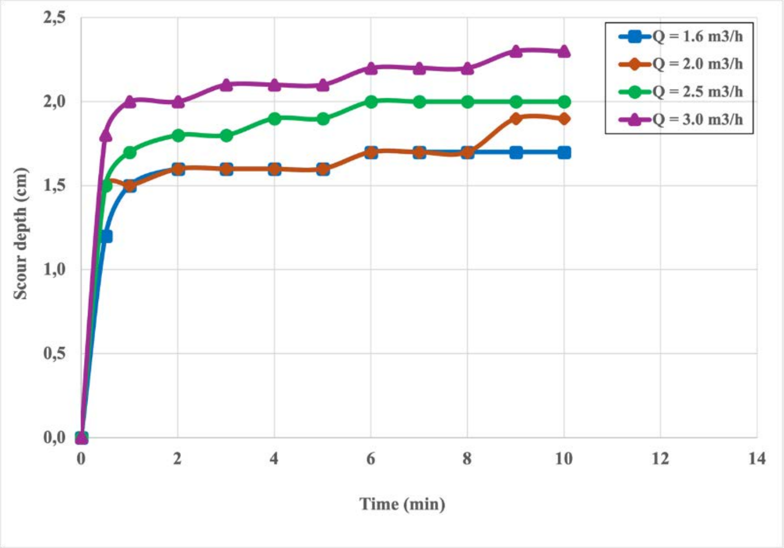

Figure 16. Temporal development of local scour at 0.25% channel slope for sediment 1 in disposition B.

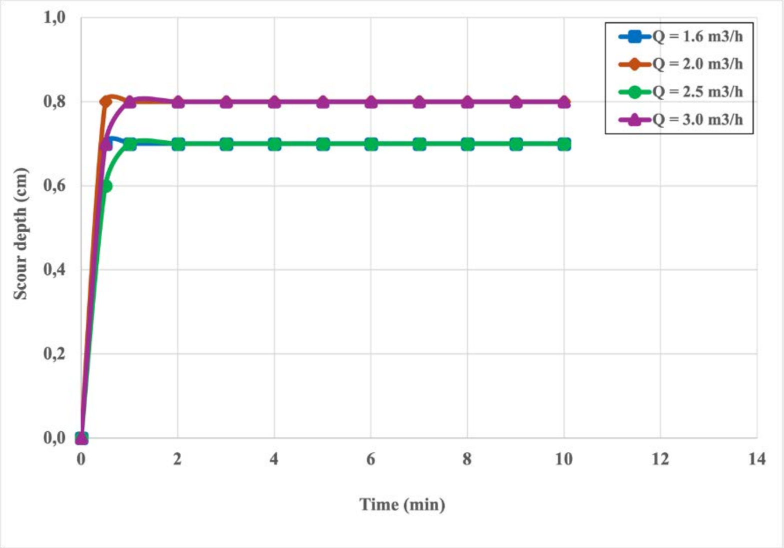

Figure 17. Temporal development of local scour at 0.25% channel slope for sediment 2 in disposition A.

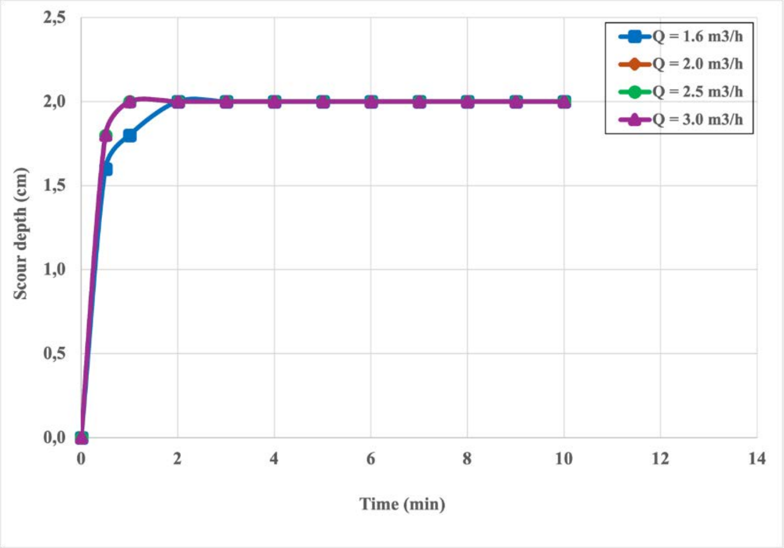

Figure 18. Temporal development of local scour at 0.25% channel slope for sediment 2 in disposition B.

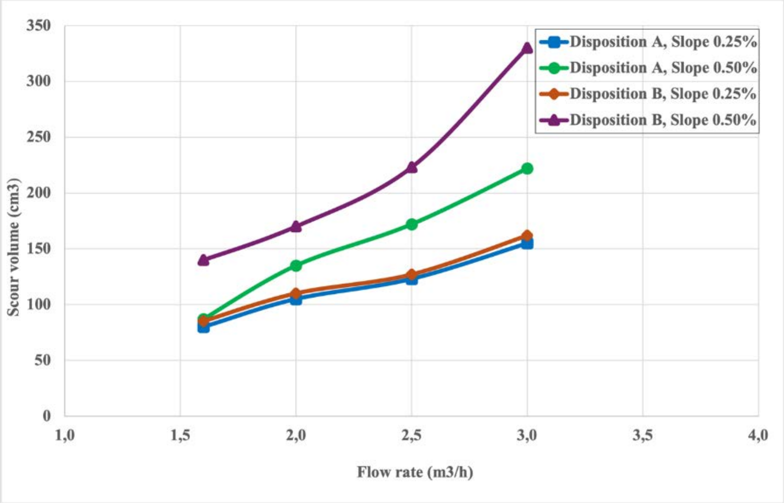

Figure 19. Variation of local scour volume within flow rate for sediment 1 for two dispositions and two channel slopes.

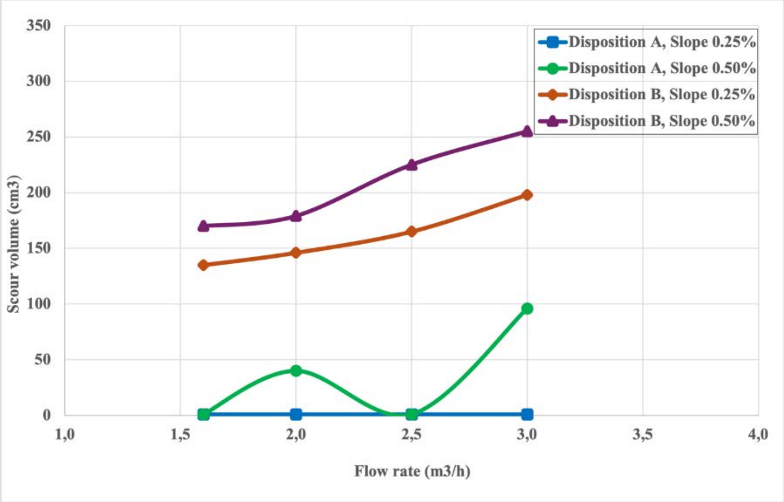

Figure 20. Variation of local scour volume within flow rate for sediment 2 for two dispositions and two channel slopes.

This behavior was observed only for Sediment 2. As fine particles are eroded, they expose underlying coarse grains, which then resist further erosion and dissipate the flow energy around the pier. Consequently, a coarse-grain protective layer is formed around the pier preventing finer particles to be transported downstream. This phenomenon explains why Sediment 2 in Disposition A exhibits minimal scour, as coarse grains mixed with fine particles are rapidly exposed, preventing further erosion. Similarly, the threshold observed for Sediment 2 in Disposition B can be explained by its layered structure. Below 2 cm depth, only coarse grains remain, forming a natural barrier against scouring.

This explains the trend reversal in scour volume shown in Figure 8, where beyond a certain depth, Sediment 2 can only erode laterally, whereas Sediment 1 continues to deepen due to its more uniform grain size distribution.

4. Conclusions

Experimental studies were conducted to investigate the effect of the sediment grain size distribution, the sediment disposition, the channel slope, and the flow rate on local scouring around a bridge pier in an open channel flow. The results demonstrate that both sediment properties and their arrangement significantly influence the scouring phenomenon in various ways.

The tested factors can be prioritized based on their impact on scour formation: sediment disposition, sediment grain size distribution, flow rate, and channel slope.

A higher uniformity coefficient and the presence of coarse grains lead to a smaller scour hole, both in depth and volume.

The influence of sediment disposition on the scouring process is highly dependent on grain size distribution. When the grain size distribution is narrow (low uniformity coefficient), sediment disposition has little effect. However, when the grain size distribution is broad (high uniformity coefficient), the scouring process encounters a threshold once the coarse grain layer is exposed.

A consistent pattern was observed when coarse grains were present. Once the fine particles are eroded, the coarse grains are uncovered, making them resistant to vortex-induced scouring and ultimately limiting further erosion. This behavior is directly related to the depth of the coarse grain layer, which determines when the scour progression is halted. These findings highlight the critical role of sediment composition and arrangement in bridge pier scour mitigation and provide valuable insights for riverbed protection and hydraulic structure design.

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