Acta Geophysica (2022) 70:2325–2339
https://doi.org/10.1007/s11600-021-00722-2

RESEARCH ARTICLE - SPECIAL ISSUE

Check for updates

Experimental study of debris-induced scour around a slotted bridge pier

Hossein Hamidifar[1] · **Damoon Mohammad Ali Nezhadian**[1] · **Iacopo Carnacina**[2]

Received: 18 July 2021 / Accepted: 21 December 2021 / Published online: 25 January 2022

Abstract
One of the most common problems for river engineers is the accumulation of waterborne debris upstream of the bridge piers. In addition to reducing the cross-sectional flow area, debris increases the drag force exerted to the pier and contributes to scour. Several studies have been carried out by previous researchers to examine the usefulness of different types of countermeasures. The effectiveness of these countermeasures is not well understood when debris accumulation occurs. In this study, the effect of debris accumulation on the efficiency of a bridge pier slot, as scour countermeasure, is investigated experimentally. A total of 54 experiments were carried out under different hydraulic and debris geometrical conditions. The results showed that slots were effective in protecting bridge piers against scouring in presence of debris. Depending on the debris shape, the reduction efficiency may increase or decrease for a slotted pier in presence of debris accumulation when compared to the standard pier conditions without debris accumulation. Except for the inverse pyramid shape, the maximum scour is generally more reduced due to sheltering effect when the debris is located on the bed. While debris accumulation can lead to a reduction of the slot efficiency, the slot can be considered a reliable countermeasure against scouring. The outcome of this study can help the design of new bridges affected by large wood debris accumulations.

Keywords Bridge pier · Scour · Debris accumulation · Slot · Structural failure

Introduction

Bridges play an important role in public transportation and their damage causes significant economic losses and significant disruption to communities. One of the most important factors in dynamic behavior, fragility, and bridge structural collapse is bed scouring around the pier and the consequent failure of the foundation (Wardhana and Hadipriono 2003; Scozzese et al. 2019; Guo et al. 2020; Tubaldi et al. 2017; Pizarro et al. 2020). Estimating scour depth around bridge piers has been thoroughly studied by many researchers in the past (Carnacina et al. 2019; Melville and Chiew 1999; Lin et al. 2012; Pandey et al. 2020). Despite the efforts made so far, sufficient understanding of the mechanism of local scouring around bridge piers has not yet been achieved, and every year many bridges around the world are damaged, which causes severe human and financial losses. In general, two methods have been proposed to protect bridge piers against bed scouring: increasing the bed material strength, and modifying the flow pattern around the pier.

In the first method, the resistance of bed particles movement caused by flow shear is increased using materials with a larger sediment transport threshold velocity, e.g., riprap (Chiew 1995, 2004; Chiew and Lim 2000; Lauchlan and Melville 2001; Froehlich 2013; Unger and Hager 2006), geo-bags (Korkut et al. 2007; Akib et al. 2014), gabions (Pagliara et al. 2010; Yoon and Kim 2001), or tetrahedral frames (Tang et al. 2009).

In the second method, the flow pattern and the turbulent structure normally observed around piers, i.e., the downflow, horseshoe vortex and wake, which are the main causes of the local erosion of the bed material, is drastically modified by making changes to the pier or in its vicinity. In particular,

Communicated by Łukasz Przyborowski, Assistant Professor (Guest Editor) / Dr. Michael Nones (CO-EDITOR-IN-CHIEF).

✉ Hossein Hamidifar
hamidifar@shirazu.ac.ir

1 Water Engineering Department, Shiraz University, Shiraz, Iran

2 School of Civil Engineering and Built Environment, Liverpool John Moores University, Peter Jost Centre, Byrom Street, Liverpool L3 3AF, UK

scouring is reduced or eliminated by reducing the strength of the erosive flow. Collars (Zarrati et al. 2004; Masjedi et al. 2010; Heidarpour et al. 2010; Bestawy et al. 2020; Memar et al. 2020; Hamidifar et al. 2022), threadings (Dey et al. 2006; Tafarojnoruz et al. 2012), bed-sills (Pagliara et al. 2010; Chiew and Lim 2003; Grimaldi et al. 2009a; Hamidifar et al. 2018a, 2018b), vanes (Ghorbani and Kells 2008; Zarei et al. 2019), splitter plates (Khaple et al. 2017), sacrificial piles (Melville and Hadfield 1999; Park et al. 2016), and slots (Bestawy et al. 2020; Chiew 1992; Kumar et al. 1999; Hajikandi and Golnabi 2018; Obied and Khassaf 2019; Hosseini et al. 2020; Osrush et al. 2020; Sharma 1999; Heidarpour 2002) are some example of the methods that have been proposed to reduce scouring around bridge piers by modifying the flow pattern.

Slot protections have shown promising results. A slot is an opening in the pier that causes a portion of the flow to pass through the pier. It has been found that the downflow and the wake vortex system is weakened due to the presence of the slot (Chiew 1992; Grimaldi et al. 2009b). The use of slots in bridge piers was first reported by Tanaka and Yano (1967) as a new method in controlling scouring around the pier. They found that a slot can reduce the maximum scour depth by up to 30% compared to the standard piers. Chiew (1992) investigated the effect of slots on scour around a cylindrical pier and concluded that using a slot with a width equal to 1/4 of the pier diameter reduces the maximum scour depth by 20%. Also, the results of an experimental study conducted by Kumar et al. (1999) indicated an 18% and 33% reduction in the maximum scour depth for a slot located above the initial bed and a slot extended beneath the bed, respectively. Tafarojnoruz et al. (2012) examined the effectiveness of six different methods for pier protection against scouring. They concluded that slot, collar, or sacrificial piles are up to 15% more effective in reducing scouring compared to threading, submerged vanes, and a bed-sill. Azevedo et al. (2014) evaluated the use of a slot in reducing the maximum scour depth around circular and elongated bridge piers and observed a reduction of the maximum scour depth up to 26% and 16% for the circular and elongated pier, respectively. Also, Hosseini et al. (2020) and Osrush et al. (2019) conducted experimental studies on the effects of the size and vertical position of slots on the reduction of scouring around rectangular abutments. They concluded that slots are more effective in abutments than bridge piers against scouring. In a more recent study, Bestawy et al. (2020) studied different types of pier slots geometries, showing that the sigma-shaped slots performed better than other geometries tested.

Several studies show that a better result is obtained if a combination of a slot and other scour countermeasures are used around the pier. For example, Chiew (1992) observed that the collar-slot combination is more effective in reducing scour depth than either the collar or the slot alone. Grimaldi et al. (2009b) studied the effect of combining a slot with bed-sill on scouring around the pier. They concluded that this method could reduce the maximum scouring depth up to 45% and could therefore be used as an effective method of controlling scouring around the pier. Also, Gaudio et al. (2012) examined five different combinations of scour reduction methods around the pier and concluded that the combination of slot and bed-sill has been more effective compared to the other four combinations tested. It has been proven that the scouring depth decreases with increasing the length of the slot, and if the slot is used in combination with a collar, almost no scouring will occur around the pier (Moncada-M et al. 2009).

The mobility and accumulation of floating debris at bridge piers is a growing problem around the world (Panici and Almeida 2018; Schalko et al. 2019; Dixon and Sear 2014; Cantero-Chinchilla et al. 2021; Panici and Kripakaran 2021). Floating debris also called large woody debris (LWD) (Wohl et al. 2019) or driftwood (Schmocker and Weitbrecht 2013; Schmocker and Hager 2013), refers to the fragments of tree trunks, branches, eroded materials, which are mainly found in areas where trees are growing near the river banks (Diehl 1997; Jamei and Ahmadianfar 2020). Many studies indicate that the accumulation of such floating objects upstream of the pier leads to an increase in the effective width of the pier, increase the shear stress, change the flow pattern, turbulence, and, consequently, the scouring mechanism, increasing the risk of bridge failure (Pagliara et al. 2010; Diehl 1997; Melville and Dongol 1992; Pagliara and Carnacina 2013, 2011; Lagasse et al. 2010; Benn 2013; Cicco et al. 2020; Mueller and Parola 1998; Melville and Coleman 2000; Ruiz-Villanueva et al. 2016; Rahimi et al. 2020, 2018).

While Briaud et al. (2006) reported that about 10% of all bridges constructed over waterways in the USA are exposed to additional scouring due to debris accumulation, Diehl (1997) estimated the incidence of debris to bridge failure as one in three cases for the US, and Benn (2013) produced similar figures for UK and Ireland. Also, heavier debris accumulation occurs in single piers (Lyn et al. 2007). Ebrahimi et al. (2018) reported that cylindrical debris located beneath the water surface increases the maximum scour depth up to 33% compared to no-debris case. Another study by Pagliara et al. (2010) revealed that the maximum scour depth around the bridge pier with debris accumulation can be increased up to three times that without debris accumulation. Also, Park et al. (2016) observed that due to debris accumulation upstream of a single pier, the maximum scour depth increased up to 60% compared to no-debris conditions. Also, Pagliara and Carnacina (2011) experimentally studied the effect of debris accumulation on bridge pier scour. They used three wood debris shapes including triangular, cylindrical, and rectangular with various thicknesses and widths.

They related the scour depth around the bridge pier to the blockage ratio due to debris accumulation. Additional studies by Park et al. (2016); Rahimi et al. (2020), Rahimi et al. (2018) and Dias et al. (2019) showed that the location and shape of debris accumulation has a considerable impact on the final scour depth.

Several mitigation measures have been developed in the past to reduce debris accumulating at bridge structures, for example, Schmocker and Weitbrecht (2013) tested a bypass system, Panici and Kripakaran (2021) a series of inclined racks, and Franzetti et al. (2011) examined wedges upstream of a pier to keep debris away. However, the efficiency of some scour countermeasures, for example, bed-sills, gabions, and sacrificial piles have been found to decrease due to debris accumulation (Pagliara et al. 2010; Park et al. 2016; Rahimi et al. 2018; Tafarojnoruz and Gaudio 2011). Although the studies done so far on scouring reduction have shown the effective role of slots, there are still gaps in its utilization in practice. For example, slots may be fully or partially clogged by the accumulation of debris carried by flood currents (Chiew 1992). Despite advances in scouring around bridge piers so far, the effect of debris accumulation upstream of the slotted bridge piers is still a concern for designers and engineers due to insufficient information. The main purpose of the present study is to investigate experimentally the effect of the accumulation of debris upstream of single circular cylindrical bridge piers with and without a slot. Also, the effect of the shape of the debris accumulated upstream of the pier as well as the flow characteristics on the scour hole around the pier has been investigated. Finally, the effect of the debris position (near the water surface or in the vicinity of the channel bed) on the scouring and the slot efficiency has been analyzed.

Materials and methods

The experimental tests were carried out at the Sediment Hydraulics Laboratory of Shiraz University, Shiraz, Iran under clear-water flow conditions. A glass-walled rectangular recirculating flume with 0.4 m width, 9 m length and a bed slope of 0.002 was used for the experiments (Fig. 1a). A series of 0.5 m long PVC pipes with 20 mm diameter was used as a flow straightener to reduce disturbances of the entrance flow as shown in Fig. 1a. The 0.2 m deep alluvial bed was composed of uniform sediments with a median particle diameter (d_{50}) of 0.8 mm, a geometric standard deviation ($\sigma_{g=}\sqrt{d_{84}/d_{16}}$) of 13 and specific gravity (S_g) of 2.65, where d_{50}, d_{84}, and d_{16} are the particle sizes for which 50, 84, and 16% of sediment grains are finer. The bridge pier was modeled based on the criteria suggested by Chiew and Melville (1987). Accordingly, the effect of the pier width on the scouring is negligible when the pier width is less than 10% of the flume width. Also, the ratio of the pier width to median particle diameter (D/d_{50}) must be greater than 30 to ensure that the sediment size does not affect the rate of scouring (Lee and Sturm 2009). A fiberglass cylinder with 0.5 m height and a diameter of $D=40$ mm was used in the experiments. A slot with a height equal to the flow depth ($h=H$) and width of $b=10$ mm ($b=0.25D$) was made in the center of the pier model based on Chiew (1992), who recommended the width of 1/4 of the pier diameter as the optimal slot width. The shape of woody debris observed in the literature ranges from a simple cylindrical log (Melville and Dongol 1992; Ebrahimi et al. 2018, 2017) to more complex shapes such as rectangular debris (Pagliara and Carnacina 2011; Lagasse et al. 2010) and inverted triangular or conical shapes (Cantero-Chinchilla et al. 2021; Pagliara and Carnacina 2011; Lagasse et al. 2010; Ebrahimi et al. 2018; Panici and Almeida 2020) and it is influenced by flow conditions, channel geometry, pier shape, and woody debris characteristics and availability. In this study, two circular cylinders of 12- and 24-mm diameters, an inverse pyramid, and a rectangular plate made of fiberglass were transversally attached to the upstream side of the pier (Fig. 1b) to simulate single logs, debris jam protruding vertically upstream of the pier, and a woody debris accumulation at the water surface. As the main purpose of the present study is to investigate the slot performance in scour depth mitigation in the presence of debris, the shape of the debris is of secondary importance here. The top of the debris was tangent to the water surface. Also, in some tests, the debris was located on the channel bed to study the effect of debris position on the scour process (Fig. 1c). The ratio of the modeled debris length in the vertical direction (L_z) to that in the transverse direction (L_y), i.e. L_z/L_y, was in the range of 0.06–0.12, which is close to the range observed by Ebrahimi et al. (2018). This range is close to the average ratio reported by several researchers in field conditions (Diehl 1997; Beechie and Sibley 1997; Kail 2003; Comiti et al. 2006; Magilligan et al. 2008). Three different flow discharges of 12.9, 15.3, and 16.7 l/s producing flow depths of 0.13, 0.16, and 0.18 m, respectively, were used in the experiments. The flow depth for each discharge mentioned above was calculated based on the flow intensity (U/U_c) of 0.83, 0.77, and 0.73, respectively, where U is the cross-sectional averaged flow velocity and U_c is the critical flow velocity for the incipient motion of the sediment particles according to the Shields diagram. While the maximum scour depth occurs for U/U_c (almost) equal to 1, there may be several cases in the field conditions where the flow intensity is much lower than 1(Hamidifar et al. 2021). Although flows with U/Uc <1 may not lead to the maximum scouring, the presence of debris can significantly alter the scouring depth and it is

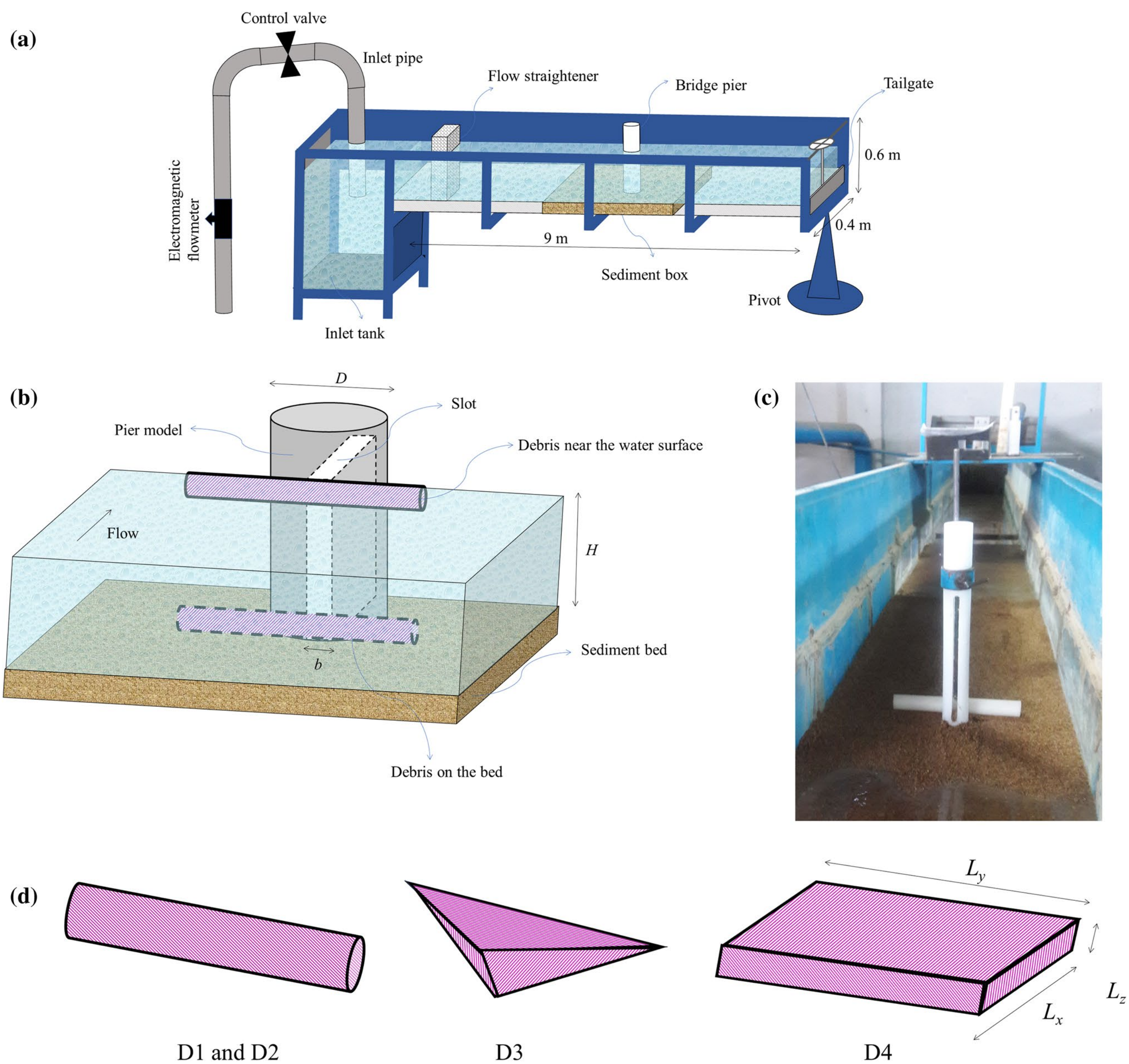


Fig. 1 **a** schematic view of the experimental flume (Not to scale), **b** slot and debris position, **c** a photo of the pier and debris located on the bed, and **d** different debris types used in the experiments

important to understand the impact of debris accumulation also at lower flow intensities, as experimented in several other works (Pagliara and Carnacina 2011; Lagasse et al. 2010; Ebrahimi et al. 2018). The flow depth was adjusted using a tailgate located at the downstream end of the laboratory flume. At the end of each experiment, the flume was drained, the debris was removed and the topography of the scoured bed was measured using an optical meter with a precision of ± 0.1 mm mounted on a carriage. The carriage was able to move in the streamwise as well as the transverse directions in a 20 mm × 20 mm grid to give a 3-D view of the scoured bed. A summary of the experimental conditions and debris dimensions are given in Table 1.

Each test was continued until reaching a quasi-equilibrium condition based on the criteria suggested by Chiew and Melville (1987) who reported that the equilibrium scouring depth can be considered when the variations in the scour depth is less than 5% of the pier diameter during 24 h. A series of 48-h long tests showed that the quasi-equilibrium conditions were met after 6 h, and this was the final duration selected for all the experimental runs. Each test is identified by a combination of letters and numbers. Thereafter, NS and

Table 1 Summary of the experimental conditions

Test code	Q (lit/s)	H (mm)	D (mm)	b (mm)	U/U_c (–)	Fr (–)	L_x (mm)	L_y (mm)	L_z (mm)
NS-ND-130	12.9	130	40	10	0.83	0.220	–	–	–
NS-ND-160	15.3	160	40	10	0.80	0.191	–	–	–
NS-ND-180	16.7	180	40	10	0.77	0.175	–	–	–
S-ND-130	12.9	130	40	10	0.83	0.220	–	–	–
S-ND-160	15.3	160	40	10	0.80	0.191	–	–	–
S-ND-180	16.7	180	40	10	0.77	0.175	–	–	–
S-D1-130	12.9	130	40	10	0.83	0.220	12	200	12
S-D2-130	12.9	130	40	10	0.83	0.220	24	200	24
S-D3-130	12.9	130	40	10	0.83	0.220	24	200	24
S-D4-130	12.9	130	40	10	0.83	0.220	100	200	12
S-D1-160	15.3	160	40	10	0.80	0.191	12	200	12
S-D2-160	15.3	160	40	10	0.80	0.191	24	200	24
S-D3-160	15.3	160	40	10	0.80	0.191	24	200	24
S-D4-160	15.3	160	40	10	0.80	0.191	100	200	12
S-D1-180	16.7	180	40	10	0.77	0.175	12	200	12
S-D2-180	16.7	180	40	10	0.77	0.175	24	200	24
S-D3-180	16.7	180	40	10	0.77	0.175	24	200	24
S-D4-180	16.7	180	40	10	0.77	0.175	100	200	12
NS-D1-130	12.9	130	40	10	0.83	0.220	12	200	12
NS-D1-160	15.3	160	40	10	0.80	0.191	12	200	12
NS-D1-180	16.7	180	40	10	0.77	0.175	12	200	12
NS-D2-130	12.9	130	40	10	0.83	0.220	24	200	24
NS-D2-160	15.3	160	40	10	0.80	0.191	24	200	24
NS-D2-180	16.7	180	40	10	0.77	0.175	24	200	24
NS-D3-130	12.9	130	40	10	0.83	0.220	24	200	24
NS-D3-160	15.3	160	40	10	0.80	0.191	24	200	24
NS-D3-180	16.7	180	40	10	0.77	0.175	24	200	24
NS-D4-130	12.9	130	40	10	0.83	0.220	100	200	12
NS-D4-160	15.3	160	40	10	0.80	0.191	100	200	12
NS-D4-180	16.7	180	40	10	0.77	0.175	100	200	12
NS-D1-130-Bed	12.9	130	40	10	0.83	0.220	12	200	12
NS-D2-130-Bed	12.9	130	40	10	0.83	0.220	24	200	24
NS-D3-130-Bed	12.9	130	40	10	0.83	0.220	24	200	24
NS-D4-130-Bed	12.9	130	40	10	0.83	0.220	100	200	12
S-D1-130-Bed	12.9	130	40	10	0.83	0.220	12	200	12
S-D2-130-Bed	12.9	130	40	10	0.83	0.220	24	200	24
S-D3-130-Bed	12.9	130	40	10	0.83	0.220	24	200	24
S-D4-130-Bed	12.9	130	40	10	0.83	0.220	100	200	12
NS-D1-160-Bed	15.3	160	40	10	0.80	0.191	12	200	12
NS-D2-160-Bed	15.3	160	40	10	0.80	0.191	24	200	24
NS-D3-160-Bed	15.3	160	40	10	0.80	0.191	24	200	24
NS-D4-160-Bed	15.3	160	40	10	0.80	0.191	100	200	12
S-D1-160-Bed	15.3	160	40	10	0.80	0.191	12	200	12
S-D2-160-Bed	15.3	160	40	10	0.80	0.191	24	200	24
S-D3-160-Bed	15.3	160	40	10	0.80	0.191	24	200	24
S-D4-160-Bed	15.3	160	40	10	0.80	0.191	100	200	12
NS-D1-180-Bed	16.7	180	40	10	0.77	0.175	12	200	12
NS-D2-180-Bed	16.7	180	40	10	0.77	0.175	24	200	24
NS-D3-180-Bed	16.7	180	40	10	0.77	0.175	24	200	24
NS-D4-180-Bed	16.7	180	40	10	0.77	0.175	100	200	12

Table 1 (continued)

Test code	Q (lit/s)	H (mm)	D (mm)	b (mm)	U/U_c (–)	Fr (–)	L_x (mm)	L_y (mm)	L_z (mm)
S-D1-180-Bed	16.7	180	40	10	0.77	0.175	12	200	12
S-D2-180-Bed	16.7	180	40	10	0.77	0.175	24	200	24
S-D3-180-Bed	16.7	180	40	10	0.77	0.175	24	200	24
S-D4-180-Bed	16.7	180	40	10	0.77	0.175	100	200	12

ND, refer to the tests without slot and debris, respectively, S stands for the tests with slot, and D1, D2, D3, and D4 refers to cylindrical debris of 12 mm diameter, cylindrical debris of 24-mm diameter, inverse pyramid, and rectangular debris shapes, respectively. The parameters affecting the scouring around a cylindrical bridge pier with impervious debris accumulations in a fluvial bed with uniform sediments are: the flow depth (h), mean flow velocity (V), bed slope (S), channel width (B), bed roughness (k_s), water (ρ_w) and bed particles (ρ_s) specific mass, acceleration due to gravity (g), viscosity (υ), pier diameter (D), particle size (d_{50}), debris dimensions in the streamwise, transverse, and vertical directions (L_x, L_y, and L_z respectively), debris specific mass (ρ_d), debris frontal area (A_d), debris distance to the water surface (h_d). By excluding the parameters that were kept constant in the present study, i.e., S, B/D, k_s/D, ρ_s/ρ_w, d_{50}/D, and ρ_d/D, and neglecting the effect of Reynolds number $Re=\rho_w Vh/\upsilon$ because of the turbulent flow conditions and flow depth as $h/D>3$, the non-dimensional maximum scour depth d_{sm}/D was found to be a function of Froude number $Fr=V/\sqrt{(g.h)}$, and the debris geometrical parameters L_x/D, L_z/D, h_d/D, and A_d/D^2.

Results

Figure 2 shows variations of the non-dimensional maximum scour depth around the pier, d_{sm}/D, for different flow and debris conditions for $Fr_1=0.22$. The slot reduces the maximum scour depth compared to the standard pier under both no-debris and debris conditions. These findings are comparable to those of previous studies on standard piers without debris (for example Chiew 1992; Grimaldi et al. 2009b; M Heidarpour 2002; Kumar et al. 1999; Moncada-M et al. 2009).

Figure 3 shows variations of d_{sm}/D against Fr and for different debris conditions. The maximum scour depth decreases due to the presence of the slot in the pier for a given debris condition and the maximum scouring depth decreases as the Froude number decreases. However, the maximum scouring depth increases compared to the no-debris conditions for all the tests with different shapes of debris placed right beneath the water surface. The maximum scouring depth increases as the debris diameter increases for the cylindrical shape debris placed near the water surface. This trend is completely reversed for a debris placed on the channel bed.

The figure also shows how the maximum scouring depth increases compared to the tests with debris located near the water surface as well as the tests with no-debris conditions in the cases of an inverse pyramid debris located above the channel bed.

Additionally, for all the slotted and standard piers tests with rectangular debris, the near-bed accumulation of debris has reduced the maximum scour depth compared to the near water surface accumulation of debris material.

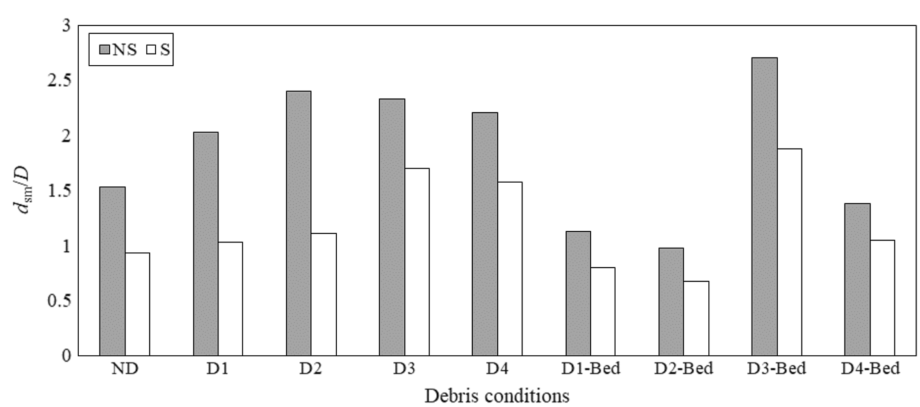


Fig. 2 Variations of the dimensionless maximum scour depth for slotted and non-slotted piers and different debris conditions ($Fr=0.22$)

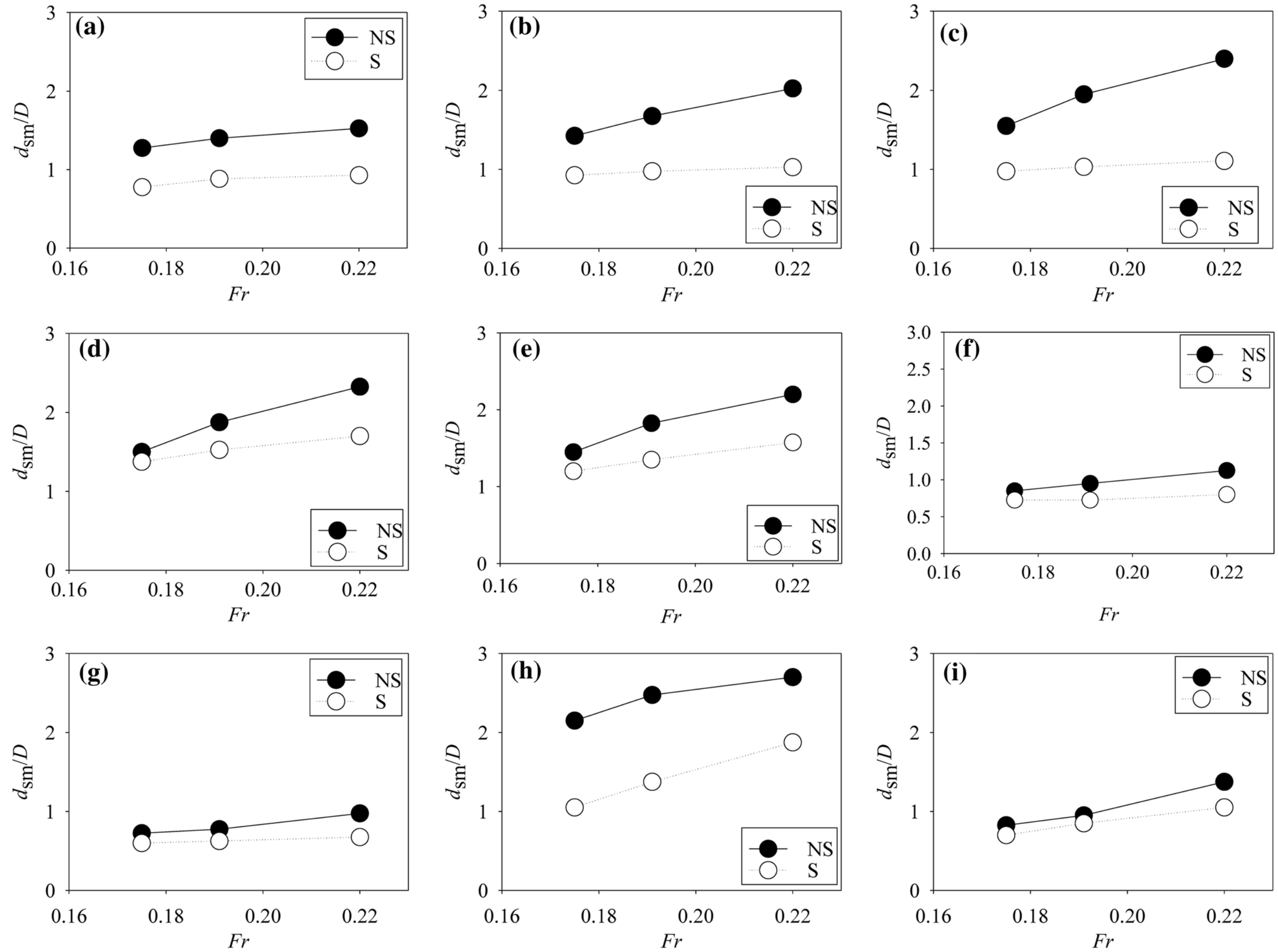
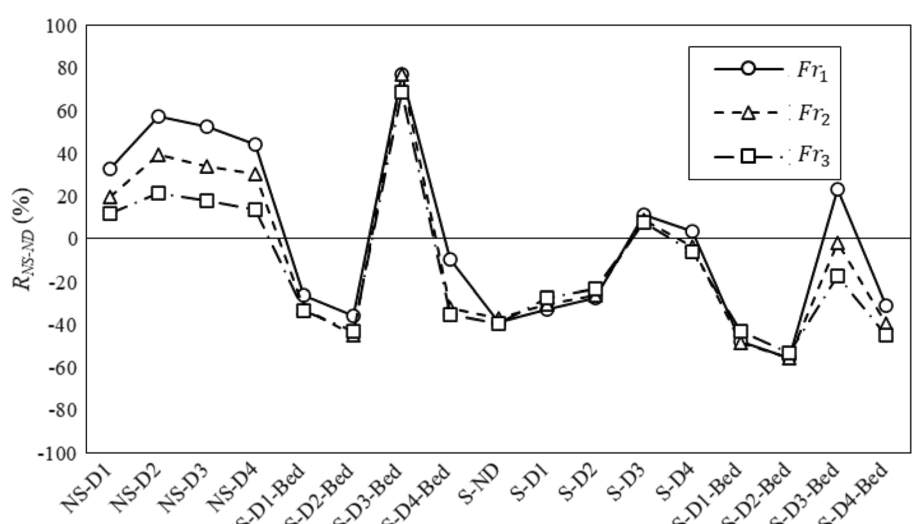


Fig. 3 Variations of the dimensionless maximum scour depth (dsm/D) against Froude number (Fr) in different tests: **a** ND, **b** D1, **c** D2, **d** D3, **e** D4, **f** D1-Bed, **g** D2-Bed, **h** D3-Bed, and **i** D4-Bed

Fig. 4 Variations of the maximum scour depth in the slotted or debris loaded piers compared to that of the control test



Discussion

To quantify the effect of the presence of slot and debris and its location on the maximum scour depth, the percentage of variation in the d_{sm} relative to the control test (no-debris and no-slot), $R_{NS\text{-}ND}$, is calculated for different tests and shown in Fig. 4 for the three flow Froude number tested. $R_{NS\text{-}ND}$ is computed as:

$$R_{NS-ND} = \frac{d_{sm} - d_{NS-ND}}{d_{NS-ND}} \times 100, \quad (1)$$

where d_{sm} and $d_{NS\text{-}ND}$ denote the maximum scour depth around the pier in each test and the control test (no-slot and no-debris conditions), respectively.

For the standard pier tests (no-slot conditions denoted with NS), it can be seen that the maximum scour depth has increased up to 32, 57, 52, and 57%, for debris types D1, D2, D3, and D2, respectively, located under the free water surface. For under-free-water-surface debris, both streamwise and downward components of the flow velocity as well as the bed shear stress increase and consequently increase the maximum scouring depth around the pier. Ebrahimi et al. (2018) also reported similar findings for sharp-nose piers. Figure 3 also shows that the maximum scouring depths for the tests with debris type D2 are greater than the corresponding tests with debris type D1. The reason can be attributed to the fact that debris type D2 produces larger blockage in the flow cross-sectional area and consequently, the flow velocity and bed shear stress will be higher than those of corresponding D1 tests.

The sheltering effect of a debris located near the bed reduces the maximum scour depth by 33%, 44%, and 35% for debris types D1, D2, and D4, respectively, for the standard pier tests, whilst the maximum scour depth increases up to 77% for the debris type D3. The different trend for the inverse pyramid debris shape may be attributed to the re-direction of the near-bed streamlines after impinging the debris (Fig. 5). The downward slope of the inverse pyramid causes the flow to redirect toward the bed, as shown in Fig. 4, increasing the maximum scouring depth compared to the cases without debris. The sheltering effect of the debris D3 has been neutralized because of the flow redirection and the maximum scour depths in the NS-D3-Bed tests are highest among all the tested conditions.

Figure 4 shows that the slot alone leads to a 37–39% reduction in the maximum scour depth compared to standard pier conditions. However, due to the effects of the debris located near the water surface, the slot efficiency in reducing the maximum scour depth reduces up to 32% and 27% for the D1 and D2 cylindrical debris shapes, respectively. It is interesting to note that when the debris is located near the channel bed, the percentage reduction in the maximum scour depth increases up to 33 and 44% for D1 and D2 cylindrical debris shapes, respectively. Figure 4 shows that the larger the cylindrical shape debris diameter located on the initial bed surface, the smaller the maximum scour depth. The reason may be attributed to the sheltering effect of debris located on

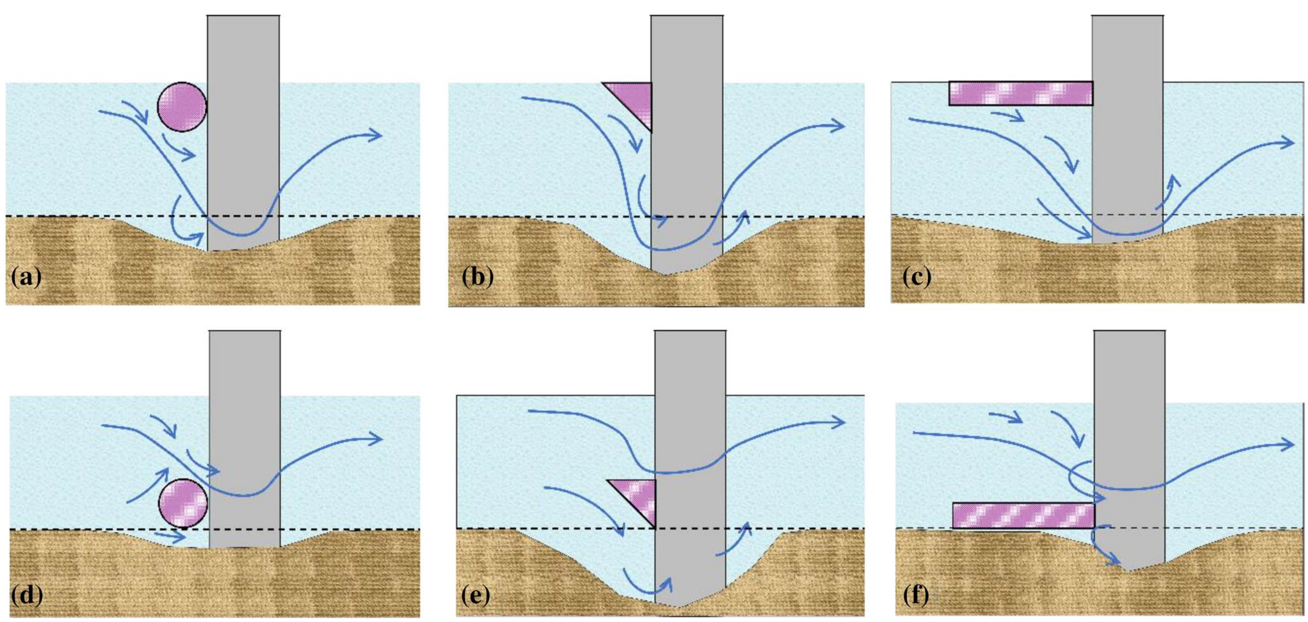


Fig. 5 Schematic view of flow around different debris types at different positions: **a** cylindrical, **b** inverse pyramid, **c** rectangular debris located just below the free water surface, **d** cylindrical, **e** inverse pyramid, and **f** rectangular debris located above the bed (Note: the velocity vectors shown in the figure are hypothesised and not observed)

the bed. When the debris is located in the vicinity of the bed, the maximum scouring depth around simple bridge piers is mitigated due to the reduced strength of the downflow (Rahimi et al. 2018; Ebrahimi et al. 2018, 2020).

Figure 4 also shows that the flow Froude number, in the range tested in the present study, has limited influence on the maximum scour values for the slotted pier without debris and with debris located near the water surface. However, for the standard pier and all of the debris shapes located near the water surface, the Froude number considerably affect the maximum scour depth. In this case, the difference between the $R_{NS\text{-}ND}$ values corresponding to the lowest and highest Froude number studied was found to be about 35% for D2 and D3 debris types.

|It is interesting to note that the maximum scour may be increased or decreased compared to the standard pier without debris conditions depending on the shape of the debris for the tests with debris located near the bed surface. On the other hand, while D1, D2, and D4 debris types cause the maximum scouring depth to be reduced up to 33%, 43%, and 35%, respectively, the maximum scour depth increases up to 82% for the inverse pyramid debris type (D3). The sheltering effects of the debris causes a considerable reduction in the maximum scouring depth for slotted piers when compared to the standard pier conditions. Additionally, the percentage reduction in the maximum scour depth is not affected by the flow Froude number for the slotted pier with D1 and debris types D2 located on the bed (Fig. 4) in the range of *Fr* values tested in the present study. The inverse pyramid debris (D3) accumulated on a slotted pier shows a different trend where the scour depth increases 23% and decreases by 17% for the tests with the highest and lowest Froude numbers studied, respectively, which could be linked to the the reduction in the near-bed flow velocity with decreasing Froude number and the weaker flow field around the slotted pier.

The percentage reduction in the maximum scouring depth increases with decreasing *Fr* for the debris type D4, which can be attributed to the sheltering effect of these particular configuration of debris.

Figure 6 shows the variations of the dimensionless scour depth (d_{sm}/D) versus dimensionless debris area (A_d/D^2) for debris located near the free flow surface. The dimensionless scouring depth increases with increasing debris blockage for the non-slotted bridge pier tests (Fig. 6a). The increase in the maximum scour depth with increasing blockage area can be attributed to the increased flow velocity beneath the debris due to the reduction of the flow passage area. On the other hand, a fraction of the flow passes through the slot opening and weakens the downward flow upstream of the pier for the slotted pier cases (Fig. 6b).

The increase in flow velocity beneath the debris is not significant compared to the non-slotted piers and a relatively constant dimensionless scour depth is observed for all of the tests with slotted piers with different A_d/D^2 values.

In contrast, Fig. 7 shows the dimensionless scouring depth versus the dimensionless debris area for the cases where the debris is near the channel bed. As shown in Fig. 7, the protective effect of the debris itself, which acts as a countermeasure against the impact of erosive flows, is more effective than the protective effect of the slot inside the pier. It should be noted that $A_d/D^2 = 0$ in Figs. 6 and 7 represents the no-debris conditions.

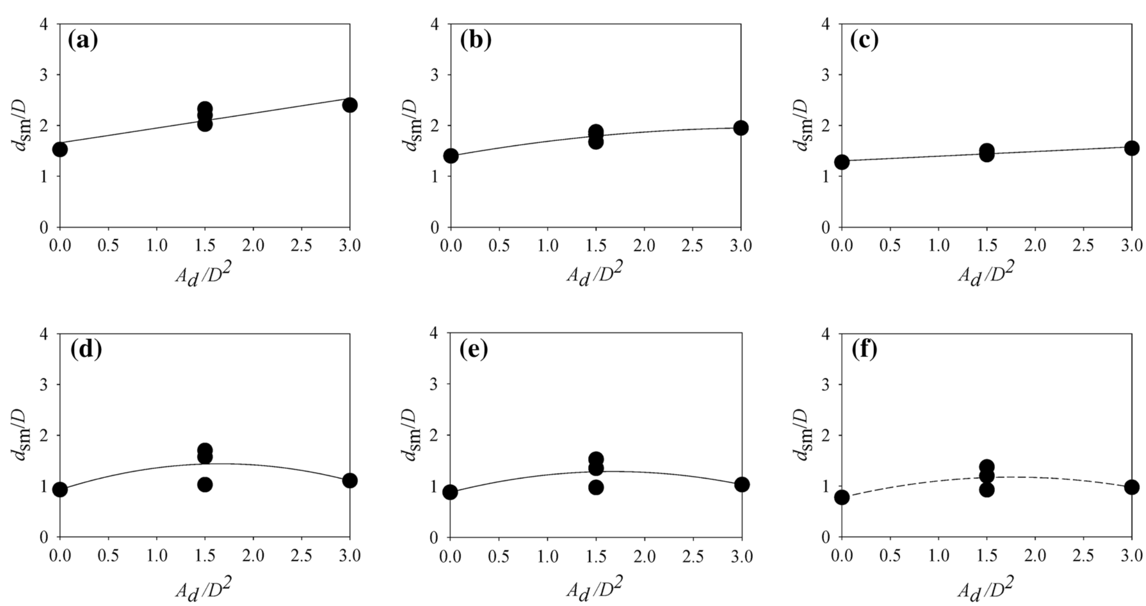


Fig. 6 Variations of the dimensionless scour depth against dimensionless debris area for the tests with debris located near the water surface, non-slotted pier: **a** $Fr = 0.22$, **b** $Fr = 0.19$, and **c** $Fr = 0.17$,and slotted pier: **d** $Fr = 0.22$, **e** $Fr = 0.19$, and **f** $Fr = 0.17$

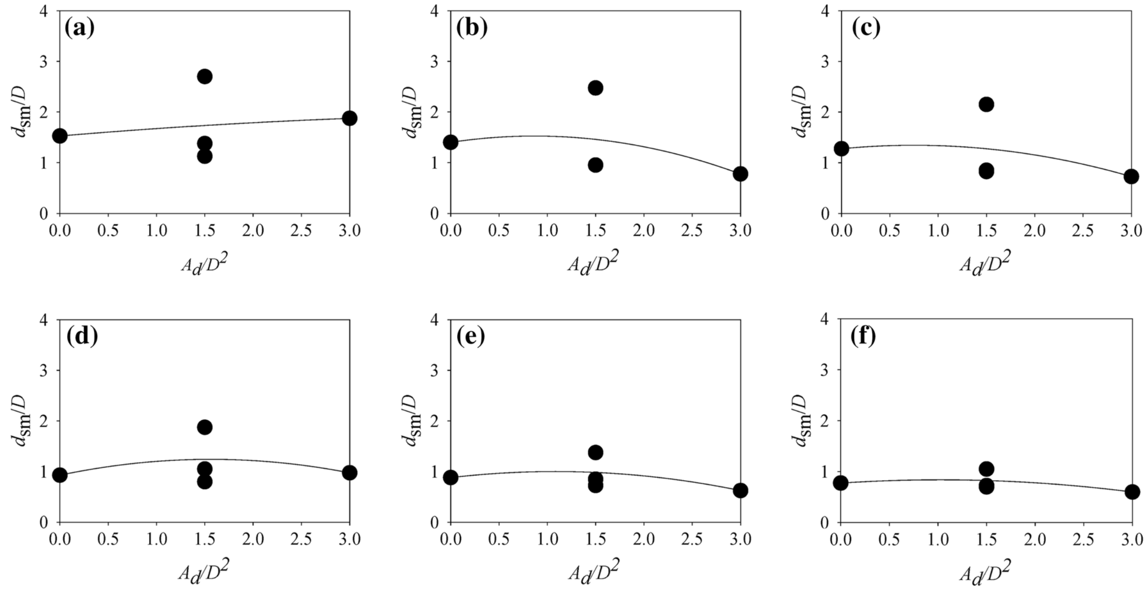
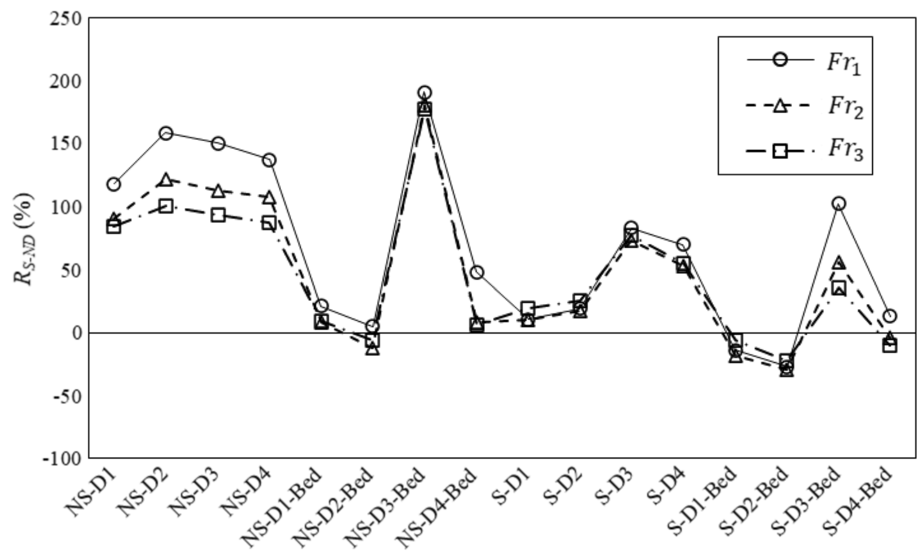


Fig. 7 Variations of the dimensionless scour depth against dimensionless debris area for the tests with debris located near the channel bed, non-slotted pier: **a** $Fr=0.22$, **b** $Fr=0.19$, and **c** $Fr=0.17$,and slotted pier: **d** $Fr=0.22$, **e** $Fr=0.19$, and **f** $Fr=0.17$

Fig. 8 Variations of the maximum scour depth in the slotted or debris loaded piers compared to that of the slotted pier without debris



Variations of the percentage reduction in the maximum scour depth compared to the slotted pier without the presence of debris $R_{S\text{-}ND}$ are shown in Fig. 8. $R_{S\text{-}ND}$ is computed as:

$$R_{S-ND} = \frac{d_{sm} - d_{S-ND}}{d_{S-ND}} \times 100, \tag{2}$$

where $d_{S\text{-ND}}$ denotes the maximum scour depth around the pier in the tests with slotted piers and no-debris conditions.

Debris types D1, D2, D3, and D4 located near the water surface increase the maximum scour depth up to 19%, 26%, 83%, and 70% for the slotted pier, and up to 118%, 159%, 150%, and 137% for the standard pier conditions, respectively. The observed results are somewhat different when the debris is located near the bed. While for the non-slotted pier tests, the maximum scour depth increases up to 21%, 190%, and 48% for D1, D3, and D4 debris types located on the bed, it decreases up to 12% for the D2 debris. Also, for the slotted pier with debris located adjacent to the bed, the slot reduces the maximum scour depth for debris types D1, D2, and D4. However, d_{sm} decreases up to 102% for D3 debris compared to the slotted pier without debris.

Figure 9 shows the dimensionless contour map of the bed scour and the effect of the slot, debris and the debris position on the scour hole for debris D2 and Fr_3, for half of

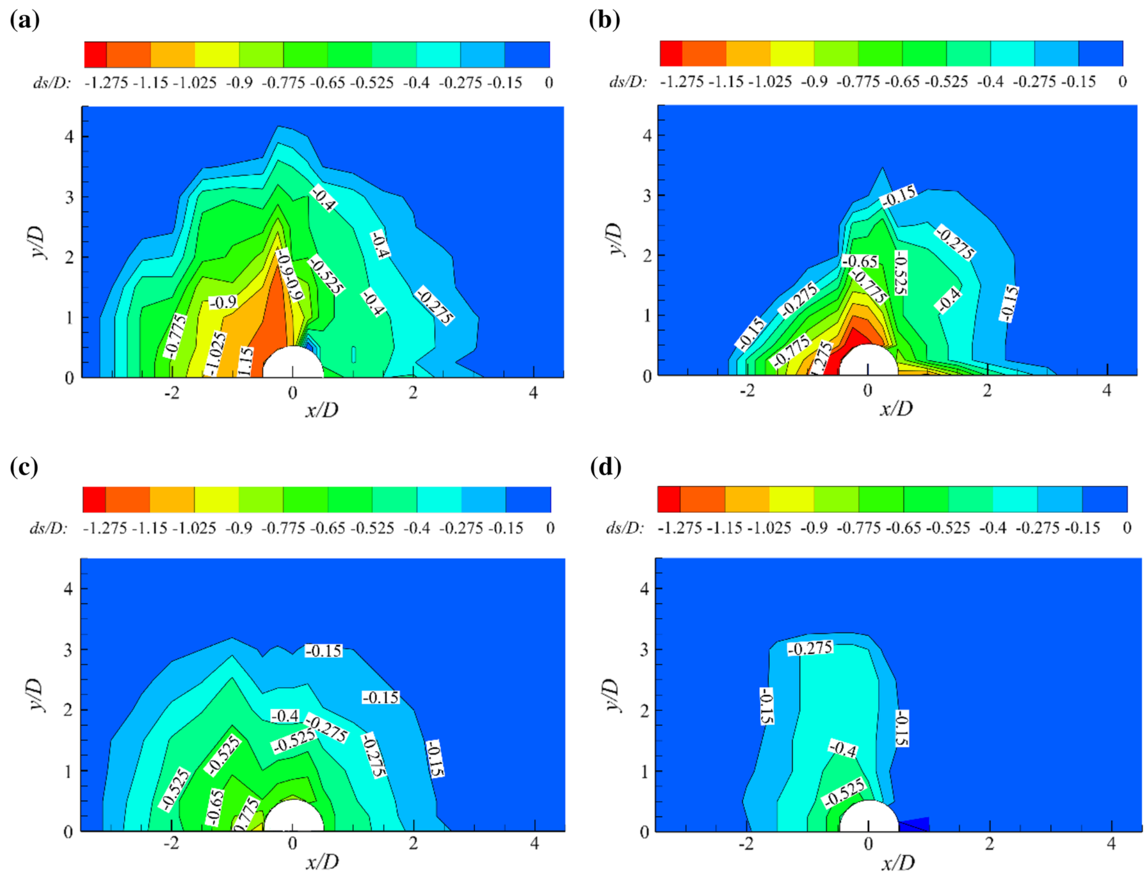


Fig. 9 Contour plots of scour depth around the pier in different tests, **a** NS-ND-Fr_3, **b** NS-D2-Fr_3, **c** S-D2-Fr_3, and **d** S-D2-Fr_3-Bed

the channel. The scour hole spreads around the pier and the maximum scour depth upstream of the pier is 1.15D for the NS-ND-Fr_3 test (Fig. 9a). The scour extends to a distance of about 3D downstream of the pier. After the addition of debris D2 under the water surface, i.e. in the NS-D2-Fr_3 test, the scour expansion area upstream of the pier narrows and the upstream slope of the scour hole increases (Fig. 9b). The maximum scouring depth increases to 1.275D. After adding the slot at the pier model (Fig. 9c), the maximum scour depth significantly reduces to 0.9D. The presence of a slot, in addition to reducing the scour depth compared to the no-slot mode, also significantly reduces the slope of the scour hole. Changing the position of the debris from the water surface to near the bed surface has led to a general deformation of the scour hole compared to other tests (Fig. 9d). Accordingly, the maximum scour depth reduces to 0.525D. Also, the development of scour holes is weakened upstream of the pier and stopped downstream, which can be due to the effect of debris on the flow structure and the weakening of the downflow and subsequently, the weakening of the horseshoe vortex and wake vortex downstream of the pier. This finding is in agreement with results obtained by Ebrahimi et al. (2018), Müller et al. (2001), Vijayasree et al. (2019).

Figure 10 shows the contour maps of the dimensionless scour depth for D3 and D4 debris types in two positions near the water surface and adjacent to the bed. The accumulation of debris near the bed leads to a reduction in the maximum scouring depth as well as a reduction in the scouring area around the pier. The combination of slot and debris reduces the erosion around the pier for the S-D4-Fr_3-Bed test. It shrinks the main scour hole near the pier and a secondary scour hole forms relatively far downstream from the pier that will not have much impact on the stability of the bridge structure. It should be noted that the secondary scour hole downstream of the pier in the presence of debris installed at the initial bed elevation was not observed by Ebrahimi et al. (2018) for masonry bridges with piers with a large length to diameter ratio.

Table 2 shows a comparison of the results obtained in the present study with data available in the literature with particular reference to the effect of slot and debris on the changes of maximum scour depth. The studies used in this table are the closest in terms of piers, flows, and slots dimensions to the present study. Accordingly, Chiew (1992), Kumar et al. (1999), and Grimaldi et al. (2009b) reported a 9%, 19%, and 30% reduction in the maximum scour depth, respectively, due

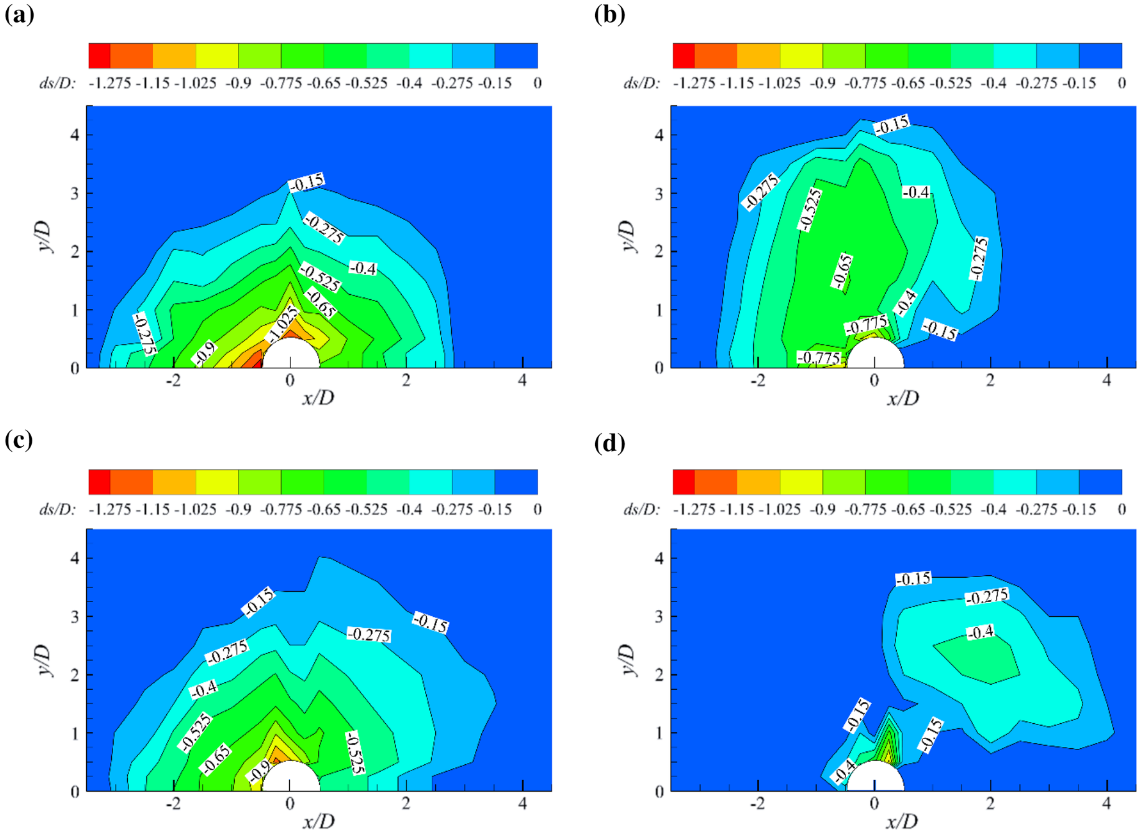


Fig. 10 Contour plots of scour depth around the pier in different tests, **a** S-D3-Fr_3, **b** S-D3-Fr_3-Bed, **c** S-D4-Fr_3, and **d** S-D4-Fr_3-Bed

Table 2 Effects of slot and debris on the variations of the maximum scour depth*

Reference	Slot location	Debris	Maximum change in d_{sm} (%)
Chiew (1992)	NB	ND	− 20
Chiew (1992)	NW	ND	− 30
Kumar et al. (1999)	FD	ND	− 30
Heidarpour (2002)	NW	ND	− 18
Grimaldi et al. (2009b)	FD	ND	− 30
Melville and Dongol (1992)	NS	NW	+ 49
Pagliara and Carnacina (2011)	NS	NW	+ 195
Pasokhi-Dargah et al. (2018)	NS	NW	+ 42
Ebrahimi et al. (2018)	NS	NW	+ 33
Ebrahimi et al. (2018)	NS	NB	− 12 to + 7
Cantero-Chinchilla et al. (2018)	NS	NW	+ 75
Present study	FD	ND	− 39
Present study	FD	NW	− 32 to + 11
Present study	FD	NB	− 55 to + 23

*NB: near the bed, NW: near the water surface, FD: full depth, NS: no-slot, ND: no debris,

to the slot in the pier. However, the results of the present study showed that although the slot in the pier alone leads to a 39% reduction in the maximum scour depth, the presence of debris can lead to a decrease or increase in the maximum scour depth compared to a standard pier without debris depending on the debris location. Accordingly, if the debris is located near the water surface,, the maximum scouring depth can be reduced up to 32% or increased up to 11%, depending on the shape of the accumulated materials. In contrast, if objects accumulate near the bed, the maximum scour depth may decrease up to 55% or increase up to 23% depending on the shape of the accumulated material. The maximum percentage increase in the d_{sm} was reported by Cantero-Chinchilla et al. (2018) for the debris loaded pier. It should be noted that different shapes and sizes of debris produce different scour depths. As a consequnce, the results presented in the present paper are limited to the tested range of debris characteristics.

Conclusion

Many rivers normally carry materials such as leaves, branches, roots and tree trunks, a phenomenon naturally observed with the decay of riparian vegetation.

Accumulation of these materials in the vicinity of hydraulic structures such as bridge piers can lead to problems in their proper operation. In this study, the effect of debris accumulated upstream of a slotted cylindrical bridge pier model was investigated experimentally. Four debris models were investigated under three different flow conditions. The results showed that, although the slot alone could reduce the maximum scour depth around the pier by up to 39%, the presence of debris could affect its performance. The maximum scouring depth around the pier decreased compared to the no-debris conditions for some shapes of debris and increased for others, indicating that the accumulation of floating objects can have a significant effect on the stability of the bridge structure. The position of debris accumulation also affects the performance of the slot and the geometry of the scour hole. In general, debris near the bed can lead to a reduction of scouring as a result of the sheltering effect. This sheltering can be different depending on the shape of the accumulation of the debris upstream of the pier. It can be concluded that the accumulation of debris upstream of the pier has an important effect on the performance of the slot in the protection of the pier against scour and it is necessary to be careful in rivers that carry large quantities of debris. Further research with different flows, sediments, bridge piers, slots and debris conditions is needed to provide a general guide to slot operation in the presence of debris for use in hydraulic and structural bridge pier design.

Funding No funding was received for conducting this study.

Data availability All data generated or used during the study appear in the submitted article.

Declarations

Conflict of interest The authors declare that they have no known competing interests.

Code availability No code was generated for conducting this study.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

References

Akib S, Liana Mamat N, Basser H, Jahangirzadeh A (2014) Reducing local scouring at bridge piles using collars and geobags. Sci World J 2014:1–7. https://doi.org/10.1155/2014/128635

Azevedo M, Leite F, Lima M (2014) Experimental study of scour around circular and elongated bridge piers with and without pier slot. In: Avilez-Valente P, Carvalho E, Silva Lopes A (eds) MEFTE 2014. Porto, Portugal, pp 195–200

Beechie TJ, Sibley TH (1997) Relationships between channel characteristics, woody debris, and fish habitat in Northwestern Washington Streams. Trans Am Fish Soc 126:217–229. https://doi.org/10.1577/1548-8659(1997)126%3c0217:rbccwd%3e2.3.co;2

Benn J (2013) Railway bridge failure during flooding in the UK and Ireland. Proc Inst Civil Eng - Forensic Eng 166(4):163–170. https://doi.org/10.1680/feng.2013.166.4.163

Bestawy A, Eltahawy T, Alsaluli A et al (2020) Reduction of local scour around a bridge pier by using different shapes of pier slots and collars. Water Sci Technol Water Supply 20:1006–1015. https://doi.org/10.2166/ws.2020.022

Briaud JL, Chen HC, Chang KA et al (2006) Scour at bridges due to debris accumalation: a review. 3rd International conference on scour and erosion (ICSE-3). The Netherlands, Amsterdam, pp 113–120

Cantero-Chinchilla FN, de Almeida GAM, Manes C (2021) Temporal evolution of clear-water local scour at bridge piers with flow-dependent debris accumulations. J Hydraul Eng 147:06021013. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001920

Cantero-Chinchilla FN, de Almeida GAM, Escarameia M (2018) Assessing the effects of debris accumulations at river bridges. Southampton, UK

Carnacina I, Pagliara S, Leonardi N (2019) Bridge pier scour under pressure flow conditions. River Res Appl 35:844–854. https://doi.org/10.1002/rra.3451

Chiew YM (1992) Scour protection at bridge piers. J Hydraul Eng 118:1260–1269. https://doi.org/10.1061/(ASCE)0733-9429(1992)118:9(1260)

Chiew YM (1995) Mechanics of riprap failure at bridge piers. J Hydraul Eng 121:635–643. https://doi.org/10.1061/(ASCE)0733-9429(1995)121:9(635)

Chiew YM (2004) Local scour and riprap stability at bridge piers in a degrading channel. J Hydraul Eng 130:218–226. https://doi.org/10.1061/(ASCE)0733-9429(2004)130:3(218)

Chiew YM, Lim F-H (2000) Failure behavior of riprap layer at bridge piers under live-bed conditions. J Hydraul Eng 126:43–55. https://doi.org/10.1061/(ASCE)0733-9429(2000)126:1(43)

Chiew YM, Lim S (2003) Protection of bridge piers using a sacrificial sill. Proc Inst Civ Eng - Water Marit Eng 156:53–62. https://doi.org/10.1680/wame.2003.156.1.53

Chiew YM, Melville BW (1987) Local scour around bridge piers. J Hydraul Res 25:15–26. https://doi.org/10.1080/00221688709499285

Comiti F, Andreoli A, Lenzi MA, Mao L (2006) Spatial density and characteristics of woody debris in five mountain rivers of the Dolomites (Italian Alps). Geomorphology 78:44–63. https://doi.org/10.1016/j.geomorph.2006.01.021

De Cicco PN, Paris E, Solari L, Ruiz-Villanueva V (2020) Bridge pier shape influence on wood accumulation: Outcomes from flume experiments and numerical modelling. J Flood Risk Manag 13:e12599. https://doi.org/10.1111/jfr3.12599

Dey S, Sumer BM, Fredsøe J (2006) Control of scour at vertical circular piles under waves and current. J Hydraul Eng 132:270–279. https://doi.org/10.1061/(ASCE)0733-9429(2006)132:3(270)

Dias AJ, Fael CS, Núñez-González F (2019) Effect of debris on the local scour at bridge piers. IOP Conf Series: Mater Sci Eng 471:022024. https://doi.org/10.1088/1757-899X/471/2/022024

Diehl TH (1997) Potential drift accumulation at bridges. US Department of Transportation, Federal Highway Administration Research and Development, McLean, Virginia, USA.

Dixon SJ, Sear DA (2014) The influence of geomorphology on large wood dynamics in a low gradient headwater stream. Water Resour Res 50:9194–9210. https://doi.org/10.1002/2014WR015947

Ebrahimi M, Kripakaran P, Prodanović DM et al (2018) Experimental study on scour at a sharp-nose bridge pier with debris

blockage. J Hydraul Eng 144:04018071. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001516
Ebrahimi M, Djordjević S, Panici D et al (2020) A method for evaluating local scour depth at bridge piers due to debris accumulation. Proc Inst Civ Eng Bridg Eng 173:86–99. https://doi.org/10.1680/jbren.19.00045
Ebrahimi M, Kahraman M;, Kripakaran R; (2017) Scour and hydrodynamic effects of debris blockage at masonry bridges: insights from experimental and numerical modelling A NOTE ON VERSIONS. International Association for Hydro-Environment Engineering and Research (IAHR)
Froehlich DC (2013) Protecting bridge piers with loose rock riprap. J Appl Water Eng Res 1:39–57. https://doi.org/10.1080/23249676.2013.828486
Gaudio R, Tafarojnoruz A, Calomino F (2012) Combined flow-altering countermeasures against bridge pier scour. J Hydraul Res 50:35–43. https://doi.org/10.1080/00221686.2011.649548
Ghorbani B, Kells JA (2008) Effect of submerged vanes on the scour occurring at a cylindrical pier. J Hydraul Res 46:610–619. https://doi.org/10.3826/jhr.2008.3003
Grimaldi C, Gaudio R, Calomino F, Cardoso AH (2009a) Countermeasures against local scouring at bridge piers: slot and combined system of slot and bed sill. J Hydraul Eng 135:425–431. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000035
Grimaldi C, Gaudio R, Calomino F, Cardoso AH (2009b) Control of scour at bridge piers by a downstream bed sill. J Hydraul Eng 135:13–21. https://doi.org/10.1061/(ASCE)0733-9429(2009)135:1(13)
Guo X, Zhang C, Chen ZQ (2020) Dynamic performance and damage evaluation of a scoured double-pylon cable-stayed bridge under ship impact. Eng Struct 216:110772. https://doi.org/10.1016/j.engstruct.2020.110772
Hajikandi H, Golnabi M (2018) Y-shaped and T-shaped slots in river bridge piers as scour countermeasures. Proc Inst Civ Eng - Water Manag 171:253–263. https://doi.org/10.1680/jwama.16.00063
Hamidifar H, Omid MH, Nasrabadi M (2018a) Reduction of Scour Using a Combination of Riprap and Bed Sill 171:264–270. https://doi.org/10.1680/jwama.16.00073
Hamidifar H, Nasrabadi M, Omid MH (2018b) Using a bed sill as a scour countermeasure downstream of an apron. Ain Shams Eng J 9:1663–1669. https://doi.org/10.1016/j.asej.2016.08.016
Hamidifar H, Zanganeh-Inaloo F, Carnacina I (2021) Hybrid scour depth prediction equations for reliable design of bridge piers. Water 2021(13):2019. https://doi.org/10.3390/W13152019
Hamidifar H, Shahabi-Haghighi SMB, Chiew YM (2022) Collar performance in bridge pier scour with debris accumulation. Int J Sediment Res 37: 328-334. https://doi.org/10.1016/J.IJSRC.2021.10.002
Heidarpour M (2002) Control and reduction of local scour at bridge piers by using slot. In: Bousmar D, Zech Y (eds) River Flow: Proceedings of the International Conference on Fluvial Hydraulics. IAHR, Louvain-la-Neuve, Belgium, pp 1069–1072
Heidarpour M, Afzalimehr H, Izadinia E (2010) Reduction of local scour around bridge pier groups using collars. Int J Sediment Res 25:411–422. https://doi.org/10.1016/S1001-6279(11)60008-5
Hosseini SA, Osroush M, Kamanbedast AA, Khosrojerrdi A (2020) The effect of slot dimensions and its vertical and horizontal position on the scour around bridge abutments with vertical walls. Sadhana - Acad Proc Eng Sci 45:1–16. https://doi.org/10.1007/s12046-020-01343-z
Jamei M, Ahmadianfar I (2020) Prediction of scour depth at piers with debris accumulation effects using linear genetic programming. Mar Georesources Geotechnol 38:468–479. https://doi.org/10.1080/1064119X.2019.1595793
Kail J (2003) Influence of large woody debris on the morphology of six central European streams. Geomorphology 51:207–223. https://doi.org/10.1016/S0169-555X(02)00337-9
Khaple S, Hanmaiahgari PR, Gaudio R, Dey S (2017) Splitter plate as a flow-altering pier scour countermeasure. Acta Geophys 65:957–975. https://doi.org/10.1007/s11600-017-0084-z
Korkut R, Martinez EJ, Morales R et al (2007) Geobag performance as scour countermeasure for bridge abutments. J Hydraul Eng 133:431–439. https://doi.org/10.1061/(ASCE)0733-9429(2007)133:4(431)
Kumar V, Raju KGR, Vittal N (1999) Reduction of local scour around bridge piers using slots and collars. J Hydraul Eng 125:1302–1305. https://doi.org/10.1061/(ASCE)0733-9429(1999)125:12(1302)
Lagasse PF, Zevenbergen LW, Clopper PE (2010) Impacts of debris on bridge pier scour. Scour and Erosion. American Society of Civil Engineers, Reston, VA, pp 854–863
Lauchlan CS, Melville BW (2001) Riprap protection at bridge piers. J Hydraul Eng 127:412–418. https://doi.org/10.1061/(ASCE)0733-9429(2001)127:5(412)
Lee SO, Sturm TW (2009) Effect of sediment size scaling on physical modeling of bridge pier scour. J Hydraul Eng 135:793–802. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000091
Lin C, Bennett C, Han J, Parsons RL (2012) Integrated analysis of the performance of pile-supported bridges under scoured conditions. Eng Struct 36:27–38. https://doi.org/10.1016/j.engstruct.2011.11.015
Lyn DA, Cooper TJ, Condon CA, Gan L (2007) Factors in debris accumulation at bridge piers. Purdue University, West Lafayette, Indiana
Magilligan FJ, Nislow KH, Fisher GB et al (2008) The geomorphic function and characteristics of large woody debris in low gradient rivers, coastal Maine, USA. Geomorphology 97:467–482. https://doi.org/10.1016/j.geomorph.2007.08.016
Masjedi A, Bejestan MS, Esfandi A (2010) Reduction of local scour at a bridge pier fitted with a collar in a 180 degree flume bend (Case study: oblong pier). J Hydrodyn Ser B 22:669–673. https://doi.org/10.1016/S1001-6058(10)60012-1
Melville BW, Coleman SE (2000) Bridge Scour . Water Resources Publication.
Melville BW, Chiew Y-MM (1999) Time scale for local scour at bridge piers. J Hydraul Eng 125:59–65. https://doi.org/10.1061/(ASCE)0733-9429(1999)125:1(59)
Melville BW, Dongol DM (1992) Bridge pier scour with debris accumulation. J Hydraul Eng 118:1306–1310. https://doi.org/10.1061/(ASCE)0733-9429(1992)118:9(1306)
Melville BW, Hadfield AC (1999) Use of sacrificial piles as pier scour countermeasures. J Hydraul Eng 125:1221–1224. https://doi.org/10.1061/(ASCE)0733-9429(1999)125:11(1221)
Memar S, Zounemat-Kermani M, Beheshti A et al (2020) Influence of collars on reduction in scour depth at two piers in a tandem configuration. Acta Geophys 68:229–242. https://doi.org/10.1007/s11600-019-00393-0
Moncada-M AT, Aguirre-Pe J, Bolívar JC, Flores EJ (2009) Scour protection of circular bridge piers with collars and slots. J Hydraul Res 47:119–126. https://doi.org/10.3826/jhr.2009.3244
Mueller DS, Parola AC (1998) Detailed scour measurements around a debris accumulation. International Water Resources Engineering Conference. ASCE, Memphis, TN, USA, pp 234–239
Müller G, Mach R, Kauppert K (2001) Mapping of bridge pier scour with projection moiré. J Hydraul Res 39:531–537. https://doi.org/10.1080/00221686.2001.9628277
Obied N, Khassaf S (2019) Experimental study for protection of piers against local scour using slots. Int J Eng 32:217–222
Osrush M, Hosseini SA, Kamanbedast AA (2020) Evaluation and comparison of the slots and collars performance in reducing scouring

around bridge abutments. Amirkabir J Civ Eng 52: 1637–1650. https://doi.org/10.22060/ceej.2019.15565.5953

Pagliara S, Carnacina I (2011) Influence of wood debris accumulation on bridge pier scour. J Hydraul Eng 137:254–261. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000289

Pagliara S, Carnacina I (2013) Bridge pier flow field in the presence of debris accumulation. Proc Inst Civ Eng - Water Manag 166:187–198. https://doi.org/10.1680/wama.11.00060

Pagliara S, Carnacina I, Cigni F (2010) Sills and gabions as countermeasures at bridge pier in presence of debris accumulations. J Hydraul Res 48:764–774. https://doi.org/10.1080/00221686.2010.528184

Pandey M, Oliveto G, Pu JH et al (2020) Pier scour prediction in non-uniform gravel beds. Water (switzerland) 12:1696. https://doi.org/10.3390/W12061696

Panici D, de Almeida GAM (2018) Formation, growth, and failure of debris jams at bridge piers. Water Resour Res 54:6226–6241. https://doi.org/10.1029/2017WR022177

Panici D, de Almeida GAM (2020) Influence of pier geometry and debris characteristics on wood debris accumulations at bridge piers. J Hydraul Eng 146:04020041. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001757

Panici D, Kripakaran P (2021) Trapping large wood debris in rivers: experimental study of novel debris retention system. J Hydraul Eng 147:04020101. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001859

Park JH, Sok C, Park CK, Do KY (2016) A study on the effects of debris accumulation at sacrificial piles on bridge pier scour: I. Experimental Results KSCE J Civ Eng 20:1546–1551. https://doi.org/10.1007/s12205-015-0207-5

Pasokhi-Dargah Z, Esmaeili-Varaki M, Shafee-Sabet B (2018) Study of local scour around vertical bridge pier groups in presence of debris accumulation. Irrig Drain Struct Eng Res 18:1–16

Pizarro A, Manfreda S, Tubaldi E (2020) The science behind scour at bridge foundations: a review. Water 12:374. https://doi.org/10.3390/W12020374

Rahimi E, Qaderi K, Rahimpour M, Ahmadi MM (2018) Effect of debris on piers group scour: an experimental study. KSCE J Civ Eng 22:1496–1505. https://doi.org/10.1007/s12205-017-2002-y

Rahimi E, Qaderi K, Rahimpour M et al (2020) Scour at side by side pier and abutment with debris accumulation. Mar Georesources Geotechnol. https://doi.org/10.1080/1064119x.2020.1716122

Ruiz-Villanueva V, Piégay H, Gurnell AA et al (2016) Recent advances quantifying the large wood dynamics in river basins: New methods and remaining challenges. Rev Geophys 54:611–652. https://doi.org/10.1002/2015RG000514

Schalko I, Lageder C, Schmocker L et al (2019) Laboratory flume experiments on the formation of spanwise large wood accumulations: part ii-effect on local scour. Water Resour Res 55:4871–4885. https://doi.org/10.1029/2019WR024789

Schmocker L, Hager WH (2013) Scale modeling of wooden debris accumulation at a debris rack. J Hydraul Eng 139:827–836. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000714

Schmocker L, Weitbrecht V (2013) Driftwood: risk analysis and engineering measures. J Hydraul Eng 139:683–695. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000728

Scozzese F, Ragni L, Tubaldi E, Gara F (2019) Modal properties variation and collapse assessment of masonry arch bridges under scour action. Eng Struct 199:109665. https://doi.org/10.1016/j.engstruct.2019.109665

Sharma S (1999) Effect of Slot on Scour around a Pier. Kurukshetra University

Tafarojnoruz A, Gaudio R (2011) Sills and gabions as countermeasures at bridge pier in the presence of debris accumulations. J Hydraul Res 49:832–833

Tafarojnoruz A, Gaudio R, Calomino F (2012) Evaluation of flow-altering countermeasures against bridge pier scour. J Hydraul Eng 138:297–305. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000512

Tanaka S, Yano M (1967) Local scour around a circular cylinder. In: Twelfth congress of the international association for hydraulic research. pp 193–201

Tang HW, Ding B, Chiew YM, Fang SL (2009) Protection of bridge piers against scouring with tetrahedral frames. Int J Sediment Res 24:385–399. https://doi.org/10.1016/S1001-6279(10)60012-1

Tubaldi E, Macorini L, Izzuddin BA et al (2017) A framework for probabilistic assessment of clear-water scour around bridge piers. Struct Saf 69:11–22. https://doi.org/10.1016/j.strusafe.2017.07.001

Unger J, Hager WH (2006) Riprap failure at circular bridge piers. J Hydraul Eng 132:354–362. https://doi.org/10.1061/(ASCE)0733-9429(2006)132:4(354)

Vijayasree BA, Eldho TI, Mazumder BS, Ahmad N (2019) Influence of bridge pier shape on flow field and scour geometry. Int J River Basin Manag 17:109–129. https://doi.org/10.1080/15715124.2017.1394315

Wardhana K, Hadipriono FC (2003) Analysis of recent bridge failures in the United States. J Perform Constr Facil 17:144–150

Wohl E, Kramer N, Ruiz-Villanueva V et al (2019) The natural wood regime in rivers. Bioscience 69:259–273. https://doi.org/10.1093/BIOSCI/BIZ013

Yoon TH, Kim D-H (2001) Bridge pier scour protection by sack gabions. Bridging the Gap. American Society of Civil Engineers, Reston, VA, pp 1–8

Zarei E, Vaghefi M, Hashemi SS (2019) Bed topography variations in bend by simultaneous installation of submerged vanes and single bridge pier. Arab J Geosci 12:1–10. https://doi.org/10.1007/s12517-019-4342-z

Zarrati AR, Gholami H, Mashahir MB (2004) Application of collar to control scouring around rectangular bridge piers. J Hydraul Res 42:97–103. https://doi.org/10.1080/00221686.2004.9641188