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PRACTICE-ORIENTED PAPER

Bed sill effect on bridge pier scour with debris obstruction: an experimental investigation

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Abstract

Flooding and scouring are two important physical phenomena in river environments. Evaluating the bridge pier scour after floods is essential owing to the woody debris accumulation upstream of these facilities. The present study considered three models of experimental tests a cylindrical pier with a diameter of D (model A), a cylindrical pier with rectangular debris (model B), and a cylindrical pier with rectangular debris protected by bed sill (model C) to investigate the pier scour values under different densimetric Froude numbers (Fr_d) and the longitudinal gap between sill and downstream pier's face (L_b). Results indicated that maximum scour depth (d_s) increases with debris accumulation. Therefore, it seems necessary to conduct the present research, the bed sill with five ratios of L_b/D was considered for three flow conditions. When the bed sill was utilized between the pier and debris in the sediment bed, d_s/D was reduced compared to the case without sill, and the best efficiency of bed sill was about 40% for $L_b/D=0$. The efficacy of the sill was reduced, by increasing Fr_d, and at $\mathrm{Fr}_d=2.4$, only the sill attached to the pier was effective for scour reduction, and L_b/D greater than 1 even increased d_s/D to a greater value than the condition of the bridge pier without debris. Finally, an equation based on the effective parameters was suggested with the observed data to predict d_s/D in the conditions of using the bed sill with debris accumulation with RMSE $=0.046$ and $R^2=0.998$. It was observed that scour depth increases in the higher densimetric Froude number and becomes larger in a farther sill case.

Keywords Bed sill · Bridge pier · Experimental model · Scour countermeasure · Woody debris

Introduction

Constructing a bridge for accessibility and transportation purposes in the river environment affects its flow regime and may lead to the local scour phenomenon. Also, the proper design and implementation of these structures can help to reduce possible damages. Sediment transport affects river morphology depending on the flood event type and its duration [1]. Thus, investigating the bridge pier scour after floods seems to be necessary. Debris carried by the flood accumulates around the pier, increasing the effective width of a pier and contracted flow; therefore, downward velocities at the pier increase [2, 3]. These debris can vary in size from small leaves to tree trunks. Debris with varied shapes accumulates upstream of the bridge piers in different locations and shapes. They are often staked in the shape of rectangular cubes upstream of piers in rivers [4]. It is better to remove this debris around the pier after the flood and use it in eco-efficient works. For example, utilizing waste wood ash as a pozzolanic material for eco-concreting works or plastics for concrete strength [5–7]. In different studies, researchers modeled scour around cylindrical bridge piers in a laboratory and predicted the maximum scour depth of bridge pier (d_s) [8–11]. Experimental studies have been performed in recent decades in the field of debris accumulation influences d_s, and the most important results of them will be reviewed in the following.

Melville and Dangol [2] estimated the maximum scour depth by defining the effective pier diameter as larger than the actual pier by investigating the effect of different shapes of debris on the pier scour. Debris accumulation depends on

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the debris length and the width of the upstream channel [12]. Debris accumulation increases the flow velocity [12, 13], and greater d_s occurred up to 3 times in comparison without it [14]. Lagasse et al. [4] presented a modified equation for the effective pier diameter based on their experimental data compared to Melville and Dangol [2]. The debris roughness does not have much influence on maximum scour depth [15]. The porosity of debris has had a small influence on the geometry of the scour hole [16]. Pagliara and Carnacina [13] provided a new relation to estimating d_s in the condition of bed drift. Pagliara and Carnacina [16] presented an equation based on their laboratory results, to predict d_s by evaluating the accumulation of rectangular, triangular, and cylindrical woody debris with different thicknesses and widths in clear water conditions. The short distance and short span of the bridge pier increase blockage and aggravate scour and damage to the bridge pier with debris accumulation [17]. As debris approaches the channel bed in elevation, d_s decreases, and when the debris stands exactly below the flow surface d_s is formed. While the debris is located on the river bed, they protect it partly and decrease d_s [3]. Maximum scour depth increases when the debris thickness increases. Also, debris with a rectangular shape creates maximum value for d_s [18]. As the gap between the debris and the flow surface increases, d_s increases at first, and when the relative submergence depth of the debris (distance between water surface to debris surface versus flow depth) is 0.46, the debris acts the same with the collar, and d_s reduces [18]. The position and shape of the debris accumulation have a major effect on the bridge pier scour, and the lower the debris level compared to the bed level, the smaller d_s occurred [19]. When debris has a vertical distance from the sedimentary bed, causes a significant increase in the maximum scour depth [20]. The position of the bridge pier affects the scour evolution and the bed topography, with a shallow depth; however, in deep flow, its effect is negligible [21]. When the pier is close to the channel wall the maximum scour depth increases, and debris accumulation increases the scour hole length [22]. An additional bridge pier scour with a woody debris jam depends on the blockage ratio of the first debris jam [23].

When debris is located upper than the bed level, it increases d_s. Therefore, it is required to study the countermeasures to prevent sedimentary be d_s and reduce d_s in this condition. Researchers used various countermeasures in experimental models such as a collar, riprap, bed sill, slots, splitter plate, and submerged vanes to decrease d_s [24–39]. The effects of some countermeasures such as delta vane, plate footing, tapered sheath, and guide wall with oblique vanes were investigated on pier scour in a CFD numerical model [40, 41]. It was concluded that the maximum reduction in bed shear stress was 30% by using the angled plate and the delta vane, 20% by using the tapered sheath, and 15% for the guide wall with oblique vanes [40].

Some studies were conducted on applying scour countermeasures with debris accumulation cases [41–44]. Park et al. [42] evaluated the debris accumulation around the sacrificial piles and its effect on the bridge pier scour. The results of their observations presented that for different flow depths and velocities, d_s depends on the debris dimensions and thickness, and with the use of sacrificial piles, d_s was reduced by 39–60%. Hamidifar et al. [43] utilized slots on the bridge pier as a scour countermeasure with different shapes of debris accumulation. They observed that slots reduced bridge pier scour in debris cases in comparison without it up to 55%. Also, the reduction efficiency variations for a slotted pier with debris compared to the case without it depend on the debris shape. Hamidifar et al. [44] evaluated the effect of using a collar as a countermeasure for scour of a cylindrical bridge pier with debris accumulation. The results of their experiments presented that installing a collar reduces the maximum scour depth by up to 39% compared to the case without the collar and debris, and the collar's efficiency was increased by up to 25% in cases with debris accumulation. Zanganeh-Inaloo et al. [45] studied the effect of riprap on the scour reduction of a rectangular bridge pier with varied debris shapes and positions. They concluded that the presence of debris has no significant influence on the performance of standard-size riprap. However, riprap stone median size was important, and by decreasing it by 25%, the efficiency of riprap protecting scour was reduced by 10% in the debris cases. Although d_s did not vary significantly by changing debris position, the scour hole volume increased in cases with debris near the bed than when it was located near the water surface [45].

Grimaldi et al. [26] investigated the influence of bed sills as countermeasures downstream of a circular bridge pier. They observed that the smaller the distance between the sill and the pier, the larger the reduction in scour depth. Grimaldi et al. [27] utilized a slot as a countermeasure for reducing circular pier in the laboratory model. They observed scour depth reduced near 30% in maximum value. They also applied a combined countermeasure consisting of a slot and a bed sill which the best scour reduction occurred about 45%. Razi et al. [30] suggested the best location for the bed sill attached to the downstream face of the pier, where a scour depth reduction is about 29%. Sanadgol et al. [34] studied the effect of bed sills in reducing the scour depth in piers with different shapes experimentally. They concluded that the best efficiency of the bed sill is when it is attached to the downstream face of the pier and its efficiency is reduced when its distance from the pier increases.

Some studies conducted on reducing bridge pier scour in the presence of debris accumulation, may not be sufficient, and it seems that more investigations are required. Although uses of collar and slot had acceptable scour reduction values, bed sill is another suggested countermeasure located downstream of the pier, not located near the debris in the upstream pier face as slot and collar, which used to control the scour reduction without debris accumulation in the previous studies. Thus, bed sill was utilized in this study for scour countermeasure in debris cases, and its efficacy compared with other countermeasures. The basis of the comparison is how much percentage reduction the use of each countermeasure occurs in the case of debris accumulation compared with the same hydraulic condition by no usage of that countermeasure with debris accumulation or without it. The present study investigated the distance of installing a bed sill from the pier with wooden debris in a rectangular cube box located equal to the bridge pier diameter (D) from the bed surface. The bed sill was installed at five distances attached, $1D$, $2D$, $3D$, and $4D$, downstream of the bridge pier, and tested under three different flow depth and Froude number conditions. d_s and its reduction for different flow intensities (U/U_c) were presented and compared to determine the optimum position of the sill for reducing d_s. Also, longitudinal scour profiles were plotted and compared with different bed sill positions. Reduction and increase in the percentage of d_s for each test were computed and verified with the previous studies. Finally, an equation for predicting d_s/D based on laboratory results was proposed, and the range of application of its parameters was presented based on dimensional analysis and effective parameters.

Materials and methods

Dimensional analysis

The pier scour depth in the condition with debris accumulation relies on the hydraulic variables of the flow and sedimentary bed, the shape of the pier and debris and their dimensions, and time, which can be written as Eq. (1):

$$d_s = f\left(y, U, U_c, b, D, L_d, W_d, T_d, d_{50}, \rho_s, \rho, \upsilon, g, t, t_e, n_d, \varepsilon, L_b, \Delta A\right) \tag{1}$$

where d_s = maximum scour depth (m), y = flow depth (m), U = flow velocity (m/s), $U_c = 5.75\log\left(5.53\frac{y}{d_{50}}\right) * (0.0115 + 0.0125 d_{50}^{1.4})$ = critical velocity of sediment movement (m/s) which was computed with Melville criteria [46], b = channel width (m), D = pier diameter (m), L_d = debris length in the flow direction (m), W_d = debris width perpendicular to the flow direction (m), T_d = debris thickness (alignment distance from top to bottom) (m), d_{50} = median sediment size (m), ρ_s = sediment specific weight (kg/m^3), ρ = water-specific weight (kg/m^3), υ = fluid kinematic viscosity (m^2/s), g = gravitational acceleration (m/s^2), t = scour time (s), t_e = scour equilibrium time (s), n_d = debris porosity is the ratio between the debris void volume and the bulk debris volume, ε = relative debris roughness (the log average diameter to the debris pier diameter), L_b = bed sill downstream gap from the bridge pier (m), and $\Delta A = \frac{(W_d - D)T_d}{by} \times 100$ = percentage blockage ratio. Buckingham's Π theory was utilized and by combining the obtained dimensionless parameters, the dimensionless variables were achieved as Eq. (2):

$$\frac{d_s}{D} = f\left(\frac{y}{T_d}, \frac{U}{U_c}, \frac{b}{D}, \frac{L_d}{D}, \frac{W_d}{D}, \frac{t_e}{t}, \frac{n_d}{D}, \frac{\varepsilon}{D}, \frac{\Delta A}{D}, \frac{uy}{\upsilon}, \frac{U}{\sqrt{\left(\frac{\rho_s}{\rho} - 1\right) g y d_{50}}} = \mathrm{Fr_d}, \frac{L_b}{D}\right) \tag{2}$$

Parameter U was included in $\mathrm{Fr_d}$, and Uc is a function of y and d_{50} which was considered in $\mathrm{Fr_d}$; thus, U/Uc was not considered as an effective parameter in dimensional analysis. Channel walls would not affect d_s if $b/D > 6.25$ [47]; thus, the effect of b/D was not considered in the present study because it was 20. As the scour hole reached the equilibrium condition, t/t_e could be ignored. When the value of d_s was less than 1 mm in 3 h, the scour hole reached the equilibrium condition [47]. Debris roughness and porosity have a slight effect on d_s [14]; hence, $n_d = 0.7$ and $\varepsilon = 0.8$ were considered in the present study owing to Pagliara and Carnacina [14]. Reynolds number ($\frac{uy}{\upsilon} = Re$ = 6765–7016), which were turbulent flows, so this parameter was not considered. The debris dimensions were fixed including $L_d = 0.10$ m, $T_d = 0.05$ m, and $W_d = 0.12$ m; thus, ΔA was constant. The variables U, d_{50}, $G_s = \frac{\rho_s}{\rho}$, and g became dimensionless in the $\mathrm{Fr_d}$ = densimetric sediment Froude number. Finally, the dimensionless effective parameters were as Eq. (3):

$$\frac{d_s}{D} = f\left(\frac{y}{T_d}, F_{rd}, \frac{L_b}{D}\right) \tag{3}$$

Experimental setup

Experimental tests were performed on a rectangular flume 0.6 m wide and 0.2 m high in the hydraulic laboratory of Babol Noshirvani University of Technology (Fig. 1). All tests were conducted with a discharge of 6.25 l/s which was measured and calibrated by a flowmeter with the accuracy of 0.05 l/s. The laboratory flume apparatus included a channel, upstream and downstream reservoirs, a pump, a point gauge, and a tailgate [48]. Flow and scour depths were measured with a movable point gauge which had a measurement accuracy of 0.1 mm. The approaching flow depth and tailwater depth were adjusted with a tailgate at the channel downstream. To ensure uniform and fully developed flow entering the channel and reducing disturbance, at the beginning of the channel in the upstream tank, a flow straightener and a grid plate were

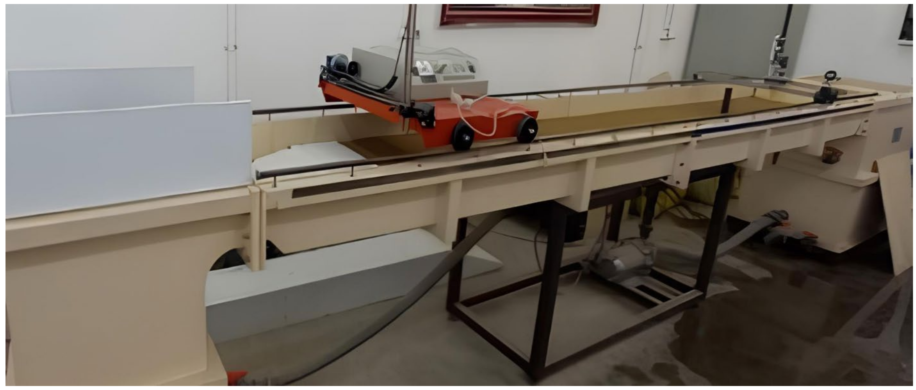


Fig. 1 Experimental flume

installed, and following it a rigid apron with a length and height of 0.5 and 0.1 m was located (Fig. 2). Selected material for the experiments was uniform sand ($\sigma_{g=}\sqrt{\frac{d_{84}}{d_{16}}}<1.3$), which was poured along the channel and around the bridge pier with $d_{50}=0.82$ m. When d_{50} is more than 0.7 mm, the ripple bed form does not generate [47], and this criterion was satisfied in the present study. The sediment recess thickness was 0.1 m, and it was 3.5 m

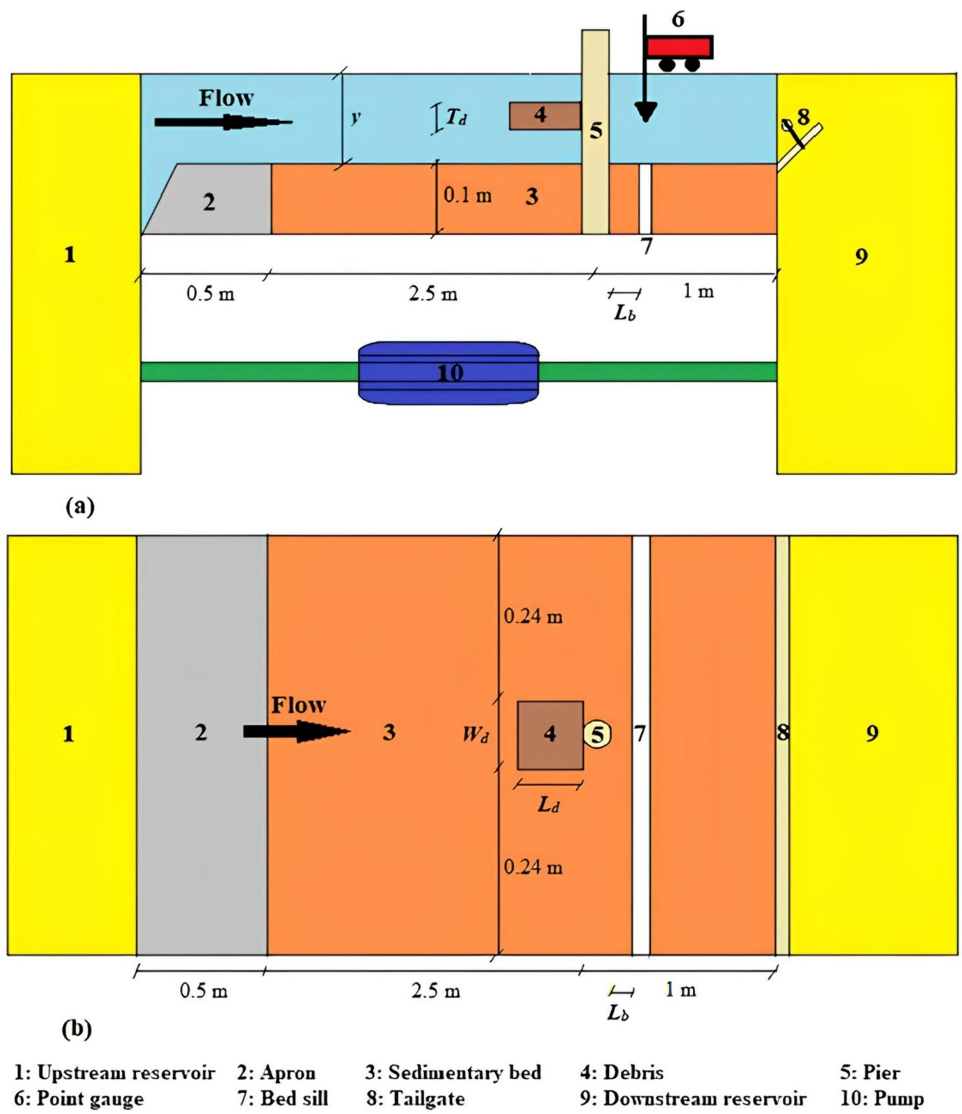


Fig. 2 Experimental setup model **a** side view and **b** plan view

long. The effect of d_{50} does not influence d_s if $D/d_{50} > 20–25$ [47]. A cylindrical pier was selected for the present study with a diameter of 0.03 m ($D/d_{50} = 36.6$). In the river, wooden debris upstream of the bridge pier accumulates in different shapes; however, rectangular shapes are common [2, 15]. In this study, a mesh wire box was used as debris accumulation in experimental tests designed in the shape of a rectangular and installed on the bridge pier upstream. This box was filled with logs made of small branches of beech trees which are grown in forests in the north of Iran, at Mazandaran province. The diameters of logs are 0.001–0.005 m and are arranged perpendicular to the flow direction in the box (Fig. 3). The dimensions of the debris box were fixed and considered constant including $L_d = 0.10$ m, $T_d = 0.05$ m, and $W_d = 0.12$ m (Fig. 2). The distance from the debris bottom to the sediment surface was 1D = 0.03 m (Fig. 2).

Temporal variations of the maximum scour depth around the bridge pier were achieved at $t = 1, 5, 15, 30, 45, 60, 120, 180, 240, 300, 360, 420$, and 480 min, during the three tests of each set of tests (A, B, and C) at $U/U_c = 0.60$. Figure 4 presents the d_s/D development with time, and it can be revealed that after 300 min, d_s/D remains constant. When the variations of d_s for 3 h become less than 1 mm, the equilibrium time is reached [47]. It can be observed from Fig. 4 that $t_e = 5$ h.

Twenty-seven tests were performed in three sets of tests including set A (A1–A6), set B (B1–B6), and set C (C1–C15). The maximum values of scour hole depth (d_s) at the equilibrium time (t_e) were extracted and became dimensionless concerning the pier diameter. The percentage variation of d_s/D compared to the initial conditions (set A) was of particular importance. The variation of d_s in each test compared to sets A and B tests was calculated as Eqs. (4 and 5) with R_A and R_B, respectively.

(a) (b)

Fig. 3 **a** Arrangement of logs in debris box upstream of pier and **b** set C of tests (pier + debris + bed sill)

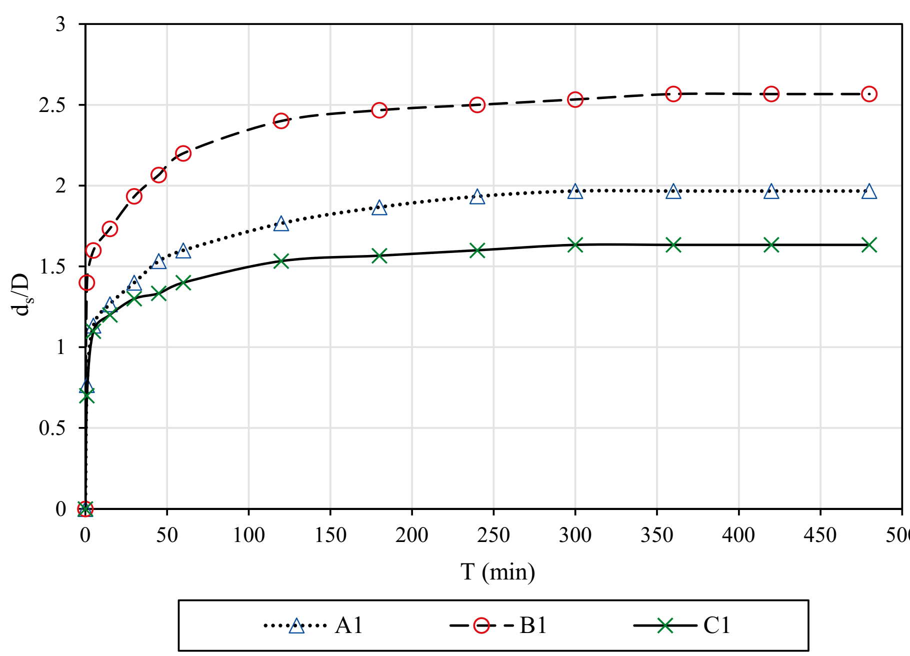


Fig. 4 Time evolution equilibrium maximum depth of scour hole

$$R_A = \frac{d_s - (d_s)_A}{(d_s)_A} \times 100 \quad (4)$$

$$R_B = \frac{d_s - (d_s)_B}{(d_s)_B} \times 100 \quad (5)$$

where d_s was the maximum scour depth in each test, $(d_s)_A$ was the maximum scour depth at set A tests (without debris and bed sill) by similar hydraulic conditions, and $(d_s)_B$ was the maximum scour depth at set B tests (without bed sill and with debris) by similar hydraulic conditions. The geometry of the debris box was constant and $L_d/D = 3.33$, $W_d/D = 4$, and $T_d/D = 1.67$.

Results

Maximum scour depth

Table 1 shows experimental results for maximum scour depth and their variations (R_A and R_B). It can be observed from Table 1 that with the increase in flow intensity (U/U_c), scour increases in all three sets of tests. d_s/D reduces with decreasing approaching flow Froude number at a constant discharge in all three sets of tests. It can also be figured

Table 1 Experimental results

Set	Test	Model	y/D(1)	U/U_c(2)	y/T_d(3)	Fr_d(4)	L_b/D(5)	d_s/D(6)	R_A(7)	R_B(8)
A	A1	Pier	1.33	0.60	0.8	2.40	–	1.97	–	–
	A2	Pier	1.66	0.46	1.0	1.72	–	1.77	–	–
	A3	Pier	2.00	0.37	1.2	1.29	–	1.27	–	–
	A4	Pier	2.33	0.31	1.4	1.03	–	1.03	–	–
	A5	Pier	2.67	0.26	1.6	0.84	–	0.87	–	–
	A6	Pier	3.00	0.23	1.8	0.70	–	0.83	–	–
B	B1	Pier + Debris	1.33	0.60	0.8	2.40	–	2.57	30.5	–
	B2	Pier + Debris	1.67	0.46	1.0	1.72	–	2.10	18.9	–
	B3	Pier + Debris	2.00	0.37	1.2	1.29	–	1.40	10.5	–
	B4	Pier + Debris	2.33	0.31	1.4	1.03	–	1.13	9.7	–
	B5	Pier + Debris	2.67	0.26	1.6	0.84	–	0.93	7.7	–
	B6	Pier + Debris	3.00	0.23	1.8	0.70	–	0.87	4.0	–
C	C1	Pier + Debris + Sill	1.33	0.60	0.8	2.40	0	1.63	− 16.9	− 36.4
	C2	Pier + Debris + Sill	2.00	0.37	1.2	1.29	0	0.83	− 34.2	− 40.5
	C3	Pier + Debris + Sill	2.67	0.26	1.6	0.84	0	0.53	− 38.5	− 42.9
	C4	Pier + Debris + Sill	1.33	0.60	0.8	2.40	1	1.93	− 1.7	− 24.7
	C5	Pier + Debris + Sill	2.00	0.37	1.2	1.29	1	0.93	− 26.3	− 33.3
	C6	Pier + Debris + Sill	2.67	0.26	1.6	0.84	1	0.63	− 26.9	− 32.1
	C7	Pier + Debris + Sill	1.33	0.60	0.8	2.40	2	2.13	8.5	− 16.9
	C8	Pier + Debris + Sill	2.00	0.37	1.2	1.29	2	1.00	− 21.1	− 28.6
	C9	Pier + Debris + Sill	2.67	0.26	1.6	0.84	2	0.67	− 23.1	− 28.6
	C10	Pier + Debris + Sill	1.33	0.60	0.8	2.40	3	2.33	18.6	− 9.1
	C11	Pier + Debris + Sill	2.00	0.37	1.2	1.29	3	1.07	− 15.8	− 23.8
	C12	Pier + Debris + Sill	2.67	0.26	1.6	0.84	3	0.73	− 15.4	− 21.4
	C13	Pier + Debris + Sill	1.33	0.60	0.8	2.40	4	2.40	22.1	− 6.5
	C14	Pier + Debris + Sill	2.00	0.37	1.2	1.29	4	1.17	− 7.9	− 16.7
	C15	Pier + Debris + Sill	2.67	0.26	1.6	0.84	4	0.83	− 3.8	− 10.7

(1) y/d = flow depth/pier diameter: [L/L]

(2) U/U_c = flow velocity/critical velocity of sediment movement: [L T^{-1}/L T^{-1}]

(3) y/T_d = flow depth/debris thickness: [L/L]

(4) Fr_d = densimetric sediment Froude number: [–]

(5) L_b/D = bed sill downstream gap from the bridge pier/pier diameter: [L/L]

(6) d_s/D = maximum scour depth/pier diameter: [L/L]

(7) R_A = percentage variations of maximum scour depth compared to set A condition: (%)

(8) R_B = percentage variations of maximum scour depth compared to set B condition: (%)

out that with debris accumulation upstream of the bridge pier, the streamlines around the pier changed, a flow blockage occurred, and the flow was diverted by colliding with the debris (Fig. 5a and b). This process caused an increase in scour in set B of tests. For this reason, it is necessary to apply countermeasures to reduce d_s/D. Therefore, the bed sill at five various intervals was located at the pier downstream, and its effects on d_s/D have been investigated (Fig. 6). Increasing the gap between the bed sill and the pier reduces the efficiency of the bed sill in protecting scour. The best efficiency was when the sill was attached to the pier ($L_b/D=0$), 38.5% and 42.9% compared with the case without debris at the same hydraulic characteristics, respectively. When the sill was far away pier ($L_b/D=4$), it had less influence on maximum scour depth, and its variation reached a 22.1% increase and 6.5% reduction compared with the case without debris under the same hydraulic condition, respectively.

Longitudinal scour profile

Figure 7a and b shows the results of longitudinal scour profiles for $Fr_d=2.40$ and 1.29, respectively, with the presence of a bed sill at distances of 0*D*, 1*D*, and 2*D*. The results show that the maximum depth of the scour hole formed upstream of the pier increases with the increase in the densimetric Froude number and decreases with the increase in the sill distance from the downstream of the pier.

Discussion

Effect of debris accumulation on maximum scour depth

As it was concluded, debris accumulation upstream of the bridge pier (set B) increases d_s/D in comparison with a single bridge pier (set A). The R_A obtained from tests was compared with Melville and Dangol [2], Park et al. [42], and Ebrahimi et al. [3] data to verify the accuracy of the results of the present study (Table 2). The observations indicate that there is a strong alignment between the present study and prior research.

Effect of bed sill on maximum scour depth

The most effective parameter to detect the efficacy of the bed sill on reducing d_s/D is L_b because it has a direct effect on the formation of scour hole and dune development. Therefore, in this research, L_b/D was considered a variable parameter

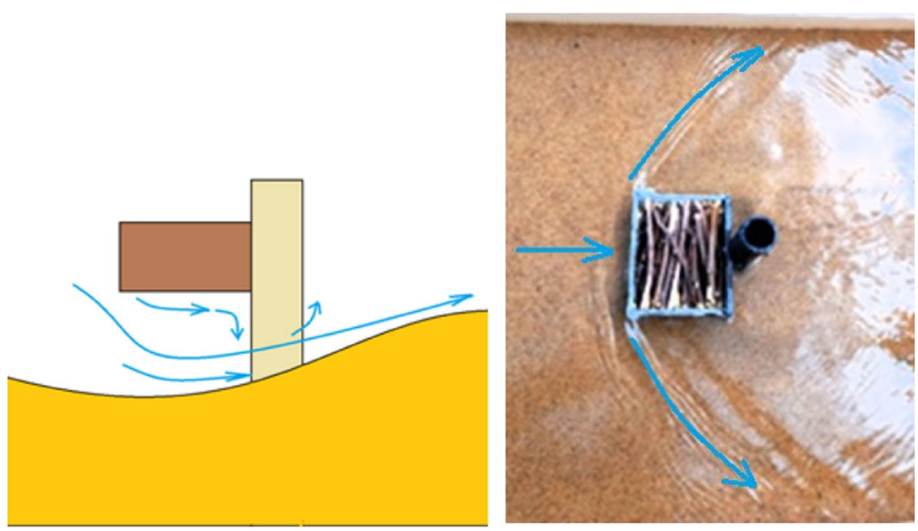


Fig. 5 Flow around the pier with debris obstruction **a** side view and **b** plan view

Fig. 6 Effect of bed sill on d_s/D with debris obstruction **a** $L_b/D=0$, $Fr_d=2.40$, **b** $L_b/D=2$, $Fr_d=2.40$, and **c** $L_b/D=3$, $Fr_d=2.40$

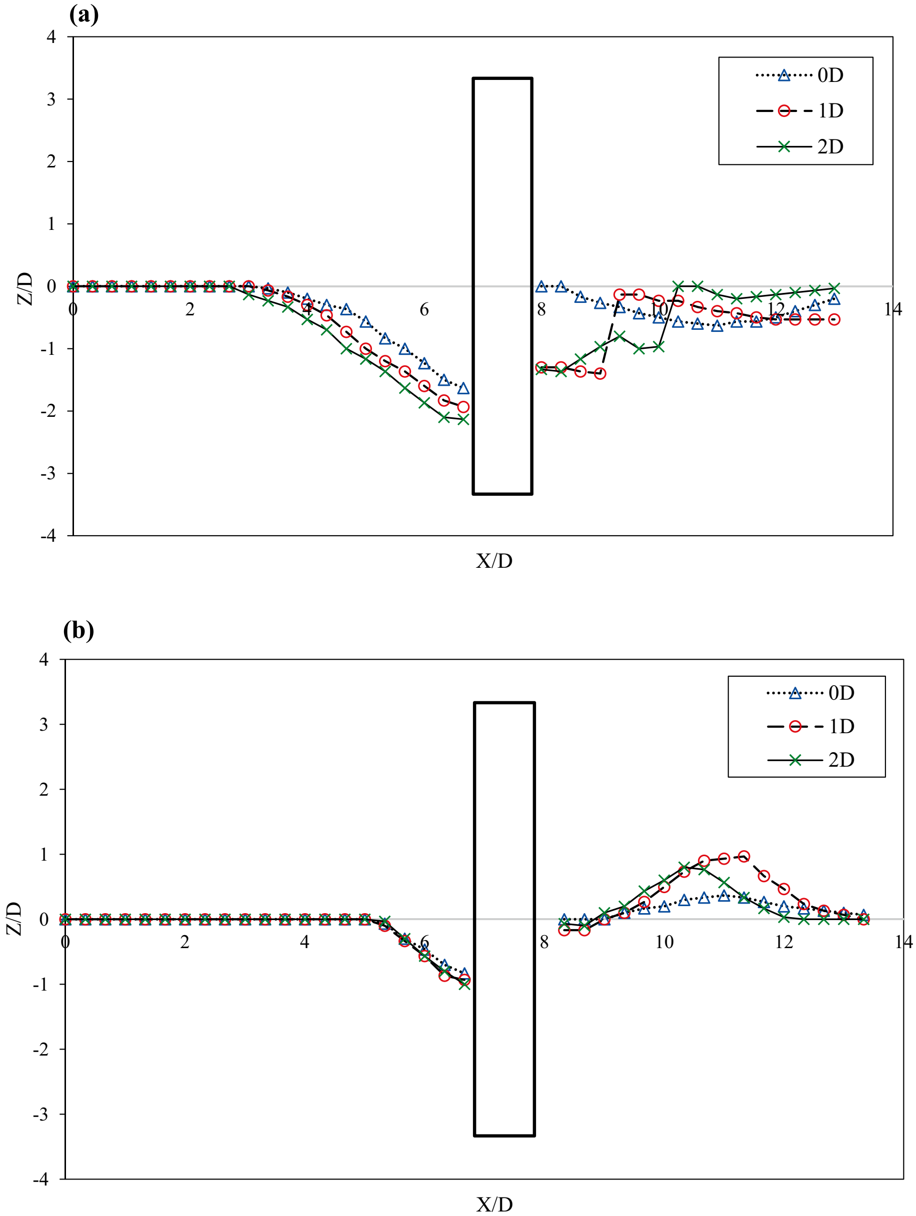


Fig. 7 Longitudinal scour profiles with bed sill **a** $Fr_d = 2.40$ and **b** $Fr_d = 1.29$

Table 2 Maximum variation of $\%R_A$ in debris cases without bed sill

Study	Debris	Maximum of R_A (%)
Melville and Dangol [2]	RD	49
Park et al. [42]	CD	60
Ebrahimi et al. [3]	CD	33
Present study	RD	31

RD rectangular debris and *CD* cylinder debris

of the bed sill. Based on the results, d_s/D increases with the increase in L_b/D in a constant densimetric Froude number (Fig. 8). Also, in a fixed L_b/D, the d_s/D increases with the increase in densimetric Froude number. Regarding the rate of scour reduction and the efficacy of the sill, it could be observed from Fig. 9 that up to 40% scour reduction in the condition of debris accumulation with the bed sill (set C) in the case without debris and sill (set A), which can be a significant amount. The results show that in low densimetric Froude number ($Fr_d \leq 1.29$) even when the bed sill is far from the pier, the sill has its reduction effect, which can be caused by the small increase in scour with debris (about 10% or less) in this flow conditions. But in higher densimetric Froude numbers ($Fr_d = 2.40$) only $L_b/D = 0$ and 1, the sill has a decreasing influence compared to the bridge pier scour condition. It could be comprehended that in high densimetric Froude number, the use of the bed sill with the debris accumulation of at $L_b/D > 1$ cannot even reduce the

Fig. 8 Variation of d_s/D to L_b/D in different Fr_d (set C of tests)

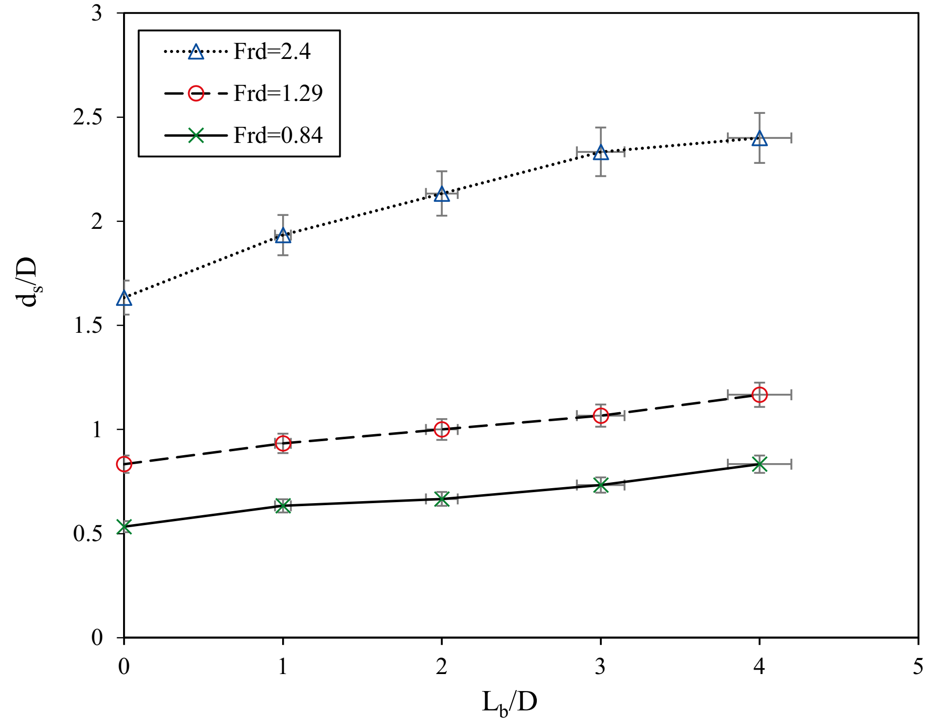
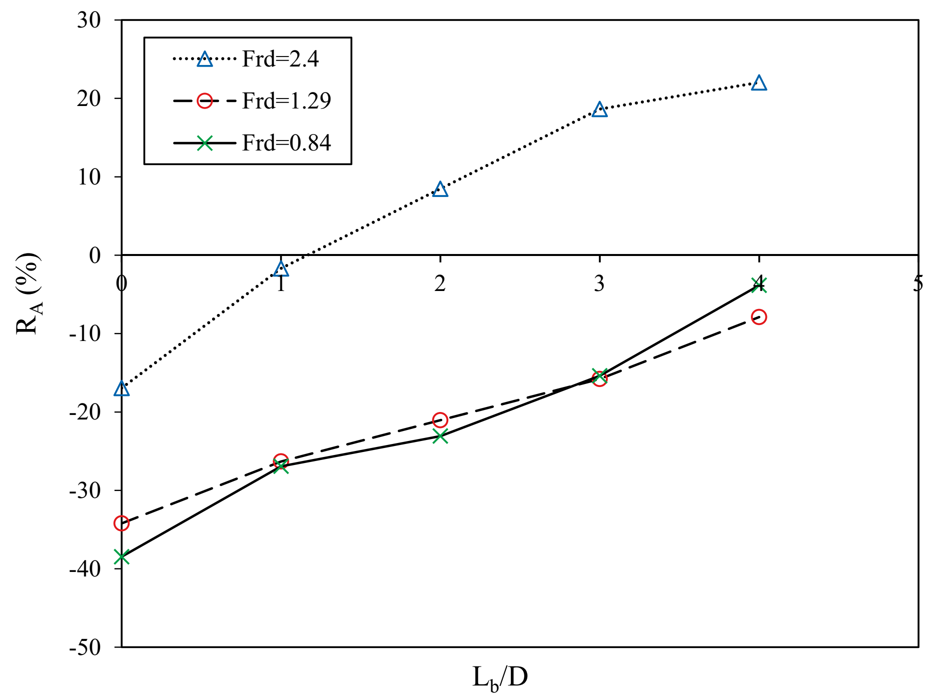


Fig. 9 Variation of R_A to L_b/D in different Fr_d (set C of tests compared to set A)



value of d_s/D to the only bridge pier scour in this condition, and it becomes more than that.

Figure 10 provides a comparison of the efficacy of using the bed sill in the cases of debris accumulation (set C) compared to the bridge pier with debris accumulation (set B). It could be comprehended that up to 43% scour reduction occurred in the condition of debris accumulation with the bed sill (set C) in comparison with the case without the bed sill (set B), which was considerable. With the increase in the distance (L_b/D) and also the increase in densimetric Froude number, the efficacy of the sill in reducing scour decreased and reached about 6%.

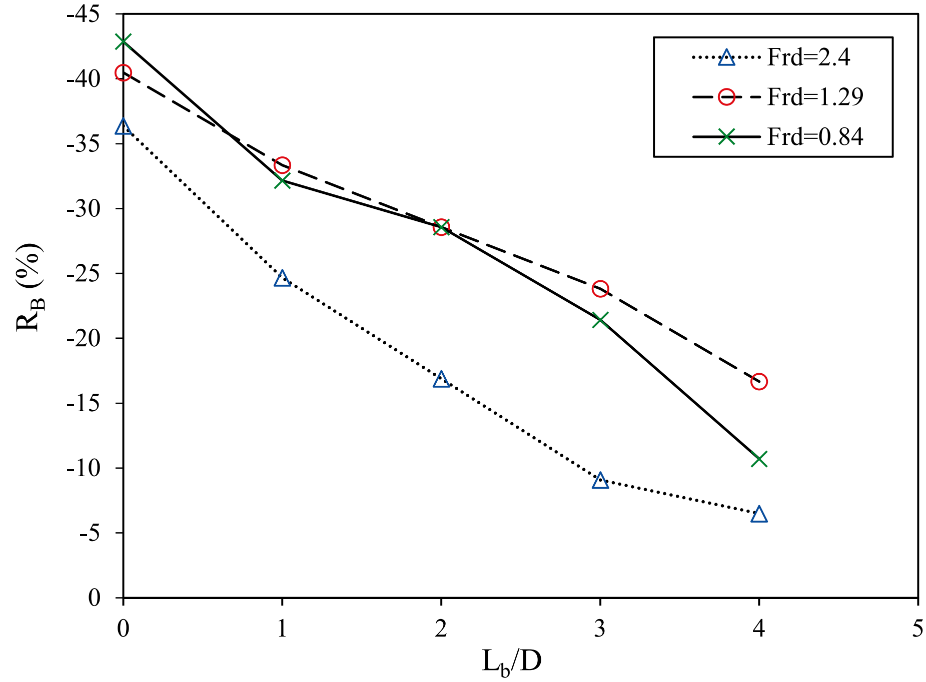


Fig. 10 Variation of R_B to L_b/D in different Fr_d (set C of tests compared to set B)

A verification between the results of the present study and available data is presented in Fig. 11 to evaluate the efficiency of bed sill distance on the results of d_s/D. In the case of pier scour without debris, the smaller the gap between the pier and the sill, the larger the efficiencies of countermeasures [26, 30, 34]. The results in Fig. 11 indicate that in the condition of the pier with debris, the R_A variations reduced with increasing L_b/D, and the best efficiency occurred in the gap 0D for all hydraulic conditions because scour depth has the largest scour reduction (R_A). In the previous studies, the bridge pier was cylindrical the same as the present study, and the bed sill was applied downstream of the pier with defined L_b/D as a countermeasure, but without debris accumulation. The higher percentage of reduction in the present study compared to the prior data can be a result of the debris accumulation influence on R_A changes versus the case with no debris.

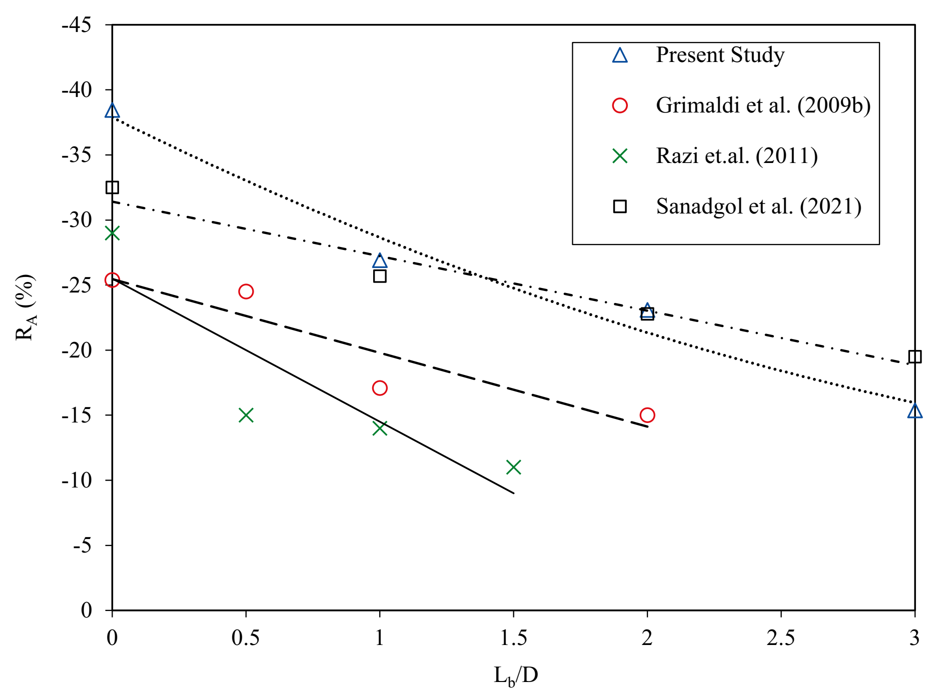


Fig. 11 Efficacy of bed sill in reducing d_s/D with L_b/D variation

Bed sill was utilized as a countermeasure, and it reduces d_s. Therefore, Table 3 proposes a comparison between the maximum variations of R_A achieved in the present study and other studies by applying countermeasures with debris accumulation and without it. It can be observed from Table 3 that using a bed sill can be a good strategy to protect the bridge pier and reduce scour in cases with debris accumulation.

Prediction of maximum scour depth

According to dimensional analysis and effective parameters on d_s/D based on Eq. 3, a relationship for predicting d_s/D by using nonlinear regression with the data of this research is presented as Eq. (6):

$$\frac{d_S}{D} = 0.7152\left(\frac{y}{T_d}\right)^{0.0006}\left(F_{d50}\right)^{1.1259}\left(\frac{L_b}{D}\right)^{0.1637} \quad (6)$$

The root-mean-square error (RMSE) coefficient was used to determine the accuracy of the proposed equation, which is obtained from Eq. (7).

$$\text{RMSE} = \sqrt{\frac{\sum_1^n \left(X_P - X_O\right)^2}{n}} \quad (7)$$

where X_P is the predicted values, X_O is the observed values, and n is the number of data [49]. As it is observed, d_s/D has a direct relationship with Fr_d, L_b/D because of exponents 1.1259 and 0.1637 in Eq. (6). It means that when the densimetric Froude number increases, maximum scour depth becomes larger. It is clear that scour depth increases with increasing flow intensity or flow velocity. Also, as was observed before, the scour depth increases with the larger gap between the pier and sill, or in other words in a farther sill, the scour reduction (R_A) is reduced. Also, y/T_d has a slight effect on d_s/D in Eq. (6) maybe due to the low ranges of y/T_d in experimental tests. This equation can be applied at $0.84 \le \text{Fr}_d \le 2.4$, $0.8 \le y/T_d \le 1.6$ and $0 < L_b/D \le 4$. Figure 12 presents the comparison of experimental data (d_s/D—observed) with predicted data from Eq. 6 (d_s/D—predicted). The error between experimental data and computed data from proposed Eq. 6 where appears in RMSE = 0.046 and R^2 = 0.998. These values for RMSE and R^2 (correlation coefficient) present a good correlation between experimental data and computed one and acceptable accuracy of the proposed prediction equation.

Table 3 Maximum variation of R_A by utilizing different countermeasures

Study	Debris	Bed sill	Slot	Collar	Maximum of R_A (%)
Grimaldi et al. [26]	ND	WBS	NS	NC	− 26
Razi et al. [30]	ND	WBS	NS	NC	− 29
Sanadgol et al. [34]	ND	WBS	NS	NC	− 32
Hamidifar et al. [43]	RD	NBS	WS	NC	− 32
Hamidifar et al. [44]	RD	NBS	NS	WC	− 39
Present study	RD	WBS	NS	NC	− 38

ND no debris, *RD* rectangular debris, *WBS* with bed sill, *NBS* no bed sill, *NS* no slot, *WS* with slot, *NC* no collar, and *WC* with collar

Conclusions

This paper evaluated the efficacy of utilizing a bed sill on the maximum scour depth (d_s) of a cylindrical pier under conditions of upstream debris accumulation in a laboratory model. Three experimental sets A (bridge pier), B (bridge pier + debris accumulation), and C (bridge pier + debris accumulation + bed sill) were designed and performed. At first, the d_s/D values of each test were extracted and the variation of it compared to set A, and set B tests were named as R_A and R_B, respectively. The results indicated that in the condition of debris accumulation (set B) compared to the condition without it (set A), d_s/D increased; also, R_A increased with increasing Fr_d, which this increase in scour could be caused by flow blockage through debris around the pier. According to the increase in d_s/D in the condition of debris accumulation, the results of set C that using the bed sill present the efficacy of this countermeasure and the reduction of scour in comparison with the debris accumulation. It was observed from experimental results that at a constant densimetric Froude number, with increasing L_b/D, the R_A was reduced, and the efficacy of the bed sill was reduced. This result was a good compatibility with the prior studies in cases without the debris. The optimal efficiency of the bed sill in all densimetric Froude numbers was observed in the distance of $0D$. In these conditions, the scour depth was the lowest, and R_A was the largest value equal to 38.5%, 34.2%, and 16.9% for Fr_d = 2.4, 1.29, and 0.84, respectively. Also, in a constant L_b/D, with the increase in Fr_d, the efficacy of bed sill as a countermeasure for scouring decreased. Based on dimensional analysis, parameters, y/T_d, Fr_d, and L_b/D, affected d_s/D. An equation for predicting d_s/D was proposed in the conditions of using the bed sill for the bridge pier scour with the debris accumulation, and the coefficients of RMSE = 0.046 and R^2 = 0.998, and the ranges of effective parameters were presented. It was concluded that d_s/D has a direct relationship with Fr_d, L_b/D. It means that the value of scour depth becomes larger by increasing the densimetric Froude number, and the scour depth increases in a farther sill case. The results of this research can be used in the field studies of rivers as an effective countermeasure for river bed erosion around bridge piers.

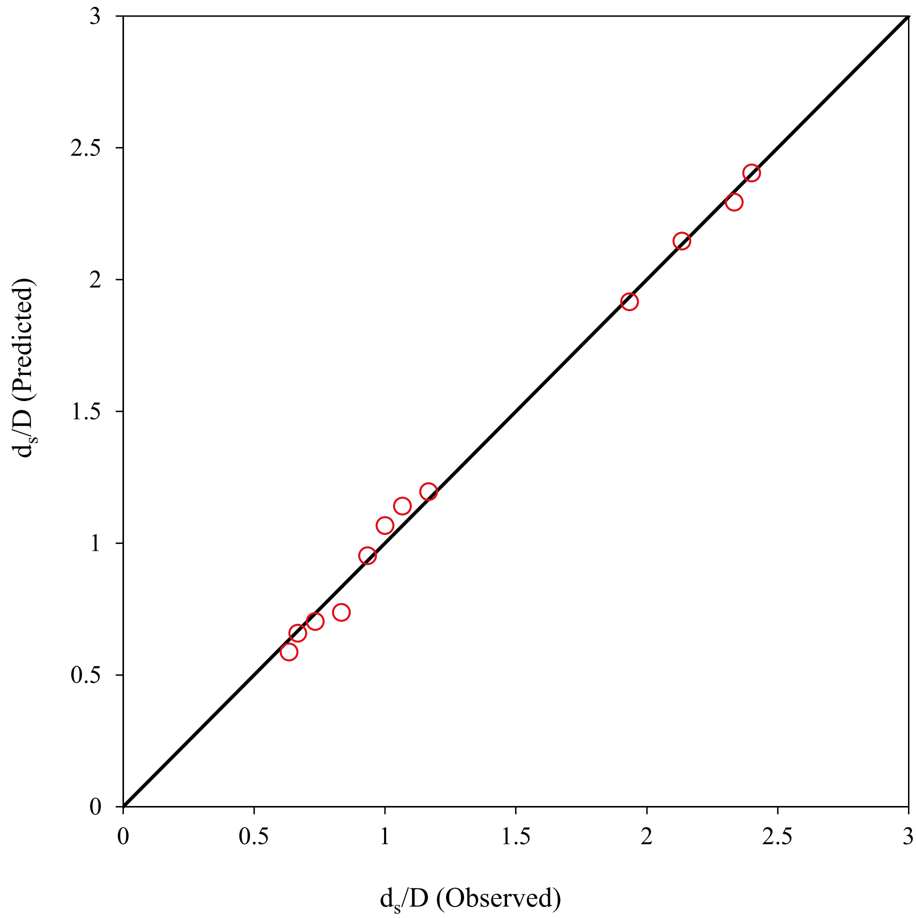


Fig. 12 Changes of d_s/D (observed) to d_s/D (predicted) with debris accumulation and bed sill

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

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