Research Article

Effect of various flow, sediment and geometrical parameters on partially or fully submerged deck scour

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Abstract

The effect of various parameters of flow, sediment and geometric features of the bridge on the depth and shape of the scour hole occurred underneath a bridge deck model without a pier was investigated by a series of experiments conducted in a flume under partially and fully submerged flow and clear water conditions. The experiments were performed with factors such as approach flow depth, discharge, sediment size, degree of submergence, girder location and depth. A total of 112 experiments were conducted for both partially and fully submerged flow conditions. The experimental data showed that the partially submerged flow increased the maximum depth of scour hole and affected the shape of the scour hole more when compared to the fully submerged flow. It was also noted that parameters that directly affected flow structure in the bridge opening such as girder height might significantly increase the maximum depth of scour hole. Effect of the distance between a single girder and the bridge edge was also tested by using three different girder location and it was found that as the distance increased, the depth of the scour hole decreased and the location of the maximum scour depth moved with the girder to where the contraction in the flow area occurred.

Keywords Partially and fully submerged flow · Local scour · Clear water scour · Girder height · Degree of submergence

1 Introduction

River bridges are exposed to free surface flow under normal flow conditions. However, when the flow of the stream gets higher and the water level reaches to the bridge low chord, the flow at the bridge becomes pressurized. In this case, the bridge deck is under partially submerged flow condition. If the stream flow and accordingly the water level keep increasing, the flow overtops the bridge so in this case fully submerged or in other terms weir type of flow takes place. These flow conditions can usually be encountered during severe flooding and can threaten the existing critical infrastructures, especially river bridges as a result of increased rate of scouring around bridge foundations because of the increased averaged flow velocity and shear stress in the bridge opening. Therefore, an improved understanding of the mechanism of scouring under partially and fully submerged flow conditions is especially crucial in investigating scouring around bridge foundations during flooding and developing appropriate design criteria to maintain the safety of river bridges after such extreme situations.

In literature, there are numerous research on scouring around piers and abutments which were mostly conducted under free surface flow condition while only in a relatively limited number of researches scouring under partially or fully submerged flow conditions has been thoroughly investigated. The pioneering work of these studies was performed by Abed [1] who conducted a series of experiments at Colorado State University which involved 10 pressure flow pier scour tests among a total of 72 experiments and developed empirical equations

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for both pressurized and free flow conditions. This study was followed by a preliminary experimental work of Jones et al. [2] at Federal Highway's Turner Fairbank Highway Research Centre at which two tests were carried out to investigate scouring around piers under slightly pressurized flow condition. Later, Umbrell et al. [3] performed a laboratory study at the same facility to investigate the effect of pressure flow beneath a bridge deck without a pier or abutment and developed an empirical pressure flow contraction scour equation. However, the maximum depth of scour was obtained by modifying the measured scour data with the fraction of total pier scour as a function of time given by Laursen's [4] differential equation since the duration of the experiments was limited to 3.5 h. Meanwhile, Arneson [5] investigated the effect of pressure flow on local scour in bridge opening in a flume at Colorado State University, same as Abed [1], through a series of experiments and then Arneson and Abt [6] proposed an empirical equation which has been implemented in the Hydraulic Engineering Circular (HEC) 18 to predict the maximum scour depth under pressure flow condition. Verma et al. [7] examined the effects of various parameters such as velocity of approaching flow, depth of flow, degree of submergence, and width of bridge on the scour beneath a submerged bridge deck under pressure flow condition. Then, a conceptual relation was developed between scour depth ad degree of submergence in the form of scour fraction and constriction ratio. Authors recommended the use of a factor of 1.5 for prediction of the maximum scour depth under submerged bridges. Lyn [8] carried out a detailed statistical study with HEC-18 and used the data of Arneson and Abt's [6] and Umbrell et al.'s [3] in his analysis. He noted the spurious correlation of the empirical equation of Arneson and Abt and proposed an alternative design equation after reanalyzing those data. Later, Guo et al. [9, 10] studied pressure flow analytically and experimentally. The results of the experiments showed that the measured scour profiles were two-dimensional, while the horizontal and vertical scour depended on deck width and maximum scour depth, respectively. Zhai [11] conducted experiments in which two sediment sizes and three different inundation levels were considered to observe time-dependent scour depth under submerged bridge deck. Then, a semi-empirical model was proposed based on the mass conservation of sediment. Lin et al. [12] investigated the flow structure under a partially inundated bridge deck measured by particle image velocimetry (PIV) and four types of flow were observed depending on the Froude number and proximity ratio which is defined as the ratio of clearance below the bridge deck h to the total depth of deck. Shan et al. [13] carried out a study both analytically and experimentally and developed an equation for the maximum clear water scour depth in non-cohesive bed materials under different approach flow and superstructure inundation conditions. Karakurt [14] studied the maximum depth of scour hole for pressurized and weir type of flows under clear water conditions with various approach flow depths, approaching mean flow velocity, sediment size and inundation levels and then proposed two empirical equations using measured scour data for partially and totally submerged flow, respectively. Kumcu [15] studied the pressurized flow scour for both steady and unsteady clear water flow conditions. In the study, different flow conditions were considered and a relationship between pressure flow scour and flow conditions was proposed. Recent studies such as Picek et al. [16] on pressurized flow involved derivation of equations for backwater and discharge. Malavasi and Guadagnini [17] carried out experiments to examine the hydrodynamic loading on a bridge deck having a rectangular cross-section for different submergence levels and deck Froude numbers. Beside experimental studies, Kara et al. [18] investigated the flow through a submerged bridge with overtopping by means of a complementary experimental/ numerical study and revealed the complex nature of the flow featuring various vortices around the bridge. Pizzarro et al. [19] proposed a bridge-pier scour entropic model based on energy concepts and entropy to estimate the scour hole under steady hydraulic conditions, hydrographs and floods and calibrated the model with the measured data of 266 experiments from literature. Carnacina et al. [20] conducted a series of experiments to investigate the scour features for the combined effect of pier scour and pressure flow scour and then analyzed the flow features of pressure scour and free surface flow conditions. Scour features were found to be strongly affected by the interaction between the pressure flow and the bridge pier yielding to deeper scour depths than the sum of the individual scours caused by pressure scour and pier scour, respectively.

Besides experimental studies, some researches performed field studies. For instance, Lu et al. [21] conducted field experiments at a bridge in Taiwan to measure both general and total scour depths by using a variety of measurement methods. A methodology was proposed to separate the scour components and simulate the temporal variations of the total scour depth at a pier under unsteady flow conditions. Authors noted that most related formulae tend to overestimate the local scour depth so usage of such formulae for practical purposes should be handled with care. Recently, Crotti and Cigada [22] installed a monitoring system they proposed at a river bridge in Italy and collected long-term related parameters to understand temporal evolution of scour around the bridge. Both the bridge and the river behavior were monitored over a five year period and monitoring was still on going at the time of the publication of the research.

The main aim of this paper is to improve the understanding of the effect of various parameters such as flow type, deck position, bed material, location and height of girder on the maximum depth and shape of the scour hole occurred at the bed beneath a bridge deck without a pier under clear water condition. The experimental program involved 121 experiments and the flow behavior and its effect on the scour hole with different flow type, parameters of flow, sediment and deck such as approach flow depth, discharge, sediment size, degree of submergence, girder depth and the distance between the edge of the bridge deck and the girder were taken into consideration. At the beginning of the study, dimensional analysis of the governing parameters were performed as presented in Sect. 2 of the manuscript to express the scour depth as a function of dimensionless independent variables. Then, details of the experimental setup and procedure were given in Sect. 3. Finally, the experimental results were presented in Sect. 4 followed by discussions in Sect. 5 and finally conclusion was given in Sect. 6 with recommendations and direction for future research.

2 Theoretical methodology

A dimensional analysis of the governing parameters can be performed to examine the interrelationship among the dimensionless terms which affect the depth of scour hole under a bridge deck. For the variables described in Fig. 1, parameters influencing the scouring process can be expressed as [14]:

$$y_s = f(y_a, V_a, V_b, u_*, \rho, \nu, g, D_{50}, b, H_b, H_t, w_s) \tag{1}$$

where y_s = depth of scour, y_a = approach flow depth, V_a = approach mean flow velocity, V_b = mean velocity of the flow passing under the bridge deck, u_*=shear velocity, ρ= density of water, ν=kinematic viscosity of water, g = gravitational acceleration, D_{50} = median particle diameter, b = girder height, H_b = initial distance between the bridge lowest point and unscoured bed at the bridge deck section, $H_t = H_b + b$ and w_s = depth of weir flow when water overtops the deck.

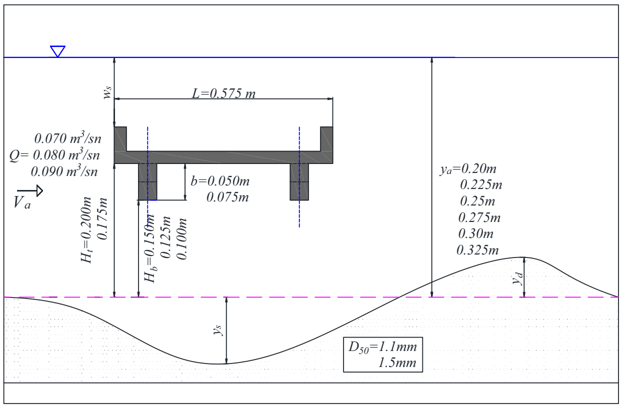


Fig. 1 Description of variables

After dimensional analysis, the dimensionless parameters for scour depth under a bridge deck without a pier or abutment are determined as given in Eq. (2)

$$\frac{y_s}{H_b} = f\left(\frac{y_a}{H_b}, R_b, \frac{u_*}{V_b}, F_b, \frac{V_a}{V_b}, \frac{D_{50}}{H_b}, \frac{H_t}{H_b}, \frac{b}{H_b}, \frac{w_s}{H_b}\right) \tag{2}$$

where $R_b = V_b H_b/\nu$ Reynolds number and F_b= Froude number of the flow underneath the bridge deck. R_b was then eliminated from the equation due to hydraulically rough flow conditions in the flume [1]. u_*/V_b and V_a/V_b were also removed since y_a/H_b includes the effect of both u_*/V_b and V_a/V_b [23]. H_t/H_b was similarly excluded since $H_t = H_b + b$ in which both H_b and b were considered. Thus, after those simplifications, the non-dimensional relation for scour depth under a bridge deck is given as in the form of Eq. (3).

$$\frac{y_s}{H_b} = f\left(\frac{y_a}{H_b}, F_b, \frac{D_{50}}{H_b}, \frac{b}{H_b}, \frac{w_s}{H_b}\right) \tag{3}$$

Some of the dimensionless parameters in Eq. (3) were further eliminated in order to derive a statistically sound equation. For instance, the particle densimetric Froude number (F_{b*}) including the sediment size D_{50} was used instead of Froude number of the flow passing under the bridge deck as given in Eq. (4) [24].

$$F_{b*} = \frac{V_b}{(\Delta g D_{50})^{1/2}} \tag{4}$$

where Δ = relative density of the sediment where $\Delta = (\rho_s - \rho)/\rho$, ρ_s = density of sediment and $\Delta \cong 1.65$ for quartz sand. Under partially submerged flow condition, there is no water overtopping the bridge deck, so the value of w_s becomes equal to zero. Thus, the dimensionless relation for scour depth was expressed as a function of the following independent variables.

$$\frac{y_s}{H_b} = f\left(\frac{y_a}{H_b}, F_{b*}, \frac{b}{H_b}\right) \tag{5}$$

For totally submerged flow condition, the dimensionless parameter w_s/H_b should also be included in Eq. (5). In the current study, the parameters H_b, y_a, V_b, b and D_{50} were varied in the experiments to investigate their effects on the scour hole.

3 Experimental procedure

The experiments were conducted at the Hydraulics Laboratory of Civil Engineering Department of Gazi University, Ankara [14]. The flume was about 10 m long, 1 m wide and 1 m deep having a very mild slope of about 0.0001 with transparent walls. A schematic of the flume and test section is presented in Fig. 2. A recessed test section, 2.5 m long, 1 m wide and 0.22 m deep, was located 4.2 m downstream of the flume inlet. Great caution was given to stabilize the flow before entering the flume by locating honeycomb in the water tank and just before the flume. Two different sediment sizes with median diameters of 1.1 and 1.5 mm and sediment uniformity coefficients (σ) of 1.273 and 1.200, respectively, were used. Taking into account the capacity of the pumps, the clear-water condition that should prevail in the experiments and available data in the literature for comparison, the median diameters of 1.1 and 1.5 mm were used to test the effect of sediment size on scour.

A simple bridge deck model without piers of 1.0 m long, 0.575 m wide and 0.025 m deep, based on a two-lane bridge scaled at 1/100 with two girders was used in the experiments and placed perpendicular to the direction of flow. In some experiments, single girder was used to examine the effect of the distance between the edge of the deck and the girder. Total height of the bridge deck and the railings was 50 mm. The deck model was fitted at two different heights (H_b) from the unscoured bed level as 0.200 and 0.175 m and two girder heights of 5.0 ad 7.5 cm were used in the experiments. Three discharges (Q) were applied as 0.07, 0.08 and 0.09 m^3/s with varying bridge deck position, approach flow depth, girder height and sediment size as summarized in Table 1.

The flow was measured by a sharp-crested rectangular weir and the flow depth was read with a point gage. The critical velocity (V_c) at which incipient sediment motion occurred was computed by Neill's [25] equation and it was found that the ratio of the approach velocity (V_a) to the critical velocity (V_a/V_c) ranged from 0.40 to 0.70 depending on flow conditions and bed material ensuring clear water condition prevailed in all experiments conducted. In the recessed section, the bathymetric measurements were performed by Leica Disto D810 Touch laser meter with typical measuring accuracy of ± 1.0 mm at 80 m certified by ISO 16,331-1, at the nodes of a grid system with a grid size of 5 × 5 cm before and after each experiment. Thus, 21 measurements were taken every time at each cross-section of the flume. At the beginning of experiments, flow was discharged into the flume very slowly without causing any disturbance to the bed bathymetry. The method applied by Guo et al. [10] and Shan et al. [13] was used to decide about the duration of the tests. According to this approach,

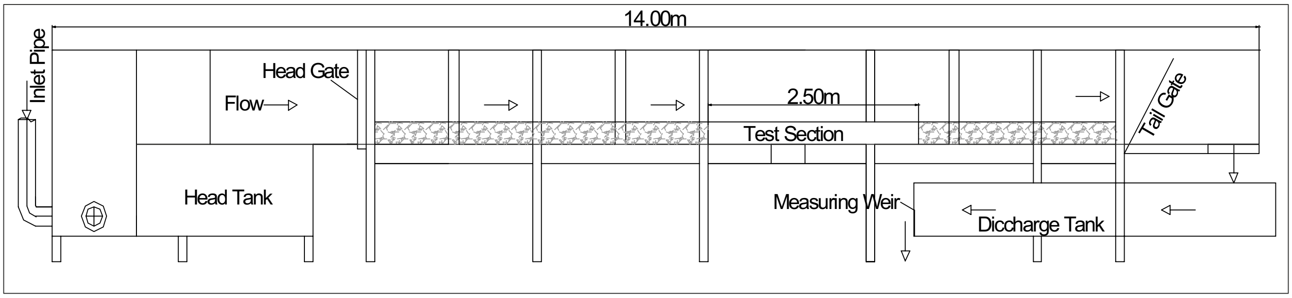


Fig. 2 Schematic representation of the experimental flume

Table 1 Parameters used in the experiments

Deck location H_t (m)	Discharge Q (m^3/s)	Girder height b (m)	Approach flow depth y_a (m)	Bed material D_{50} (mm)	σ (–)
			Y1 = 0.20		
H1 = 0.200	Q1 = 0.070		Y2 = 0.225		
H2 = 0.175	Q2 = 0.080	b1 = 0.050	Y3 = 0.25	$D_{50,1}$ = 1.1	1.273
	Q3 = 0.090	b2 = 0.075	Y4 = 0.275	$D_{50,2}$ = 1.5	1.200
			Y5 = 0.30		
			Y6 = 0.325		

scour processes were monitored by grades in a clear side wall of the flume and when scour changes at a reference point were less than 1 mm for three continuous hours, it was decided that the maximum scour depth was reached. However, in this study due to the working hours and regulations at the laboratory, the time for 1 mm change at a reference point was taken as one hour and the preliminary tests conducted showed that this condition was attained in approximately 7.0 h. Thus, each experiment in the test program was run for 8 h [10, 13]. At the end of experiments, the pumps were turned off and the water was drained very slowly from the flume so as not to cause any change in the bed bathymetry. The deck was removed and the new bathymetry of the bed after the experiment was measured at the same nodes. So, the difference between the initial and final measurements gave the change in the bed bathymetry. In order to have both the pressure and weir type of flows at the same approach flow depth, height of the bridge deck railing which was originally 25 mm from deck, was increased to 75 mm by mounting an additional piece of PVC band.

4 Experimental results and analysis

Table 1 shows the parameters and their values adopted in the experiments. A total of 121 experiments were conducted and the experimental series were named according to the flow type and values of parameters adopted such as PH1Q2Y4b2 where P = partially submerged flow, H_t = H1 = 0.200 cm, Q2 = 0.08 m^3/s, y_a = Y4 = 0.275 m and b_2 = 0.075 m. Similarly, the same experimental test for weir flow (W) was named as WH1Q2Y4b2.

4.1 Effect of approach flow depth

In order to investigate the effect of approach flow depth y_a on the maximum depth of scour hole y_s, experiments were conducted at six different y_a values as given in Table 1. Table 2 shows the results of experimental series in which the change in y_a had the highest effect on y_s for partially and fully submerged flows where F_a is the Froude number of the approach flow. When y_a values were examined, it was observed that in case of weir flow, the highest y_s was measured at the smallest y_a and thereby at the largest

Table 2 Variation of y_s with the approach flow depth y_a

Deck location (m)	Q (m^3/s)	Test characteristics	y_a (m)					
			0.200	0.225	0.250	0.275	0.300	0.325
H1 = 0.20	0.070	Flow type	Pressure	Pressure	Pressure	Weir	Weir	Weir
		F_a	0.250	0.209	0.179	0.155	0.136	0.121
		1.1 mm	13.4	12.0	13.1	11.6	11.2	5.9
		1.5 mm	8.8	8.9	8.3	7.6	–	–
	0.080	Flow type	–	–	Pressure	Weir	Weir	Weir
		F_a	–	–	0.204	0.177	0.155	0.138
		1.1 mm	–	–	14.1	13.0	10.5	9.0
		1.5 mm	–	–	10.3	8.1	–	–
	0.090	Flow type	–	–	–	–	Weir	Weir
		F_a	–	–	–	–	0.175	0.155
		1.1 mm	–	–	–	–	13.0	10.6
		1.5 mm	–	–	–	–	8.0	6.1
H2 = 0.175	0.070	Flow type	Pressure	Pressure	Weir	Weir	Weir	–
		F_a	0.250	0.209	0.179	0.155	0.136	–
		1.1 mm	14.2	15.4	13.6	12.3	10.4	–
		1.5 mm	12.0	12.5	8.9	7.7	–	–
	0.080	Flow type	–	–	Weir	Weir	Weir	
		F_a	–	–	0.204	0.177	0.155	
		1.1 mm	–	–	14.4	13.6	12.9	–
		1.5 mm	–	–	11.4	11.1	7.1	–
	0.090	Flow type	–	–	–	–	Weir	
		F_a	–	–	–	–	0.175	
		1.1 mm	–	–	–	–	13.2	–
		1.5 mm	–	–	–	–	8.0	–

Froude number for both bed material and girder height while it decreased as y_a increased.

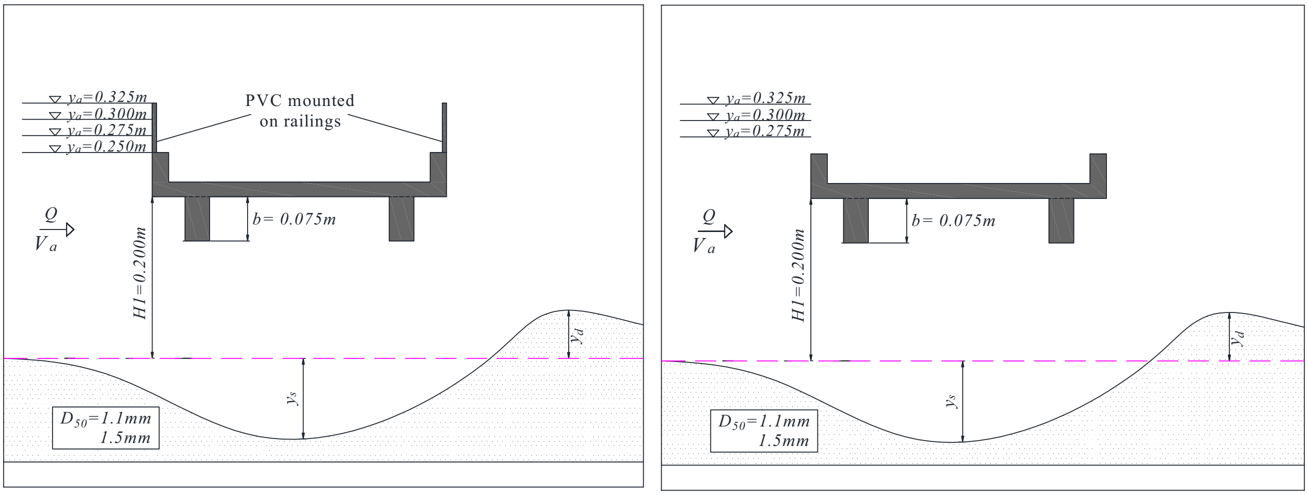
This means that as the y_a and so the depth of overtopping water w_s increased, the mean flow velocity and the bed shear stress in the bridge opening decreased, resulting in smaller depth of y_s under the bridge deck. Therefore, it can be concluded that as the y_a increases, the y_s decreases under fully submerged flow condition. Though the same trend was mostly observed for partially submerged flow condition in case of fine bed material ($D_{50,1} = 1.1$ mm), the largest y_s was measured neither at the lowest ($y_a = 0.200$ m) nor the highest depth ($y_a = 0.25$ m) of approach flow but at the middle depth ($y_a = 0.225$ m) in all experimental series for coarse sediment material ($D_{50,2} = 1.5$ mm), independent of girder height. This can be explained by the vortices formed at the water surface and at the bottom of the bridge deck which were also clearly observed during experiments. It is thought that those vortices dissipated the energy of flow, thus decreased the depth of scour hole at the highest approach flow depth at which the water level was at the top of the bridge deck railing ($y_a = 0.25$ m) under partially submerged flow. When the shape of the scour hole was examined, no noticeable change was observed for partially submerged flow while the scour hole was only shifted a little to the upstream direction of the bridge deck so the graphics of scour hole are not given herein.

4.2 Effect of flow type

In the study, a set of experiments conducted for weir flow with an approach flow depth of 0.27, 0.30, and 0.325 cm was repeated with a piece of PVC of 75 mm height mounted on the railings of the deck. Thus, this PVC piece prevented the flow to overtop the bridge deck and thereby submerged flow as shown in Fig. 3 was obtained. The results of the experiments for both partially submerged and weir flows with relative percentile changes in y_s due to the flow type are given in Table 3.

In this series of experiments, the bridge deck was located at H1 = 0.200 m and both bed materials and girder heights were varied. At $y_a = 0.275$ m, both flow types had similar y_s values at lower discharge of 0.070 m^3/s. However, as the y_a and discharge increased, it was seen that there was serious increase in y_s under partially submerged flow condition where the flow could not overtop the bridge deck. It is thought that the potential energy of the flow substantially increased with the increase in y_a at the upstream of the bridge deck in case of partially submerged flow, thereby, y_s got larger of up to about 660%. However, in case of weir flow, as the y_a increased, the depth of overtopping water w_s also increased. By considering the continuity of flow passing under and over the bridge deck, it can be concluded that the flow passing under the deck and so the mean velocity of flow decreased. This, in turn, resulted in a decrease in y_s as seen in Table 3. This emphasizes the need for a through and comprehensive investigation of the effect of debris accumulation at bridge piers and in the openings. Since even a slight increase in water level of the stream, enough to have partially submerged flow at the deck, might result in a deeper scour hole than that of fully submerged flow besides causing additional trouble by carrying debris and blocking the watercourse, consequently further increasing the scouring [26].

When the shape of the scour hole was investigated, it was found that for 0.070 m^3/s, there was almost no



(a) (b)

Fig. 3 Schematic representation of the parameters used for **a** Partially submerged flow condition **b** Weir flow condition

Table 3 Variation of y_s with flow type and girder height

Q (m^3/s)	F_a (-)	y_a (cm)	D_{50} (mm)	b (cm)	Partially submerged flow y_s (cm)	Weir flow y_s (cm)	Percentile change due to flow type (%)	Partially submerged flow Percentile change due to girder height (%)	Weir flow
0.070	0.155	27.5	1.1	5.0	7.2	7.9	– 8.86	52.78	46.84
				7.5	11.0	11.6	– 5.17		
			1.5	5.0	1.5	1.5	0	360.00	406.67
				7.5	6.9	7.6	– 9.21		
	0.136	30.0	1.1	5.0	8.3	4.7	76.60	56.63	138.30
				7.5	13.0	11.2	16.07		
	0.121	32.5	1.1	5.0	7.5	4.1	82.93	57.33	43.90
				7.5	11.8	5.9	100.00		
0.080	0.177	27.5	1.1	5.0	8.7	8.5	2.35	49.43	52.94
				7.5	13.0	13.0	0		
			1.5	5.0	5.9	3.3	78.79	59.32	145.45
				7.5	9.4	8.1	16.05		
	0.155	30.0	1.1	5.0	10.5	5.6	87.50	27.62	87.50
				7.5	13.4	10.5	27.62		
			1.5	5.0	4.7	–	–	82.98	–
				7.5	8.6	–	–		
	0.138	32.5	1.1	5.0	13.4	3.2	318.75	2.99	181.25
				7.5	13.8	9.0	53.33		
			1.5	5.0	4.8	–	–	85.42	–
				7.5	8.9	–	–		
0.090	0.175	30.0	1.1	5.0	11.9	7.7	54.55	38.66	68.83
				7.5	16.5	13.0	26.92		
			1.5	5.0	7.9	2.9	172.41	50.63	175.86
				7.5	11.9	8.0	48.75		
	0.155	32.5	1.1	5.0	14.2	6.6	115.15	21.83	60.61
				7.5	17.3	10.6	63.21		
			1.5	5.0	7.6	1.0	660.00	59.21	510.00
				7.5	12.1	6.1	98.36		

significant difference in the shape of the dimensionless maximum scour profiles between partially and fully submerged flow. However, as the discharge and the approach flow depth y_a increased, the shape of the scour hole profiles started to change. Figure 4 shows the dimensionless scour hole profiles for both partially and fully submerged flow conditions at various F_a values for 0.080 m^3/s and 0.090 m^3/s, respectively, with a girder height of 0.075 m and bed material of 1.1 mm median size. In Fig. 4, the longitudinal distance X measured from the section where scouring began was normalized by X_{max}, the longitudinal length from that starting section to the point where the maximum scour depth was observed. As can be seen from Fig. 4a, when discharge was 0.080 m^3/s and y_a increased to 0.30 m, the scour hole profile for weir flow got narrower with steeper slopes while there was not much difference in the profiles of partially submerged flow.

As discharge and approach flow depth further increased to 0.090 m^3/s, as presented in Fig. 4b, the effect of flow type on the shape of the scour hole was much more apparent where the scour hole became much narrower for weir flow and much wider for partially submerged flow. In case of weir flow, the scour hole became much narrower with steeper slopes especially in the downstream part of the deck while the scour hole became much wider for partially submerged flow but did not change significantly with approach flow depth. Figure 5 shows the dimensionless scour hole profiles for both partially and fully submerged flow conditions for all three discharges with girder height of 0.075 m and fine bed material with $y_a = 0.30$ m. As can be seen from the figure, slopes of the scour holes for weir flow were always steeper than those of partially submerged flow. The widest profile for partially submerged flow was obtained for the highest discharge. It

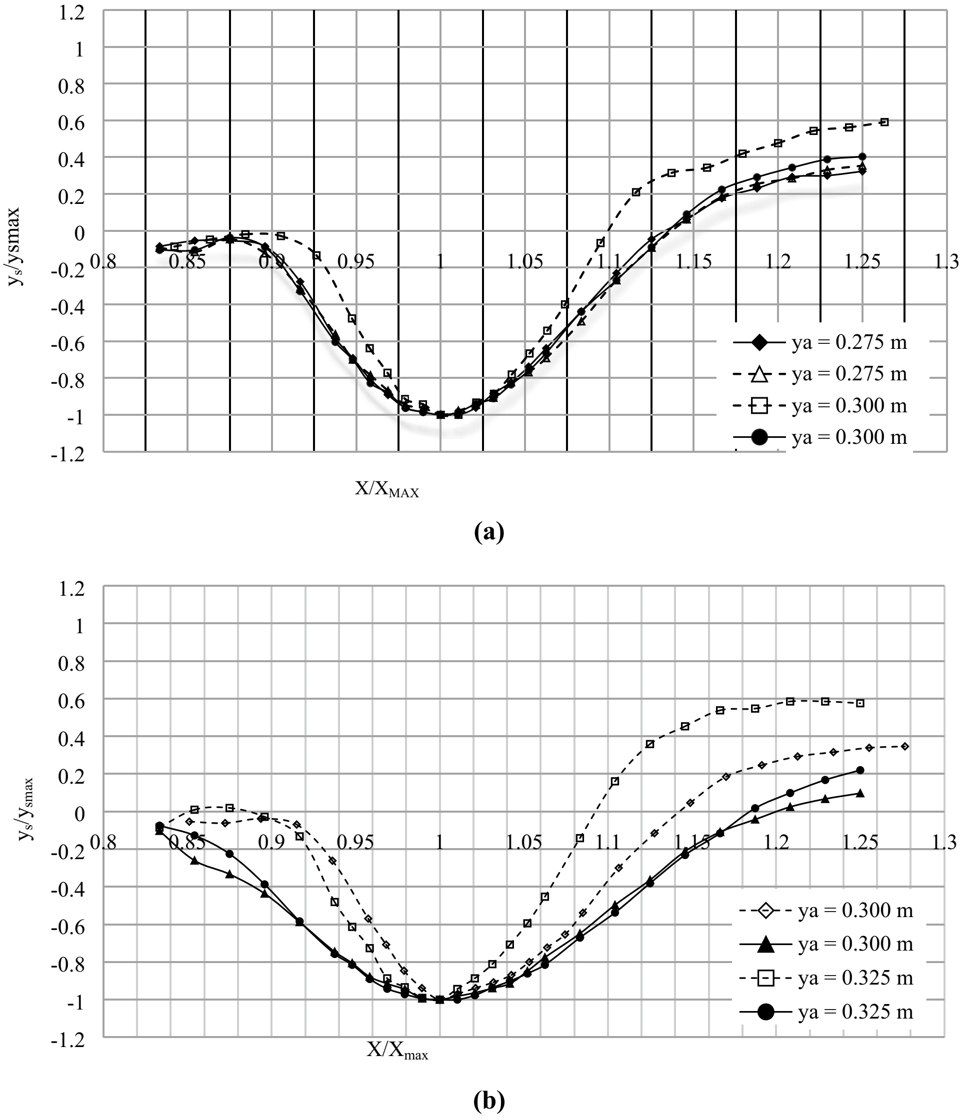


Fig. 4 Dimensionless scour hole profiles for both partially submerged (solid lines) and fully submerged (dashed lines) type of flows for **a** $F_a = 0.177$ and 0.155 for 0.080 m^3/s, **b** $F_a = 0.175$ and 0.155 for 0.090 m^3/s

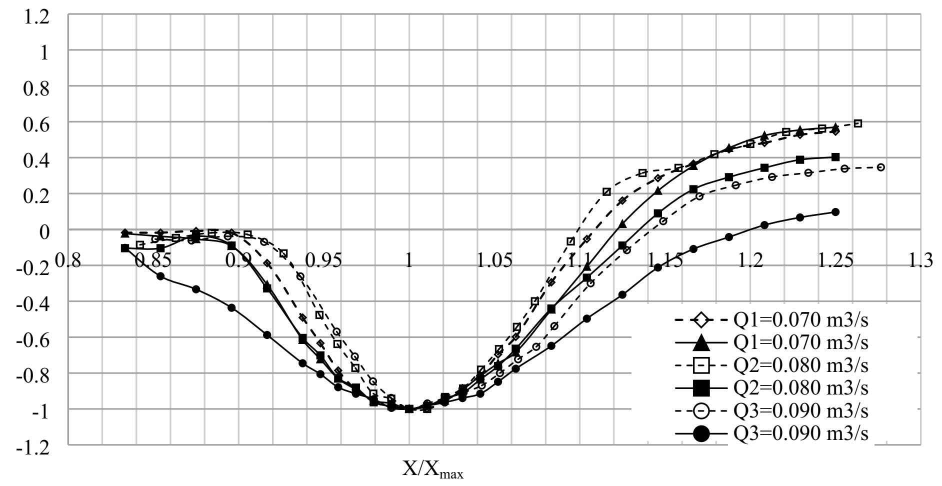


Fig. 5 Dimensionless scour hole profiles at the approach flow depth of 0.30 m for 0.070, 0.080 and 0.090 m^3/s and girder depth of 0.075 m for both partially submerged (solid lines) and fully submerged (dashed lines) flow conditions

can therefore be concluded that a wider and deeper scour hole occurs under partially submerged flow.

4.3 Effect of girder height

According to the percentile changes given in Table 3, the percentile change in y_s due to the change in girder height from b2 = 0.075 m to b1 = 0.050 m for partially submerged flow ranged from 21.83% to 57.33% for fine bed material and from 50.63 to 360.0% for coarse material while for fully submerged (weir) flow these values ranged between 43.90 to 181.25% and 145.45 to 510.00%, respectively. These results showed that further vertical contraction of flow area due to the increase in girder height seriously affected the flow structure in the bridge opening thus increasing scouring especially for tests with coarser bed material and weir flow. From these results, it can thus be said that the change of flow structure affected the depth of maximum scour hole more than the mean flow velocity or the Froude number of the flow for weir flow especially for coarser material. On the other hand, change of girder height had minor effect on y_s in partially submerged flow which can be explained by the fact that increased potential energy plays a much profound effect in scouring of bed than the increase in girder height. Furthermore, for the same $F_a = 0.155$ values with different discharge and y_a, the percentile change in y_s was inspected. It was noted that the percentile changes in y_s for partially submerged and weir flow at 0.070 m^3/s were close, about 0.9 and 1.13 for fine and coarser bed materials, respectively. However, as the discharge increased to 0.090 m^3/s, these ratios raised to about 2.8 to 8.6 times. This might imply that as the discharge increased, the girder height had more pronounced effect in scouring for weir flow than the partially submerged flow had.

4.4 Effect of bed material

The effect of bed material size on y_s was investigated using two bed materials with median diameters of 1.1 and 1.5 mm. Table 4 shows the variation of y_s due to bed material size for various flow conditions where the percentile changes in y_s were found to be larger for weir flow, ranging

Table 4 Effect of bed material size on the y_s

Q (m^3/s)	F_a	y_a (cm)	b (cm)	D_{50} (mm)	Partially submerged flow	Weir flow	Partially submerged flow	Weir flow
					y_s (cm)	y_s (cm)	Change due to bed material (%)	
0.070	0.155	27.5	5.0	1.1	7.2	7.9	380.00	426.67
				1.5	1.5	1.5		
			7.5	1.1	11.0	11.6	59.42	52.63
				1.5	6.9	7.6		
0.080	0.177	27.5	5.0	1.1	8.7	8.5	47.46	157.58
				1.5	5.9	3.3		
			7.5	1.1	13.0	13.0	38.30	60.49
				1.5	9.4	8.1		
	0.155	30.0	5.0	1.1	10.5	5.6	123.40	–
				1.5	4.7	–		
			7.5	1.1	13.4	10.5	55.81	–
				1.5	8.6	–		
	0.138	32.5	5.0	1.1	13.4	3.2	179.17	–
				1.5	4.8	–		
			7.5	1.1	13.8	9.0	55.06	–
				1.5	8.9	–		
0.090	0.175	30.0	5.0	1.1	11.9	7.7	50.63	165.52
				1.5	7.9	2.9		
			7.5	1.1	16.5	13.0	38.66	62.50
				1.5	11.9	8.0		
	0.155	32.5	5.0	1.1	14.2	6.6	86.84	560.00
				1.5	7.6	1.0		
			7.5	1.1	17.3	10.6	42.98	73.77
				1.5	12.1	6.1		

from 52.63% to 560.0% while for partially submerged flow the change ranged from 38.30 to 380.0%.

The percentile change in y_s due to bed material was found to be larger for girder height of 0.05 m in both flow types. These percentile changes showed that the change in girder height from 0.05 to 0.075 m affected scouring and increased the y_s more than the bed material did. The results showed that as the size of the bed material got smaller, greater percentile change in y_s occurred even at smaller flow and girder height, as expected.

4.5 Effect of deck position

In order to examine the effect of bridge deck position on y_s, the deck was first located at 0.200 m and then lowered to 0.175 m from the unscoured bed. Thus, with this configuration, it was also possible to investigate the effect of bridge opening on y_s with the girder heights of 0.050 and 0.075 m. The experimental results for both partially submerged and weir flows and percentile changes due to deck position and bridge opening are given in Table 5. The results given in column (8) show the relative percentile changes in y_s when the deck was lowered from 0.200 to 0.175 m, for both partially submerged and weir flow with a girder height of 0.075 m, fine bed material ($D_{50,1}$ = 1.1 mm) and the same approach flow depth. It can be seen from those results that when the flow was pressurized at both deck positions, there was an increase in percentile changes of y_s of up to 28.33%. However, when partially submerged and weir flow prevailed, the corresponding percentile changes were relatively smaller like 3.82 and 2.13%.

When weir flow was present at both deck positions, a small but irregular behavior of increase in the percentile change of y_s was observed with changing y_a and discharge values. The greatest changes were observed for cases where the height of the railing was increased to obtain partially submerged flow. However, the corresponding series of experiments were not conducted for H2 = 0.175 m so a precise conclusion could not be made in this case. It was also observed for weir flow that as the w_s increased, the y_s decreased. In all cases, the y_s was greater for partially submerged flow than weir flow at the same y_a. Furthermore, different deck positions and girder heights were used to obtain the same bridge opening of 0.125 m and corresponding percentile changes in y_s were given in column (9). As can be seen from the results, the y_s decreased with smaller girder height where the decrease in percentile changes ranged between 7.63% and 61.54%. These results show that though the bridge opening was the same and the bridge deck was further away from the bed, the larger girder height caused a deeper scour hole than the closer deck with smaller girder height. So, it can be concluded that the height of the girder affected the y_s more than the location of the deck which might be the result of flow structure formed in the cavity. The dimensionless scour hole profiles for 0.070, 0.080 and 0.090 m^3/s at the same

Table 5 Variation of y_s with deck position and girder height

Q (m^3/s)	F_a (–)	y_a (m)	H_t = 0.20 m		H_t = 0.175 m		(7)	Percentile change due to (%)	
(1)	(2)	(3)	b = 0.075 m		b = 0.050 m	b = 0.075 m		Deck position	Bridge opening
			(4)		(5)	(6)		(8)	(9)
			y_s (m) (a)	Flow type	y_s (cm) (b)	y_s (m) (c)	Flow type	For (c)-(a)	For (b)-(a)
0.070	0.250	0.200	0.134	P	0.123	0.142	P	5.97	– 8.21
	0.209	0.225	0.120	P	0.098	0.154	P	28.33	– 18.33
	0.179	0.250	0.131	P	0.121	0.136	W	3.82	– 7.63
	0.155	0.275	0.116	W	0.065	0.123	W	6.03	– 43.97
				P (*)				11.82	– 40.91
	0.136	0.300	0.112	W	0.050	0.104	W	– 7.14	– 55.36
			0.130	P (*)				20.00	– 61.54
0.080	0.204	0.250	0.141	P	0.137	0.144	W	2.13	– 2.84
	0.177	0.275	0.130	W	0.087			4.62	– 33.08
			0.130	P(*)		0.136	W	4.62	33.08
	0.155	0.300	0.105	W	0.076	0.129	W	22.86	– 27.62
			0.134	P(*)				– 3.73	43.28
0.090	0.175	0.300	0.130	W	0.085	0.132	W	1.54	– 34.62
			0.165	P(*)				– 20.0	48.48

P Partially submerged flow, *W* Weir flow (fully submerged)

(*)Experiments in which the height of the railing was increased by mounting additional PVC band

y_a were plotted to investigate the shape of the scour hole as shown in Fig. 6. With the increase in discharge and F_a, it was found that the width and slopes of the scour hole were affected. When discharge was increased to 0.090 m^3/s, it was seen that the partially submerged flow resulted in more prolate slopes than the weir flow did. As a result, it was noted that the discharge in the bridge opening and the flow type were more dominant on scouring although the position of the deck influenced the depth and shape of the scour hole. Similarly, the dimensionless scour hole

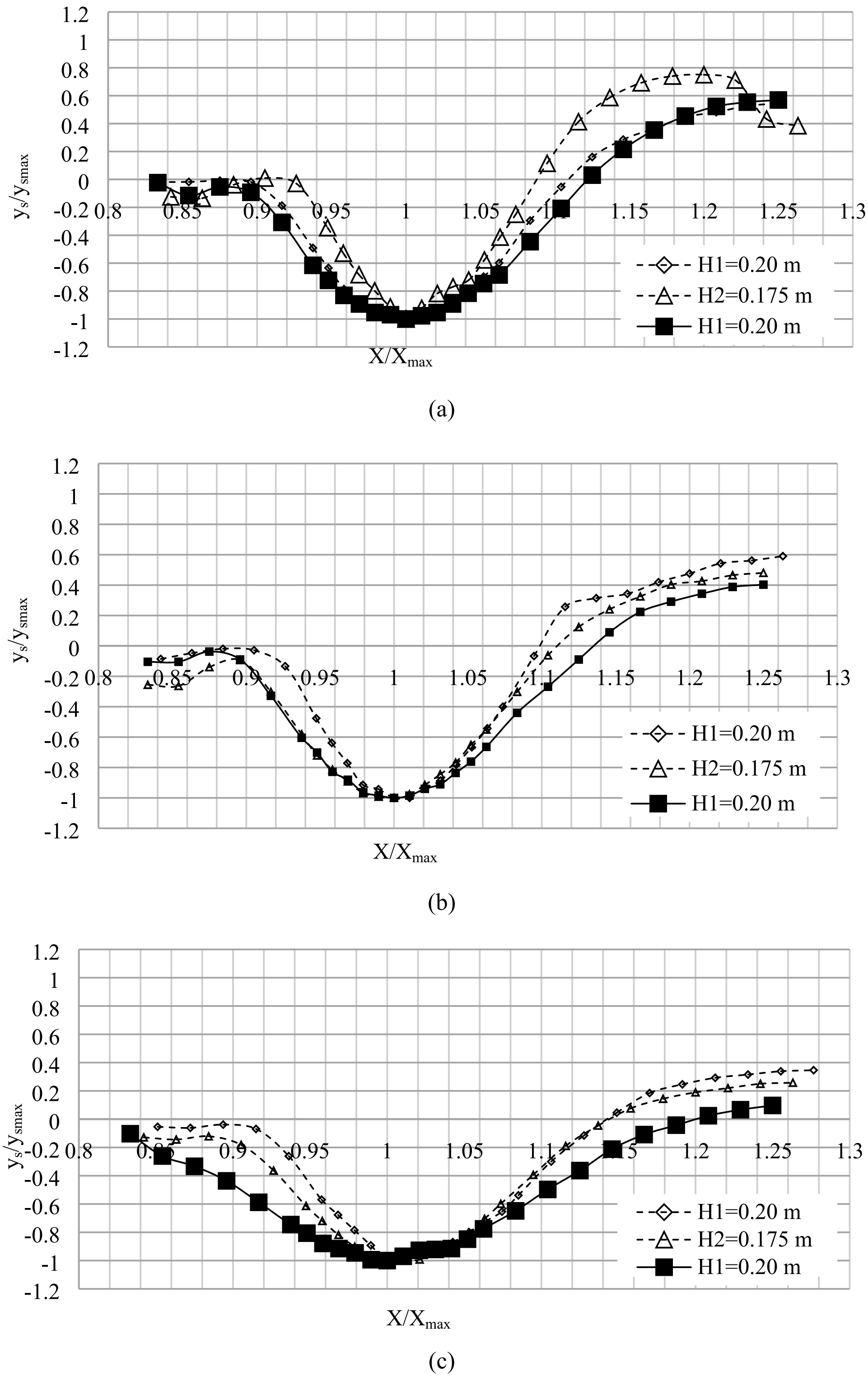


Fig. 6 Dimensionless scour hole profiles under partially submerged (solid lines) and weir (dashed lines) flow conditions at $y_a = 0.30$ m for **a** $Q_1 = 0.070$ m^3/s and $F_a = 0.136$, **b** $Q_2 = 0.080$ m^3/s and $F_a = 0.155$, **c** $Q_3 = 0.090$ m^3/s and $F_a = 0.175$

profiles for 0.080 m^3/s and 0.090 m^3/s for the same bridge opening are shown in Fig. 7. As can be seen from the figures, the slopes of the scour hole are much steeper for weir flow, especially at higher discharge values but same y_a.

4.6 Effect of the distance between the deck edge and the girder

In this series of experiments conducted, the deck was located at 0.200 m above the bed and only one girder was used with a constant depth of 0.075 m. The girder was located at three different locations on the deck; (1) close to the upstream of the deck (GU), (2) in the middle (GM), and (3) close to the downstream of the deck (GD) in which the distance between the deck edge and the girder was 0.0100, 0.28 and 0.475 m, respectively. The measured y_s and the relative percentile changes of y_s with respect to different girder locations is given in Table 6. It can be seen from the results that the highest scour hole depth was obtained for GU for both partially submerged and weir flow types. This could be explained by the fact that the flow had just entered the constricted area in case of GU, not much energy of the flow was yet dissipated so the y_s was larger due to the stronger flow field. However, it can be seen that the y_s was larger for GD when compared with GM, but not as much as GU, probably due to an amount of dissipated energy. So, it can be concluded that it was not only for the flow field but also the vortices formed just before and after the contracted bridge area significantly affected the y_s. Thus, the y_s was the smallest for GM case.

Figures 8 and 9 shows the scour profiles along the test section at the axis where the maximum scour hole depth occurred for partially submerged and weir flows. It can be seen from the figures that for 0.070 m^3/s, the location of the y_s moved with the girder location. In case of partially submerged flow, the upstream slope of the hole was smoother in case of GU while for GD, the downstream slope was found to be smooth. As the discharge increased, the shape of the scour hole got closer for all girder locations with smoother downstream slope. For weir flow,

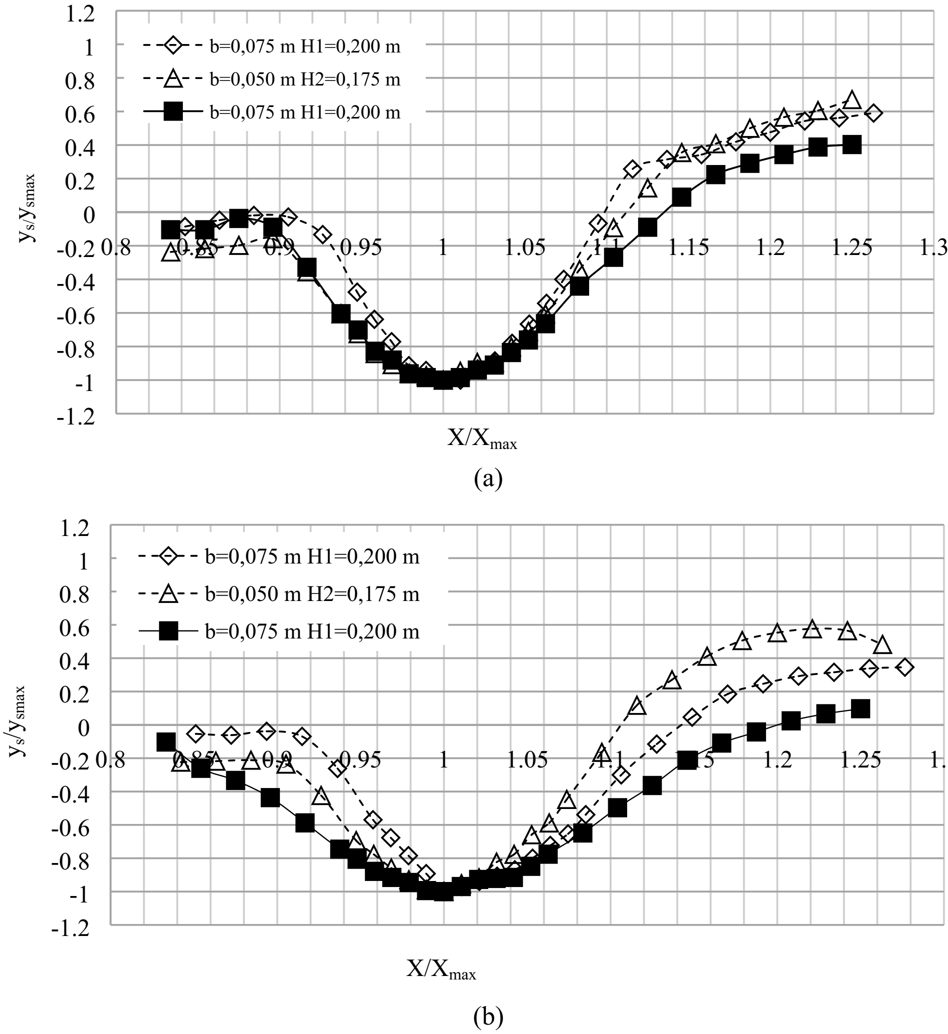
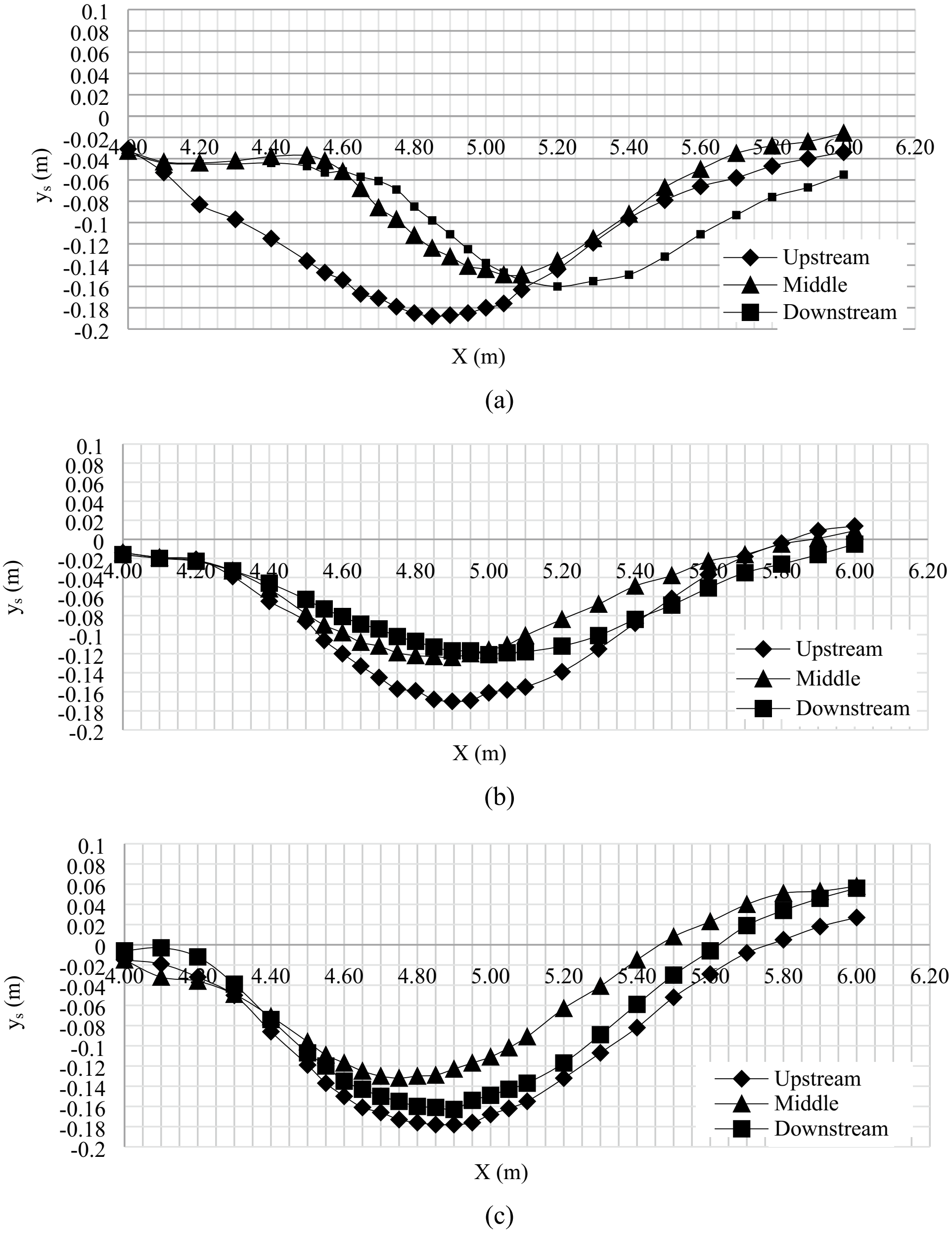


Fig. 7 Dimensionless scour hole profiles under partially submerged (solid lines) and weir (dashed lines) flow conditions at $y_a = 0.30$ m for **a** $Q_2 = 0.080$ m^3/s and $F_a = 0.155$, **b** $Q_3 = 0.090$ m^3/s and $F_a = 0.175$

Table 6 Effect of the distance between the deck edge and the girder

Q (m^3/s)	Fr_a (-)	y_a (m)	Flow type	y_s with two girder (cm) (TG)	Maximum scour hole depth y_s (cm)			Percentile change (%)			
					Upstream (GU)	Middle (GM)	Downstream (GD)	GU-GM	GU-GD	GD-GM	GU-TG
0.07	0.250	0.200	P	13.4	18.8	14.9	16.0	26.17	17.5	7.38	40.30
	0.155	0.275	W	11.6	12.4	8.1	8.5	53.09	45.88	4.94	6.90
0.08	0.204	0.250	P	14.1	17.0	12.4	11.5	37.10	47.83	− 7.26	20.57
	0.177	0.275	W	13.0	13.5	9.2	11.9	46.74	13.45	29.35	3.85
0.09	0.155	0.325	P	17.3	17.8	13.2	16.3	34.85	9.20	23.48	2.89
	0.175	0.300	W	13.0	14.1	8.3	11.0	69.88	28.18	32.53	8.46

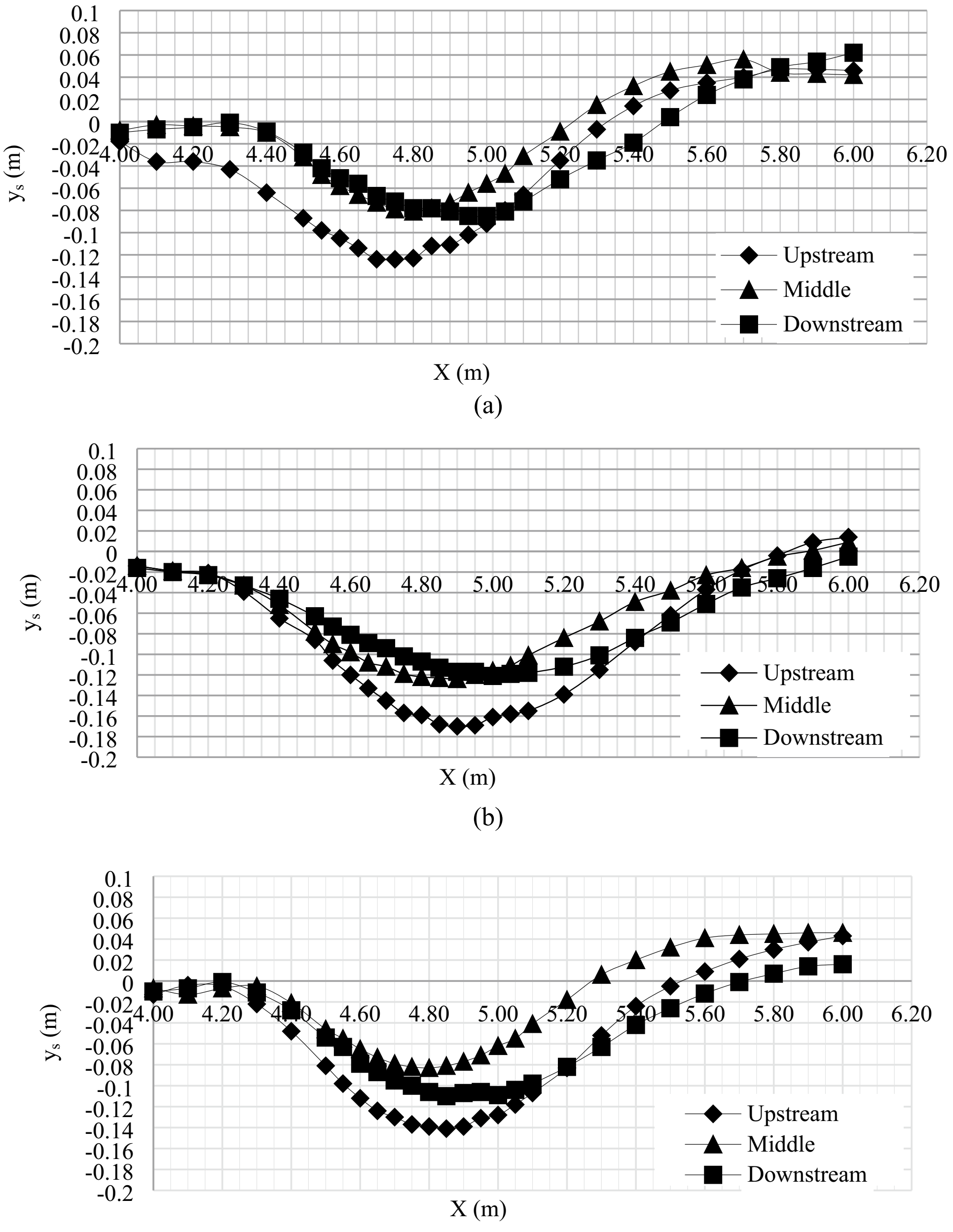


(a)

(b)

(c)

Fig. 8 Profiles of measured scour hole under partially submerged flow condition for H1 = 0.20 m, b = 0.075 m and single girder location for **a** y_a = 0.20 m and Q = 0.070 m^3/s, **b** y_a = 0.25 m and Q = 0.080 m^3/s, **c** y_a = 0.325 m and Q = 0.090 m^3/s



(a)

(b)

(c)

Fig. 9 Profiles of measured scour hole under fully submerged flow condition for H1 = 0.20 m and b = 0.075 m for **a** $y_a = 0.275$ m and Q = 0.070 m^3/s, **b** $y_a = 0.275$ m and Q = 0.080 m^3/s, **c** $y_a = 0.30$ m and Q = 0.090 m^3/s

similar profiles of scour hole were plotted. The results show that as the girder gets closer to the edge of the bridge deck, the depth of the maximum scour hole increases and the slope of the upstream gets prolate.

5 Discussion

When the findings of the current study are deliberated, an improved understanding of the effect of various parameters was achieved. For instance, locating the bridge deck closer to the bed would certainly increase the mean velocity of flow passing through the bridge under submerged flow condition, resulting in an increase in bed shear stress and depth of scour hole. However, it was observed that the effect of the vertical contraction in the bridge opening due to the girder height was more dominant than the effect of the bridge deck location. This can be explained by the fact that the girder height affects the size of cavities and vortices formed under the deck and changes the flow structure resulting in increased scouring. Furthermore, it was observed that deeper and wider scour holes formed beneath the deck under partially submerged flow than fully submerged flow. This means that designing

Table 7 Some details of the related experimental studies

	Author				
	Abed [1]	Arneson and Abt [6]	Umbrell et al. [3]	FHWA [27]	Current Study
Flow type	F, P	P	P	P	P
Pier	Yes No	Yes No	No	No	No
Bed material D_{50} (mm)	3.2	0.6 0.9 1.5 3.3	0.3 1.2 2.4	1.1 2.2	1.1 1.5
Test duration (h)	Min. 3	NA	3.5	36–48	8
Q (m^3/s)	0.18–1.39	0.227–0.680	0.07–0.21	0.1–0.13	0.07, 0.08, 0.09

F Free flow, *P* Pressure flow, *NA* Not Available.

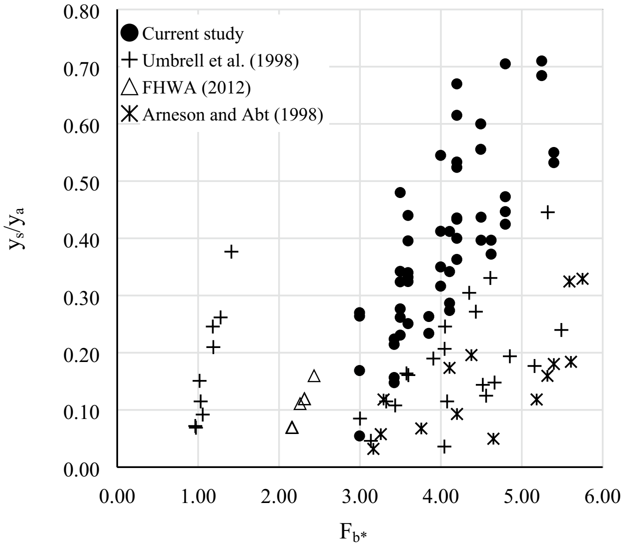


Fig. 10 Comparison of y_s/y_a with F_b* under partially submerged flow

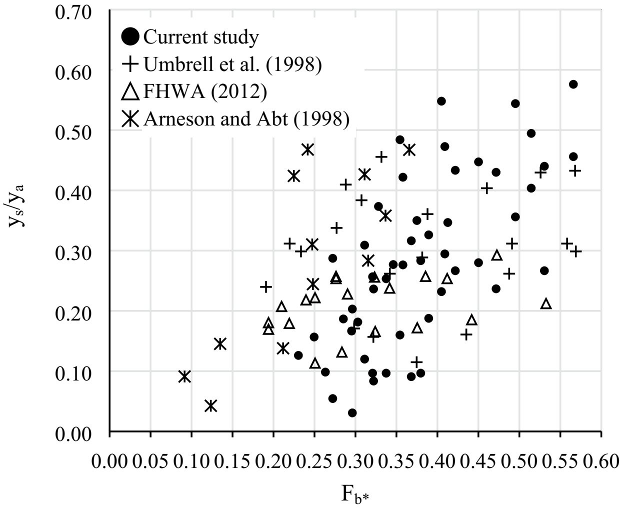


Fig. 11 Comparison of y_s/y_a with D_{50}/H_b under fully submerged flow

the bridge with a larger design return period may not always be an adequate criteria regarding the excessive scour problem around bridges. It was also observed that the distance between the edge of the deck and the girder might also play an important role on scour hole, both on its depth and shape. Hence, the effect of velocity field, not just the magnitude but the structure as well, plays a very important role on scouring and this strong interaction between scour, girder and deck should be investigated in detail in order to develop new design criteria for river bridges and simple countermeasures that can be effective during partially and fully submerged flow conditions.

Results of the current study were then compared to the results of available, widely known studies in the literature, namely Arneson and Abt [6], Umbrell et al. [3] and Turner Fairbank Highway Research Center [27] which were also used for the development of pressure scour estimation formula in FHWA HEC 18. Table 7 shows a brief summary of a number of parameters used in those studies including the initial study of Abed [1]. In Figs. 10 and 11 are plotted the values of y_s/y_a versus F_{b*} under partially and fully submerged flow conditions. As seen in Fig. 10, there is a similar trend between data of current study with those of Umbrell et al. [3] and FHWA [27] while especially data of Arneson and Abt [6] showed a more scattered pattern whose features were defined as unphysical by Lyn [8] who examined the scour equation in HEC-18. Umbrell et al. [3] used three different sediment sizes with median diameters of 0.3, 1.2 and 2.4 . The smallest F_{b*} values were determined for $D_{50} = 2.4$ mm as seen in Fig. 10 while good agreement was observed between the values of current study and Umbrell et al. [3] for $D_{50} = 1.1$ mm and $D_{50} = 1.2$ mm, respectively. Though the behavior was similar, the relative scour depth y_s/y_a values of Umbrell et al. [3] were smaller than those of current study. This means that the experimental duration of 3.5 h of Umbrell's was not enough to compute the maximum scour depth using measured scour data and Laursen's [4] differential equation. In case of fully submerged flow, data of Arneson and Abt [6] were more

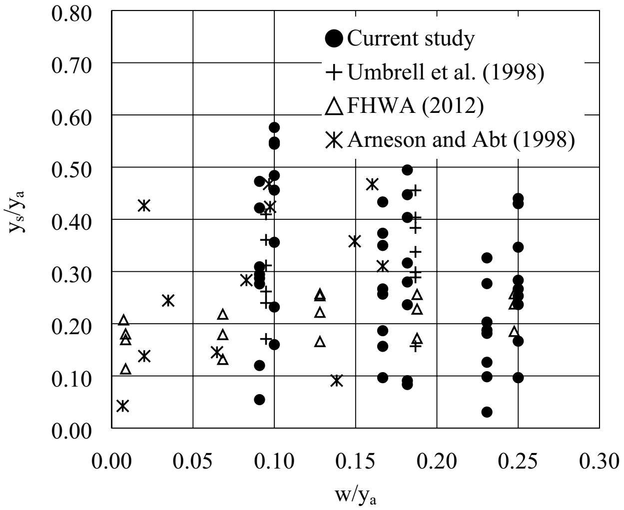


Fig. 12 Comparison of y_s/y_a with w/H_b under fully submerged flow

scattered but overall, the agreement between the data were good. Another finding of the current study was the effect of girder height on scouring. However, since other studies compared herein did not investigate the effect of girder height, no comparison was made for this parameter. Since the height of girders of a bridge is determined according to structural criteria, the observations might be used during development of countermeasures for inundated bridges. Finally, the depth of overtopping water w_s was compared as seen in Fig. 12. It can be seen that all data had a similar trend for relative scour depth y_s/y_a and w_s/y_a relationship.

6 Conclusions

Experiments were carried out to investigate the effect of various parameters of flow, sediment and geometric features of the bridge on the depth and shape of the scour hole occurred underneath a bridge deck model without a pier. When the values of y_s under the same flow conditions were examined, it was found that the approach flow depth greatly increased the depth of scour hole under partially submerged flow condition. In case of weir flow, the depth of overtopping water increased with increasing approach flow depth while the depth of the scour hole decreased. The increase in the maximum scour hole depth in case of partially submerged flow could be explained with the increase in potential energy of flow due to increasing approach flow depth causing velocity of flow passing under the bridge deck to increase. It was also observed that the effect of the vertical contraction in the bridge opening due to the girder height was more dominant than the effect of the bridge deck location. This could be the result of changing flow structure, cavity and vortices formed due to the height of the girder. As expected, as the bed material became finer, greater percentile change in y_s occurred even at smaller flow girder height. Furthermore, the height of the girder affected the y_s more than the location of the deck. As the girder got closer to the edge of the bridge deck, the y_s increased and the slope of the upstream got prolate. It was also noted that not only the flow field but also the vortices formed just before and after the contracted bridge were significantly affected the maximum scour depth y_s.

With the increase in devastating floods and their effects on communities and infrastructures, further research is inevitable for river bridges to be conducted under such extreme hydraulic situations. From available studies, it is obvious that reliable data is still scare for especially submerged flow condition so further experimental studies with wider parameter range is crucial for the development of appropriate design criteria for river bridges with regard to scouring. This study showed that the velocity field plays a very important role on scouring. Thus, further visualization of the flow structure underneath the deck could be carried out with Particle Image Velocimetry (PIV) as done by Lin et al. [12] and numerous scenarios of scouring under various situations can be simulated using Computational Fluid Dynamics (CFD) models. However, reliable and sufficient variety of data is yet required for such studies. Authors hope to continue their experimental studies with wider range for various parameters and develop a simple but effective countermeasure to decrease scouring under submerged flow conditions.

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Compliance with ethical standards

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

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