RESEARCH NOTE

CONSTRICTION SCOUR IN PRESSURIZED FLOW CONDITION

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Abstract When depth of flow past a river bridge exceeds opening under the bridge, the flow under the bridge becomes pressurized. The water is directed downward and under the bridge deck, causing increase in velocity and shear stress on the bed thereby increasing bed scour. This is termed as Pressure Flow Scour. The present study investigates the phenomenon of pressure flow scour resulting from a submerged bridge deck over an unprotected erodible bed. Velocity of approaching flow, depth of flow, degree of submergence and width of bridge are some of the parameters that are likely to affect the scour under a submerged bridge. The effect of fluctuations in the flow depth on the depth of scour increases with decrease in constriction. The experimental data available in the literature has been merged with the present study and a conceptual relation is developed between scour depth and degree of submergence in the form of scour fraction and constriction ratio. For incipient flow conditions on the upstream of a submerged bridge, the final clearance under the bridge is equal to the depth of approaching flow. The study has been extended to include effect of unsteady flow in the form of a hydrograph, interference of two similar submerged bridges, interference of a submerged bridge with an un-submerged pier and a submerged bridge in conjunction with a circular bridge pier.

Key Words Pressurized Flow, Constriction Scour, Submerged Bridge

چکیده وقتی عمق جریان عبوری از پل روی رودخانه از دهنه پل بیشتر می شود، فشار جریان زیر پل افزایش می یابد. آب به طرف پایین و زیر سطح پل هدایت شده و سبب افزایش سرعت و تنش برشی روی بستر و در نتیجه شسته شدن بستر می شود. این مقاله به پدیده شسته شدن بستر غوطه ور زیر پل تحت فشار جریان در قسمت حفاظت نشده از خوردگی می پردازد. سرعت جریان عبوری، عمق جریان، درجه غرق شدن و پهنای پل برخی از پارامترهایی است که احتمال دارد بر سایش زیر پل غرق شده تاثیر بگذارد. با تنگ تر شدن دهنه، نوسانات عمق جریان بر عمق سایش بیشتر تاثیر می گذارد. در این مقاله، داده های تجربی موجود در منابع علمی با نتایج این تحقیق ادغام شده تا رابطه قابل درکی بین عمق شسته شدن و درجه غرق شدگی و نسبت تنگی دهنه بدست آید. با شرایط اولیه جریان در پل مغروق، فاصله نهایی زیر پل مساوی عمق جریان است. نتایج تحقیق از طریق فرم نقشه جریان به تاثیرجریان غیرپایا توسعه یافته است. تداخل دو پل مغرق مشابه، فصل مشترک پل غرق شده با یک پایه غرق نشده و یک پل غرق شده متصل به یک پایه پل مدور نیز مورد توجه قرار گرفته است.

1. INTRODUCTION

It is not always possible to provide high-level bridges for highways crossing rivers or drains. Therefore, the chances of their getting submerged during the floods are fairly high. Such a submergence not only offers great inconvenience to the traffic passing over the bridge, but also endangers its stability by increasing the rate of scouring by about three to ten times depending upon its submergence [1]. Therefore, an understanding of the process of the pressure flow scour is important while analyzing the safety of such bridges.

As the depth of flow increases, the bridge deck may get partially or fully submerged with the result that flood water may flow both under and over the bridge deck, creating an increase in flow velocity and a corresponding increase in bed scour. This is referred to as pressure flow scour. Such bridges that get submerged during the floods are subjected

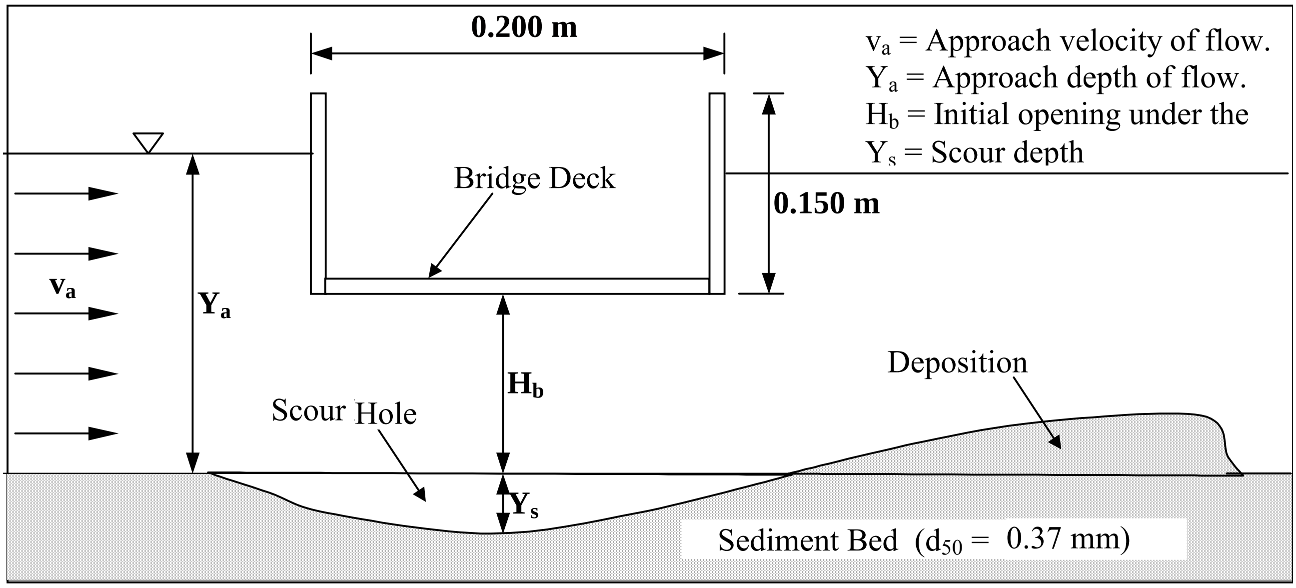


Figure 1. Schematic of the experimental setup.

to pressurized flow conditions and hence face aggravated scour situations.

The present work is the result of an experimental investigation carried out on a pressurized bridge model. The setup involved a bridge model with and without a pier, studied under laboratory controlled flow conditions. After having conceived the problem, the theoretical solution would be difficult because of the pressure phenomenon, mobile bed and associated turbulence in the pressurized flow. The various aspects investigated into included mechanism of scour for such a bridge, its parametric study and its interference effect with another similar bridge and a pier. The bridge model was also tested in conjunction with a pier for comparison between pier scour, bridge scour and their combined effect.

2. SCHEME OF EXPERIMENTATION

Experiments were carried out in the Fluid Mechanics laboratory of Civil Engineering Department at National Institute of Technology, Kurukshetra, India [2]. A re-circulating flume measuring 12.5 m. long, 0.4 m. wide and 0.55 m. deep was used for the experimentation. An erodible bed of fine sediment (d_{50} = 0.37mm, σ_g=2.30, SG=2.65) was laid up to a depth of 25cm in the flume. A model bridge measuring 0.4m long, 0.2m wide and 0.15m high was used to study the scour under different pressurized flow conditions. The sidewalls of the bridge were kept sufficiently high to avoid overtopping of flow over the bridge and to provide only the pressure flow conditions. Figure 1 presents the schematic of the experimental setup. A similar bridge model was also employed to study the interference effects of two bridges under pressurized flow conditions simultaneously. A cylindrical pier model 62 mm in diameter was used to study the combined scour of bridge and pier and interference effect of a submerged bridge and a bridge pier. Table 1 gives the scheme and results of the experimentation. Except for the experiments conducted to investigate the effect of velocity on pressurized scour, the remaining experiments were carried out at incipient velocity of the sediment. Due to the presence of the bridge deck, the flow depth constriction ranged between 22.3% and 75% of the depth of approaching flow. Under the effect of all these conditions, most of the scouring activity occurred within first 20 minutes of the run and hence the duration of each experiment was maintained as 60 minutes.

TABLE 1. Scheme and Results of Experimentation.

Run No.	H_b (m)	Y_a (m)	Q ($m^3/s/m$)	v_a (m/s)	v_b (m/s)	S	Y_{sm} (m)		Remarks
1	0.06	0.100	0.0203	0.2029	0.3383	-	0.0153		Effect of velocity
2	0.06	0.100	0.0236	0.02361	0.3936	-	0.0256		of approach
3	0.06	0.100	0.028	0.28	0.4667	-	0.0506		
4	0.06	0.100	0.0308	0.3075	0.5125	-	0.0618		H_b=60 mm
5	0.06	0.100	0.0317	0.3169	0.5282	-	0.0727		Y_a=100 mm
6	0.06	0.100	0.0406	0.4055	0.6759	-	0.0827		
7	0.06	0.130	0.0142	0.1092	0.2367	-	0.0147		Effect of velocity
8	0.06	0.130	0.0203	0.1561	0.3383	-	0.0229		of approach
9	0.06	0.130	0.0308	0.2365	0.5125	-	0.0633		H_b=60 mm
10	0.06	0.130	0.0355	0.2733	0.5923	-	0.0961		Y_a=130 mm
11	0.06	0.160	0.0156	0.0978	0.2609	-	0.0350		-do-
12	0.06	0.160	0.0203	0.1268	0.3383	-	0.0454		H_b=60 mm
13	0.06	0.160	0.0245	0.1529	0.4078	-	0.0535		Y_a=160 mm
14	0.06	0.099	0.0203	0.205	0.3383	-	0.0153		Hydrographic run
		0.105	0.0245	0.23	0.4078	-	0.0363		
		0.112	0.0289	0.2581	0.4818	-	0.0453		Discharge varied
		0.129	0.0416	0.3224	0.6931	-	0.0833		after every 20 min.
		0.110	0.0271	0.2464	0.4517	-	0.0783		
		0.100	0.0219	0.2193	0.3656	-	0.0783		
		0.088	0.0142	0.1614	0.2367	-	0.0783		
15	0.07	0.120	0.0236	0.1968	3373	-	0.0491		Effect of opening
16	0.06	0.120	0.0236	0.1968	0.3935	-	0.0437		under the bridge
17	0.05	0.120	0.0236	0.1968	0.4723	-	0.0756		at incipient
18	0.04	0.120	0.0236	0.1968	0.5904	-	0.0801		velocity of
19	0.03	0.120	0.0236	0.1968	0.7872	-	0.0920		approach
20	0.07	0.105	0.0211	0.201	0.3016	-	0.0332		
21	0.06	0.105	0.0211	0.201	0.3518	-	0.0489		-do-
22	0.05	0.105	0.0211	0.201	0.4222	-	0.0655		
23	0.04	0.105	0.0211	0.201	0.5277	-	0.0820		
24	0.07	0.090	0.0179	0.1991	0.256	-	0.0086		
25	0.06	0.090	0.0179	0.1991	0.2987	-	0.0200		-do-
26	0.05	0.090	0.0179	0.1991	0.3584	-	0.0517		
27	0.04	0.090	0.0179	0.1991	0.4481	-	0.0574		
28	0.06	0.120	0.0236	0.1968	0.3936	B/2	0.0368	0.0298*	Interference of two
29	0.06	0.120	0.0236	0.1968	0.3936	B	0.0446	0.0266*	submerged bridges at
30	0.06	0.120	0.0236	0.1968	0.3936	3B/2	0.0462	0.0222*	incipient velocity
31	0.06	0.120	0.0236	0.1968	0.3936	2B	0.0597	0.0427*	of approach
32	0.06	0.120	0.0236	0.1968	0.3936	B	0.0630	0.0590^+	Interference of a
33	0.06	0.120	0.0236	0.1968	0.3936	3B/2	0.0433	0.0610^+	submerged bridge and pier
34	0.06	0.120	0.0236	0.1968	0.3936	2B	0.0500	0.0580^+	at incipient
35	0.06	0.120	0.0236	0.1968	0.3936	5B/2	0.0410	0.0560^+	velocity of
36	0.06	0.120	0.0236	0.1968	0.3936	-3B/2	0.0500	0.0540^+	approach
37	0.06	0.120	0.0236	0.1968	0.3936	-5B/2	0.0510	0.0230^+	
38	0.06	0.120	0.0236	0.1968	0.3936	-7B/2	0.0530	0.0290^+	Spacing is center to center
39	0.08	0.120	0.0236	0.1968	0.2952	-	0.1120		Combination of
40	0.07	0.120	0.0236	0.1968	0.3374	-	0.1150		bridge and pier at
41	0.06	0.120	0.0236	0.1968	0.3936	-	0.1320		incipient velocity
42	0.05	0.120	0.0236	0.1968	0.4723	-	0.1393		of approach
43	-	0.120	0.0236	0.1968	-	-	0.0738^+		Only pier

* indicates scour depth under the downstream bridge, + indicates scour depth at the upstream front of the bridge

The present work is the basic experimental work and not a case study of any particular bridge site. In this case, the approach velocities far upstream of the bridge model have been maintained at the incipient velocity of the sediment. At this velocity, sediment particles are just on the verge of movement along with the flow. This would always result in giving the maximum scour depth, as only clear water scour conditions would be set in. Any velocity higher than this would cause the bed sediment to move and live bed conditions would prevail. Thus present model is a dynamic model with rigid boundary but mobile bed. It does not require a scale.

3. MECHANISM OF SCOUR

Local scour around any hydraulic structure is generally initiated because of the change in the direction of flow and its separation in two or three dimensions. This modification results in change in various forces acting on the sediment particles, which disturbs the state of equilibrium. When the disturbing forces exceed stabilizing forces, the particles start moving in the direction of modified flow and scouring of erodible surface begins. This process continues in such a way that the difference in the disturbing and stabilizing forces reduces and the system proceeds towards a new equilibrium.

The scour under an isolated submerged bridge is initiated mainly because of increase in tractive shear stress on the sediment particles. Water flowing in the flume is directed downwards, when encounters an obstruction in the form of bridge deck. The velocity of flow increases because of the reduction in natural flow area. Consequently, shear stress on the bed increases which initiates pressure flow scour. While the bed material gets transported out of the constriction zone, the flow area under the bridge increases. It results in the reduction of flow velocity, which eventually falls below incipient value and scour equilibrium is reached. For higher discharges and higher submergences, the flow under the bridge becomes recirculatory [3]. The flow diagram along with the velocity profiles is shown in Figure 2.

Since in actual practice, bridge deck and pier co-exist, the two mechanisms discussed earlier, get superimposed on each other resulting in a highly complex flow modification. The horseshoe vortex around the pier is expected to get compressed vertically, causing more turbulence and shear stress on the bed. To understand this phenomenon of flow modification, a detailed study, giving due emphasis to the visualization of vertically compressed horseshoe vortex, is required.

4. RESULTS AND DISCUSSION

The experiments were conducted as per the scheme given in Table 1.

A series of 13 different sets of experiments for bridge openings of 30, 40, 50, 60, and 70 mm. for three flow depths viz. 90, 105 and 120 mm were conducted at approach velocity corresponding to incipient velocity of bed sediment particles. The results have been plotted in the form of a relation between two non-dimensional parameters, constriction ratio $(Y_a\text{-}H_b)/Y_a$ and scour fraction $Y_{sm}/(Y_{sm}+H_b)$, where Y_{sm} is the maximum scour depth. The experimental data of present investigation and that obtained by Umbrell, et al. [4] was worked out in the form of constriction ratio and scour fraction. For this, the experiments run by Umbrell, et al. [4] at or very near to incipient velocity only were considered. The plot between constriction ratio and scour fraction is given in Figure 3. A computer generated relationship by using Microsoft Excel, between these two parameters viz. constriction ratio $(Y_a\text{-}H_b)/Y_a$ and scour fraction $Y_{sm}/(Y_{sm}+H_b)$ is expressed as:

$$Y_{sm}/(Y_{sm}+H_b) = 0.9982\,(Y_a\text{-}H_b)/Y_a + 0.0036 \qquad (1)$$

$$r^2 = 0.9446\ (r = 0.9719)$$

Here r is the coefficient of correlation and its value of 0.9719 indicates a very good correlation. Ignoring the small value of the additive constant, Equation 1 can be accepted in the form

$$Y_{sm}/(Y_{sm}+H_b) = (Y_a\text{-}H_b)/Y_a \qquad (2)$$

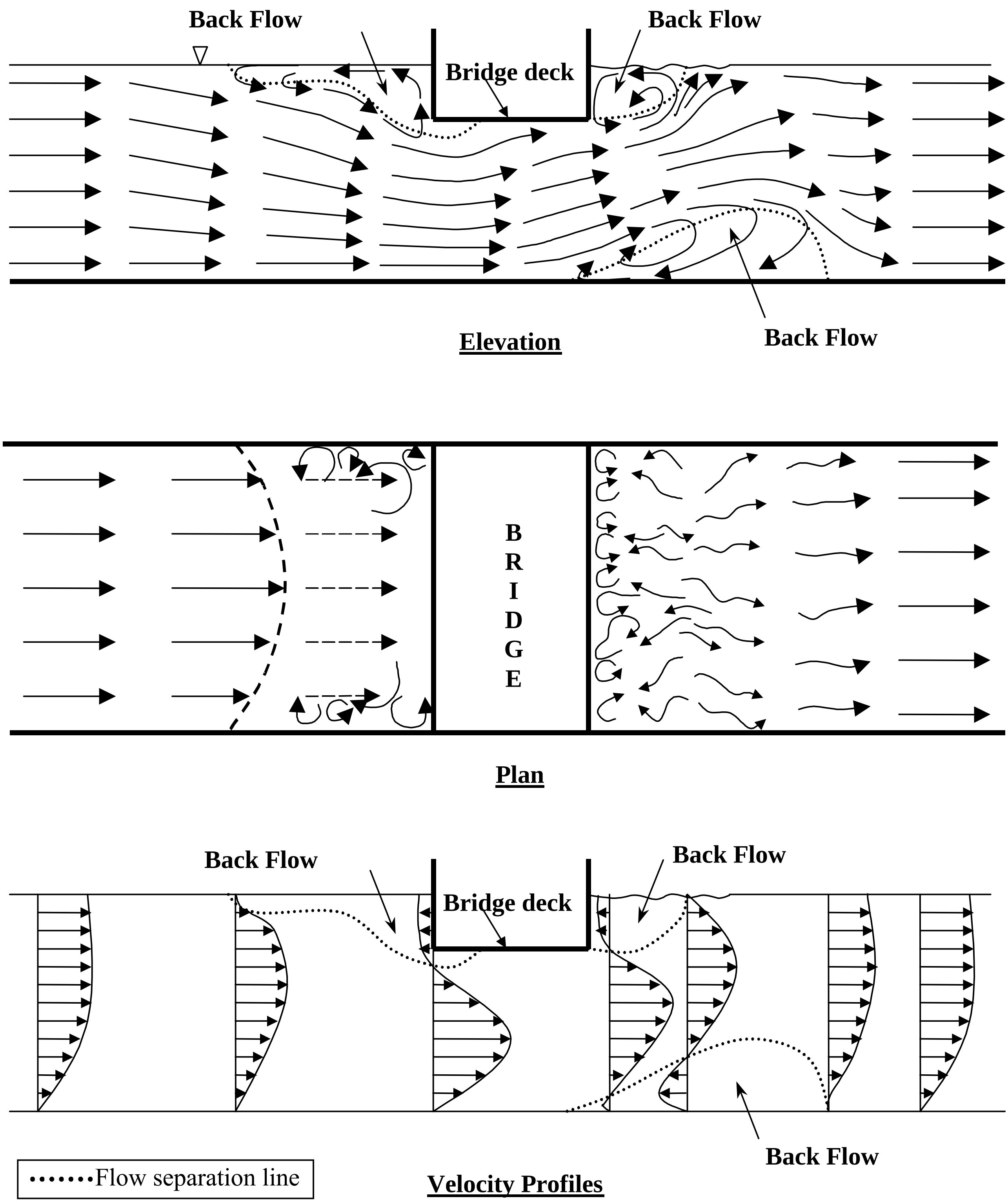


Figure 2. Flow lines and velocity profiles under a submerged bridge.

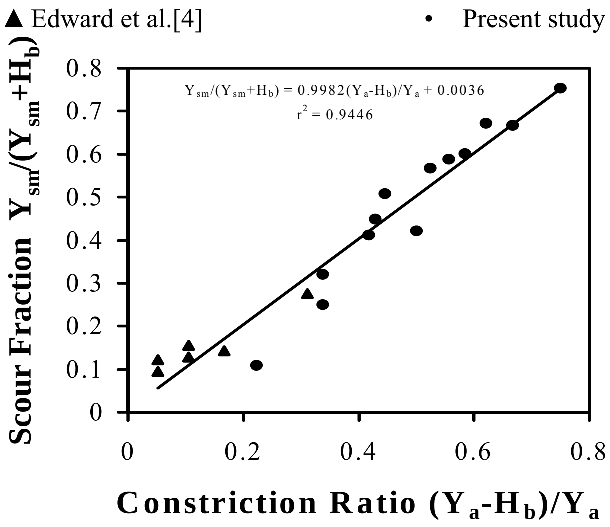


Figure 3. Effect of initial opening under the bridge on scour fraction $Y_{sm}/(Y_{sm}+H_b)$.

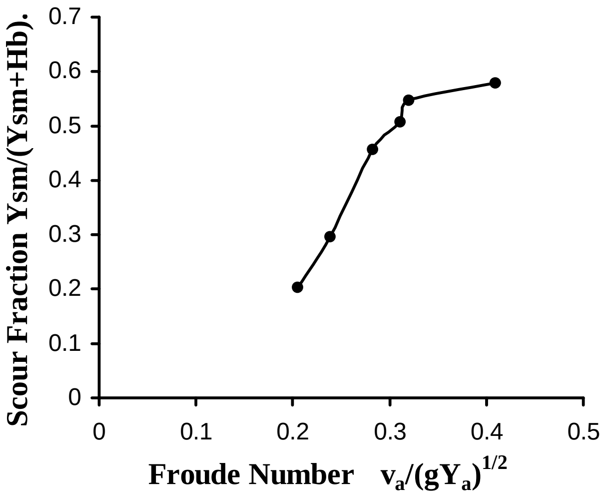


Figure 5. Effect of velocity on scour fraction $Y_{sm}/(Y_{sm}+H_b)$.

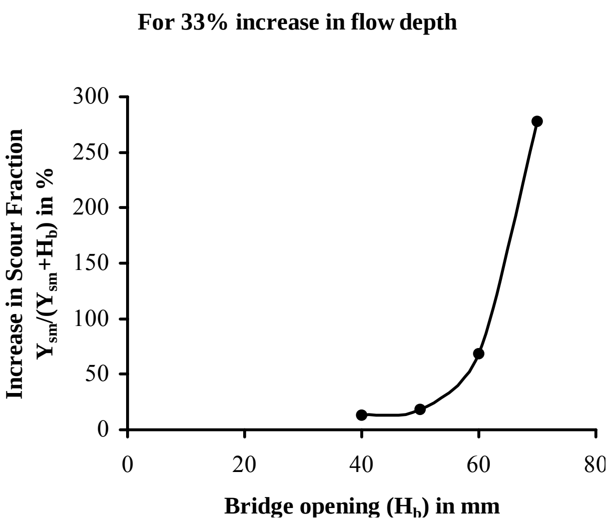


Figure 4. Effect of depth of flow on scour fraction $Y_{sm}/(Y_{sm}+H_b)$.

Equation 2 can easily be acknowledged as the governing equation between scour fraction and constriction ratio. The simplified form of Equation 2 is expressed as

$$Y_{sm} = Y_a - H_b \tag{3}$$

This simple equation reveals that for incipient conditions on the upstream of the bridge deck, the scour depth will be equal to the amount by which the depth of flow is constricted.

Investigation was further carried to study the effect of flow depth on scour depth. A general increase in scour depth has been observed with increase in depth of flow, but the effect of flow depth fluctuations is more prominent for lower constrictions. For 33% increase in flow depth, the increase in scour fraction has been observed to be 13.24, 18.50, 68.40 and 277.98% for bridge openings 40, 50, 60 and 70mm respectively (Figure 4).

After testing a wide range of velocity from clear water scour condition to live bed scour condition, it has been found that the effect of velocity is prominent up to approaching Froude number $v_a/(gY_a)^{1/2}$ of 0.32 beyond which its effect seems to diminish (Figure 5).

In order to study the effect of unsteady flow, the flow conditions were varied from clear water to live bed and then from live bed to clear water condition, thereby simulating a single peaked hydrographic flood. The flow conditions were changed after every 20 minutes, increasing the discharge in four time steps to reach the peak under live bed condition and then brought back to clear water condition in the same way. For each

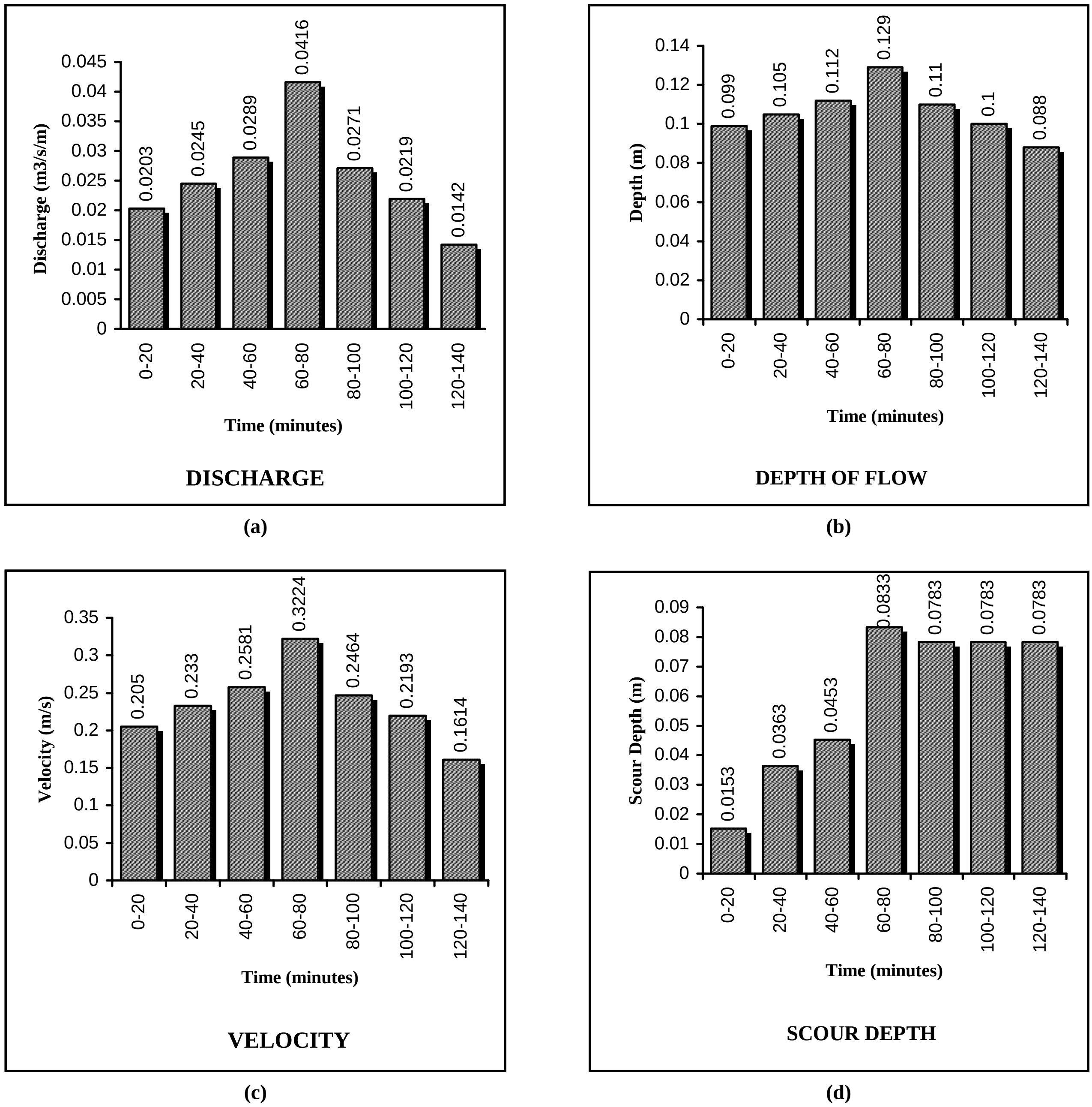


Figure 6. Combined effect of clear water and live bed conditions on the scour depth.

discharge, the change in flow depth, flow velocity and corresponding scour depths were noted and have been presented in Figure 6. A maximum of 8.33cm of scour depth was observed under the bridge corresponding to a maximum discharge intensity of 0.0416 m^3/s/m, depth of flow 0.129m and velocity 0.3224m/s. As expected, the highest rate of scour in the entire experimental run was observed during this period.

When two bridges are constructed in close proximity, they will have an interference effect on each other. To study this effect two similar bridge models were spaced at 0.5B, 1.0B, 1.5B and 2.0B, for bridge opening H_b as 60mm, flow depth Y_a as

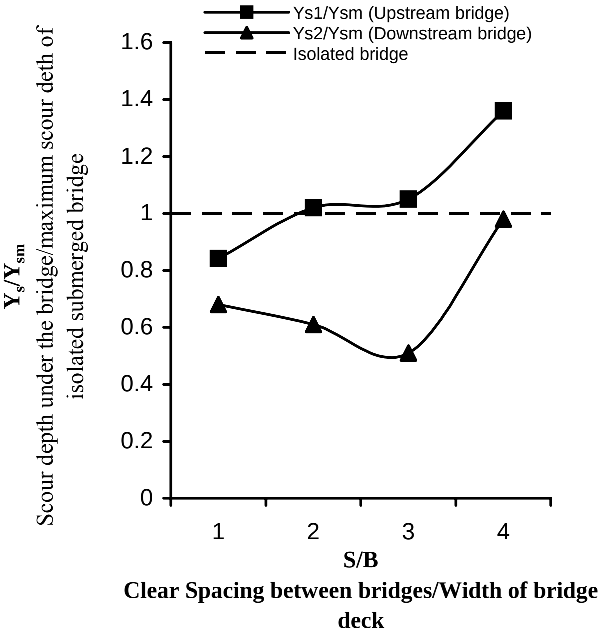
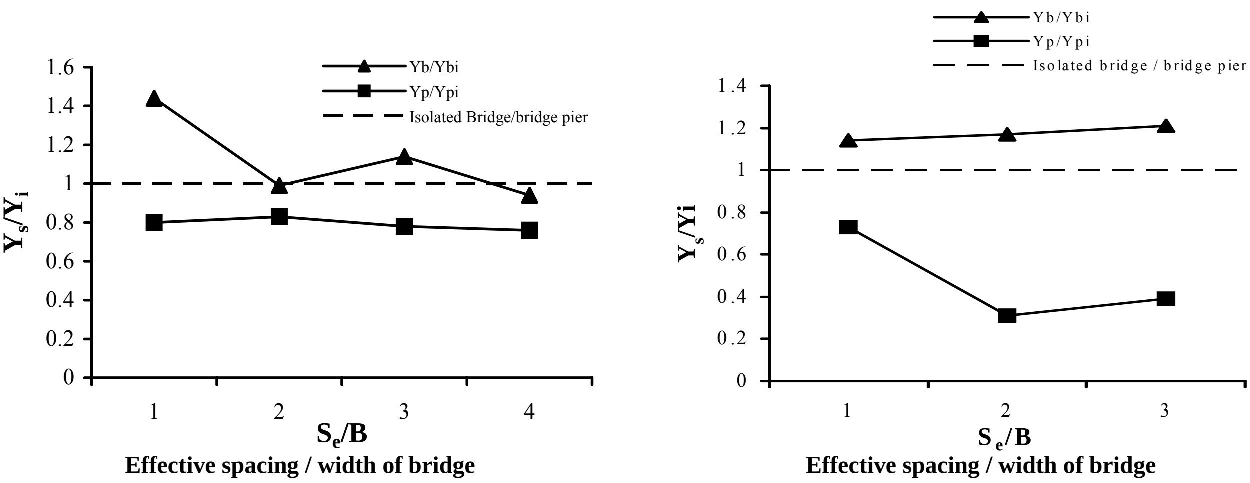


Figure 7. Effect of interference of two submerged bridges.

0.120m and approach velocity corresponding to the incipient velocity of bed sediment. Here B refers to the width of bridge. The results have been presented in the form of a plot between Y_s/Y_{sm} and S/B, (Figure 7), where Y_s is the scour depth under the bridge, Y_{sm} is maximum scour depth under an isolated submerged bridge in similar conditions and S is the clear spacing between the bridges. From the observed data, it may be predicted that two bridges when required to be constructed in close proximity and if they are likely to get submerged during floods, they may be spaced at a clear distance of 1.5 times the width of bridge for smaller scour depths. Interference of a submerged bridge and a pier is studied through experimental run no. 32 to 38 (Table 1) by varying the center-to-center spacing between the submerged bridge and pier and locating the pier on upstream and downstream side of the submerged bridge. It is observed that the bridge and pier have their separate scour holes when a pier is located at a distance of 2.0B or more on upstream side or at a distance greater than 1.5B on the downstream side of the submerged bridge. In spite of the separate scour holes, the maximum scour depth at bridge and the pier is influenced by the presence of each other. It is clear from Figure 8 that when the pier is located on the upstream of the bridge, pier scour reduces by 17 to 24% as compared to isolated pier scour and it is reduced by 69% when it is placed at 2.5B on the downstream of submerged bridge. So, an effective spacing of 2.5B or more can be considered safe for a pier on the downstream of a



(a) Pier on the upstream of Bridge

(b) Pier on the downstream of Bridge

Figure 8. Effect of Interference of Bridge and Pier.

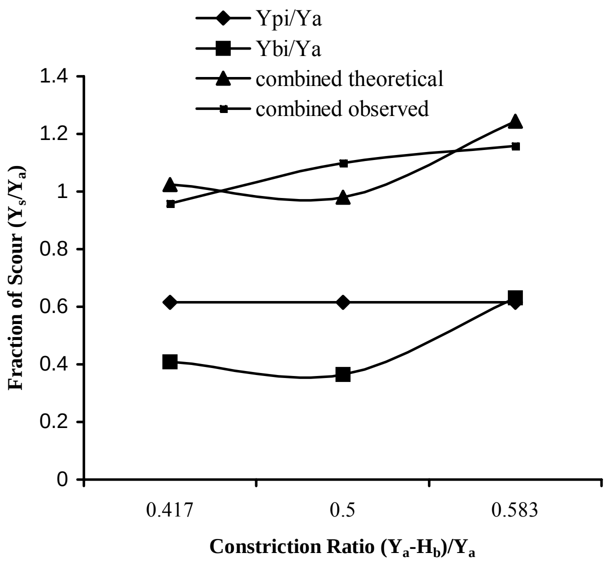


Figure 9. Effect of combination of a submerged bridge and a pier on the fraction of scour with respect to approach depth of flow.

submerged bridge. Further, when pier is placed at 2.5B upstream, bridge scour practically becomes less than that of an isolated bridge by about 6%. Therefore, a distance of 2.5B or more for a pier on either side of a bridge can be considered safe for a submerged bridge.

Experiments were also conducted to study the combined effect of local scour around a pier and constriction scour due to a bridge deck. For this, the bridge model was installed in conjunction with a circular bridge pier and experimented under pressurized flow conditions. The results have been plotted in terms of constriction ratio and fraction of scour with respect to flow depth (Figure 9). The plot shows 12.36% more scour for a submerged bridge in conjunction with pier than the algebraic sum of their individual scours. Presently the maximum scour depth for a bridge is considered as the algebraic sum of general scour, local scour and constriction scour. Here the constriction scour is the sum of two components i.e. scour due to constriction in horizontal direction and scour due to pressure flow condition because of vertical constriction. The results of present study emphasize the use of a multiplication factor of more than 1.1236 (say 1.5), to take into effect the pressurized flow conditions wherever such conditions are encountered in the real field.

5. CONCLUSIONS

At incipient velocity of flow, the maximum scour depth Y_{sm} is equal to the magnitude by which the flow depth is constricted because of bridge submergence. The final clearance under the bridge will be equal to the approach depth of flow, Y_a. The effect of flow depth fluctuations on the pressure flow scour is more prominent for lower constrictions due to bridge deck. Two similar bridges in close proximity when likely to get submerged during floods may be spaced by at least 1.5 times the width of bridge. A pier, if required to be constructed on the upstream or downstream of a submerged bridge, may be spaced by at least 2.5 times the width of bridge. A multiplication factor of 1.5 is suggested while predicting maximum scour depth for designing a submerged bridge.

6. LIST OF SYMBOLS

B	Width of bridge model.
d_{50}	Median size of sediment.
σ_g	Geometric standard deviation of sediment.
SG	Specific gravity of sediment.
H_b	Initial opening under the bridge.
Y_a	Approach depth of flow.
Q	Specific discharge.
v_a	Approach velocity of flow.
v_b	Velocity of flow below the bridge.
S	Spacing between interfering bodies.
S_e	Center to center spacing between interfering submerged bridge and unsubmerged pier.
Y_s	Scour depth under the bridge.
Y_{sm}	Maximum scour depth.
r	Coefficient of correlation.
Fr_a	Approaching Froude number.
Y_{bi}	Maximum scour depth for an isolated submerged bridge.
Y_{pi}	Maximum scour depth for an isolated pier.

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