COMPUTATION OF AFFLUX WITH PARTICULAR REFERENCE TO WIDENING OF BRIDGES ON A ROADWAY

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ABSTRACT

Computation of afflux is extremely important to ensure adequate freeboard and avoid submergence in a bridge. Bridges with inadequate waterway may result in choking of flow and hydraulic jump. Various causes and methods of computation of afflux have been discussed. Out of 72 existing bridges on a highway 12 bridges had extremely high afflux due to inadequate waterway. Afflux is high afflux due to inadequate waterway. Afflux is reduced with increased waterway. Two options of either dismantling the old bridges or retaining them downstream of the new long span bridges have been examined. It is found that there is substantial increase in free board under the old bridge due to draw down effect. Reconstruction of old bridges is costly but retaining them causes problem of road safety.

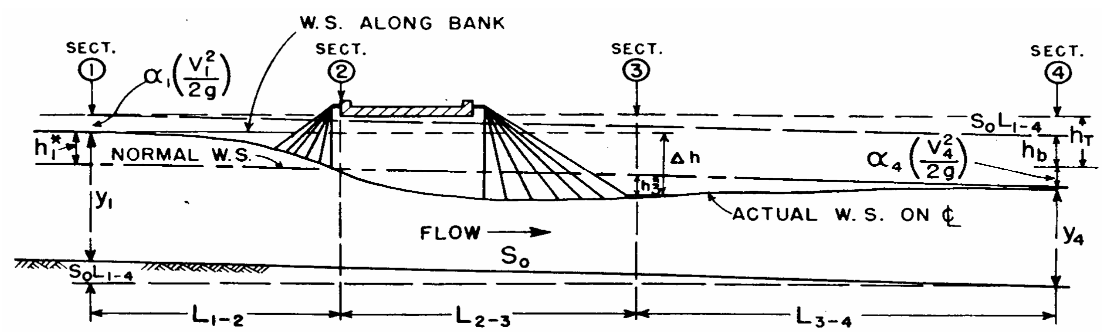
INTRODUCTION

Large number of bridges is to be constructed on roads being built/widened under the Prime Minister's 'Gram Sadak Yojna'. On an average, bridges and culverts cost about 30 to 40 per cent of the total cost of a road. For achieving economy, waterway under the bridge is often restricted. IRC: 5(1998) and IRC:SP-13 (2000 recommends that the waterway should be provided for a design flood of 50 years of return period. Except large rivers, which may have gauging records, design discharge and waterway for medium and minor bridges are to be estimated by different methods as prescribed in the code. Afflux is one of the most important parameters governing waterway. If the waterway is inadequate, afflux will be high resulting in rise in upstream high flood level which in turn will reduce free board under the bridge. IRC –5 prescribes the minimum free board varying from 150 mm to 1500 mm depending on design discharge. Additional free board may have to be provided if the river is aggrading or it carries large amount of debris,. For navigable rivers, the free board requirement will be decided by the type of vessels moving under the bridge. Extremely inadequate waterway under a bridge may result in choking of flow causing very high afflux, submergence of the bridge and overtopping of approach roads. Choked flow results in hydraulic jump formation downstream and a large back water effect upstream. Apart from submergence of large areas up stream (unless protected by flood embankments) such high afflux will result in deposition of sediments in the backwater reach upstream resulting in further rise in high flood level and loss of free board. The river tends to develop meander upstream and may ultimately outflank the bridge by breaching the approach embankments. Downstream high velocity flow arising out of high afflux will cause scour of beds and banks and may result in meandering and even change in river course.

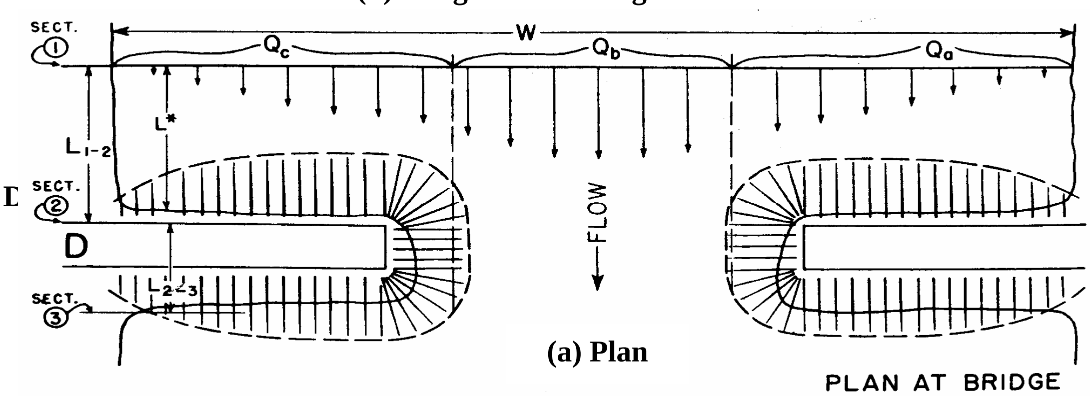
In this paper, authors estimated waterway, afflux and free board for bridges in a section of roadway proposed to be widened from existing 2 lane to 4/6 lanes. Most of these bridges are recently constructed. It is reported that 5 bridges were washed out due to heavy rainfall (a maximum of 620 mm in a day) occurring over a period of three days.

AFFLUX AND PARAMETERS GOVERNING AFFLUX

Afflux is the difference in water surface elevation at any point upstream of the bridge before and after the construction of the bridge for a given flow. It is the rise in HFL at any point upstream of the bridge compared to the normal HFL at the same point before the bridge is constructed. As shown in Fig. 1, highest afflux (h_1*) occurs just upstream of the bridge and it reduces to zero at a point far upstream where the new HFL merges with the normal HFL i.e. where the back water effect of the bridge ends. Usually the term afflux and back water in bridge design refers to the design maximum afflux corresponding to design flood discharge immediately upstream of the bridge as indicated in **Fig. 1**. IRC handbook (2000) state that afflux should not be harmful and generally limited to a maximum of 10 to 30 cm. Free board is the vertical clearance between the lowest point of the bridge deck/girder (soffit) and the design affluxed HFL upstream corresponding to design flood discharge. The minimum free board corresponding to the maximum permissible afflux for different discharge in a bridge is given in IRC-5. Various parameters governing the afflux in a bridge are briefly discussed below:



(b) Long Section along Flow Axis



(a) Plan

Fig. 1: Showing (a) Plan and (b) Section of a Bridge with non-uniform approaching flow.

Design Discharge

Afflux is principally governed by design discharge. Higher the design discharge, higher will be the flow velocity resulting in higher afflux. The design afflux corresponds to the design peak flood with a return period of 50 years. In very important bridges, the design flood discharge may be considered for a return period of 100 years or so.

Waterway

For any given design discharge, afflux is primarily dependant on effective waterway provided under the bridge from abutment to abutment. IRC code recommends waterway under the bridge as equal to Lacey's regime waterway given by the relation:

$$P = 4.8\ Q_d^{0.5} \qquad \text{.................} \qquad (1)$$

Where P is Lacey's regime waterway in metre and Q_d is the design peak flood discharge in m^3/sec. The decision to restrict waterway should be very carefully made considering various other aspects (Mazumder 2002) like choking of flow, scouring, sediment deposition, flooding of upstream area, velocity of flow downstream, possibility of outflanking of bridge etc. **Fig. 2** depicts inter relation between design discharge, waterway and cost as function of afflux (taken from reference 1).

Flow Choking

Flow is said to be choked when a control section develops in the bridge with inadequate waterway. With level and rigid bed, the relation between fluming ratio (B_o/B_1), approach Froudes number of flow, (F_1) and the Froudes number of flow in the constricted portion under the bridge, (F_o) can be expressed as

$$B_o/B_1 = (F_1/F_o)[\ (2+F^2o)/(/2+F_1^2)]^{3/2} \qquad \text{..........} \qquad (2)$$

Fig. 3 gives a plot of B_o/B_1 for different F_o and F_1 values. Flow is choked when F_o= 1 and the critical value of B_o/B_1 corresponding to F_o = 1 gives the choking limit

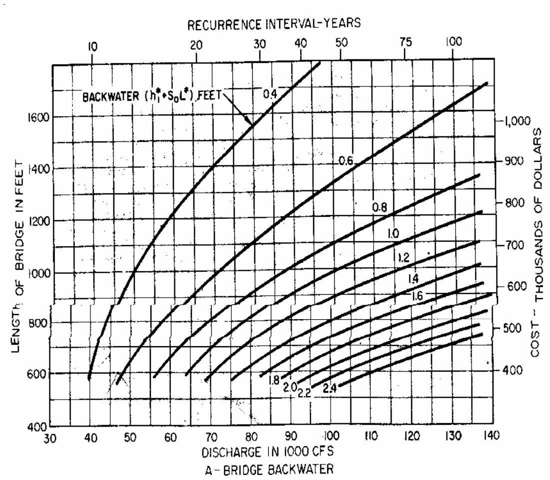


Fig. 2: Showing Interrelation between Design Discharge Waterway and Cost as Function of Afflux

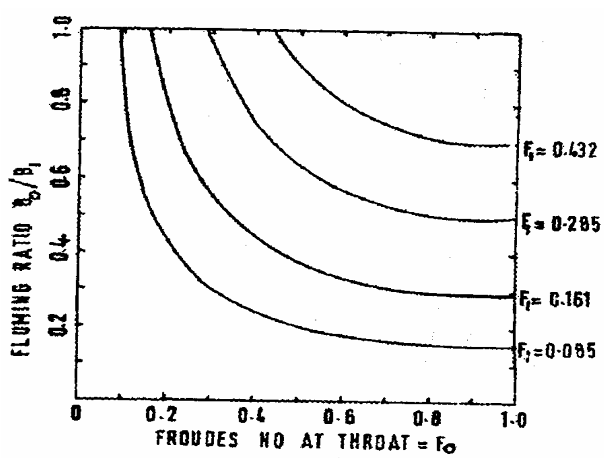


Fig.3: Showing Interrelation between F_1, F_0, and B_0/B_1

Waterway under a bridge should be sufficiently more than the critical value at choking to avoid unprecedented high afflux and consequent jump formation downstream. If the flow is choked, afflux will be determined by the head loss as well as minimum specific energy (E_{min}) required corresponding to the discharge intensity ($q_o = Q/B_o$) where

$$E_{min} = E_c = 3/2\ (q_o^2/g)^{1/3} \qquad \text{..............} (3)$$

Adding head losses (H_L) with E_{min} (or E_c), the actual specific energy required (E'_1) upstream to pass a given discharge (Q_d) with waterway, B_o (less than critical waterway at choking) is given by eq. 4 below.

$$E'_1 = E_c + H_L \qquad \text{.................} \qquad .(4)$$

Neglecting the change in approach velocity due to bridge constriction

$$\text{Afflux} = (E'_1 - E_1) \qquad \ldots \qquad .(5)$$

where E_1 is the normal specific energy upstream prior to bridge construction. Higher the discharge intensity (q_o), more is the minimum specific energy (E_c) required and more is the head loss and as such higher will be afflux.

Non-Uniformity of Approaching Flow

For any given design discharge and waterway, afflux will be higher with greater non-uniformity of approaching flow (Fig. 1). For a deep channel with higher banks, flow is more uniform and available specific energy of flow is high. As a result, afflux will be less for any given constriction (B_o/B_1). However, when the channel is shallow accompanied with wide flood plane, afflux will be much more for the same design discharge and waterway under the bridge, since the approach flow is highly non-uniform and the normal specific energy (E_1) available is low.

Scouring

When a bridge is constricted, it scours the bed increasing the waterway in vertical direction. Such scouring increases specific energy of flow and the afflux gets reduced. Bed erosion and afflux are interrelated. Afflux depends on the amount of restriction of normal waterway i.e. extent of fluming, the inlet geometry and obstruction to flow in the approaches and piers on the one hand and the type of flood hydrograph on the other. In rivers with sustained floods, the full bed scour would develop giving negligible afflux while in flashy rivers, the time for bed scour may not be adequate causing very high afflux.

DIFFERENT METHODS OF COMPUTING AFFLUX

With level bed (or mild sloping bed), afflux (h^*_1 as shown in Fig. 1) can be found directly if the water levels upstream and downstream of bridge are known. Unfortunately there is hardly any such gauging data available in our country. Afflux can be estimated by using several empirical equations e.g. IRC:89 (1985) Nagler (1918), Rhebock (1921), Yarnel (1934), Rao (1997) etc. IRC-SP 13 recommends use of wier /orifice formula for computing flow with known afflux or vice versa. For shallow channels with wide flood planes (as observed in most of the rivers across the bridges on this roadway a rough first approximation of finding afflux can be obtained from the following expression, (Bradley 1970)

$$h^*_1 = 3(1 - M)\, V^2_{n2}/2\,g \qquad \ldots\ldots\ldots\ldots\ldots \qquad (6)$$

In eq. 6, $M = Q_b/Q$, where Q_b is that portion of the total discharge Q in the approach channel within a width equal to the projected length of the bridge (Fig. 1) and $V_{n2} = Q/A_{n2}$ and A_{n2} is the gross area of waterway under the bridge opening below normal stream depth corresponding to design flood discharge.

IRC:5 and 89 recommend use of Molesworth's equation for computing approximate afflux given below:

$$h^*_1 = [V^2/17.88 + .015]\,[(A/A_1)^2 - 1] \quad \ldots\ldots. \quad (7)$$

Where V is the mean velocity of flow in the river prior to bridge construction i.e. corresponding to normal HFL, A and A_1 are the areas of flow section at normal HFL in the approach river section and under the bridge respectively.

For minor and medium bridges, weir and orifice formula given in IRC:SP-13 can be used for computing afflux depending on whether the flow under the bridge is choked or free

For choked weir type flow: $Q = C_d\, L_{eff}\, (D_u + u^2/2g)^{3/2}$ if $h^*_1 D_d > 0.25$ 8(a)

For orifice flow : $Q = C_d\, L_{eff}\, D_d\ \sqrt{2g.\, h_1^*}$- if $h_1^*/D_d < 0.25$ 8(b)

Where C_d & C_o are the coefficients of discharges for weir and orifice type flows respectively. Cd and Co values are given in the IRC code, h^*_1 = afflux = $(D_u - D_d)$. D_u and D_d are the upstream and downstream depths measured from the lowest bed level under the bridge taken as datum.

COMPUTATION OF AFFLUX AND FREE BOARD FOR THE EXISTING BRIDGES

Hydraulic computations were carried out for finding the adequacy of waterway for 72 existing bridges on a roadway, in a stretch of about 200 km. It is proposed to widen the road from 2 lane to 4/6 lanes under the Prime Minister's 'Gram Sadak Yojna'. Afflux was found corresponding to design discharge for all these bridges. Existing 39 bridges were found to be unsafe due to inadequate or negative free board. In 1993 flood, 5 bridges were reported to be washed out. It was decided to retain all those bridges, which had positive free board. Free board of 17 minor bridges out of 39 bridges was further increased by providing smooth transitions both upstream of the existing bridges and downstream of the new bridges. Provision of transitions reduced head loss and decreased afflux. Out of the remaining 22 bridges, 10 bridges were to be made 4 lane new bridges either due to realignment for improvement of road geometry or due to other reasons. In the case of 12 bridges, however, afflux was too high as shown in **Table- 1**. Afflux computed by equations 6,7,8 are compared with the afflux given by the difference between upstream and down stream HFL -both found from local enquiry. Obviously, both estimated afflux and the afflux found from local enquiry may not be true afflux which can be found only when gauge record is available both up stream and downstream of the bridges. It was decided to increase the waterway for all the 12 new two lane bridges for widening the road as indicated in **Table –2**. The two possible options are either the existing bridges should be dismantled or they should be retained.

POSSIBLE OPTIONS OF DISMANTLING OR RETAINING OLD BRIDGE

Option I

One option is to provide adequate waterway for both the new two lane bridge as well as the existing two lane bridge either by adding extra spans required or by dismantling the old bridge and constructing a new one of the span same as that of the new bridge. Both are costly and difficult propositions. Opening new span and raising deck level for the existing old bridges are extremely difficult to execute. **Fig. 4(a)** gives a sketch indicating this option. Afflux for option I estimated by equation (8) is given in Table-2. Obviously because of longer spans, the afflux reduced substantially as compared to the afflux given in Table –I for the existing two lane bridges with inadequate waterway.

Table –1 : Afflux and Freeboard for Existing 12 Bridges on a Roadway

Sr. No.	Existing Bridge Details						Design Dischage (cumecs)	Estimated Afflux (m)		
	Effective Water way (m)	Deck Level (m)	HFL as per local enquiry (m)		Afflux from local enquiry (m)	Free Board (m)				
			U/S	D/S				Eq. (6)	Eq (7)	Eq. (8)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	116	112.29	110.24	108.2	2.04	0.06	1594	2.56	0.72	1.95
2	57.3	108.508	106.608	104.9	1.708	0.05	1022	1.29	2.3	1.76
3	76.4	89.669	89.576	86.5	3.076	-1.71	1140	3.5	0.84	1.35
4	56	91.759	91.176	88.39	2.786	-1.42	679.5	2.16	0.85	1.2
5	6	94.997	94.406	92.673	-	0.09	61	2.59	3.82	1.733
6	48	118.282	116.15	113.36	2.79	0.03	943	1.25	2.22	3.155
7	37.8	97.337	96.137	94.35	1.787	-0.4	198	0.94	0.45	1.234
8	25	80.01	77.51	76.3	-	0.27	409	1.38	2.53	1.207
9	42.8	59.06	57.128	55.15	1.978	0.53	383.7	1.28	0.71	2.128
10	56.8	49.326	48.026	46.46	1.566	-0.6	647	1.22	0.65	0.732
11	9	51.155	51.089	48.913	-	-0.93	33.77	1.43	0.64	2.13
12	9	50.353	49.7	48.113	-	-0.25	64.32	0.81	2.13	2.12

Table – 2 : Afflux for different options and Freeboard under Existing Bridge

Sr. No.	Design Discharge (cumecs)	Lacey's waterway (m)	Effective waterway (m)		Option I (4 - Lane New Bridge)		Option II (2 - lane new Bridge upstream and 2- lane existing Bridge downstream)				
			New Bridge	Existing Bridge	Estimated Afflux (m) Eq. (8)	u/s HFL (m)	Estimated Afflux (m) Eq. (8)	Soffit Level for Existing Bridge (m)	HFL u/s of new bridge (m)	HFL u/s of old bridge (m)	Free Board under existing Bridge (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1	1594	191.64	140	116	1.4	109.002	1.00	110.19	109.200	107.839	2.351
2	1022	153.44	90	57.3	0.709	105.609	1.23	105.935	106.130	104.583	1.352
3	1140	164.09	100	76.4	0.211	87.325	1.00	87.869	87.500	85.628	2.241
4	679.5	125.12	75	56	0.585	89.048	0.80	89.759	89.190	88.790	0.969
5	61	37.96	15	6	0.35	93.027	1.36	94.497	94.033	93.336	1.161
6	943	147.4	88	48	1.308	114.715	2.71	116.182	116.070	114.486	1.696
7	198	68.39	50	37.8	0.938	95.288	0.98	95.737	95.332	94.090	1.647
8	409	97.07	45	25	0.43	76.733	0.80	77.78	77.100	75.887	1.893
9	383.7	95.2	60	42.8	0.174	55.324	1.65	57.66	56.795	54.474	3.186
10	647	123.62	75	56.8	0.36	47.070	0.67	47.426	47.130	46.795	0.631
11	33.77	28.24	18	9	0.7	49.611	1.97	50.55	50.883	49.829	0.721
12	64.32	38.98	20	9	0.53	48.638	1.88	49.453	49.993	48.870	0.583

Option II

Since the old two lane bridges are in good condition, the second option is to retain the old two lane bridge on the downstream side of the new long span two lane bridge at higher elevation (as per free board requirement), and connecting the old and new bridges by a well-designed contracting transition as shown in **Fig. 4(b)**.

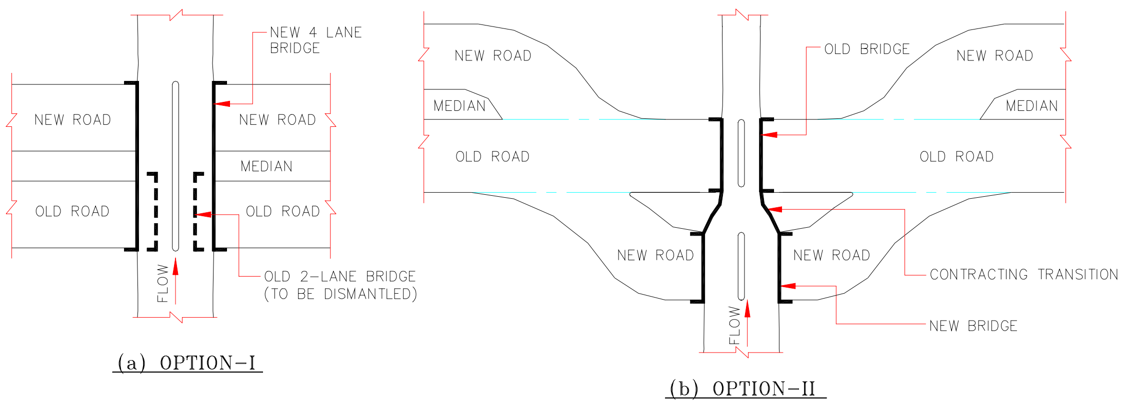


Fig. 4: Showing two different Options of (a) Dismantling (Option-I) and (b) Retaining (Option-II) old Bridge

Since the old bridge is placed downstream of the new bridge, free board in the old existing bridges is sufficiently increased due to draw down in water surface as shown in Table-2. Except two bridges all other bridges develop weir type control at the entry to the existing bridge of shorter span resulting in draw- down from affluxed depth (y_1) at u/s of new bridge to critical depth (y_c) at u/s of old bridge. High flood levels upstream of long span-new bridges and short span old bridges and the corresponding free board under the old existing bridges are given in Table-2. Even if the old bridge fails, it will not cause any damage to the new bridge, which is located upstream of the old bridge. It may be pointed out that the afflux for the four lane bridges in option II (table –2) is less than that in Table-1 (for the existing 2 lane bridges) due to improved bell mouth entry to the control section (old bridge) resulting in higher values of coefficient of discharge in equation (8). Second option has, however, some shortcomings. The road is being widened on the downstream side of the existing bridges, due to available right of way on the down stream side. In case of option II, however, the road has to be widened on the upstream side as the new bridges are to be constructed upstream of the old bridges on the existing road. For shifting the new road from downstream side to the up stream side of the existing road, it is necessary to provide suitable road transitions locally resulting in curved approaches to the bridges as shown in fig. 5(b). Moreover, the deck levels of the old bridges (at lower level) and new bridges (at higher level) will be different thereby introducing a vertical curve too. Both the horizontal and the vertical curves in the bridge approaches are not desirable from traffic safety point of view.

SUMMARY AND CONCLUSIONS

Computation of afflux is extremely important for deciding the design HFL and free board in a bridge. Afflux was computed by using three different methods and compared with that found from local enquiry. Out of 72 bridges on a roadway in a stretch of about 200 km, 39 bridges were found to be unsafe due to high afflux and inadequate free board. Afflux was reduced and free board increased in case of 17 minor bridges by introducing smooth hydraulic transition. Ten bridges had to be made four lane new bridges for realignment of road.

Waterway for 12 bridges, however, is found to be inadequate resulting in very high afflux. Table-1 and Table-2 give the afflux and free board for existing two lane and proposed four lane bridges. One option (table –2) is to provide increased waterway for both the new and the existing bridges by dismantling the old bridge and building the four lane new bridge with increased span and at higher deck level as per required free board. The second option is to retain the old bridge just downstream of the new bridge and connecting the two by smooth contracting transition. In the first option, the cost will increase due to reconstruction of additional two lane bridges. In the second option, the free board under the old existing bridge will substantially increase due to draw-down effect and the old bridges can be retained. But the road has to be provided with both horizontal and vertical curves for shifting the new two-lane road from down stream to upstream side. Such curves near approach to bridges on a National Highway may not be desirable from the point of view of road safety.

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