

RESTRICTION OF WATERWAY UNDER BRIDGES

By

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1. INTRODUCTION

Ministry of Road Transport & Highways has an ambitious programme of constructing/widening National Highways of about 13000 km length connecting Kashmir with Kanyakumari and Assam with Gujarat and a golden quadrilateral connecting the four metropolis, namely, Delhi, Kolkata, Chennai and Mumbai. Apart from National Highways, a network of State Highways, District Roads and Village Roads are also going to be constructed. Large numbers of bridges are going to be built/widened on these roads. On an average, bridges cost 30 to 40 per cent of the total cost of highways depending on the size of streams, their bed and bank conditions. For achieving economy, the waterway under a bridge is often restricted compared to the regime waterway of the channel. Waterway to be provided under a bridge is governed by design discharge. IRC:5 recommends design discharge as the peak flood discharge with a return period of 50 years. Objective of the present Paper is to critically examine the current practice of restriction of regime waterway for determining the design waterway under the bridge.

Kand and Saxena (1989) observed that the rivers with deep channel in midgorges and flat banks where water spreads a long distance once the gorge banks are overtopped, length of bridges should be decided on the basis of following considerations:

- (a) The length of the bridge should be equal to that length of the river (in the midgorges) through which 80 per cent of the design flood passes, i.e., approximately 80 per cent of normal waterway under design HFL
- (b) Afflux should not exceed 60 cm
- (c) Increase in scour depth due to contraction is not large.

The Authors analysed the statistical data of 100 major and 100 minor bridges in Madhya Pradesh and recommend following approximate length of bridges based on catchment area at the bridge crossing:

$$L = 5.7 \sqrt{CA} \text{ for minor bridges (} L < 30 \text{ m)}$$
$$L = 3.8 \sqrt{CA} \text{ for major bridges (} L > 60 \text{ m)}$$

Where, L is the length of bridge in metre and CA is the catchment area in square kilometre.

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Spring (1903) developed a new technique in which he suggested different permissible maximum scour depths under bridges for different types of bed materials. Applying the estimated velocities, he recommended length of bridge where the scoured section under the bridge will discharge the incoming flow. Lacey (1929) introduced a totally new concept of regime waterway for the design of bridges and other hydraulic structures discussed in more detail in the following sections.

2. LACEY'S REGIME WATERWAY/ BANKFULL WIDTH OF RIVER

Regime waterway is developed by a stream when it attains a state of stability under equilibrium of forces causing the flow and opposing it. Historically, a stream carries different flows in different years, depending on rainfall and runoff. Waterway developed by a stream over the years of its journey is not occupied fully when floods of lesser intensity pass through it. Obviously, regime waterway of a river will vary with variation in design discharge. For example, regime waterway for a flood of 100 years return period will be much larger than that for a flood of 25 years return period.

Eminent River engineers, like, Lacey (1929), Lane (1955), Blench (1957), Kondap and Grade (1979) Garde and Ranga Raju (2000), White (1982), Diplas (1990) and others have conducted a lot of original research study for finding regime waterway. Starting from different concepts, all these River Scientists predicted the stable waterway parameters, e.g. width, depth, shape and slope of the stream from known values of independent variables like

discharge (Q), sediment size (d), sediment concentration (C) bed and bank conditions etc. For the design of waterway under bridge, IRC Code 5 (1998) recommends use of Lacey's regime waterway given by equation (1).

$$W = MQ^N \quad \dots (1)$$

Where W is the Lacey's regime waterway and M and N are empirical constants which are found to vary widely depending on bed and bank materials. For unbraided straight channels in alluvium, M is usually taken as 4.8 and N as 0.5 as per IRC Code. Meandering channels flowing in fine alluvial materials, such as, silts and sand, bank full width of the stream is found to be almost the same as Lacey's regime Waterway. In braided channel like Kosi river, however, bank full width is found to be 15 times Lacey's Waterway. It is 12 times in Brahmaputra river and 8 times in Sone river. On the other hand, in case of incised rivers, like, Tapi in Gujarat and other rivers in the Indian peninsular region, bank full width is found to be 50 per cent or even less than Lacey's regime waterway.

3. MODIFIED LACEY EQUATION FOR CHANNELS WITH STABLE BANK

Fig. 1 shows a plot of bank full width against flood discharge as observed in 46 channels crossing Durg-Nagpur Section of NH-6. By regression analysis, it is found that modified Lacey's type equation $W = MQ^N$, (with $M = 4.16$ and $N = 0.389$) gives best fit with a coefficient of correlation $r = 0.91$. Similar modified Lacey's equations (2a, 2b, 2c) have been recommended by CWC (1987) for the east flowing rivers lying in subzones 4a, 4b, 4c, comprising upper, lower and south coasts (below Mahanadi basin).

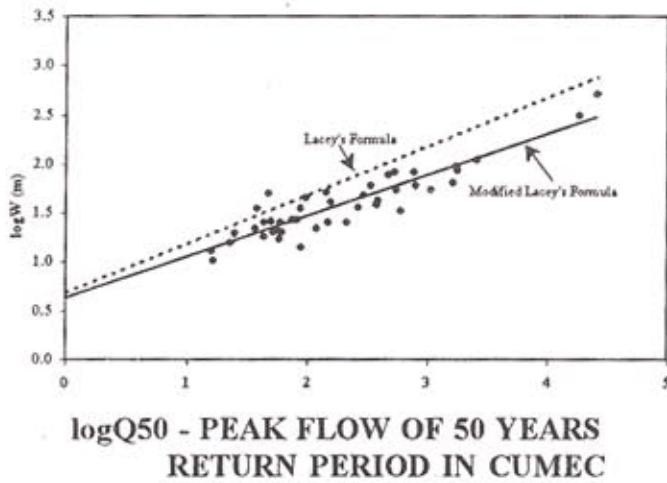


Fig. 1. Variation of bankful width (W) with design discharge (Q_{50}) for rivers crossing Durg-Nagpur Section of NH-6

$$W_{25} = 8.67 (Q_{25})^{1/3} \quad \dots (2a)$$

$$W_{50} = 9.84 (Q_{50})^{1/3} \quad \dots (2b)$$

$$W_{100} = 8.20 (Q_{100})^{1/3} \quad \dots (2c)$$

Where W_{25} , W_{50} and W_{100} are the regime waterways in metres corresponding to design flood discharge (in cumec) of 25, 50 and 100 years return periods respectively.

4. LIMITATIONS OF LACEY'S EQUATION

Although Lacey's concept of stable channel has been universally acknowledged, it has several limitations, namely,

- (i) It does not consider any other variables, like, sediment size and sediment concentration
- (ii) Bank condition and landuse
- (iii) Flood flow duration
- (iv) Longitudinal slope of the river
- (v) State of the river, e.g., aggrading, degrading, meandering, braiding and other river dynamics.

Eventhough Lacey's regime waterway is based on empirical relation, it gives values very close to the ones predicted by recent advanced methods²¹. Table 1 below gives regime waterway found from Lacey's and Yalin's equation and compared with actual observed widths. It may be seen that upto a sediment size of 0.8 mm, Lacey's and Yalin's methods give almost identical results and the predicted waterway are almost the same as observed. With $d = 31$ mm, Lacey's equation over-estimates whereas, Yalin's equation give very good prediction of waterway. Thus, for small size sediments say upto 2 mm or so, Lacey's method gives an excellent guideline for finding regime waterway. With larger size of bed materials, Lacey's method should not be used and advanced methods, like, Yalin

TABLE 1. COMPARISON OF STABLE CHANNEL WIDTH BY YALIN'S EQUATION AND LACEY'S EQUATION

Name of river	Q (m ³ /s)	d (mm)	Regime Width (m)		Measured width (m)
			Yalin's Equation	Lacey's Equation	
Bhagirathi River	1,669.7	0.18	221.3	196.1	218.1
Beaver River	141.4	0.50	61.0	57.1	54.9
Mississippi River	13,252.0	0.66	653.6	552.6	532.2
Savannah River	848.9	0.80	140.0	139.8	106.7
North Saskatchewan River	4,386.0	31.00	236.3	317.8	244.0

may be used for finding regime waterway. However, use of such advanced methods need a large number of data which may be difficult to obtain.

5. DESIGN WATERWAY UNDER BRIDGES

For non-meandering channels with alluvial bed but with rigid non-erodible boundaries, IRC: 5(1998) recommends that the design waterway under the bridge shall be the distance between the banks at HFL corresponding to the design flood which can be safely passed without producing any harmful afflux. In case of meandering channels with erodible boundaries, code recommends use of Lacey's waterway as the design waterway. Meandering and braided channels have large widths of flood plane (meander belt) in which the river is found to constantly move its position, especially where the regime condition has not been achieved. In such cases, design waterway provided under the bridge is equal to Lacey's waterway. Guide bundhs are usually provided both upstream and downstream of the bridge to ensure parallel flow approaching and leaving the bridge. Even though the guide bundhs are costly, considering the overall savings due to reduced bridge length, flood plains of major rivers are usually restricted by providing guide bundh with approach embankments as shown in Fig. 2.

Although the waterway for the major bridges are hardly restricted beyond Lacey's waterway, in medium and minor bridges the design waterway under the bridge is usually kept less than Lacey's Waterway for achieving economy. If the waterway based on design discharge is made equal to Lacey's waterway, there is slack flow for floods of lesser intensity. In

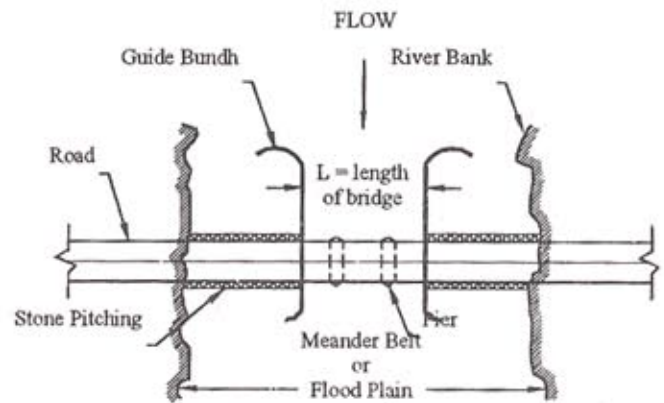


Fig. 2. Showing flood plain and guide bundh for bridge

such circumstances, the river has a tendency to meander with skew flow causing erosion on one side and deposition on the other, Fig. 3(a) & (b). Since guide bundhs are not normally provided in such medium and minor bridges, oblique flow with high angle of attack may cause more scour and damage to piers and abutments. It is, therefore, perhaps desirable to flume the channel to some extent, so that, the bridge waterway is less than Lacey's waterway corresponding to design flood of 50 years return period. A maximum restriction upto $2/3^{\text{rd}}$ of regime waterway is recommended.

6. FLUMING OF WATERWAYS FOR BRIDGES ON DURG-NAGPUR SECTION OF NH-6

Table 2 gives the fluming ratio (expressed as the ratio between linear waterway under the bridge and Lacey's regime waterway) adopted for the existing bridges on the National Highway-6 (Durg-Nagpur Section). Fluming ratio given in column 7 is found to vary from 0.21 to 0.91. column 8 of Table 2 gives the fluming ratio for the same bridges when the modified Lacey's type equation ($M=4.16$, $N= 0.396$) as discussed under Section-3 is used.

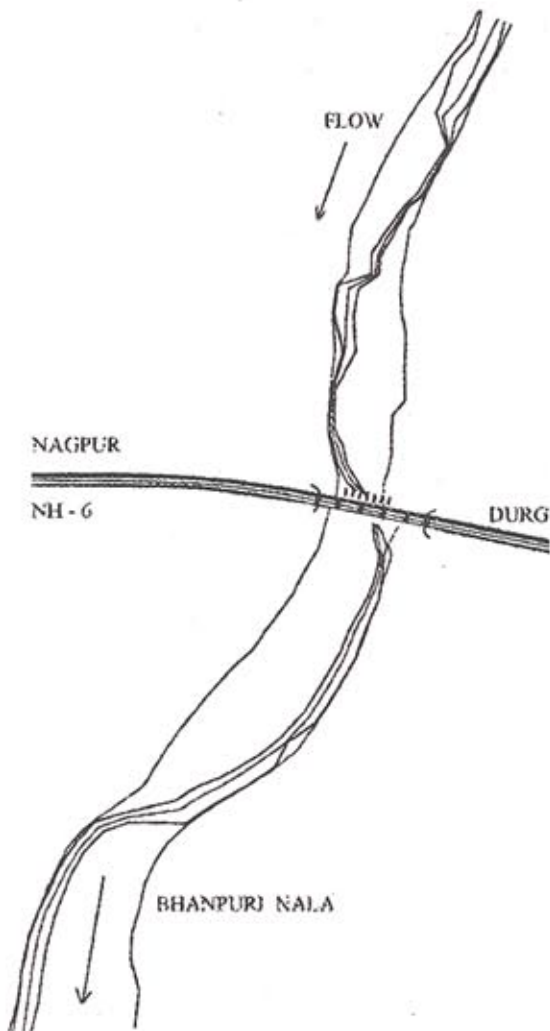


Fig. 3(a). Bridge No.353/8 at chainage 352.85 (Fluming ratio = 1.214) showing skew flow with Meander

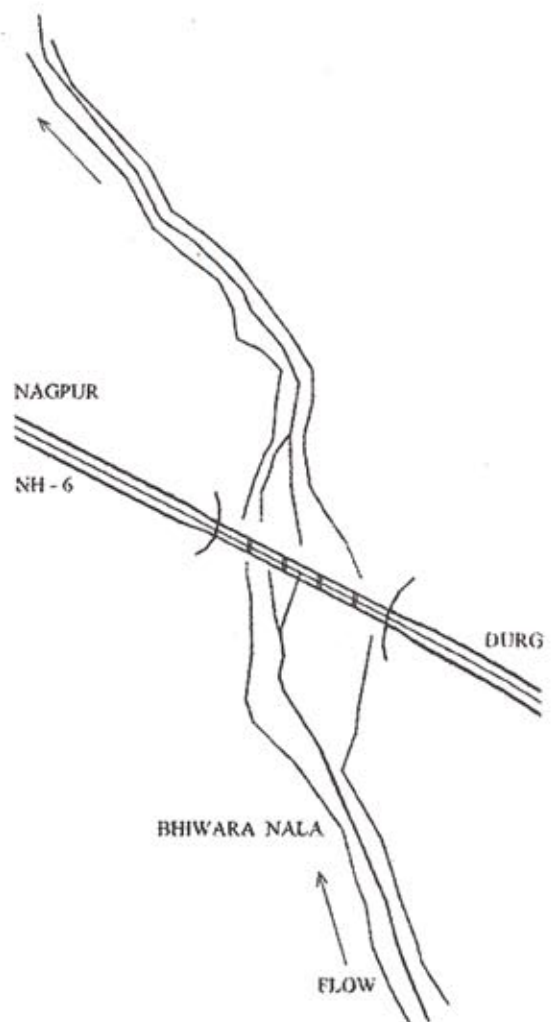


Fig. 3(b). Bridge No.487/2 at chainage 486.8 (Fluming ratio = 2.107) showing skew flow with tendency to Meander

Fluming ratio is found to vary from 0.51 to 2.1. Eventhough, fluming ratio is very low in some cases, no adverse effect has been reported from the field so far. If that be so, the question which automatically arises is whether there is any limit to fluming or restriction of regime waterway under a bridge. Some rational criteria to decide the extent of restriction to be adopted for safe design of waterway under innumerable medium and minor bridges have been discussed in the following section.

7. CRITERIA FOR RESTRICTION OF REGIME WATERWAY

Designer of a bridge must be well

acquainted with the risks involved in excessive restriction of normal waterway to reduce length of a bridge. The various adverse effects of excessive restrictions are discussed in this Paper.

7.1. Afflux

Afflux is the rise in water level just upstream of the bridge before and after the construction of the bridge. IRC code recommends fluming without creating any harmful afflux which may be limited to 30 cm or so. Large afflux due to excessive fluming causes submergence of agricultural lands, forests, human habitations, etc. lying

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TABLE 2. FLUMING RATIO ADOPTED IN 46 EXISTING BRIDGES IN NH-6 (DURG-NAGPUR SECTION)

Sl. No.	CD. No.	Design Discharge, Q	Linear waterway provided in the existing bridges, m	Regime waterway, $W = MQ^N$		Fluming Ratio	
				Lacey's waterway, m (M=4.8, N=0.5) (as per IRC Code)	Waterway using modified (M=4.16, N=0.389)	With Lacey's Waterway	With Modified Lacey's equation
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	327/6	96	22.1	47.030	24.558	0.470	0.900
2	328/4	38.13	9	29.640	17.148	0.304	0.525
3	332/4	47.03	15	32.918	18.606	0.456	0.806
4	334/6	333	47.8	87.592	39.840	0.546	1.200
5	338/8	358.1	50.8	90.833	40.983	0.559	1.240
6	348/6	63.92	16.5	38.376	20.965	0.430	0.787
7	353/8	2094.611	98.900	219.681	81.471	0.450	1.214
8	358/8	50	13.45	33.941	19.054	0.396	0.706
9	373/2	74.988	13.600	41.566	22.308	0.327	0.610
10	376/4	59.38	15.55	36.988	20.372	0.420	0.763
11	381/2	796.840	28.400	135.496	55.941	0.210	0.508
12	385/6	51.431	9.400	34.423	19.265	0.273	0.488
13	405/200/1	1732.322	100.045	199.782	75.669	0.501	1.322
14	408/600	86.525	16.200	44.649	23.585	0.363	0.687
15	412/800	55.989	12.500	35.916	19.912	0.348	0.628
16	414/600/1	588.712	28.430	116.464	49.726	0.244	0.572
17	422/600/1	43.61	11.95	31.698	18.067	0.377	0.661
18	429/200/1	292.58	36.5	82.104	37.885	0.445	0.963
19	431/200	547.838	40.140	112.349	48.354	0.357	0.830
20	435/600/1	88	10.7	45.028	23.741	0.238	0.451
21	441/800/3	2562.327	133.10	242.973	88.115	0.548	1.511
22	448/800/1	147	12.4	58.197	28.985	0.213	0.428
23	450/400/1	765.666	58.500	132.819	55.079	0.440	1.062
24	455/800/2	1623.966	56.390	193.433	73.792	0.292	0.764
25	459/1	371.963	32.145	92.574	41.593	0.347	0.773
26	471/1	118	24.6	52.141	26.611	0.472	0.924
27	473/1	264	30.29	77.991	36.400	0.388	0.832
28	481/1	58	14.25	36.556	20.187	0.390	0.706
29	484/2	210	22.16	69.559	33.299	0.319	0.665
30	487/2	522	100	109.667	47.453	0.912	2.107
31	491/1	25930	495.6	772.934	216.802	0.641	2.286

(Table Contd.)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
32	495/1	43	12.65	31.476	17.969	0.402	0.704
33	496/1	143	23.59	57.400	28.676	0.411	0.823
34	499/1	155	24.02	59.760	29.589	0.402	0.812
35	503/1	468	39.5	103.840	45.480	0.380	0.869
36	509/2	23	7.9	23.020	14.087	0.343	0.561
37	511/1	1749	104.3	200.741	75.952	0.520	1.373
38	521/2	16.5	9.5	19.498	12.379	0.487	0.767
39	521/3	18186.903	364.750	647.322	188.860	0.563	1.931
40	529/1	16	8.4	19.200	12.232	0.438	0.687
41	531/1	25	9.3	24.000	14.551	0.388	0.639
42	532/1	81	17.62	43.200	22.988	0.408	0.766
43	536/1	36.64	20.1	29.055	16.884	0.692	1.190
44	539/2	60.97	10.65	37.480	20.583	0.284	0.517
45	541/1	1052.671	77.200	155.736	62.340	0.496	1.238
46	547/1	383.37	35.9	93.983	42.084	0.382	0.853

upstream of the bridge. In hilly terrain, afflux resulting from fluming may not cause submergence but it may cause overtopping and damage of the road. When banks are of low height, afflux bundhs may have to be constructed in the back water reach to protect areas upstream. All these are costly propositions and require annual maintenance. The additional costs may be much more than the saving achieved due to restriction of waterway.

Afflux occurs due to the head losses upstream and downstream of the bridge¹⁴. Afflux can be reduced substantially by providing well designed splayed transitions connecting the constricted waterway with the normal waterway, Fig. 4. Cost of the splayed transitions and their foundations may outweigh the savings achieved after a certain amount of restriction since the length of transition structures become excessively high. Average splay governing transition length is not linearly proportional

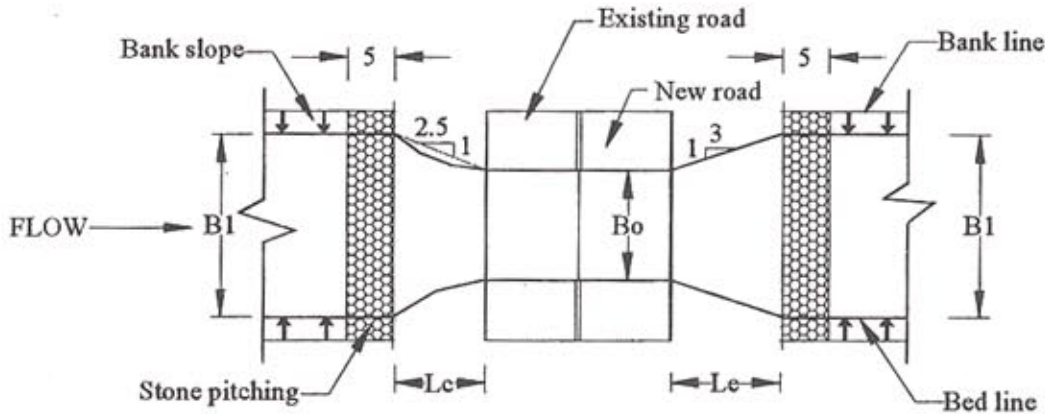
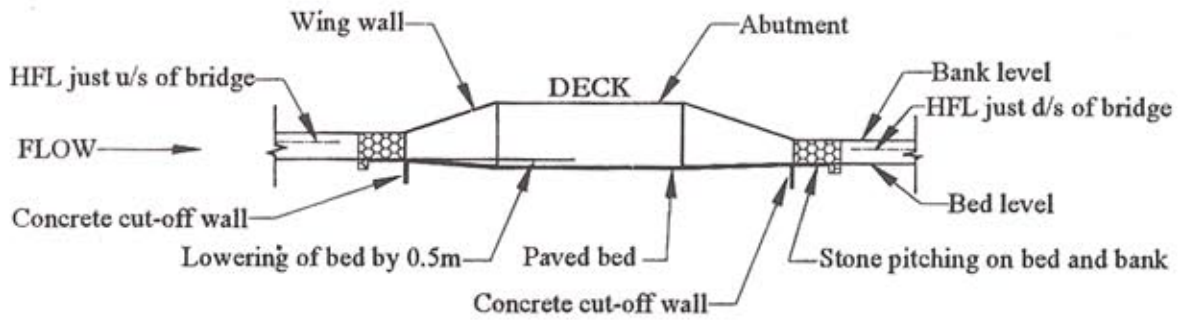
to fluming. For example, an average splay of 2:1 may be sufficient when fluming ratio is 0.6 or more. With fluming as low as 0.2, average splay required to prevent separation of flow and excessive head loss may be as high as 7:1 depending on the shape of transition¹³.

7.2. Flow Choking

If the normal waterway is restricted beyond a certain limit, the flow gets choked. In an unchoked flow, afflux results from head loss due to friction, entry and exit losses. When the flow is choked, additional afflux occurs due to hydraulic jump which invariably forms in a choked flow.

Mazumder (1979) derived the following relation between F_0 and B_0/B_1 (fluming ratio) for a channel with level bed.

$$\frac{B_0}{B_1} = \left(\frac{F_1}{F_0} \right) \left(\frac{2 + F_0^2}{2 + F_1^2} \right)^{3/2} \quad \dots (3)$$



All dimension are in meters

Fig. 4. Splayed transitions connecting bridge with normal channel

Where B_0 is the restricted waterway under the bridge, B_1 is the mean width of approaching channel, B_0/B_1 is the fluming ratio, F_1 is the Froudes number of approaching flow and F_0 is the Froudes number of flow under the bridge. Fig. 5 shows the variation of fluming ratio with F_0 . It is apparent from Fig.5 that the extent of fluming (so that flow is not choked at $F_0 = 1$) is governed by incoming Froudes number of flow (F_1) and the desired value of Froudes number under the bridge. Lower the value of F_1 greater is the opportunity for fluming without choking of flow. It is also observed that although fluming helps in substantial reduction of waterway in the beginning at low F_0 value, the saving becomes negligibly small as F_0 increases. With the rise in F_0 , the flow becomes wavy. Highest degree of instability and waves occur at $F_0 = 1$, i.e.,

at critical flow stage when the flow is just choked. It is advisable not to flume a bridge beyond $F_0 = 0.6$. Also, greater is F_0 , higher is the afflux.

7.3. Scouring

Excessive restriction of waterway under the bridge results in scouring of the river bed and bank. Laursen (1962) derived equation (4) for depth of scour (ds) below river bed as:

$$\frac{ds}{y_1} = \left(\frac{B_1}{B_0} \right)^m \quad \dots (4)$$

Where, y_1 is the depth of flow in the unobstructed natural channel. Exponent $m = 0.59$ for $u_* / u_{*c} = 0.5$, $m = 0.64$ for $u_* / u_{*c} = 1$ and $m = 0.69$ for $u_* / u_{*c} \geq 2$, where u_* is the shear velocity and u_{*c} is the critical velocity

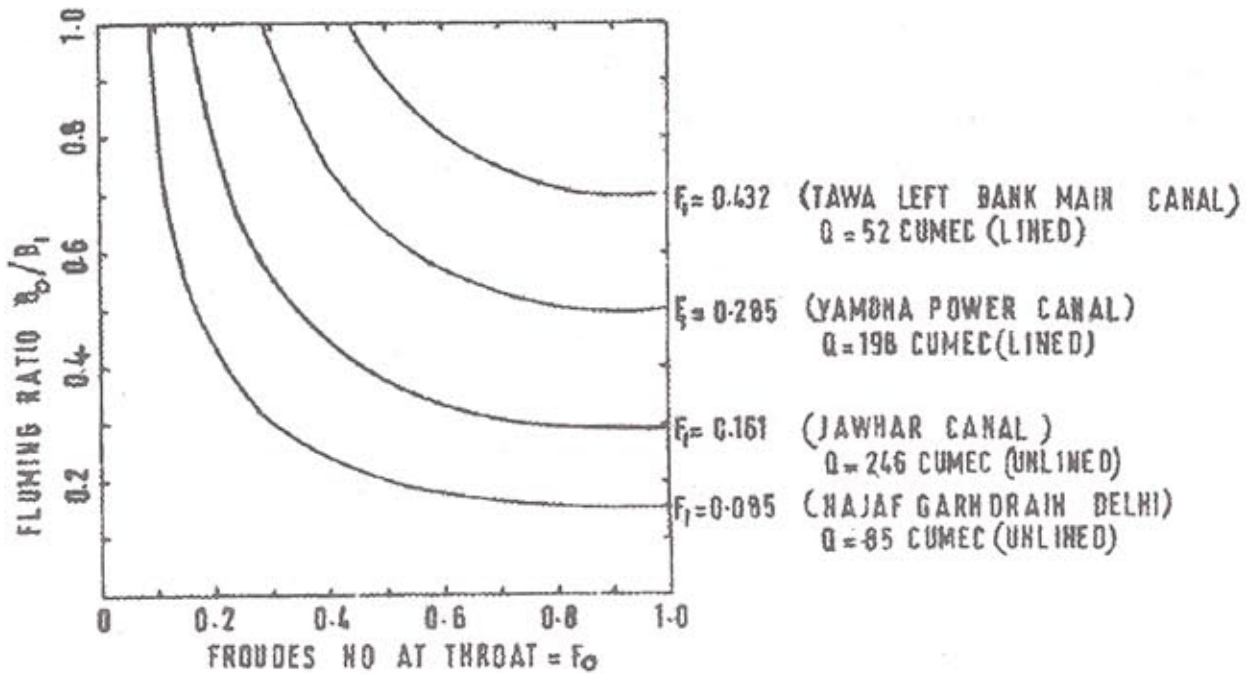


Fig. 5. Relation between F_1 , F_0 and B_0/B_1

at which the particles start moving. u_* and u_c are given by the equations (5) and (6).

$$u_* = \sqrt{\frac{\tau_c}{\rho}} = \sqrt{gR_0 S_f} = \frac{\sqrt{g}(U_0 n_0)}{R_0^{1/6}} \quad \dots (5)$$

$$u_c = \frac{1}{n_0} R_0^{1/6} \sqrt{K_s d (S_s - 1)} \quad \dots (6)$$

Where U_0 is the mean velocity of flow. R_0 is hydraulic mean depth of flow, n_0 is the Manning's roughness coefficient - all under the bridge. K_s is the Shield's non-dimensional function (Raudkivi, A.J.) given by $\tau_c/\gamma d(S_s - 1)$ where τ_c is the critical tractive stress corresponding to the mean size of sediments (d) under the bridge, γ is the unit weight of water, S_s is the specific gravity of sediments.

Lacey's equation for regime depth in a restricted (flumed) section can be expressed as:

$$R_L = 1.35 (q_0^2/f)^{1/3} \quad \dots (7)$$

Where R_L is the Lacey's scour depth measured below HFL at the restricted section and q_0 is the discharge intensity

i.e. Q/B_0 and f is the Lacey's silt factor. Apart from the normal general scour in the restricted reach given by Laursen's d_s or Lacey's R_L , there will also be local scour due to horse shoe vortices formed at the pier nose. IRC Code recommends $2R_L$ as the deepest scour depth (for piers) measured below HFL, i.e., approximately R_L below the normal scoured level in the flumed reach or $(d_s + R_L)$ below general bed level in the approach channel. Extra cost of pier foundation may exceed the gain in savings due to fluming. Scouring is helpful in the reduction of afflux, but it cannot be depended upon especially in flash floods. If the required scour do not occur during the passage of peak flood, the flow may be choked resulting in high afflux.

7.4. Embayment/Outflanking

When the waterway under a bridge is restricted too much, the stream has a tendency to outflank by embaying upstream. There is scouring of the banks and the approach embankments protruded

inside the flood plain. IRC: 89 (1997) provides for fluming with the condition that the protruded portion of the approach embankments should be adequately protected by stone pitching as shown in Fig. 2. These are very costly and involve recurring expenditure. Several cases of outflanking by embayment have been reported where the restriction of waterway is found to be too high. There is damage to the bridge and the approach embankment has been breached resulting in disruption of traffic.

7.5. Sediment Deposition and Channel Erosion

When waterway is restricted, the resulting afflux causes flattening of hydraulic and energy gradient upstream. Sediment carrying capacity of a stream upstream of the bridge is considerably reduced due to flatter gradient. There is an imbalance between the carrying capacity and the incoming sediment load resulting in sediment deposition in the backwater reach upstream. River stability is lost and the stream tends to meander and change its course. Fig. 6 shows a fan shaped river flood plain formed upstream of a typical bridge where waterway is excessively restricted. Due to steeper energy gradient downstream and comparatively clear water (due to sediment deposition upstream), downstream reach of the stream is found to degrade through erosion of bed and banks. Uncontrolled erosion may cause meandering of stream downstream.

7.6. Flow Instability

In the conventional design of minor and medium bridges, wing walls are usually set at right angle to the abutments resulting in

abrupt contraction and abrupt expansion of flow. Whenever the waterway under the bridge is restricted, eddies occur in such abrupt change in flow. Mazumder (2001) found that upto an expansion ratio $(B_1/B_0) = 1.5$ or in other words fluming ratio of 0.67 the eddies remain symmetric. If the expansion ratio exceeds 1.5, the eddies become asymmetric in the expanding reach downstream. Asymmetric eddies interact with the incoming jet flow coming out of the flumed section. Mazumder (1993) studied such flow instability both theoretically and experimentally. If the fluming exceeds the above limit of 0.67, there is possibility that the unstable flow may cause undesired erosion downstream. It may eventually lead to meandering or even shifting of the stream requiring costly river training and protection works. It is desirable, therefore, to avoid restriction of flow with fluming ratio less than 0.6 times the regime waterway (or Bankful width) corresponding to the design flood discharge.

8. USE OF SPLAYED TRANSITION

While widening a road, it is noticed that some of the existing bridges have fluming ratio less than 0.6. For example, 43 out of 46 bridges on Durg-Nagpur Section of NH-6 were found to have fluming ratio less than 0.6 (Table 2) when Lacey's regime waterway was considered. When modified, Lacey equation was used to find regime waterway, only 7 bridges had fluming ratio less than 0.6. In bridge nos. 16 and 36, fluming ratios are 0.572 and 0.562 which are almost equal to 0.6. Splayed transition as shown in Fig. 4 is recommended for the other five bridges (Nos. 11, 12, 20, 22 and 44) where fluming

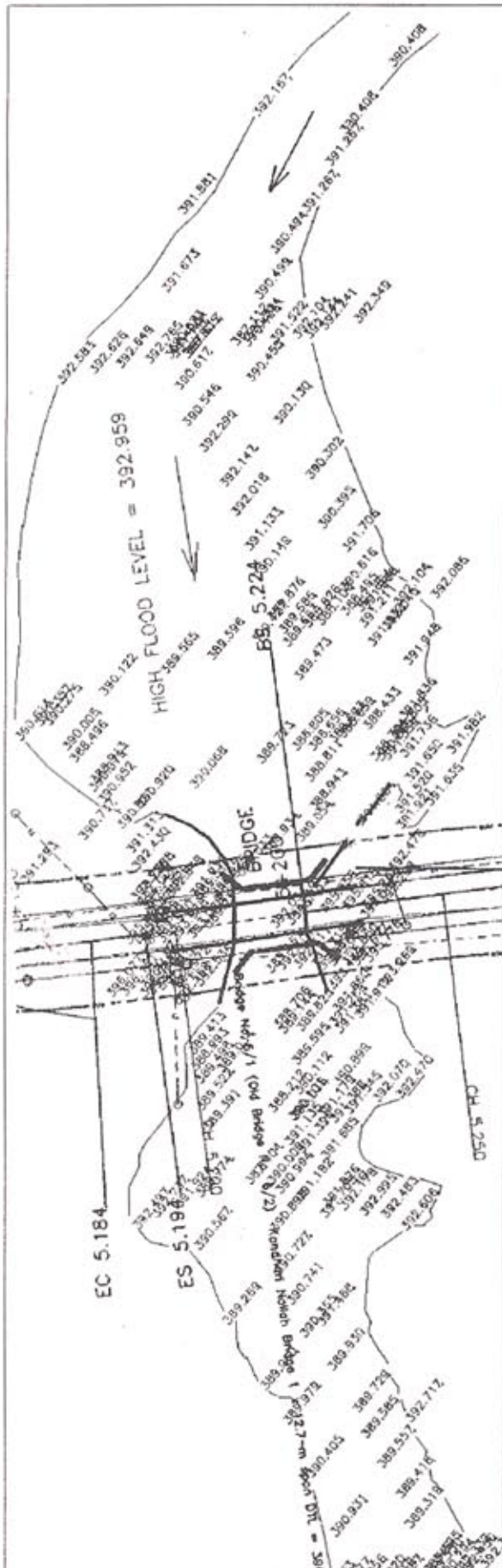


Fig. 6. Showing fan shaped river flood plain formed upstream of a typical bridge where waterway is flumed excessively

ratio is less than 0.6. Since the existing bridges are in good condition they cannot be dismantled nor can the road be diverted, use of splayed transitions will be very helpful in reducing losses as well as improving flow performance. In fact, splayed transitions indirectly help to increase the effective linear waterway under a bridge.

9. CONCLUSIONS

Conventionally, linear waterway for major bridge in alluvial meandering or braided rivers is kept equal to regime waterway for the design flood discharges and corresponding HFL. Although Lacey's equation is adopted to find the regime waterway, it has several limitations especially where banks are stable and strong. IRC Code permits restriction of waterway when banks are stable. It is advisable to develop suitable formula for finding normal waterway for every region in India, such as the one developed by CWC for eastern coast region subzone 4(a), (b) and (c). Authors have developed similar equation from actually observed data for NH-6 (Durg-Nagpur section). Although fluming of waterway results in savings of bridge costs, it has several ill effects e.g. afflux, scouring, deposition of sediments upstream, erosion downstream, meandering of stream and flow instability. Under no circumstances fluming should cause any choking of flow. It is recommended that Froudes number under bridges and fluming ratio should be limited to 0.6. Where fluming below a critical value (say about 0.6 of normal waterway) becomes unavoidable, as in the case of some of the existing bridges in Nagpur-Durg section of NH-6, it is advisable to provide properly

designed splayed transitions upstream and downstream connecting the flumed section with the normal section.

ACKNOWLEDGEMENTS

Authors would like to express their gratitude to ICT authorities for providing the facilities and the data used in this Paper. They are grateful to CWC authorities for providing Flood Estimation Reports and other help. They would like to thank other colleagues in the hydrology section for extending all help and co-operation.

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