Scour around spur dikes and bridge abutments

Affouillement autour des digues en épi et des butées de pont

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ABSTRACT

Realistic estimation of scour depth around spur dikes and bridge abutments in alluvial rivers is important for safe and economic design of their foundations. Procedures have been developed by previous investigators for determination of design scour depth in steady flows at abutments and spur dikes by making use of the design discharge. However, the time required by the design discharge to scour to its full potential is generally much larger than the time for which it runs. Therefore, computations on temporal variation of scour depth are also important for design purposes.

Scour processes at bridge piers, abutments and spur dikes have been found to be similar except that the boundary layer effect induced by the channel wall upstream of the abutment or spur dike causes less scour around these as compared to the case of piers. In the present study, therefore, the concept of an analogous pier is developed. The analogous pier would have the same equilibrium scour depth as the given abutment or spur dike under similar hydraulic conditions. The parameters relating to drag due to flow around abutment/ spur dike and bridge pier have been found to be useful in establishing a relationship for the diameter of the analogous pier. The temporal variation of scour depth and the equilibrium scour depth at the spur dike and the abutment are then computed using pier scour equations with size of the analogous pier being taken as the pier diameter. Results obtained are verified using laboratory data of several investigators for both clear-water and live-bed scour conditions.

RÉSUMÉ

L'estimation réaliste de la profondeur d'affouillement autour des digues en épi et des butées de pont dans les rivières alluviales est importante pour une conception sûre et économique de leurs fondations. Des procédures ont été développées dans les investigations antérieures pour estimer la profondeur d'affouillement autour des butées et digues en épi, dans les écoulements permanents, en utilisant le débit de conception. Cependant, le temps requis par le débit de conception pour atteindre l'affouillement potentiel maximum est généralement beaucoup plus grand que le temps durant lequel il se maintient. C'est pourquoi des calculs sur l'évolution temporelle de l'affouillement sont également importants pour la conception.

Les processus d'affouillement aux piles de pont, butées et épis se sont avérés semblables sauf que l'effet de couche limite induit par la paroi du canal à l'amont de la butée ou de l'épi conduit à un affouillement plus faible que pour les piles de pont. De ce fait, dans la présente étude, on introduit la notion de pile équivalente. La pile équivalente devrait avoir la même profondeur d'affouillement à l'équilibre que la butée ou l'épi sous des conditions hydrauliques équivalentes. Les paramètres du dragage dû à l'écoulement autour de la butée/épi et de la pile de pont se sont avérés utiles pour établir une relation donnant le diamètre de la pile équivalente. La variation temporelle de la profondeur d'affouillement et la profondeur à l'équilibre pour l'épi et la butée sont alors calculés avec les équations d'un affouillement de pile en prenant comme diamètre celui de la pile équivalente. Les résultats obtenus sont vérifiés en utilisant les données de laboratoire obtenues par plusieurs investigateurs, en eau claire, et dans un lit à fond mobile.

1. Introduction

Local scour of alluvial river beds around obstructions is a problem of continuing interest. The complex three - dimensional flow and sediment transport around such structures have defied an analytical solution to the problem and there are wide divergences in the scour depths estimated through the available empirical and semi-empirical methods. The scour around bridge piers has been studied in greater detail than that around abutments and spur dikes.

The scour phenomena at bridge abutments and spur dikes are considered to be practically the same (Melville, 1992). Therefore any reference made to abutment scour hereafter, also holds good for scour at spur dikes. Considerable similarity also exists between the flow patterns and scour processes at a bridge pier and at a bridge abutment (Melville, 1997). In Fig. 1 the downflow and the vortex system at a pier and at the abutment are illustrated as per Kwan (1984), for the purpose of comparison. The horse-shoe vortex and associated downflow which are considered to be the prime agents causing scour at a bridge pier were found to be the main cause of scour at abutments as well. Recently Ahmad and Rajaratnam (2000) have presented the results of experimental studies on flow around bridge abutments. It has been indicated that on an average the bed shear stress amplifies by nearly 3.63 times near the nose of an abutment. This observation compares well with the average of four times amplification of bed shear stress that is found to occur at the nose of a circular bridge pier (Ettema; 1980, Kothyari et al.; 1992 a). Kwan and Melville (1994) indicated the similarity of mechanism of scour at an abutment extending only to short distances into the flow and around bridge piers. For abutments extending upto longer distances into the flow, pockets of stagnant flow are found to exist near the junction between the abutment and the channel bank upstream to the abutment (Kwan, 1984), thus reducing the effective length of the abutment responsible for the scour. However, for the purpose of scour computations, the abutment with its mirror image in the channel wall was considered to be similar to the pier of equivalent shape. Nevertheless, the scour depth at the abutment was found to be less than that at the equivalent pier due to the boundary layer effects induced by the channel wall.

Most of the previous investigations on scour at abutments and spur dikes are concerned with prediction of the equilibrium or design scour depth. Ahmad (1953), Liu et al. (1961), Garde et al. (1961), Laursen and Toch(1956) and Gill (1972) are some of the earlier investigators in this respect. More recent studies are those

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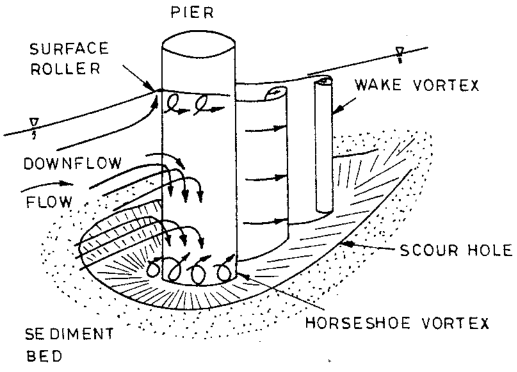
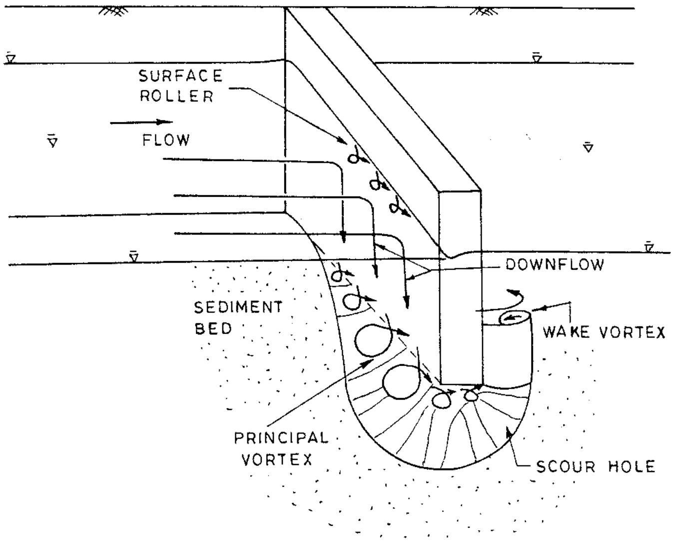


(a) DOWNFLOW AND VORTEX SYSTEMS AT CIRCULAR BRIDGE PIER



(b) DOWNFLOW AND VORTEX SYSTEM AT VERTICAL WALL ABUTMENT

Fig. 1. Comparison of vortex systems at a pier with those at an abutment (Kwan 1984)

of Ahmad and Rajratnam (2000), Rajaratnam and Nwachukwu (1983), Kwan and Melville (1994), Lim (1997), Melville (1992), Froehlich (1989). Melville (1992, 1997) summarized the results of comprehensive scour studies undertaken at the University of Auckland by Wong (1982), Tey (1984), Kwan (1984 and 1988), Kandasamy (1989) and Dongol (1994). An integrated approach for determination of design scour depth at bridge piers and abutments is presented by Melville (1997) in terms of empirical enveloping curves accounting for the effects of flow depth and intensity, foundation type, shape, size and alignment and approach channel geometry.

Most of the above methods are useful in determination of the design scour depth at bridge abutments and spur dikes for steady flow. However, the flow in a river during a flood is unsteady and discharge changes in it are quite rapid. Also many rivers are observed to have stratified bed condition (Ettema, 1980). The computations on temporal variation of scour depth assumes importance in the context of these as it forms an important tool for realistic estimation of scour depth in case of flood flows and in stratified beds (Kothyari et al., 1992, a).

The temporal variation of scour around spur dikes and bridge abutments has not been studied much. Sufficient data are thus not available at present for development and validation of any new model for computing the temporal variation of scour depth at abutments or spur dikes. Chabert and Engeldinger (1956), Ettema (1980), Yanmez and Altinbilek (1991), Kothyari et al. (1992, a & b), Melville and Chiew (1997) etc. have undertaken such a study for bridge piers. Realising the possibility of treating a bridge abutment as an analogous pier, the writers have attempted to establish such an equivalence and then applied the model for temporal variation of scour (Kothyari et al. 1992, a) to the analogous pier, thereby achieving the capability of handling unsteady flows past spur dikes and bridge abutments. The results of this study are reported herein.

2. Conceptual Model

As mentioned earlier, the main mechanism causing scour at bridge abutments is the horse-shoe vortex in association with downflow as in the case of bridge piers. Thus the abutment with its mirror image in the channel wall was considered by earlier investigators to be similar to the pier of equivalent shape. However, due to the boundary layer effects induced by the channel wall, the scour depth at the abutment is less than that at the pier of equivalent shape. Also pockets of stagnant flow are found to exist near the junction between the abutment and the channel bank upstream of the abutment. Therefore, the effective length of the abutment responsible for scour is less than its actual length (Kwan, 1984). The foregoing hypothesis was found to be generally true since scour depths calculated using Kothyari et al.(1992,a & b) method, by treating the abutment as a pier of size equal to length of abutment gave computed scour depths larger than those observed.

Therefore, the analysis was carried out on the premise that by appropriate choice of parameters describing the flow structure at bridge abutments and bridge piers a rational expression can be derived for the scour depth at the abutment. For this purpose, let us define a cylindrical pier having diameter b_d which experiences the same drag force as the given abutment under given flow conditions. Thus

$$F_{Dp} = F_{Da} \tag{1}$$

Hence $C_{Dp}.\ b_d.\ h\ \rho_f\ U^2/2 = C_{Da}.\ L.\ h.\ \rho_f\ U_L^2/2$ (2)

In the above, F_{Dp} is the drag force on the pier and F_{Da} is the drag force on the abutment, C_{Dp} is drag coefficient for the pier, U is the cross-sectional averaged flow velocity upstream of the pier, ρ_f is mass density of water, h is flow depth, C_{Da} is drag coefficient for the abutment, L is abutment length and U_L is flow velocity upstream of the abutment depth averaged over the abutment length.. The value of C_{Dp} depends on pier Reynolds number i. e. (Ub_d/ν). A graphical relation between C_{Dp} and pier Reynolds number was established by Roshko (1961) for a wide range of the values of pier Reynolds number. The following polynomial is fitted (coefficient of determination = 0.82) to represent the relation between C_{Dp} and pier Reynolds number (Fig. 2 of Roshko, 1961) for the pupose of computations:

$$C_{Dp} = 1.2 - 2*10^{-6}(Ub_d/\upsilon) + 9*10^{-13}(Ub_d/\upsilon)^2 - 2*10^{-19}(Ub_d/\upsilon)^3 + 10^{-26}(Ub_d/\upsilon)^4 \quad (3)$$

Equation (3) is valid in the range $10^4 \leq Ub_d/\upsilon \leq 10^7$ (Roshko, 1961) and thus it covers both the laboratory and the field conditions of flow. Substitution of the above expression into Eq.(2) produce the following implicit expression for b_d :

$$\{1.2 - 2*10^{-6}(Ub_d/\upsilon) + 9*10^{-13}(Ub_d/\upsilon)^2 - 2*10^{-19}(Ub_d/\upsilon)^3 + 10^{-26}(Ub_d/\upsilon)^4\} b_d h \rho_f \frac{U^2}{2} = C_{Da} L h \rho_f \frac{U_L^2}{2} \quad (4)$$

For computation of C_{Da} the abutment is considered to be a two-dimensional solid fence kept in a boundary layer. Ranga Raju and Sharma(1999) analysed experimental data collected by various investigators on the variation of drag coefficient of a fence placed in disturbed and undisturbed boundary layers. Figure 2 shows the variation for the fence drag coefficient in terms of the parameter $P(\theta/\delta_*)^{0.5}$. Here θ is the momentum thickness of the boundary layer and δ_* is the displacement thickness of the boundary layer and P represents the ratio of the kinetic energy over the fence length to that in the free stream over the same length in the absence of a boundary layer i.e.

$$P = \frac{\int_0^L u^2 \, dz}{U_0^2 L} \quad (5)$$

Here U_o is the free stream velocity which is taken for abutment as equal to U and z is the distance measured along the abutment length, while u is local velocity vertically averaged at a given section along the length of the abutment. In a fully developed turbulent boundary layer with the $1/7^{th}$ power of velocity distribution $\delta_* = (7/72)\delta$ and $\theta = (1/72)\delta$. The velocity distribution along the abutment length is computed as per the equation

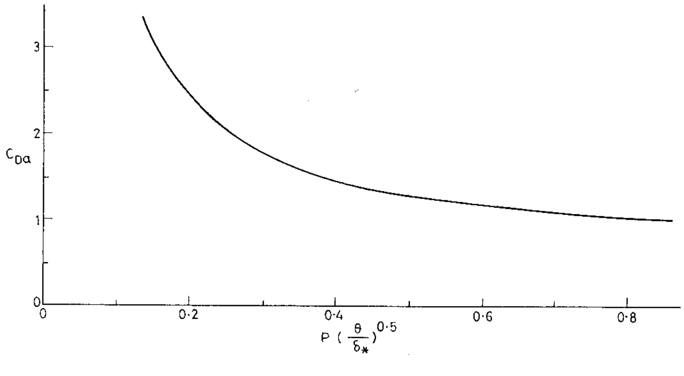


Fig. 2. Variation of C_{Da} with $P\left(\frac{\theta}{\delta_*}\right)^{0.5}$ for solid fence in disturbed and undisturbed boundary layers (Ranga Raju and Sharma, 1999)

$$\frac{u}{U} = \left(\frac{z}{\delta}\right)^{1/7} \quad (6)$$

In the above, δ is the thickness of the boundary layer on the channel wall, which has been taken as half of the channel width considering fully developed flow. The value of U_L to be used in Eq.(4) is computed by averaging over the abutment length the velocity distribution obtained through Eq.(6). Effect of the boundary layer due to channel bed is more significant near the channel bottom and is thus ignored in assuming the above velocity distribution.

The value of P is computed using Eq. (5) and C_{Da} is then computed using Fig. 2. Finally b_d is computed using Eq. (4). It may be noted that the flow separation line and the distance of center of vortex core upstream of a pier / abutment and the wake size are strongly influenced by the pier / abutment Reynolds number (Roshko, 1961, Baker, 1979 and Graf and Yulistiyanto (1999) . These parameters and hence Reynolds number or C_{Dp}/C_{Da} are therefore considered to affect the strength of the horse-shoe vortex. The parameter b_d which is derived using C_{Dp} and C_{Da} values is, therefore, considered to be appropriate for use in relation for scour at the abutment.

Now let us define a circular cylindrical pier having size b_s such that the equilibrium scour depth around this pier is the same as that around the given abutment of length L under similar characteristics of flow, sediment and channel. Such a pier is termed herein as the analogous pier.

Temporal variation of scour depth and equilibrium scour depth at the analogous pier and hence at the abutment can be computed through the use of pier scour relations provided the value of b_s is known.

3. Data Used in Analysis

Laboratory data on both live - bed and clear -water scour around abutments and spur dikes were collected from several studies available in literature for use in the present study. The data pertained to varying shapes and lengths of abutment and spur dikes. These data have been taken from the publications of Melville (1992,1997), Kwan (1984), Lim (1997), Garde et al. (1961), Gill (1972), Nambudaripad (1961), Sastri (1962) and Ramu (1964). The ranges of various parameters pertaining to the flow, abutment geometry and spur dike geometry are presented in Table-1. Data on both the equilibrium scour depth and the temporal variation of scour depth were compiled. For abutments, 129 runs on equilibrium scour depth were available in all, while 10 runs on temporal variation of scour depth were available. In case of spur dikes, 127 and 12 runs respectively for equilibrium scour depth and temporal variation of scour depth were available. Data on spur dikes aligned perpendicular to the flow only are used. Different abutment shapes were accounted for by making use of the abutment shape factors given by Melville (1992).

4. Results And Discussion

Available data on flow velocity, depth, abutment length etc. were used first for computations of b_d values as per the procedure described earlier. The following equations as per Kothyari et al. (1992,a & b) were then used for computation of b_s values from the known equilibrium scour depths.

Clear - water scour:

$$\frac{d_{se}}{b_s} = 0.66\left(\frac{b_s}{d}\right)^{-0.25}\left(\frac{h}{d}\right)^{0.16}\left(\frac{U^2 - U_c^2}{\frac{\Delta\gamma_s}{\rho_f}d}\right)^{0.4} a^{-0.3} \qquad (7)$$

$$\text{with} \quad a = \frac{B - b_s}{B} \qquad (8)$$

$$\text{and} \quad \frac{U_c^2}{\frac{\Delta\gamma_s}{\rho_f}d} = 1.2\left(\frac{b_s}{d}\right)^{-0.11}\left(\frac{h}{d}\right)^{0.16} \qquad (9)$$

Live - bed scour:

$$\frac{d_{se}}{b_s} = 0.99\left(\frac{b_s}{d}\right)^{-0.33}\left(\frac{h}{d}\right)^{0.4} a^{-0.3} \qquad (10)$$

Here d_{se} is the equilibrium scour depth measured from the original bed, $\Delta\gamma_s = \gamma_s - \gamma_f$, γ_s = specific weight of sediment, γ_f is specific weight of water and B is the channel width.

The temporal variation of scour depth at the analogous bridge pier is computed as per the method illustrated in Fig. 3 which is based on Kothyari et al. (1992, a & b) for clear-water and live-bed conditions respectively. The correct values of b_s were determined using Eqs. (7) to (10) with abutment scour values taken as known. The data were next analysed to develop a predictor for b_s. Graphical plotting of data confirmed a strong correlation between b_s and b_d. The following functional relationship was arrived at for b_s through a number of trials and analysis of all the data.

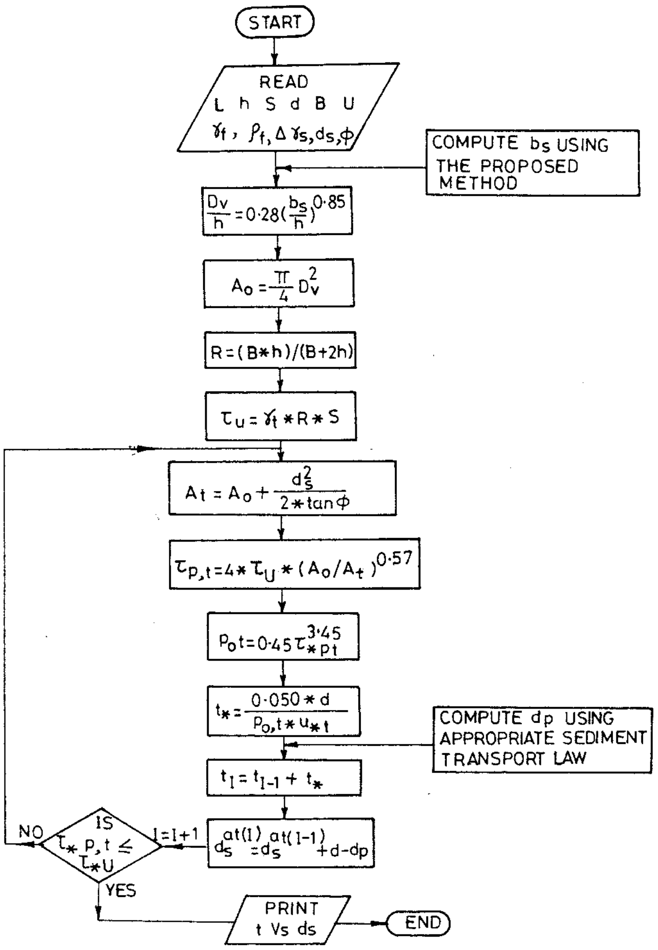


Fig. 3. Algorithm for calculation of temporal variation of scour depth at analogous pier [Kothyari et al. 1992 (a) and 1992 (b)]

$$\frac{b_s}{b_d} = f\left\{\frac{L}{b_d}, \frac{U}{\sqrt{gd\frac{\Delta\rho_s}{\rho_f}}}, \xi\right\} \qquad (11)$$

Here ξ denotes the shape factor which accounts for differences in shapes of the abutment, $\Delta\rho_s = \rho_s - \rho_f$, ρ_s = mass density of sediment, ρ_f is mass density of water. Values of ξ for different abutment shapes suggested by Melville (1992) are used in the present

Table 1. Range of Data Used

S.No	Variable	Range		Remarks
		From	To	**Abutment Shapes**:
1	Length of abutment/spur dike(L)	0.1 m	1.4 m	Vertical Wall,
2	Flume width (B)	0.6 m	2.4 m	Wing wall,
3	Approach flow velocity (U)	0.17 m/s	1.02 m/s	Spill through
4	Approach flow depth (h)	0.03 m	0.6 m/s	**Spur Dike Shapes**:
5	Sediment size (d)	0.29 mm	10.5 mm	Narrow vertical
6	Equilibrium scour depth (d_{se})	0.03 m	0.72 m	Wall

study. A strong dependence of $b_s/\xi b_d$ on L/b_d and $\frac{U}{\sqrt{gd\frac{\Delta\rho_s}{\rho_f}}}$ is evidently depicted by Fig. 4 . Detailed analysis of data produced the following relation for b_s in non-dimensional form;

$$\frac{bs}{\xi\, b\, d} = 0.074\left(\frac{L}{bd}\right)^{2.7}\left(\frac{U}{\sqrt{gd\,\frac{\Delta\rho_s}{\rho_f}}}\right) + 0.46 \qquad (12)$$

Equation (12) holds good for both clear - water and live-bed scour conditions.

4.1 Temporal Variation of Scour Depth.

Values of b_s were recomputed using Eq. (12) for the available runs on temporal variation of scour depth. The b_s values so computed were then used along with b_d values computed earlier and the other hydraulic data for computation of temporal variation of scour depth using the algorithm shown in Fig. 3. Data on clear-water scour conditions only were available. For comparison, the computed temporal variation of scour depth was plotted along with the corresponding observations for all the data. Such comparison is presented in Figs. 5 to 10 for a few runs by way of illustration. It may be noted that data on temporal variation of scour have not been used in development of relationships used herein. The estimation of temporal variation by the present method is generally satisfactory as shown by Figs. 5, 6, 8 and 9. Excellent results are also obtained for some of the runs, for example Fig. 9. However, the prediction was poor (Fig. 7, for instance) only for a few runs. Unsatisfactory results obtained particularly in the initial period of some runs are attributed to the fact that in these experiments the area around the abutment or spur dike was not protected prior to the actual start of the run; thus some scour might have taken place before the actual start of the run (Kothyari et al., 1992,b)).

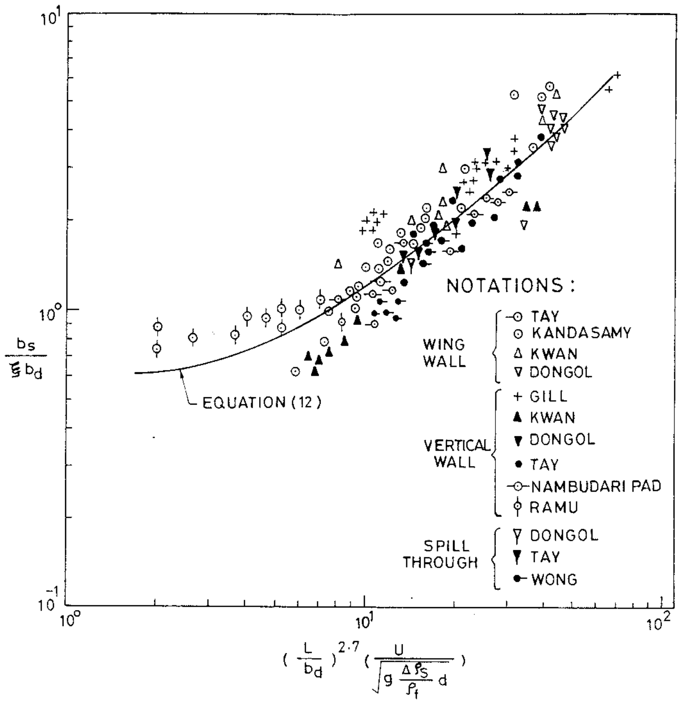


Fig. 4. Variation of $b_s/\xi b_d$ with $\left\{\left(\frac{L}{bd}\right)^{2.7}\left(\frac{U}{\sqrt{g\frac{\Delta\rho_s}{\rho_f}d}}\right)\right\}$

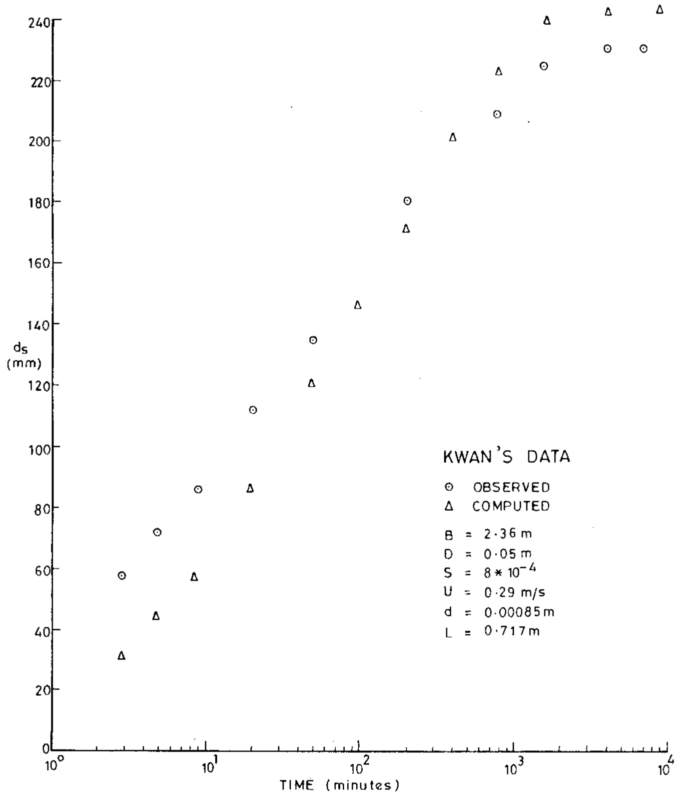


Fig. 5. Temporal variation of scour depth at bridge abutment

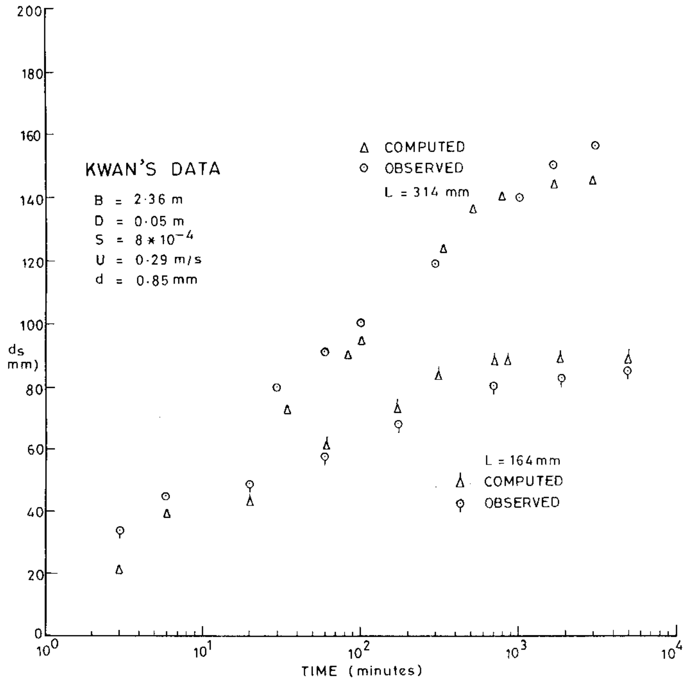


Fig. 6. Temporal variation of scour depth at bridge abutment

The foregoing figures also reveal that the proposed method also

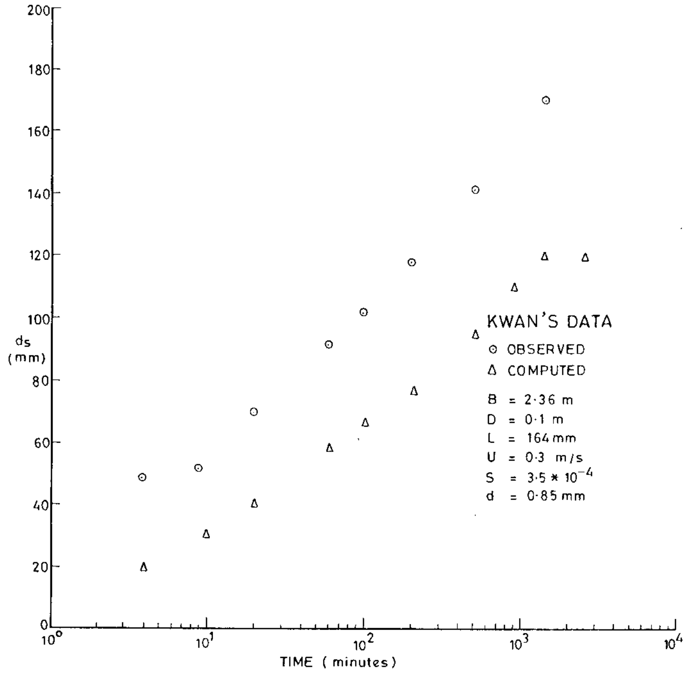


Fig. 7. Temporal variation of scour depth at bridge abutment

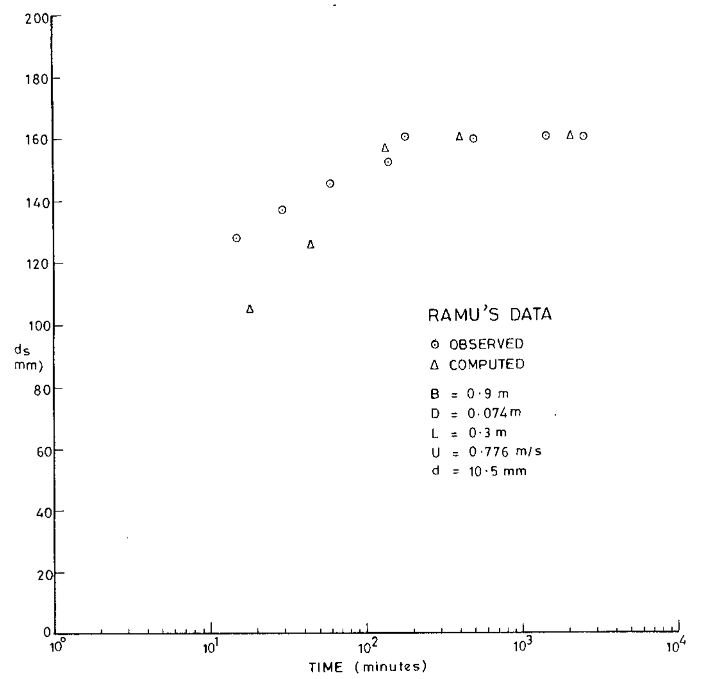
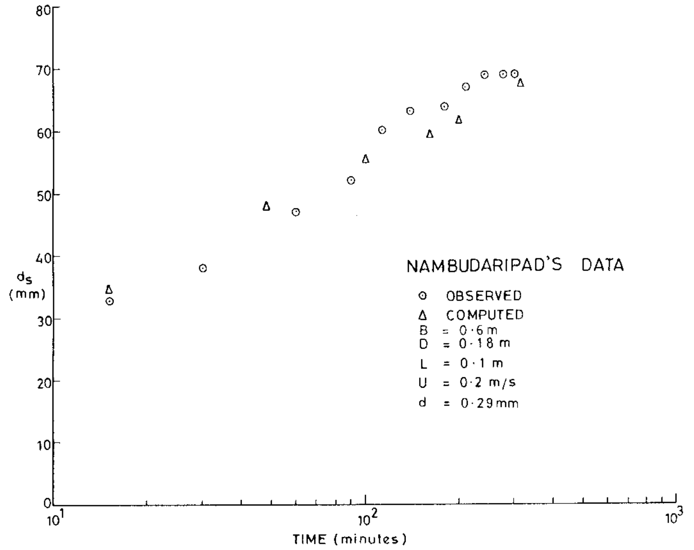


Fig. 8. Temporal variation of scour depth at spur dike



Fig, 9. Temporal variation of scour depth at spur dike

gives good results for all the runs as far as the equilibrium scour depth is concerned. In addition, the proposed method of computing the temporal variation of scour depth during steady flows can be used in unsteady flow conditions by discretizing the hydrograph causing unsteadiness into different segments so that each segment of flow can be considered as steady (Kothyari et al. 1992,a & b).

4.2 Equilibrium Scour Depth

The equilibrium scour depth can be obtained from the temporal variation as the scour at large time period. However, from practical consideration, use of the pier scour equation in conjunction with diameter of the analogous pier renders a simple method for estimation of equilibrium scour at the abutments. Thus Eqs. (7) and (10) were used respectively for clear-water and live-bed conditions for estimation of equilibrium scour at the abutments and the spur dikes. The steps involved in the use of present method for calculation of equilibrium scour depth are summarized in the flow chart given in Fig. 10.

The equilibrium scour depths thus computed are compared graphically with the corresponding observed values in Fig. 11. The purpose of preparing this figure is only to show the order of errors which may be expected in the finally computed values of scour depth after going through the several steps given in Fig.10. It can be noted in Fig. 11 that the present method estimates the equilibrium scour depth with a maximum error of ± 30% for most of the data. This accuracy is deemed to be satisfactory particularly considering that data from a large number of sources for both live-bed and clear-water conditions and for varying abutment geometries are used. It may also be noted that Eq.(7) becomes an enveloping equation if the constant 0.66 is replaced by 0.86. Likewise Eq. (10) would also become an enveloping equation if its constant is replaced by 1.29. In that condition the present method will produce the design values for scour at abutments and spur dikes.

5. Conclusions

An analogous pier is defined herein which has such a size that scour around it is the same as that around the given abutment or spur dike under similar hydraulic conditions. A relation is proposed in the form of Eq.(12) for determining the size of the analogous pier. The parameters relating to drag due to flow past abutment/ spur dike and pier are found to influence the size of the analogous pier. Relationships for estimation of pier scour are then used for calculation of abutment and spur dike scour with size of the analogous pier taken as the pier diameter. Satisfactory estimates have been thus obtained for equilibrium scour depth and temporal variation of scour depth at spur dikes and abutments in

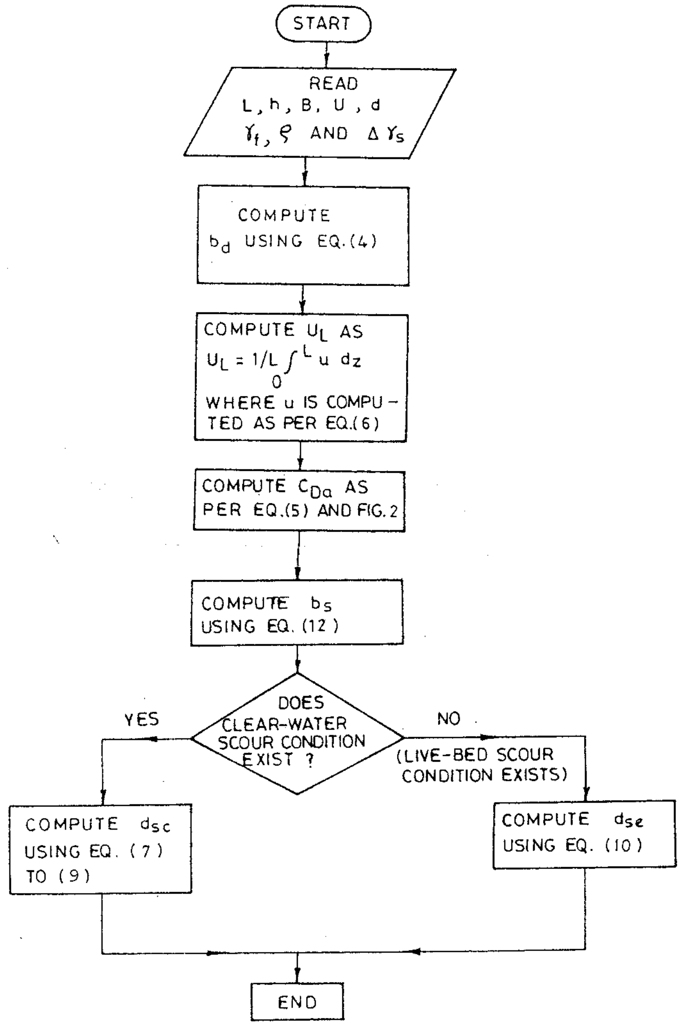


Fig. 10. Flow chart depicting the steps for computation of equilibrium scour depth

case of laboratory studies for both the clear-water and live-bed conditions.

Acknowledgement

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Notations

B = flume width

b_d = width of cylindrical pier which experiences same drag as the given abutment under similar hydraulic conditions.

b_s = size of analogous pier

C_{Dp} = drag coefficient for the pier

C_{Da} = drag coefficient for the abutment

d = sediment size

d_{se} = Equilibrium scour depth

F_{Dp} = drag force on the pier

F_{Da} = drag force on the abutment

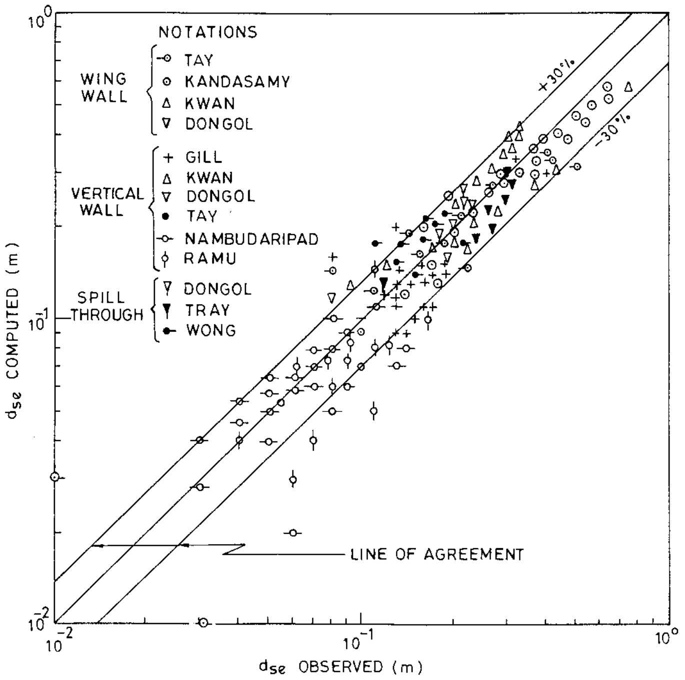

Fig. 11 Comparison of observed and computed values of d_{se}

g = Acceleration due to gravity

h = flow depth

l = length measured along the abutment

L = abutment length

P = ratio of Kinetic energy over the fence length to that in free stream over the same length in the absence of a boundary layer

u = local velocity vertically averaged at a section along the abutment

U = average velocity of flow

U_o = free stream velocity

U_L = flow velocity upstream of abutment averaged over abutment length

θ = momentum thickness

δ = boundary layer thickness

δ_* = displacement thickness

ξ = Abutment shape factor

$\Delta\gamma_s$ = γ_s - γ_f; γ_s= specific weight of sediment, γ_f = specific weight of water

$\Delta\rho_s$ = ρ_s - ρ_f; ρ_s= mass density of sediment, ρ_f= mass density of water

α = opening ratio = $[(B-b)/B]$

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