A FRESH APPROACH TO ABUTMENT-SCOUR ESTIMATION

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The writers' laboratory and field observations of abutment scour lead to a fresh approach for estimating scour depth at bridge abutments. The experiments were conducted with abutments with approach embankments subject to a range of erodibility conditions: fixed embankment on fixed floodplain; riprap-protected erodible embankment on readily erodible floodplain; and, unprotected readily erodible embankment on readily erodible floodplain. The approach discards the old notion of linearly combining bridge-waterway constriction scour and local scour at the abutment structure, a notion that laboratory experiments do not support. Instead, the approach entails estimating an abutment-induced local amplification of constriction scour at the bridge opening, and separately estimating a maximum local scour depth at the abutment when exposed by embankment failure. For some abutment sites the two depths coincide. The paper adumbrates the fresh approach.

1 INTRODUCTION

Few situations of flow and boundary erosion are more complex than those associated with scour in the vicinity of a bridge abutment, especially one located in compound channel. Accordingly, few situations of scour-depth estimation are as fraught with difficulty. Therefore, it is not surprising that considerable uncertainty is associated with scour-depth estimation for abutments, and that the existing estimation relationships are not well accepted; a concern being that existing relationships tend to predict scour depths that seem excessive. The present paper introduces a fresh approach to scour depth estimation for abutments. The approach is still in development, its estimation relationships are being formed using the findings from an extensive laboratory study presently underway.

Many bridge abutments are located in compound channels whose geometry is rather complex. Additionally, many abutments are located where the channel is formed of several bed materials, occupying different locales within a bridge site; sands may form the bed of a main channel, silts and clay may predominate in riverbanks and underlying floodplains, and rocks may have been placed as riprap protection for the abutment, as well sometimes along adjoining riverbanks. Early work on abutment scour focused on the simpler and perhaps idealized situations of scour. Commensurately, the existing relationships and guidelines apply to simplified abutment situations, such as an abutment placed in a straight rectangular channel, and can only be extended with considerable uncertainty to actual field conditions. Often extrapolation causes existing scour relationships to predict substantially greater extents of scour than actually may occur at many actual bridge sites.

And yet, all difficulties and complexities aside, a common feature of abutment scour suggests a reasonably straightforward approach to obtaining design estimates of scour-depth at abutments. The feature is abutment and embankment constriction of flow through a bridge waterway. The flow locally around the abutment is part of the overall field of constricted flow through a bridge waterway, to the extent that it can be difficult to distinguish between what conventionally are termed "local scour" and "constriction scour." The fresh approach adumbrated in this paper treats abutment scour as a local amplification of constriction scour. Only when flow erodes and passes through an approach embankment, then fully exposing an abutment as if it were a pier, does local scour occur at an abutment. The writers currently are further developing the approach.

2 CONSIDERATIONS OF ABUTMENT CONSTRUCTION

Though many studies have focused on the several of the component scour processes at play, and have delineated sets of important parametric trends, few studies have considered the usual construction features of abutments and their approach embankments in compound channels:

1. Most abutments comprise an abutment structure, such as the standard-stub abutment used for spill-through abutments (Figure 1), and that structure is a pile-founded structure (the other common type of abutment is a "wing-wall" abutment used typically for smaller bridges);
2. The earthfill embankment approaching the abutment structure is erodible and subject to geotechnical instabilities;
3. The portion of the embankment near the abutment usually is riprap protected;
4. The floodplain (often largely formed of cohesive soils) may be much less readily eroded than the main-channel bed;

The fact that most abutments usually are piled structures with an earthfill embankment influences scour depths at abutments. Most scour case-studies show that the embankment fails before the abutment structure fails (e.g., Ettema et al. 2002).

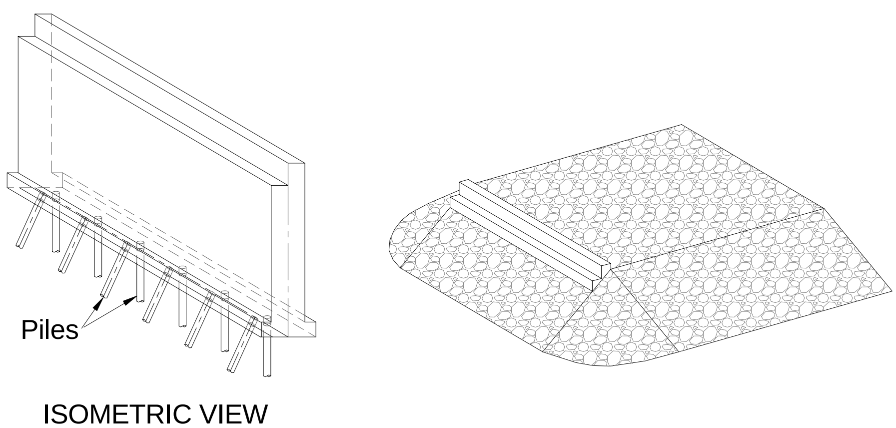

Figure 1: Most abutments are pile-supported (e.g., standard-stub abutment used by the Iowa DOT) set in an erodible earthfill, approach embankment

The writers conducted experiments with abutments in a compound channel subject to several conditions of embankment and floodplain erodibility: fixed embankment and floodplain (such as a floodplain formed of largely cohesive soil); erodible floodplain and riprap-protected embankment; and erodible floodplain with erodible embankment. The main channel had a bed of uniform sand. Figure 2 shows the scour that developed for one configuration of fixed abutment on a fixed floodplain. The scour, by lowering the bed near the abutment, potentially could make the channel bank and embankment face unstable.

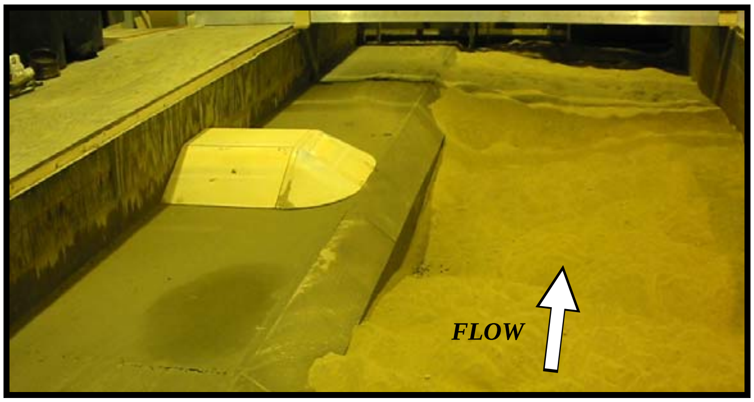

Figure 2. Scour in main channel near fixed floodplain and embankment (flume width is 4m)

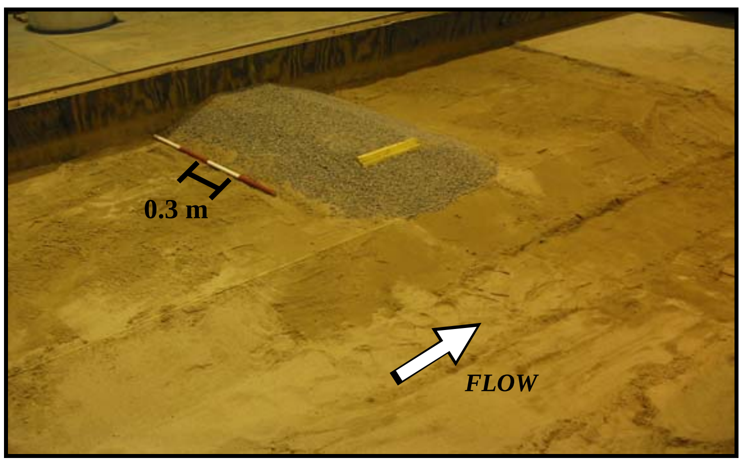

Figure 3. Layout of the writers' experiment with riprap-protected abutment on erobible floodplain

Most embankments are erodible, and it is common for the approach embankment near the abutment to fail and wash out before the abutment itself fails, if indeed the abutment does fail. This observation is borne out by the writers' laboratory experiments, which were conducted with a floodplain simulated with sand, as shown in Figure 3. Observations from case studies in the field and from the writers' laboratory experiments show that, as abutment scour develops, the channel bank erodes eventually causing the embankment side-slope to undergo a slope-stability failure. Failure and erosion of the embankment isolates the abutment, practically exposing it as if it were a pier. Also, embankment failure may somewhat relax constriction scour.

Moreover, the writers' experiments show that maximum scour depth may not occur at the abutment. As the width of floodplain increases, and flow constriction concomitantly increases, the location of deepest scour can shift downstream of the abutment. Figure 4 depicts one scour condition resulting from the writers' experiments with an erodible wingwall abutment – though the embankment failed partially, the deepest scour occurred a short distance downstream of the abutment. Evidently, the location of deepest scour varies with the flow field developed around the abutment. Figure 5 depicts the deepest scour condition occurring at the abutment structure itself – this condition occurred when the embankment was eroded through such that the abutment structure became exposed, and scour developed as if the abutment were a form of pier.

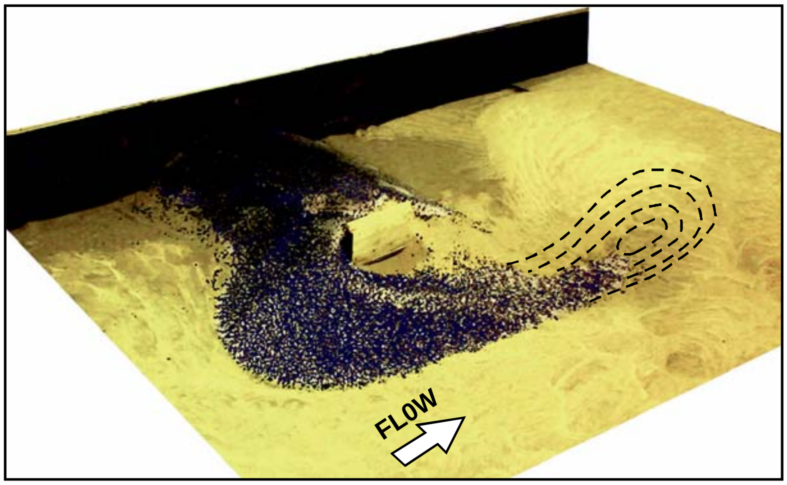

Figure 4: Scour near abutment with riprap-protected embankment

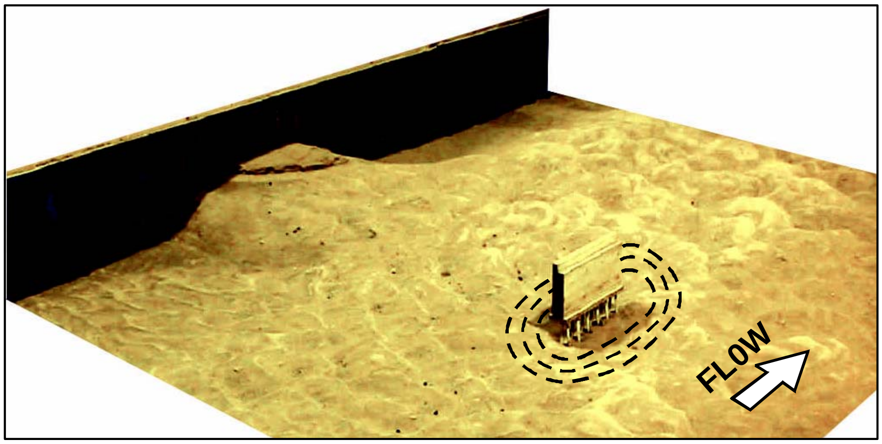

Figure 5. Scour at stub abutment exposed when embankment and floodplain eroded

For some configurations of intact embankment, depending on the approach flow orientation and flow field generated by the embankment and abutment, the maximum scour depth may occur right at the abutment. Based on observations from the writers' experiments, and a review of published data, it would seem that the maximum scour depth occurs right at the abutment in cases where the abutment and its embankment are taken to be a fixed, solid body that extends deeply into the bed of a channel; this form of abutment and embankment have been extensively tested in prior flume studies.

3 FRESH APPROACH TO SCOUR-DEPTH ESTIMATION

The existing relationships for scour-depth estimation treat abutments and approach embankments as fixed, solid structures extending deep into the bed. However, scant few abutments and embankment approaches are built like that. Illustrations like Figures 1 through 4, as well as the writers' observations of scour development at piled-supported abutments and earthfill embankments, suggest the need for a "fresh" approach to scour-depth estimation.

The writers' fresh approach focuses on estimates of maximum flow depth associated with two primary scour forms:

1. *Maximum scour as near-abutment amplification of constriction scour*. The writers suggest that, especially for spill-through abutments, the deepest scour develops essentially as a near-abutment amplification of constriction scour, with the amplification caused by the increased flow velocity and turbulence local to the abutment and its approach embankment. This depth occurs when an abutment's embankment is either fully or largely intact, such that the flow is constricted through the bridge opening. The term "embankment largely intact" here means that the flow has not broken through the approach embankment.

   Actually, for an abutment on a compound channel, deepest scour should be checked at two locations: in the main channel if the abutment is close to the main channel; and, on the floodplain if the abutment distant from the main channel.

2. *Maximum scour as local scour at fully exposed abutment structure*. This scour form occurs when the embankment has eroded so that the abutment structure (e.g., standard stub or wingwall) is fully exposed as if it were a pier.

Maximum flow depths in the main channel, Y_{max}, and on the floodplain, Y'_{max}, are indicated in Figure 6. Figure 7 conceptually relates Y_{max} and Y'_{max}, to the flow depths associated with constriction scour, Y_C (fixed floodplain), Y'_C (erodible floodplain), and local-scour at a fully exposed abutment, Y_L. Because constriction scour integrates the influences of several variables (e.g., approach-flow depths and discharge, bed sediment), it is meaningful and convenient to relate Y_{max} to Y_C. Figure 7 indicates flow depth on the floodplain and in the main channel, and it shows three curves for Y_{max}:

- Curve 0 is

$$Y_{max} = Y_C; \text{ or } Y'_{max} = Y_C \quad (1)$$

- Curve 1 (***for fixed embankment and floodplain***) is

  Y_{max} versus Y_C; or $Y_{\max} = Y_C\ \varphi()$ (2)

  The functional relationship $\varphi()$ is a factor that amplifies Y_C near the abutment (as evident in Figure 3). The magnitude of $\varphi()$ depends on flow velocity distribution at the bridge site, and it must account for turbulence. Site morphology, along with the presence of vegetation, and sundry physical peculiarities complicate estimation of flow distribution and scour depth for sites. In particular, it is difficult to identify precisely where flow velocity will be largest, turbulence greatest, and scour depth likely deepest. The relationship $\varphi()$ has yet to be determined. The writers presently propose Eq. (2) be expressed as

  $$Y_{\max} = Y_C\ \varphi\left[\left(U_p / \overline{U}\right)^2\right] \quad (2a)$$

  In which U_p = peak velocity near abutment, and $\overline{U}$ = average velocity of flow through bridge opening. The parameter $\left(U_p / \overline{U}\right)^2$ also expresses a shear stress ratio.

- Curve 2 (***for partially eroded embankment and floodplain***)

  Y'_{Smax} versus Y_C' (3)

  This curve cuts across Curve 1 and lies between Curves 1 and 0, possibly crossing Curve 0 too, because floodplain and embankment erosion may release material that partially fills or armors the scour hole (e.g., as in Figure 4), or weakens abutment generation of flow turbulence. Erosion of the bridge waterway may ease flow constriction and reduce Y_C'. Given the substantial uncertainties attending the extent of partial erosion, Curve 2 is shown as a broad band. Moreover, no scour relationship is ventured here.

- Curve 3 (***for fully exposed abutment***) indicates the flow depth, Y_L, when the embankment is washed out, and the floodplain is eroded (as in Figure 5), such that flow passes fully around the exposed abutment, which then is subject to local scour owing to the flow field around the exposed abutment structure, and

  $Y_{Smax} = Y_L$; or $Y'_{Smax} = Y_L$ (4)

  Note that Y_L may exceed Y_0 at some bridge sites.

The curves in Figure 7 are useful for describing how embankment and floodplain resistance to erosion may influence maximum flow depth at an abutment. Such resistance to erosion could be attributable to embankment and floodplain being formed of cohesive soils, and/or possibly to the protective effects of riprap or vegetation. If the floodplain and embankment do not erode as constriction scour progresses (as in Figure 3), the maximum scour depth attains Curve 1. If constriction scour partially erodes the floodplain and the embankment near the abutment, the maximum scour depth only attains Curve 2. If the embankment washes out near the abutment, scour attains only a depth commensurate with Curve 3.

The two flow depths of prime interest for abutment design are those associated with Curve 1 and local scour at an exposed abutment: Eqs (2) and (3) respectively. The larger flow depth should then be used in design. The writers are completing experiments to quantify Eqs (2) and (3). Some of their data associated with Eq. (2) are presented below. Data for Eq. (3) presently are being gathered.

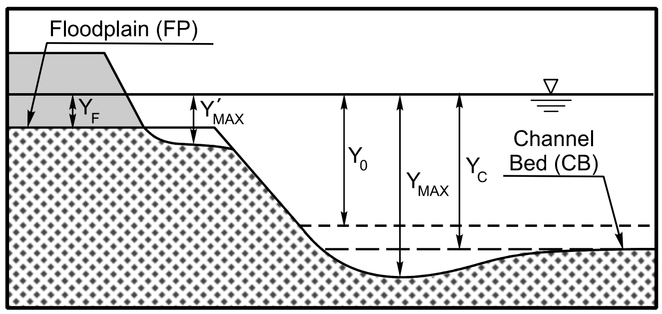

Figure 6. Flow depths in bridge waterway; Y_{max} refers to scour of waterway if floodplain and embankment do not erode (fixed), and Y'_{max} refers to scour of waterway if floodplain and embankment are erodible.

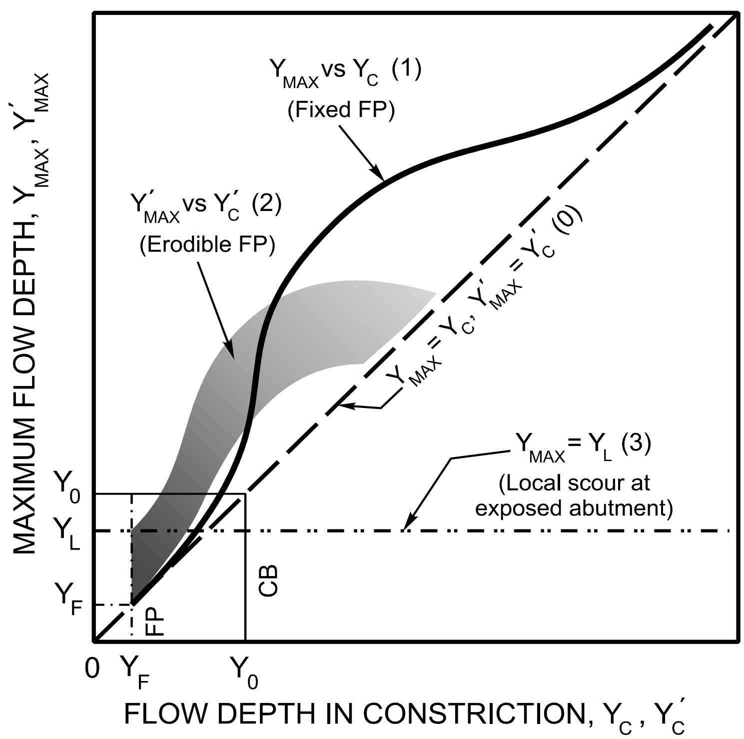

Figure 7. Flow depth trends associated with scour near spill-through abutments

4 LABORATORY DATA

Figure 8 plots the writers' data on the maximum scour depths measured at a spill-through abutment of fixed-embankment and floodplain (like Figure 3), and of riprap-protected erodible embankment and an erodible floodplain (like Figure 4). The figure plots scour depth relative to the floodplain elevation. The abscissa is abutment length, *L*, normalized with floodplain width, B_f. Data are given for two floodplain widths relative to half-width of channel, $B_f/(0.5B)$. Also shown are the calculated depths of constriction scour estimated using Equation 5.16 from Melville and Coleman (1999).

The data are re-plotted in Figure 9, using the format outlined in Figure 6. In terms of Eq. (2), and for the experiment conditions involved, the data tentatively suggest that $\varphi()$ attains a maximum value of about 2. For this value of $\varphi()$, the measured values of $U_p/\overline{U}$ ≈ 1.45. In approximate terms, for spill-through abutments at least, this finding suggests the following rather simple relationship based on a nominal, boundary shear-stress ratio:

$$Y_{max} = Y_C \left(U_p/\overline{U}\right)^2 \tag{4}$$

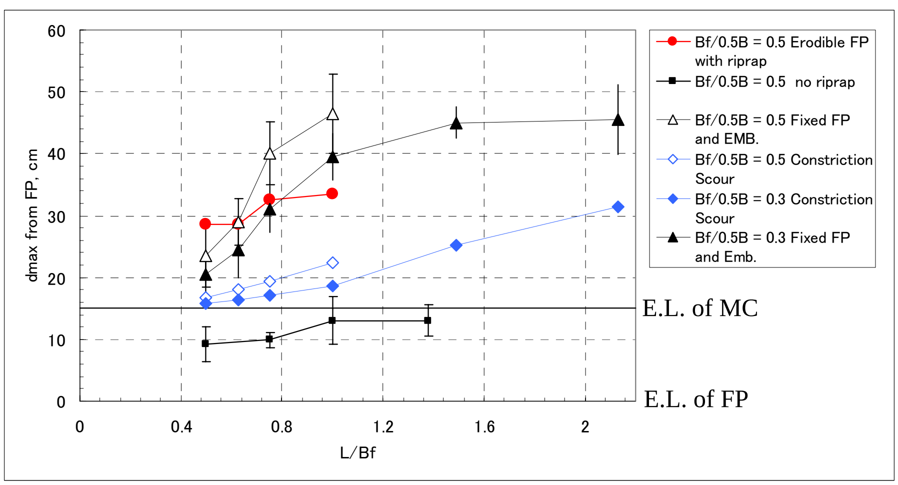

Figure 8. Maximum scour depths measured for fixed floodplain and embankment, and calculated constriction scour depths

For actual bridge sites, a practical means of defining the flow field and determining the value of the velocity ratio $U_p/\overline{U}$ is through the use of a numerical model of the flow filed, notably (for the foreseeable future) a 2D (depth-averaged) flow model. Such a numerical model is needed in order to ascertain the maximum velocity of flow near the embankment and (with due allowance for flow turbulence intensity) determine the maximum scour depth.

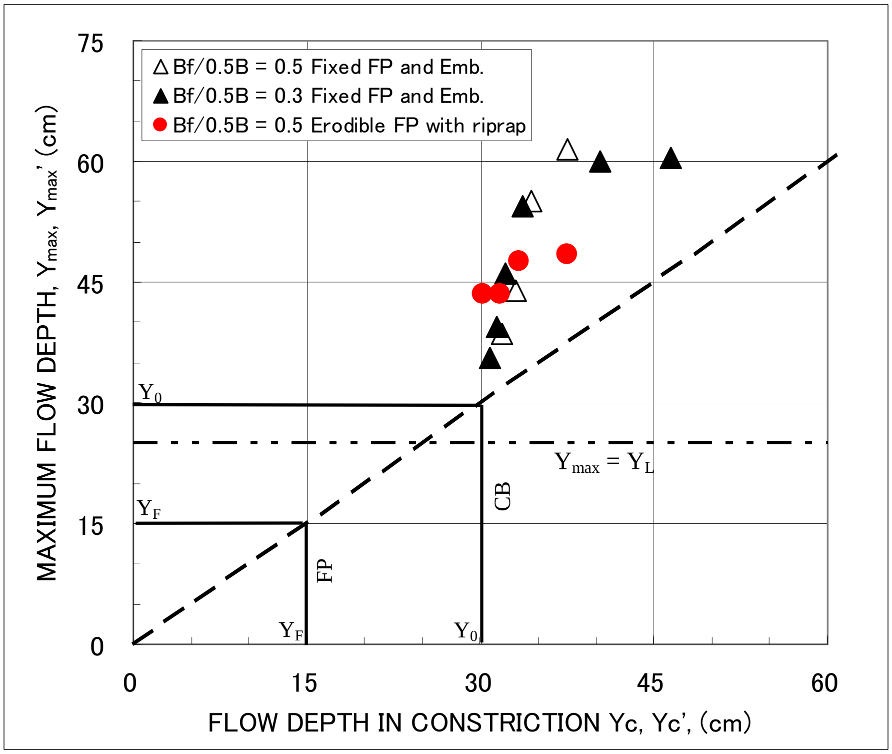

Figure 9. Maximum flow depth versus calculated flow depth based on constriction scour

5 CONCLUDING COMMENT

The fresh approach for scour-depth estimation pursued by the writers holds good promise of being practicable and providing scour-depth estimates closer to those observed in the field. This paper outlines the approach. The writers presently are conducting further experiments towards determining the relationships expressed in Eqs (2) through (4), and adumbrated in Figure 6. The outcome of the experiments may place the estimation approach on a suitably quantitative footing.

6 ACKNOWLEDGEMENT

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7 REFERENCE

Melville, B. W. and Coleman, S. (1999). Bridge Scour. Water Resources Publications, Littleton, CO, USA.