Practical Approach to Estimating Realistic Depths of Abutment Scour

Robert Ettema
Department of Civil and Environmental Engineering
IIHR-Hydroscience and Engineering
University of Iowa
Iowa City, IA 52242
robert-ettema@uiowa.edu

Atsuhiro Yorozuya
Department of Civil and Environmental Engineering
IIHR-Hydroscience and Engineering
University of Iowa
Iowa City, IA 52242
atsuhiro-yorozuya@uiowa.edu

Tatsuaki Nakato
Department of Civil and Environmental Engineering
IIHR-Hydroscience and Engineering
University of Iowa
Iowa City, IA 52242
tatsuaki-nakato@uiowa.edu

Marian Muste
Department of Civil and Environmental Engineering
IIHR-Hydroscience and Engineering
University of Iowa
Iowa City, IA 52242
marian-muste@uiowa.edu

ABSTRACT

Observations of bridge abutment scour lead to a practical new approach for estimating realistic scour IIHR-Hydroscience and Engineering depths at bridge abutments. Prior design approaches usually led to unrealistically deep estimates of abutment scour depth. The observations presented stem from flume experiments 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.

Key words: abutment—bridge waterways—scour

Proceedings of the 2005 Mid-Continent Transportation Research Symposium, Ames, Iowa, August 2005. © 2005 by Iowa State University. The contents of this paper reflect the views of the author(s), who are responsible for the facts and accuracy of the information presented herein.

INTRODUCTION

Scant situations of hydraulic engineering are more complex than those associated with scour in the vicinity of a bridge abutment, especially one located in a compound channel. Accordingly, few situations of scour depth estimation are as difficult. Therefore, it is not surprising that considerable uncertainty and debate has been associated with scour depth estimation for abutments, and that the existing estimation relationships are not well accepted; a concern is 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 currently underway.

As shown in Figure 1, abutment scour involves hydraulic erosion with consequent slope stability failure of the earth-fill embankment at the abutment. 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 as 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. Extrapolation often causes existing scour relationships to predict substantially greater extents of scour than actually may occur at many actual bridge sites.

Figure 1. Scour-induced failure of the earth-fill embankment at a spill-through abutment

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 contraction 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 are conventionally termed local scour and contraction scour. The fresh approach explained in this paper treats abutment scour as a local amplification of contraction 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 are currently developing the approach further.

ABUTMENT CONSTRUCTION

Though many studies have focused on 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, including the following items:

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

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

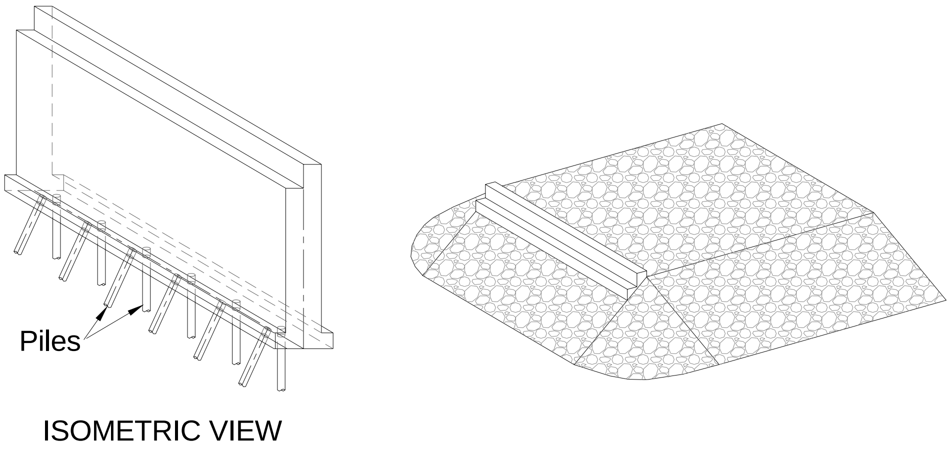

Figure 2. Most abutments are pile-supported (e.g., standard stub abutment used by the Iowa DOT) set in an erodible earth-fill, approach embankment

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 3 shows the scour that developed for one configuration of a fixed abutment on a fixed floodplain. The scour, by lowering the bed near the abutment, could potentially make the channel bank and embankment face unstable.

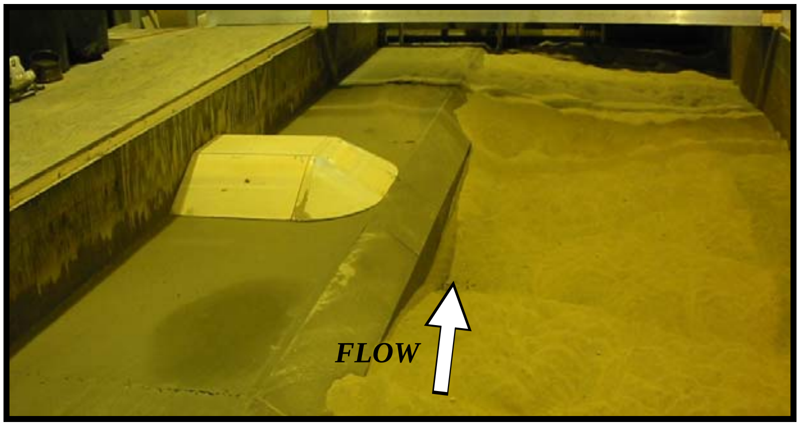

Figure 3. Scour in main channel with fixed floodplain and embankment

Most embankments are erodible, and it is common for the approach embankment near the abutment to fail and breach 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 4. 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 contraction scour.

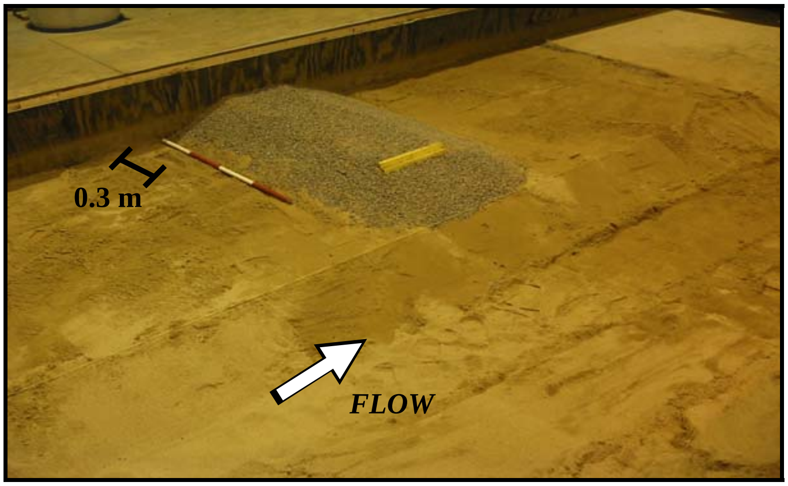

Figure 4. Layout of experiment with riprap-protected abutment on erobible floodplain

Moreover, the experiments show that maximum scour depth may not occur at the abutment. As the width of the floodplain increases and flow contraction concomitantly increases, the location of deepest scour can shift downstream of the abutment. Figure 5 depicts one scour condition resulting from the writers' experiments with an erodible wing-wall 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 such that the abutment structure became exposed, and scour developed as if the abutment were a pier.

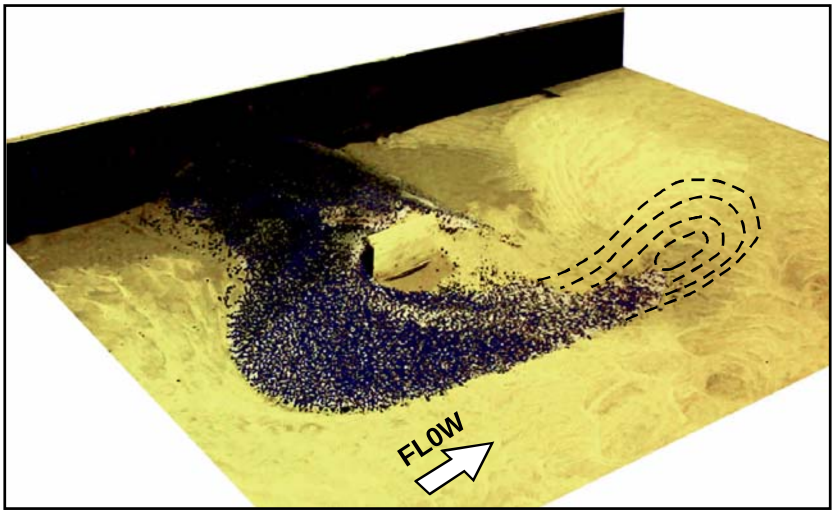

Figure 5: Scour near abutment with riprap-protected embankment

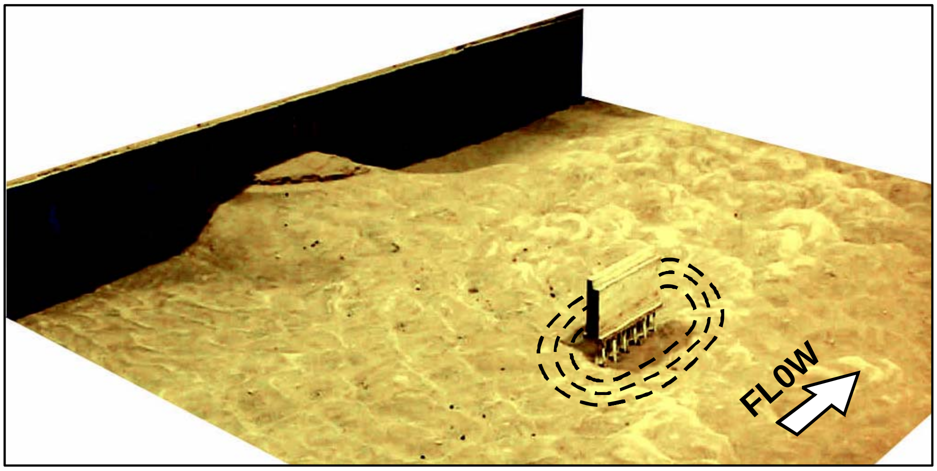

Figure 6. Scour at stub abutment exposed when embankment is breached

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 tested extensively in prior flume studies.

SCOUR DEPTH AT ABUTMENTS NEAR MAIN CHANNEL

The existing relationships for scour depth estimation treat abutments and approach embankments as fixed, solid structures extending deep into the bed. However, few abutments are built in this way. Illustrations such as Figures 1 through 4, as well as the writers' observations of scour development at piled-supported abutments and earth-fill embankments, suggest the need for a fresh approach to scour depth estimation.

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

1. *Maximum scour as near-abutment amplification of contraction scour*. The writers suggest that, especially for spill-through abutments, the deepest scour develops essentially as a near-abutment amplification of contraction 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. A largely intact embankment 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 is well set back 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 wing-wall) is fully exposed as if it were a pier.

Because contraction scour integrates the influences of several variables (e.g., approach flow depths and discharge, bed sediment), it is meaningful and convenient to relate maximum scour depth, Y_{max}, to contraction scour depth, Y_C. That is, for a fixed embankment and floodplain,

$$Y_{\max} = \alpha Y_C \qquad (1)$$

The factor α amplifies Y_C near the abutment (as evident in Figure 3). The magnitude of α 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 α has yet to be determined. The writers suggest that Equation (1) be expressed as

$$\left(\frac{Y_{\max}}{Y_1}\right) = C_T \left(\frac{q_{\max}}{q_1}\right)^{6/7} \qquad (2)$$

where q_{max} is the unit discharge coinciding with the location of deepest scour in the main channel. If all the floodplain flow entered the main channel, in the situation of a long abutment extending practically across the floodplain, $q_{\max} = m\overline{q}_2$, where $\overline{q}_2 = \left(Q_{1m} + Q_F\right)/B_2$, Q_{1m} is the approach flow in the main channel, and Q_F is the approach flow over the floodplain. The values of m and C_T have to be determined from laboratory or numerical-simulation data.

An approximate relationship for flow depth at the location of maximum scour is

$$Y_{MAX} = Y_1 C_T m^{6/7} \left(\frac{\overline{q}_2}{\overline{q}_1}\right)^{6/7} \qquad (3)$$

where $\overline{q}_1 = Q_{1m} / B_1$. For a long contraction, $m \approx 1$, $C_T \approx 1$, and thus Equation (3) simplifies to

$$Y_{MAX} = Y_1 \left(\frac{\overline{q}_2}{\overline{q}_1} \right)^{6/7} = Y_C \tag{4}$$

which essentially is the relationship proposed by Laursen (1960) for estimating the scour depth associated with live bed flow through a long contraction. Comparison of Equations (1), (3), and (4) indicates that

$$Y_{MAX} = \alpha Y_C = C_T m^{6/7} Y_C \tag{5}$$

The main difficulty to be overcome for design estimation of scour depth, therefore, is estimation of *m* and C_T.

SCOUR DEPTH AT ABUTMENTS SET BACK FROM MAIN CHANNEL

This condition of abutment failure is of primary concern for abutments on wide floodplains and those set well back from the main channel. Because clearwater flow predominantly occurs on floodplains, it is assumed herein that scour of a floodplain at an abutment occurs as clearwater scour. Moreover, it is assumed that the scour development is not affected by flow or scour of the main channel bed. Analysis leads to the following equation:

$$\left(\frac{Y_{\max}}{Y_F} \right) = C_T m^{6/7} \left(\frac{\tau'_F}{\tau_C} \right)^{3/7} \left(\frac{\overline{q}_2}{\overline{q}_F} \right)^{6/7} \tag{6}$$

Where τ'_F and τ_C are boundary shear stress on the floodplain and critical for boundary sediment entrainment, respectively. Ettema et al. (2005) provide details as to the derivation and use of Equation (6), as well as Equations (1) through (5).

ESTIMATION OF SCOUR AT EXPOSED ABUTMENT STRUCTURE

Scour depth prediction for this scour condition has to rely on an empirical relationship, owing to the complexity of flow and sediment entrainment from an abutment structure exposed once the approach embankment has been breached. The approach being developed by the writers is basically that used for estimating scour depth at a bridge pier; the exposed abutment is a pier-like structure.

LAB EXPERIMENTS RESULTS

The scour data are being obtained for three states of floodplain and embankment erodibility:

1. Fixed floodplain and embankment
2. Erodible floodplain and riprap-protected embankment
3. Erodible floodplain and an unprotected embankment

Figure 7 presents data on maximum flow depths, Y_{MAX}, plotted versus unit-discharge ratio, $\overline{q}_2/\overline{q}_1$, for the fixed and erodible floodplain states. The data are for the simulated spill-through abutments. Also plotted in this figure is contraction flow depth, Y_C, versus $\overline{q}_2/\overline{q}_1$, with Y_C estimated using the long contraction relation given as Equation (4). Here, L is abutment length, B_F is floodplain width, and 0.5B is half the width of the main channel.

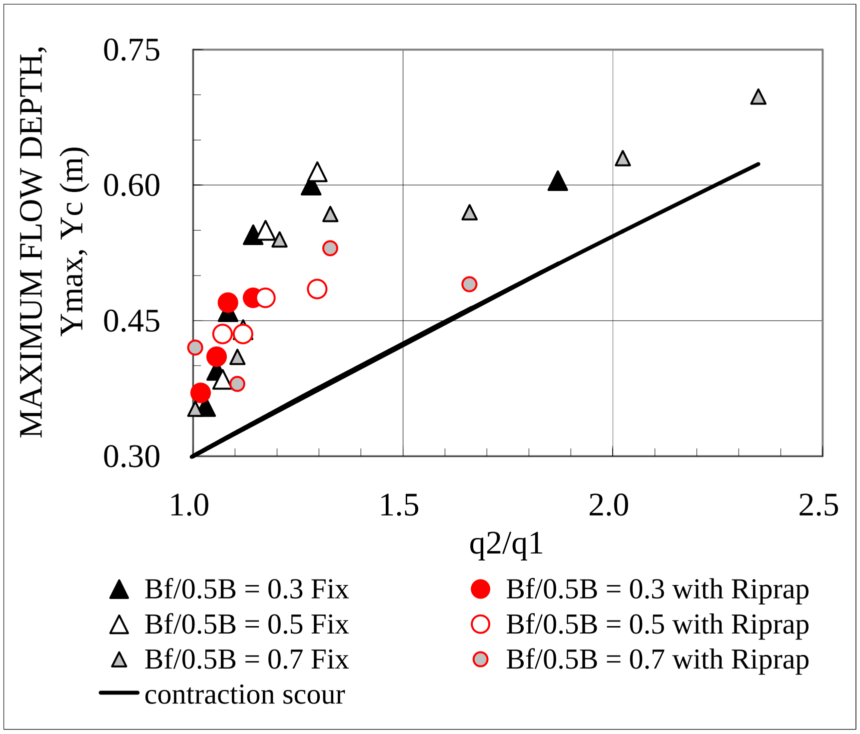

Figure 7. Variation of Y_{MAX} and Y_C with unit-discharge ratio $\overline{q}_2/\overline{q}_1$ and lab data on spill-through abutments

To assess the depth amplification factor, $\alpha = C_T m^{6/7}$, expressed in Equation (5), Figure 8 plots the ratio Y_{MAX}/Y_C versus $\overline{q}_2/\overline{q}_1$ for fixed floodplain and embankment. This figure provides some important insights:

1. The data appear to conform to a reasonably consistent trend.
2. At the lesser values of $\overline{q}_2/\overline{q}_1$ (and flow contraction), Y_{MAX} substantially exceeds Y_C. Eventually as the bridge waterway becomes more contracted, $\overline{q}_2/\overline{q}_1$ increases, and values of Y_{MAX} approach Y_C. This portion of the trend reflects the dominance of scour caused primarily by flow contraction as opposed to that attributable the local change in bed form height in the contraction combined with the turbulence generated by flow passing around the abutment and over the edge of the main channel bank.
3. It is intriguing that the values of Y_{MAX}/Y_C attain a maximum value of around 1.5~1.6 when $\overline{q}_2/\overline{q}_1 \approx 1.2$~1.3.

4. It also is intriguing that the values of Y_{MAX}/Y_C decline quite markedly after the maximum. The values then asymptote to a level of about 1.1.
5. The parameter floodplain width divided by channel half width, $B_f/0.5B$, exerts a small influence, especially in the maximum values of Y_{MAX}/Y_C. The maximum value of Y_{MAX}/Y_C is larger for the smaller value of $B_f/0.5B$. This influence is attributable to the fact that, in absolute lengths, the abutment is closer to the main channel, thereby causing more of the turbulence generated by the abutment to be diffused to the main channel.

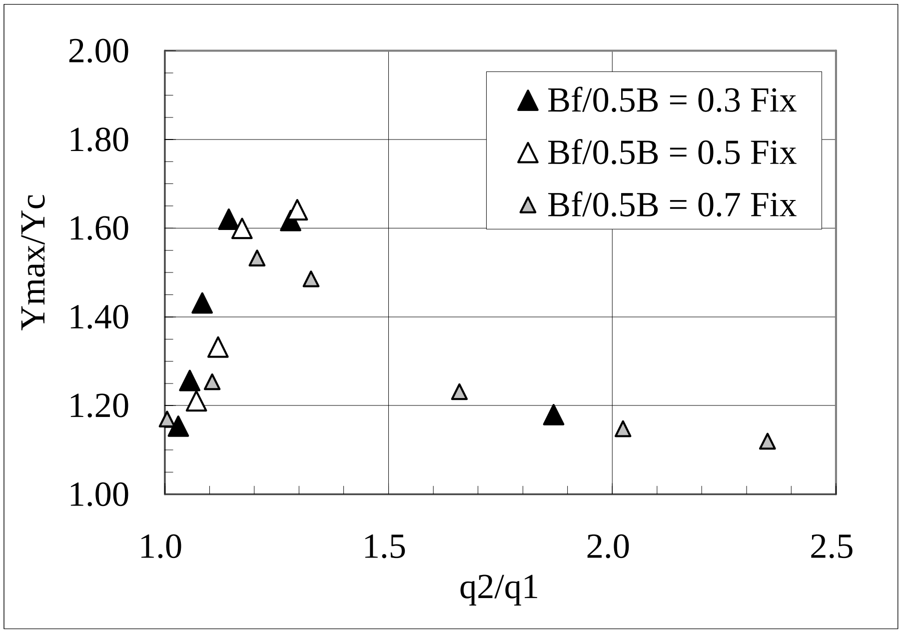

Figure 8. Variation flow depth increase, Y_{MAX}/Y_C, with $\overline{q}_2 / \overline{q}_1$; spill-through abutments on fixed (erosion-resistant) floodplain

Figure 9 plots the ratio Y_{MAX}/Y_C versus $\overline{q}_2 / \overline{q}_1$ for the erodible floodplain and riprap-protected embankment. This figure contains a combination of scour conditions 1 and 2:

1. For the lesser values of $\overline{q}_2 / \overline{q}_1$ (and flow contraction), Y_{MAX} substantially exceeds Y_C. Moreover, for some experiments, the value of Y_{MAX}/Y_C exceeds that obtained when the floodplain was fixed. For these latter experiments, scour condition 2 prevailed and produced a deeper scour than did scour condition 1.
2. As values of $\overline{q}_2 / \overline{q}_1$ increased, scour conditions 1 and 2 jointly increased the flow cross-sectional area at the abutment, and thereby relaxed the flow contraction, resulting in a leveling off of flow depths at the scour location.

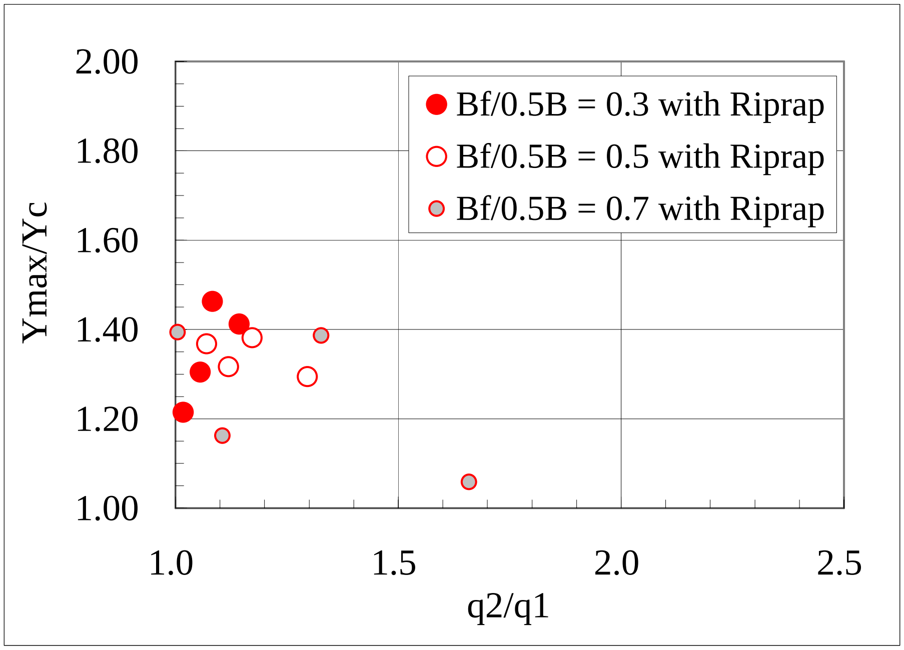

Figure 9. Variation flow-depth increase, Y_{MAX}/Y_C, with $\overline{q}_2/\overline{q}_1$; spill-through abutments (armored with riprap) on erodible floodplain

Figure 10 includes data obtained with the wing-wall abutments for this scour condition; i.e., for the cases $B_f/0.5B$ = 0.3, 0.5, and 0.7, note that L/B_f = 1. When the floodplain and the embankment are erodible, the three scour conditions occurred. When the flow breached the embankment, the abutment itself becomes exposed, so that scour depth estimation must treat the abutment as if it were a pier-like structure. The writers are completing a design relationship for this condition.

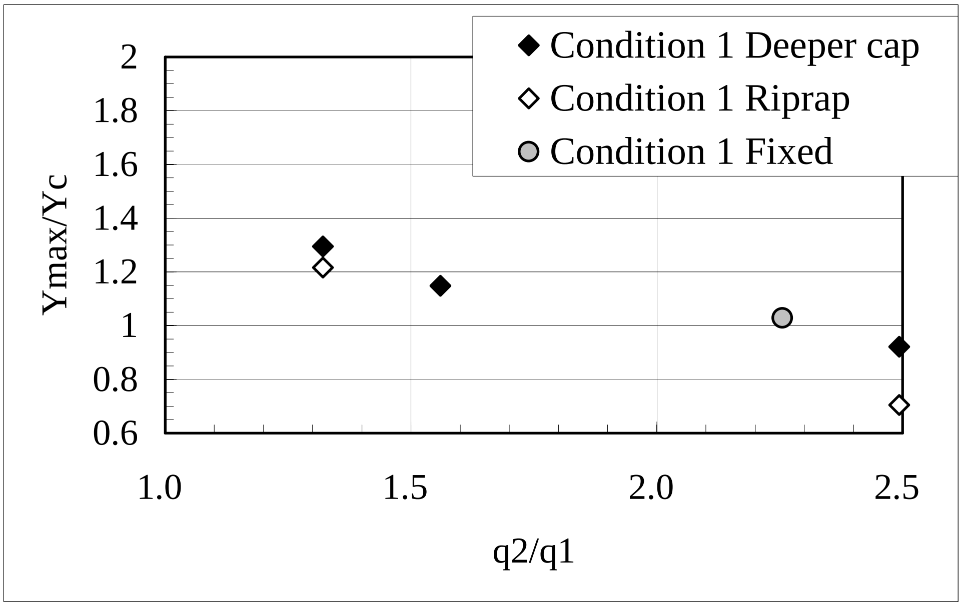

Figure 10. Variation flow-depth increase, Y_{MAX}/Y_C, with $\overline{q}_2/\overline{q}_1$; wing-wall abutments on fixed or erodible floodplain

It is interesting to see that $Y_{MAX}/Y_C \approx 1$ when the floodplain and embankment were fixed. This finding suggests that the scour was largely due to flow contraction and was not much affected by turbulence generated by flow around the abutment. The flow field observations and measurements taken in the lab support this finding.

DESIGN APPROACH

The observations and data indicate that a practical and adequately reasonable approach to estimating scour depth at an abutment can be obtained using Equations (4), (5), and (6). To use these equations entails determining the unit discharge ratio, $\overline{q}_2 / \overline{q}_1$, along with m and C_T. A two-dimensional numerical flow model can be used to estimate $\overline{q}_2 / \overline{q}_1$ along with m, though C_T will have to remain empirically derived (with field verification) from laboratory data. The present data, though, suggest that approximate estimation can be made for scour of the main channel using the following equation:

$$Y_{MAX} = C_T m^{6/7} Y_C \approx \alpha Y_C = 1.75 Y_C \tag{7}$$

This relationship is applicable to spill-through and wing-wall abutments. The suggestion of using $\alpha = 1.75$ requires further verification, but results to date indicate it to be quite appropriate for design estimation. If no contraction scour is estimated to occur, Equation (7) gives Y_{max} as twice the design flow depth through the bridge waterway.

Further work is underway to complete the estimation of a comparable relationship for scour at abutments set back on floodplains.

CONCLUSIONS

The new and practical 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 are currently conducting further experiments towards determining the relationships expressed in Equations (2) through (4). The outcome of the experiments may place the estimation approach on a suitably practical and reasonably accurate footing.

ACKNOWLEDGMENTS

The work presented here is being conducted under project NCHRP 24-20 of the U.S. Transportation Research Board.

REFERENCES

Ettema, R., A. Yorozuya, T. Nakato, M. Muste. 2005. *Quarterly Progress Report #8, NCHRP Project 24-20, Prediction of Abutment Scour*. Washington, D.C.: National Cooperative Highway Research Program.