

Design Estimation of Abutment Scour Depths

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ABSTRACT

Considerable uncertainty and debate surround scour-depth estimation for abutments, to the extent that the existing estimation relationships are not well accepted. The crux of the concern is that existing relationships tend to predict scour depths that seem excessive. The present paper introduces a practical design approach to scour depth estimation. The approach is still in development, its estimation relationships are being formed using the findings from an extensive laboratory study.

I. INTRODUCTION

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 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.

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 conventionally are termed "local scour" and "contraction scour." The fresh approach adumbrated 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 currently are further developing the approach.

II. 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 (Figure 2);
3. The portion of the embankment near the abutment usually is 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 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's foundation fails (e.g., Ettema et al. 2002).

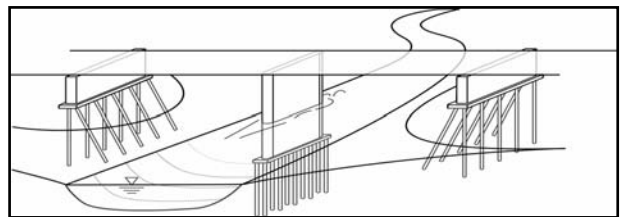


Figure 1. Many abutments are pile-supported and have an earthfill embankment



Figure 2. Failure of earthfill embankment at abutment

III. EXPERIMENTS

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 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.

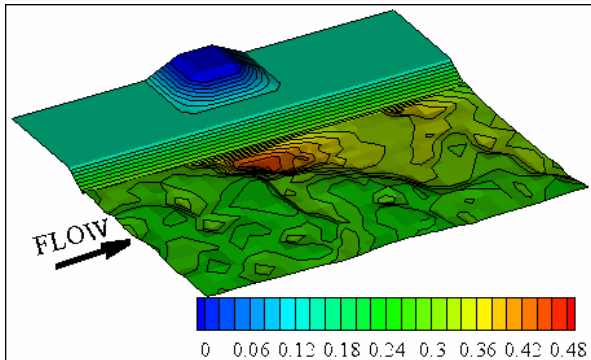


Figure 3. Bathymetry of scour zone at abutment (lab)

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 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 contraction scour.

Moreover, the experiments show that maximum scour depth may not occur at the abutment. As the width of floodplain increases, and flow contraction concomitantly increases, the location of deepest scour can shift downstream of the abutment. Figure 3 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 4 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.

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.

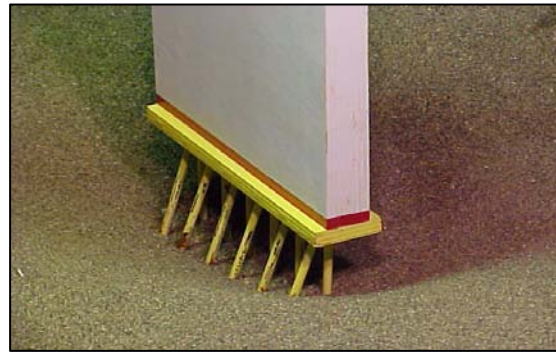


Figure 4. deepest scour at abutment base occurs when embankment washed out

IV. 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 like that. Illustrations like Figures 1 and 2, as well as the writers' observations of scour development at piled-supported abutments and earthfill embankments, suggest the need for a practical estimation approach to scour-depth estimation. The practical approach offered here 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. The term "embankment largely intact" here means that the flow has not broken through the approach embankment.
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.

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 well set back from the main channel.

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 : i.e., for a fixed embankment and floodplain,

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

The factor α amplifies Y_C near the abutment. 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 (1) be expressed as

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

In which 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, $q_{\max} = m\bar{q}_2$; $\bar{q}_2 = (Q_{1m} + Q_F)/B_2$; Q_{1m} is approach flow in the main channel, and Q_F is approach flow over the floodplain. Values of m and C_T have to be determined from laboratory or numerical-simulation data.

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

$$Y_{\max} = Y_1 C_T m^{6/7} \left(\frac{\bar{q}_2}{\bar{q}_1}\right)^{6/7} \quad (3)$$

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

$$Y_{\max} = Y_1 \left(\frac{\bar{q}_2}{\bar{q}_1}\right)^{6/7} = Y_C \quad (4)$$

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 (1), (3), and (4) indicates that

$$Y_{\max} = \alpha Y_C = C_T m^{6/7} Y_C \quad (5)$$

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

V. ABUTMENTS SET-BACK ON FLOODPLAIN

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

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

in which 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 (6), as well as (1) through (5).

VI. EXPERIMENT 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; and,
3. Erodible floodplain and an unprotected embankment.

To assess the depth-amplification factor $\alpha = C_T m^{6/7}$ expressed in (5), Figure 5 plots the ratio Y_{\max}/Y_C versus \bar{q}_2/\bar{q}_1 for fixed floodplain and embankment.

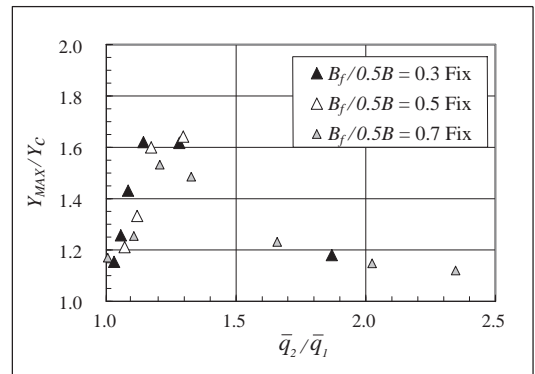


Figure 5. Variation flow-depth increase, Y_{\max}/Y_C , with \bar{q}_2/\bar{q}_1 ; spill-through abutments on fixed (erosion-resistant) floodplain

This figure provides some important insights:

1. The data appear to conform to a reasonably consistent trend;
2. At the lesser values of \bar{q}_2/\bar{q}_1 (and flow contraction), Y_{\max} substantially exceeds Y_C . Eventually as the bridge waterway becomes more contracted, \bar{q}_2/\bar{q}_1 increases, and values Y_{\max} of 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 $\bar{q}_2/\bar{q}_1 \approx 1.2\sim 1.3$;
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; and,
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. Here B_F is floodplain width, $0.5B$ is half width of main channel, and L is abutment length.

Figure 6 plots the ratio Y_{MAX}/Y_C versus \bar{q}_2/\bar{q}_1 for the erodible floodplain and riprap-protected embankment.

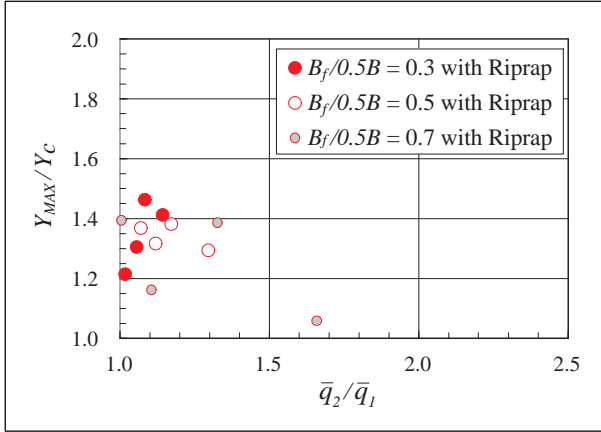


Figure 6. Variation flow-depth increase, Y_{MAX}/Y_C , with \bar{q}_2/\bar{q}_1 ; spill-through abutments (armored with riprap) on erodible floodplain

This figure combines the data trends obtained for scour conditions 1 and 2:

1. For the lesser values of \bar{q}_2/\bar{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 \bar{q}_2/\bar{q}_1 increased, scour conditions 1 and 2 jointly increased the flow cross-sectional area at the abutment, and thereby relaxed the flow contraction, thereby resulting in a leveling off of flow depths at the scour location.

Figure 7 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. 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.

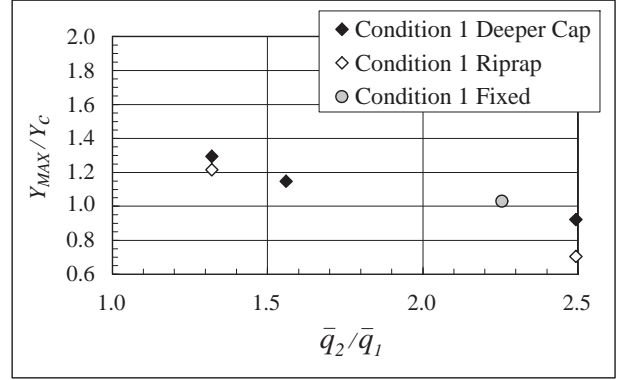


Figure 7. Variation flow-depth increase, Y_{MAX}/Y_C , with \bar{q}_2/\bar{q}_1 ; wing-wall abutments on fixed or erodible floodplain

VII. 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 (4), (5), and (6). To use these equations entails determining the unit discharge ratio \bar{q}_2/\bar{q}_1 along with m and C_T . A 2-dimensional, numerical flow model can be used to estimate \bar{q}_2/\bar{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:

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

In which Y_C is the flow depth associated with maximum unit discharge through the bridge waterway. 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, (7) gives Y_{max} as twice the design flow depth through the bridge waterway.

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

IX. ACKNOWLEDGMENT

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