Conference Paper, Published Version

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Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/100218

Vorgeschlagene Zitierweise/Suggested citation:
Lagasse, Peter F.; Zevenbergen, Lyle W.; Clopper, Paul E. (2010): Impacts of Debris on Bridge Pier Scour. In: Burns, Susan E.; Bhatia, Shobha K.; Avila, Catherine M. C.; Hunt, Beatrice E. (Hg.): Proceedings 5th International Conference on Scour and Erosion (ICSE-5), November 7-10, 2010, San Francisco, USA. Reston, Va.: American Society of Civil Engineers. S. 854-863.

Impacts of Debris on Bridge Pier Scour

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ABSTRACT

Waterborne debris (or drift) often accumulates on bridges during flood events. The effects can vary from minor flow constrictions to severe flow contraction resulting in significant bridge foundation scour. The results of National Cooperative Highway Research Program (NCHRP) Project 24-26, "Impacts of Debris on Bridge Pier Scour" represent a significant advance to predicting debris scour considering the variable geometry of debris clusters observed at bridge piers in the field. The study produced results on two related problems: predicting the accumulation characteristics of debris from widely varying source areas, and developing improved methods for quantifying the depth of scour at bridge piers. This paper highlights the observations from laboratory testing and the development of improved algorithms for predicting the depth of scour at debris-laden bridge piers.

INTRODUCTION

Waterborne debris (or drift), composed primarily of tree trunks and limbs, often accumulates on bridges during flood events. Debris accumulations can obstruct, constrict, or redirect flow through bridge openings resulting in flooding, damaging loads, or excessive scour at bridge foundations. The size and shape of debris accumulations vary widely, ranging from a small cluster of debris on a bridge pier to a near complete blockage of a bridge waterway opening. Debris accumulation geometry is dependent on the characteristics and supply of debris transported to bridges, on flow conditions, and on bridge and channel geometry. The effects of debris accumulation can vary from minor flow constrictions to severe flow contraction resulting in significant bridge foundation scour.

At the outset of NCHRP Project 24-26 in June 2004 there was a pressing need for State Departments of Transportation (DOTs) and other bridge owners to have improved prediction methods for the geometry (size and shape) of typical debris accumulations, and the conditions under which debris can be expected to develop. In addition, there was a need for accurate methods of quantifying the effects of debris on scour at bridge-pier foundations for use by DOTs and other agencies in the design, operation, and maintenance of highway bridges.

The objectives of NCHRP Project 24-26 were to produce results on two related problems: (1) predicting the accumulation characteristics of debris from potentially widely varying source areas, in rivers with different geomorphic characteristics, and on bridges with a variety of substructure geometries, and (2) developing improved methods for quantifying the depth and extent of scour at bridge piers considering both the accumulation variables and the range of hydraulic factors involved (Lagasse et al. 2010). This paper highlights the observations from laboratory testing and the development of improved algorithms for predicting the depth of scour at debris-prone bridges.

OVERVIEW OF RESEARCH APPROACH

As an extension of the original work by Diehl (1997) for the Federal Highway Administration (FHWA), guidelines and flow charts were developed for estimating the potential for debris production and delivery from the contributing watershed of a selected bridge, and the potential for accumulation on individual bridge elements. The application of the guidelines was illustrated by a case study of a debris-prone bridge on the South Platte River in Colorado. The case study introduces and illustrates the use of Field Reconnaissance Data Sheets for evaluating the potential for debris production and delivery from a given watershed.

As a basis for laboratory testing, an extensive photographic archive of debris accumulations at bridges nationwide was assembled. This archive includes 1079 photos at 142 sites in 31 states. The archive together with a field pilot study of debris sites in Kansas, and the South Platte River case study were examined to develop a limited number of debris shapes that would represent the maximum number of configurations found in the field. Simplified, yet realistic, shapes that could be constructed and replicated with a reasonable range of geometric variables were needed for laboratory testing. Rectangular and triangular shapes with varying planform and profile dimensions were selected to represent prototype debris accumulations. To account for additional variables thought to be relevant to debris clusters in the field, a method to simulate both the porosity and roughness of the clusters was developed.

The laboratory testing program included the use of a large indoor flume at Colorado State University and model bridge pier shapes, development of state-of-the-art instrumentation for data acquisition, and a wide range of materials to fabricate the debris clusters. Baseline tests were conducted and results were compared with several pier scour prediction equations. A series of tests under clear-water conditions with the various debris shapes were completed. The following sections highlight the laboratory testing and analytical phases of the project.

LABORATORY TESTING OF DEBRIS

Testing Requirements

The objective of laboratory testing was to provide sufficient data for a range of debris accumulations to develop adjustment factors to FHWA's HEC-18 pier scour equation (Richardson and Davis 2001). The laboratory plan was designed to develop a series of tests for a wide range of debris configurations that could be run quickly and efficiently. The tests were performed for single debris clusters at individual piers, which was the most prevalent type of debris accumulation identified for all physiographic regions in the U.S. The majority of the testing was performed for clear-water sediment transport conditions (approach flow velocity (V) less than the critical velocity to initiate sediment transport (V_c)) for durations much less than would be required to achieve ultimate scour. The duration was, however, sufficient to achieve at least 60% of ultimate scour.

Debris Dimensions

All of the physical modeling was conducted in the 2.4 m (8 ft) wide flume at Colorado State University under clear-water flow conditions. Square piers 10.2 cm (4 inches) in width were used for most runs, although slender wall-type piers and multiple-column piers were also tested. All of the dimensions were normalized by the pier width so the field conditions could be used to develop a realistic range of laboratory runs. The range of debris dimensions was selected to encompass the range observed in the field +/- one standard deviation around the mean.

The testing considered a range of debris characteristics including debris accumulation shape, thickness, width, and length. The range of debris accumulation size tested in the laboratory was related to actual debris accumulations observed in the field or from the photographic archive. Figures 1 and 2 illustrate typical debris shapes (rectangular and conical in profile and either rectangular or triangular in planform) that were modeled and define the dimensions for the various shapes.

Figure 3 shows a 1.22 m (4 ft) wide by 0.9 m (3 ft) long by 0.3 m (1 ft) high triangular debris configuration incorporating roughness and porosity before testing. Figure 4 shows the results of testing the debris configuration after 8 hours of testing at 1.0 V_c. The upper segment of the pier has been removed for data collection purposes. Ambient bed elevation is represented by the top of the lower segment of the pier.

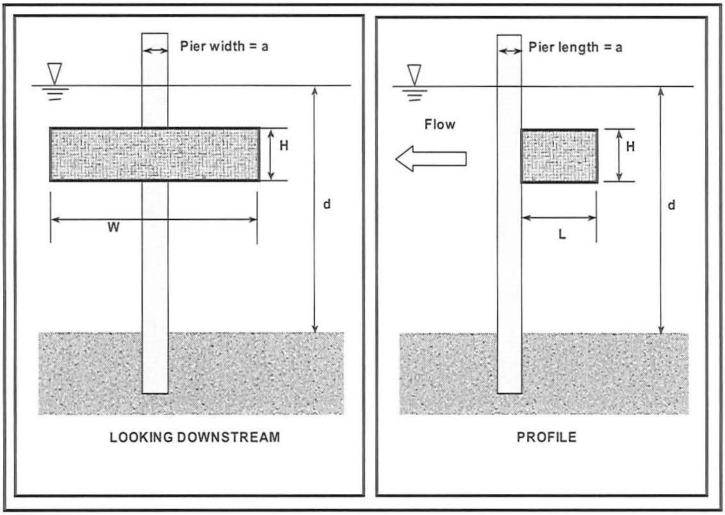

Figure 1. Rectangular shape definition sketch.

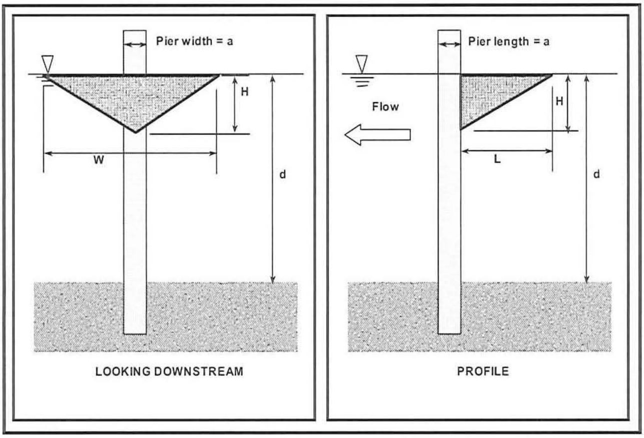

Figure 2. Triangular/conical shape definition sketch.

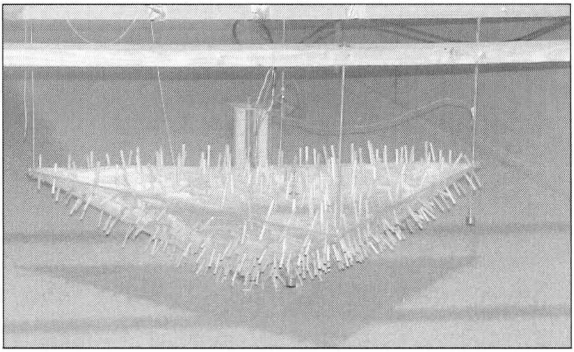

Figure 3. Triangular/conical debris cluster before Test 007_02A, mounted such that the top surface of the debris was located at the water surface.

SCOUR PREDICTION AT BRIDGE PIERS WITH DEBRIS LOADING

Introduction

The laboratory testing program was conducted to develop information on a variety of factors related to debris accumulations at piers including:

- Shape:	Rectangular or triangular
- Size:	Width, length, and thickness
- Location:	Surface (floating), mid-depth, or bed (partially buried)
- Roughness:	Smooth or roughened
- Porosity:	Impermeable or 25% porosity
- Approach velocity:	V/V_c ratios of 0.70 and 1.0

Figure 4. Scour hole resulting from Test 007_02A after 8 hours of testing at 1.0 V_c.

Selected combinations of these factors were also tested; for example, a particular debris shape might be tested as (1) a smooth impermeable body, (2) a smooth porous body, (3) a rough impermeable body, and (4) a rough porous body. Factors not considered in the test program include the effect of bed material grain size, flow depth, live-bed conditions, and contraction scour. Fifty-three tests of debris-laden piers were run under clear-water scour conditions. Most of the tests (35) were conducted with the top surface of the debris at the water surface, forming a "raft." Selected tests were also performed with the debris located in the center of the water column, resting on the bed, or buried into the bed.

Equivalent Pier Width

All pier scour prediction equations use pier width as a factor that contributes to the estimated scour depth. Intuitively, the accumulation of debris on a pier causes the pier to appear larger in the flow field, thereby increasing the total area blocked by obstruction. HEC-18 (Richardson and Davis 2001) uses the width W of the debris perpendicular to the flow direction to estimate the additional obstruction.

Melville and Dongol (1992) provide an equation to calculate the "equivalent width," b_e, of a bridge pier that is loaded with debris. The equation uses both the width W and thickness T of the debris, and is based on scour data from a limited number of tests (17 tests) in a laboratory flume. Only floating (surface) debris at cylindrical piers was tested, with the debris wrapped around the pier in all directions. The effect of the vertical location of the debris mass within the water column was not investigated. Their equation to calculate equivalent pier width is:

$$b_e = \frac{K_{d1}(TW) + (y - K_{d1}T)a}{y} \tag{1}$$

where:

b_e = Effective width of the pier, m (ft)
K_{d1} = Dimensionless coefficient equal to 0.52 from lab tests (Dongol 1989)
T = Thickness of debris, m (ft)
W = Width of debris normal to flow, m (ft)
a = Pier width (without debris) normal to flow, m (ft)
y = Depth of approach flow, m (ft)

Comparing a calculated effective pier width (b_e) with an observed effective width indicates that the Melville-Dongol equation tends to overestimate the effective width of the pier when debris is present, particularly for triangular shapes. The Melville-Dongol equation does not take into account the shape of the debris mass (e.g., rectangular vs. triangular), nor does it consider the length L of the debris extending upstream from the pier.

A modification to the equivalent width equation was, therefore, proposed and tested against the laboratory data. The proposed modification is denoted as "a^*_d" to distinguish it from the Melville and Dongol "b_e," and is given as:

$$a_d^* = \frac{K_{d1}(TW)\left(L/y\right)^{K_{d2}} + (y - K_{d1}T)\,a}{y} \tag{2}$$

where:

K_{d1} = Dimensionless coefficient optimized from lab test data
K_{d2} = Dimensionless exponent optimized from lab test data
L = Length of debris upstream from pier face, m (ft)
Other terms are as defined previously.

Optimizing the coefficient K_{d1} and exponent K_{d2} to the observed laboratory data revealed that the shape and upstream extent of the debris do affect the resulting scour at the pier face. For rectangular debris shapes, K_{d1} and K_{d2} were found to be 0.39 and -0.79, respectively, whereas for triangular shapes, K_{d1} and K_{d2} were 0.14 and -0.17, respectively. **The coefficient K_{d1} is thus seen to be a shape factor, while the exponent K_{d2} is a factor that describes the intensity of the plunging flow created by the debris blockage**.

A relationship better suited to design should tend towards conservatism; that is, underestimation of the observed (i.e., actual) scour should be relatively rare. Based on the laboratory data developed for an approach velocity of 1.0 V_{crit}, the shape coefficient K_{d1} that provides overestimation 90% of the time (underestimating 10% of the observations) is 0.79 for rectangular debris shapes, and 0.21 for triangular shapes.

The recommended design equations for estimating an equivalent pier width for use with the HEC-18 pier scour equation are, therefore:

$$a_d^* = \frac{K_{d1}(TW)\left(L/y\right)^{K_{d2}} + (y - K_{d1}T)\,a}{y} \qquad \text{for } L/y > 1.0 \tag{3}$$

and

$$a_d^* = \frac{K_{d1}(TW) + (y - K_{d1}T)a}{y} \qquad \text{for } L/y \le 1.0 \qquad (4)$$

where:

K_{d1} = 0.79 for rectangular debris, 0.21 for triangular debris
K_{d2} = -0.79 for rectangular debris, -0.17 for triangular debris
L = Length of debris upstream from pier face, m (ft)
y = Depth of approach flow, m (ft)
Other terms are as defined previously.

The design or "envelope" values using the recommended equations are shown in Figure 5 for all runs with debris at the water surface and an approach velocity of 1.0 V_{crit}. In this figure, the HEC-18 pier scour equation is used to predict ultimate clear-water scour at the pier face, using the equivalent pier width calculated by Equations 3 and 4 and the recommended K_{d1} and K_{d2} values presented above.

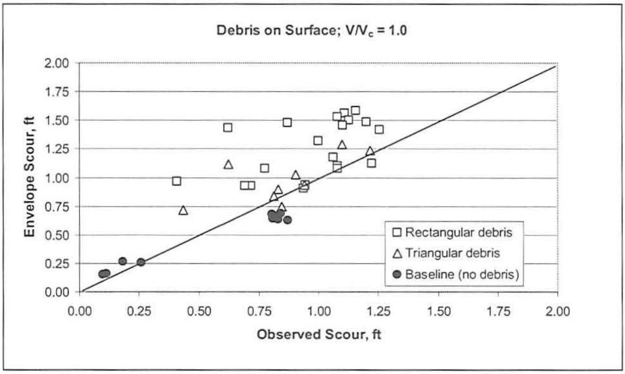

Figure 5. Comparison of observed scour to the recommended design equation using 90% envelope values.

CONCLUSIONS

Observations From Laboratory Testing

The scour processes observed in the laboratory can be visualized by comparing idealized flow lines at a pier with no debris to those at a pier with rectangular and triangular debris clusters. In Figure 6, the flow lines at an unobstructed pier are essentially uniform in the approach section. At the pier, the flow dives down the front face and spirals past the pier in the classic "horseshoe vortex" pattern.

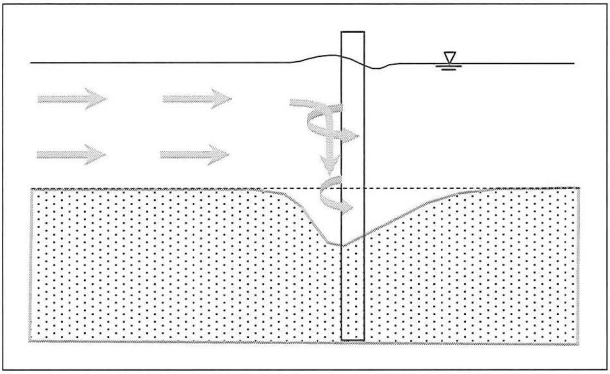

Figure 6. Idealized flow pattern at an unobstructed pier.

In contrast, flow at a pier with a rectangular debris cluster is significantly obstructed and forced to plunge beneath the upstream face of the debris as shown in Figure 7. **The plunging flow creates the upstream scour trough that was observed consistently during the laboratory testing program.**

Because of the blockage created by the debris, some flow is forced around the sides as well. As the flow beneath the debris approaches the pier, the diving and spiral horseshoe patterns are still observed. Depending on the degree of blockage compared to the entire channel (flume) cross section, the relative strengths of the diving flow and horseshoe vortex may be greater or less than the unobstructed case.

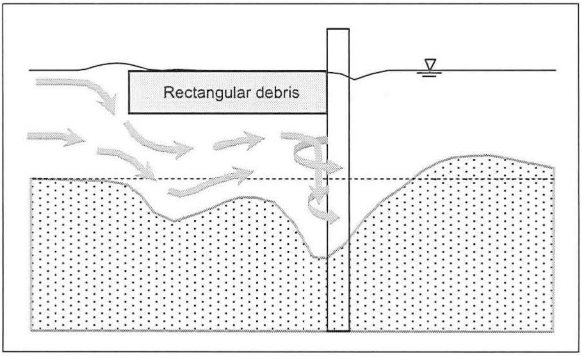

Figure 7. Idealized flow pattern at a rectangular debris cluster.

Rectangular, blocky debris masses tended to produce the greatest scour at the pier when the extent ("length" dimension) of the debris upstream of the pier was on the order of one flow depth. This condition produced plunging flow that was directed toward the channel bed in the immediate vicinity of the pier face, resulting in a worst-case scour condition (i.e., when the upstream trough coincides with scour generated by the pier). Total scour at the pier was also significantly increased when the total frontal area of flow blockage (as a percent of the cross-sectional area of the approach channel) was large. In that case, the debris-induced scour appeared to be similar to that created by pressure flow and contraction effects, for example, pressure flow beneath bridge decks that are submerged during floods.

Triangular-shaped debris clusters were also investigated, because the debris photo archive revealed that this is another very common shape that can be produced in the field as drift accumulates at a pier. In a triangular configuration, the thickness of the debris is greater at the pier face, tapering upward and thinning toward the leading (upstream) point. The scour pattern created by triangular debris clusters (Figure 8) was markedly different from that exhibited by the rectangular clusters. **No scour troughs upstream of the pier were observed with any of the triangular debris clusters**.

The portion of the flow that plunges beneath a triangular/conical blockage is seen to be funneled towards the pier face, creating additional scour at the pier compared to the baseline condition. The scour at the pier face was found to be related to the thickness of the debris blockage at the pier face; i.e., a greater thickness of debris lodged directly against the pier created more scour at the pier face, with the triangular debris shapes.

As with the rectangular debris tests, lateral extent of scour created by triangular debris clusters was directly related to the width of the cluster. However, the lateral extent of scour caused by a triangular debris cluster was shown to be greater than that of a rectangular one. This appears to be caused by the shedding of flow around the triangular shaped debris, and has implications regarding the effect of this shape at adjacent piers or abutments.

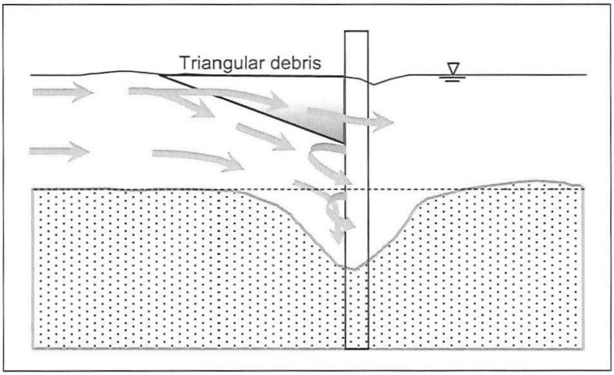

Figure 8. Idealized flow pattern at a triangular debris cluster.

The laboratory studies revealed that the roughness and porosity of a debris mass do not significantly affect the pattern of scour or the magnitude of the scour depth at the pier face. For the range of these properties examined, debris roughness and porosity can be considered, at most, second-order variables that are not significant compared to the size, shape, and location of the debris mass.

Scour Prediction at Bridge Piers with Debris Loading

Building on the algorithm originally proposed by Melville and Dongol and using an equivalent pier width, a^*_d, an improved predictive equation is now available. Considering the most common shapes of debris clusters (rectangular in planform and profile, and triangular in planform but conical in profile) length, width, and thickness of the debris accumulation upstream of a bridge pier can now be considered. Different coefficients and exponents based on more extensive laboratory testing are recommended, but the basic form of the effective width equation is retained. The recommended equation is stable, can be adapted to most conditions found at bridge piers in the field, and complements the approach to estimating pier scour currently recommended in FHWA's HEC-18.

The end results of NCHRP Project 24-26 are practical, implementable guidelines for bridge owners that enhance their ability to predict debris-related hazards at bridges and design, operate, inspect, and maintain bridges considering those hazards. The results of this research were published by the Transportation Research Board as NCHRP Report 653 in June 2010.

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