METHOD FOR RAPID ESTIMATION OF SCOUR AT HIGHWAY BRIDGES BASED ON LIMITED SITE DATA

By Stephen R. Holnbeck and Charles Parrett

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CONVERSION FACTORS, VERTICAL DATUM, AND SYMBOLS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
cubic foot per second per foot-width ($ft^3/s/ft$)	0.092904	cubic meter per second per meter-width
foot (ft)	304.8	millimeter (mm)
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per second (ft/s)	0.3048	meter per second
foot per second squared	0.3048	meter per second squared
inch (in.)	25.4	millimeter (mm)
mile	1.609	kilometer
square foot	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

SYMBOLS:

$<$ less than
$\leq$ less than or equal to
$\geq$ greater than or equal to
$>$ greater than

METHOD FOR RAPID ESTIMATION OF SCOUR AT HIGHWAY BRIDGES BASED ON LIMITED SITE DATA

By Stephen R. Holnbeck and Charles Parrett

Abstract

Limited site data were used to develop a method for rapid estimation of scour at highway bridges. The estimates can be obtained for a site in a matter of hours rather than several days as required by more-detailed methods. Such a method is needed because scour assessments are needed for a large number of bridges as part of a national program to inventory scour-critical bridges throughout the United States. In Montana, for example, about 1,600 bridges need to have scour assessments completed. Using detailed scour-analysis methods and scour-prediction equations recommended by the Federal Highway Administration, the U.S. Geological Survey, in cooperation with the Montana Department of Transportation, obtained contraction, pier, and abutment scour-depth data for 122 sites. Data from these more detailed scour analyses, together with similar data from detailed scour analyses performed by the U.S. Geological Survey in Colorado, Indiana, Iowa, Mississippi, Missouri, New Mexico, South Carolina, Texas, and Vermont, were used to develop relations between scour depth and hydraulic variables that can be rapidly measured in the field. Data from the various States generally were comparable and indicate that the rapid-estimation method generally is applicable throughout the United States. Some differences in interpretation of hydraulic variables were noted, however, and methods for estimating hydraulic variables need to be verified and perhaps modified for use in States other than Montana.

Relations between scour depth and hydraulic variables were based on simpler forms of the detailed scour prediction equations and graphical plots. The relations were developed as envelope curves rather than best-fit curves to ensure that the rapid-estimation method would tend to overestimate rather than underestimate scour depths. Equations for estimating contraction scour from variables that can be rapidly measured were derived for both live-bed and clear-water scour conditions. Variables that need to be measured for determining live-bed contraction scour include main-channel width and depth at the approach section, Manning's roughness coefficients for the main channel and overbank areas at the approach section, overbank depths and widths at the approach section, and main-channel width at the bridge section. Variables that need to be measured to apply the equation for estimation of clear-water contraction scour in the main channel are main-channel width at the bridge section, main-channel depth at the approach section, and the median size of bed material. For the complex case involving clear-water scour in the bridge setback area along with live-bed scour in the main channel, hydraulic variables for the setback area also need to be measured. Except for special conditions where streambeds are composed of small cobbles or larger streambed material or where stream velocity is very low, the equation for live-bed scour is assumed to be applicable for main channels. For main-channel conditions where clear-water scour conditions may be more likely, a determination of scour condition can be made on the basis of median bed particle size and a critical velocity calculation. Two envelope curves for final estimation of contraction scour depth from the rapid-estimation method were developed by plotting scour depths from more-detailed scour analyses against scour depths calculated from the derived equations.

Important variables for estimation of pier scour using the rapid-estimation method included pier width and length, flow angle of attack, and average Froude number of flow in the bridge section. The envelope curve for pier scour relates pier width to a pier scour function that was developed using average Froude number, a correction factor for flow angle of attack, pier length, and pier width obtained from detailed analyses. The envelope curve is used to determine a value for the pier scour function, which is then used to calculate pier scour depth.

Variables found to be important for estimating abutment scour included flow depth blocked by the abutment, as defined for use in detailed studies in Montana, and abutment shape coefficient. The envelope curve for abutment scour relates flow depth blocked by the abutment to an abutment scour function that depends upon abutment scour depth and a coefficient for abutment shape. The envelope curve is used to determine a value for the abutment scour function, which is then used to calculate abutment scour depth.

Two approaches were used to field test the rapid-estimation method. In the first approach, several individuals experienced in bridge scour-related fields independently applied the method to the same selected sites, and the average results were compared to results from more-detailed methods. In the second approach, the mean and standard deviation determined from results obtained by each individual for each site were used to obtain an indication of variability among individuals. Results were reasonably close in both approaches and demonstrated that the method can be successfully used to rapidly estimate scour depths at bridge sites.

To apply the method, a peak discharge having a 100-year recurrence interval is estimated from existing methods. The 100-year discharge and bridge-length data are used in the field with graphs relating unit discharge to velocity and velocity to bridge backwater as a basis for estimating flow depths and other hydraulic variables required for using the envelope curves. Estimated scour depths from the envelope curves are entered on a standardized scour analysis and reporting form together with various qualitative observations about hydraulic and geomorphic conditions that may affect scour.

Because considerable judgment may be involved in applying the rapid-estimation method to site-specific conditions, reasonable estimates of scour depth are likely only if the method is applied by a qualified individual possessing knowledge and experience in the subjects of bridge scour, hydraulics, and flood hydrology. The rapid-estimation method is useful for estimating scour depths to identify potentially scour-critical bridges; however, it does not replace more-detailed methods commonly used for design purposes in the rehabilitation or replacement of bridges. The rapid-estimation method is also subject to the same limitations as more detailed methods for the estimation of scour.

INTRODUCTION

Evaluating the scour potential of highway bridges in the United States is a priority of Federal and State transportation agencies because the most common cause of bridge failure has historically been the scour or erosion of foundation material away from piers and abutments during large floods. The magnitude of the potential problem is demonstrated in the fact that almost 485,000 bridges, or about 84 percent of the bridges in the National Bridge Inventory, are over waterways (Richardson and others, 1993). Since 1987 at least 80 bridge failures nationwide were flood related (Resource Consultants, Inc., Fort Collins, Colo., written commun., 1992). Nationally, the annual cost for scour-related bridge failures is about $30 million, and annual repair costs for flood damage to bridges receiving Federal aid are about $50 million (Jorge E. Pagan-Ortiz, Federal Highway Administration, written commun., 1996).

To address the problem, the Federal Highway Administration (FHWA) established in 1991 a national bridge scour program to (1) conduct scour-related research and data collection, (2) improve methods for evaluation of scour, and (3) identify potentially scour-critical bridges on primary and interstate roads and highways. Because the U.S. Geological Survey (USGS) has the expertise to conduct bridge scour-related research, data collection, and investigation, the Montana USGS and the Montana Department of Transportation (MDT) began a cooperative bridge-scour program in 1991. This cooperative project was multi-faceted and included the task of estimating scour depths for selected bridges using detailed methods.

Estimation of scour depth using detailed methods requires significant resources and several days to a week or more for each site. Consequently, the number of bridges for which detailed bridge scour studies could be conducted in Montana was limited to 83. Because the total number of bridges in Montana needing scour assessments is more than 1,600, a method for rapid estimation of scour depth was needed. Accordingly, the objectives of the cooperative bridge-scour program in Montana were modified, and the USGS began a study to develop a method for rapid estimation of scour that would (1) require only limited onsite data, (2) provide estimates of scour depth that would be reasonably comparable to estimates from detailed methods and would tend to overestimate rather than underestimate scour depths, and (3) provide estimates at each site in a few hours or less, so that scour assessments could be completed at most, if not all, of the more than 1,600 bridges by the prescribed deadline set forth by the FHWA.

The purpose of this report is to describe the method developed for the rapid estimation of scour. Although the method was developed specifically for application in Montana, it is believed to be applicable to a wide range of hydrologic and hydraulic conditions throughout the United States. To ensure that results from the method would generally be comparable to results from the detailed methods and be applicable to geographic areas other than Montana, results from 122 detailed bridge scour analyses in 10 States were used to develop the method. The scour estimates and various hydraulic variables from the detailed methods were used together to prepare envelope curves relating scour depth to various easy-to-measure hydraulic variables similar to those used in the detailed methods. The rapid-estimation method is intended to provide estimates of scour depth that would approximate those obtained from detailed methods. Accordingly, the various types of bridge scour and the detailed methods used to estimate their depths are described before the rapid-estimation method.

SCOUR AT HIGHWAY BRIDGES

Scour at highway bridges is a complex hydraulic process that occurs when a bridge contracts the flow, or when flow impinges on piers and abutments. The resultant high velocities and vortex action transport streambed material away from the foundation area of the structure. If the scour depth is excessive, footings can be undermined, leading to failure of the foundation system and collapse of the superstructure. Bridges considered especially vulnerable to scour include those supported on spread footings or shallow piles and those having greatly reduced cross-sectional area for conveyance of flood flow (high degree of contraction) compared to the upstream channel and flood plain. The following sections describe background information about the scour process and various levels of scour analyses, and describe in detail the most common detailed, scour-estimation procedure currently in use.

BACKGROUND

Scour at highway bridges involves sediment-transport and erosion or hydraulic processes (high velocities and vortices) that cause soil to be removed from the bridge vicinity and is separated into components of general scour, contraction scour, and local scour within the bridge opening and at piers and abutments. Total scour for a particular site is the combined effects of each component. Although different bed materials scour at different rates, the ultimate scour attained for materials ranging from fine sand to cohesive or well-cemented soils and glacial tills can be similar, and would depend mainly on the duration of flow acting on the material (Lagasse and others, 1991, p. 90). Scour can occur within the main channel, on the flood plain, or both.

General scour involves long-term geomorphological processes that cause degradation (lowering) or aggradation (filling) of the natural stream channel and may also involve lateral instability of the streambank. Even though general scour can be important for scour analyses of bridges on highly unstable streams where a geomorphic investigation may also be warranted, most scour analyses concentrate on the determination of contraction and local-scour components. Contraction and local scour have an impact to some degree on virtually all bridges; therefore, the focus of this study is on these scour components.

Contraction and local scour are related to movement of sediment in the channel. When sediment moves through a stream-channel reach and bed particles are in motion, the scour condition is termed "live-bed" scour. With live-bed scour, the depth of scour at the bridge is affected by the incoming sediment supply. When no sediment supply is incoming, the scour condition is termed "clear-water" scour, and scour depth is limited only by velocity, resultant shear stresses at the bridge contraction, and the size and mobility of the bed material. The critical velocity for movement of bed material can be obtained using the following equation by Neill (1968) for bed material having a specific gravity of 2.65:

$$V_c = 11.52 y_1^{\frac{1}{6}} D_{50}^{\frac{1}{3}} \qquad (1)$$

where

V_c is the critical velocity for movement of bed material, in feet per second,
y_1 is the average flow depth in the main channel in the reach upstream of the bridge, in feet, and
D_{50} is the median diameter of bed material, in feet.

When the mean velocity in the stream-channel reach, V, equals or exceeds the critical velocity, the scour condition is presumed to be live-bed, and when V is less than the critical velocity, the scour condition is presumed to be clear-water. Although the coefficient in equation 1 (11.52) is generally a function of the particle-size range involved and tends to vary inversely with size (Richardson and others, 1993, p. 10-31), the form of equation 1 shown here is used for most scour analyses. Actual scour is a dynamic and complicated process, and scour conditions may change from clear-water to live-bed back to clear-water during a single flood because of rapidly changing hydraulic and sediment-transport conditions. On the other hand, the distinction between live-bed and clear-water scour may be subtle and ill-defined in many instances. Overall, methods for scour estimation based on a single, constant scour condition are considered to reasonably approximate the predominant scour process at the site.

Contraction scour occurs when the cross-sectional flow area of the stream is reduced or contracted as flow is conveyed through the bridge opening. The contraction in cross-sectional area increases average stream velocity and bed shear stress, resulting in scour at the bridge opening. The minimum cross-sectional flow area and resultant largest stream velocity usually occur at the downstream face of the bridge (fig. 1). As the contracted section is being scoured, cross-sectional area increases and average stream velocity and shear stress decrease. Under live-bed scour conditions, maximum scour depth is attained when the average velocity has decreased to the point that the rate of bed material transported out of the contracted section just equals the rate of sediment transported into the contracted section (Richardson and others, 1993, p. 8). Under clear-water scour conditions, scour depth reaches a maximum when the average velocity has decreased to the critical value required to move bed material. Richardson and

Richardson (1994, p. 7) indicate that, even under some live-bed scour conditions, scour may be limited by the size of bed material, and thus be more like clear-water scour in terms of scour processes involved.

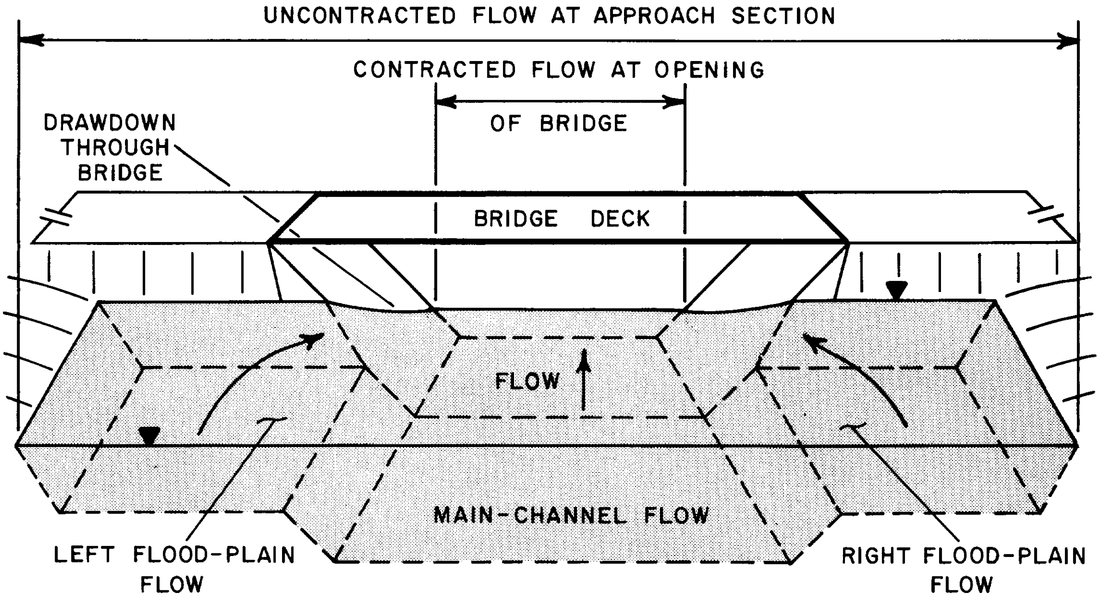


Figure 1. Flow contraction at a typical bridge.

Streambed armoring can affect contraction scour. Armoring occurs when only finer-grained materials are eroded away from the streambed surface, leaving behind a layer of coarse material capable of resisting further scour. Armoring potential is considered to be largely a function of streambed particle size; however, other important factors include particle shape, gradation, and interlocking capability. An armored condition at a particular discharge can revert to a non-armored condition at a larger discharge. Scour can occur quickly if the armored layer is eroded away and smaller-sized particles are again exposed to high-velocity streamflow.

Scour at piers is created when the pileup of water on the upstream face of the pier produces a vortex action that removes streambed material from the base region of the pier structure (fig. 2). The downstream side of a pier undergoes scour when vortices form as flow accelerates around the structure.

Although the pier scour process and resultant scour depth are affected by the scour condition, the calculation of maximum pier scour depth ignores the distinction between live-bed and clear-water scour. The distinction is important, however, when inferences about maximum scour are made after a flood. Under live-bed conditions, receding flood discharge can result in deposition of transported sediment into the scour hole (infilling) and the misleading conclusion that the scour hole observed after the flood reflects maximum or ultimate scour during the flood.

Abutment scour is caused by vortex action that forms near the abutment when flood-plain flow converges with main-channel flow (fig. 3). The vortices cause scouring action near the toe of the abutment, which can lead to undermining of abutment footings. The abutment component of total scour is perhaps the most controversial because (1) prediction equations have been derived on a highly conservative basis and sometimes yield large and seemingly unrealistic calculated scour depths, (2) important variables in equations were defined on the basis of scaled down and simplified hydraulic model studies in laboratory flumes that may not accurately reflect actual flood conditions, and (3) the lack of on-site scour data for actual sites reduces the capability to confirm or improve upon existing equations. Because calculated abutment scour depths often are conservatively large, scour countermeasures, like engineered guide banks or spur dikes (Lagasse and others, 1991, p. 134-142) or riprap (Richardson and others, 1993, p. 118-123) are commonly used to mitigate abutment scour rather than more costly deep foundation engineering treatments that might otherwise be required.

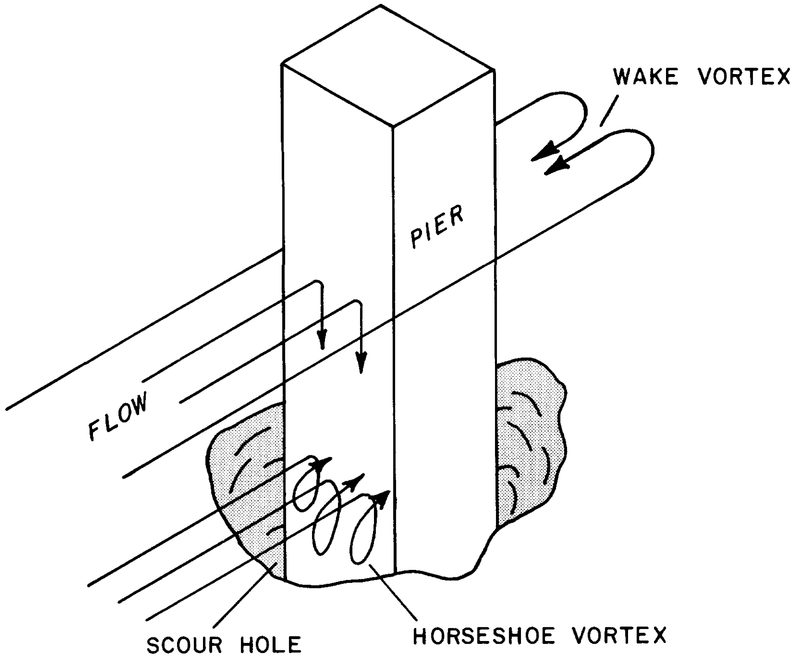


Figure 2. Typical vortex action causing pier scour (modified from Richardson and others, 1993).

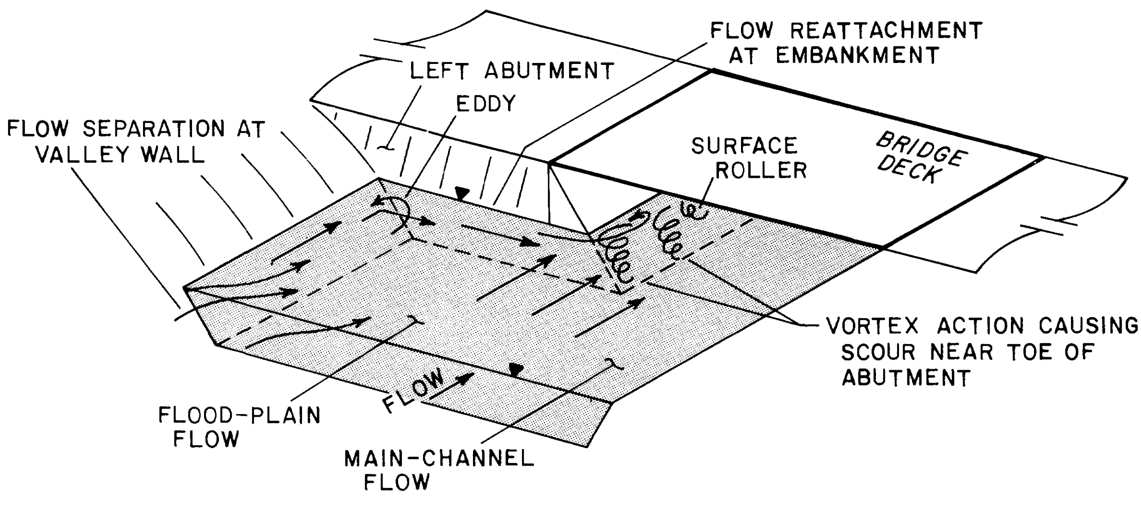


Figure 3. Typical vortex action causing abutment scour.

Scour analyses are categorized into three levels, depending on the degree of complexity and effort needed to meet study objectives (Lagasse and others, 1991). The first level (Level 1 analysis) emphasizes qualitative analyses of stream characteristics, simple geomorphic concepts, land-use changes, and stream stability to qualitatively indicate the scour potential of a bridge. The second level (Level 2 analysis), given much attention by the FHWA, uses hydrologic, hydraulic, and sediment-transport-related engineering concepts to perform scour-depth investigations that result in quantitative scour-depth estimates. The third level (Level 3 analysis) involves mathematical and physical modeling studies that, because of the additional time and expense required, are used only for investigation of highly complex situations and in forensic studies.

Although the rapid-estimation method described in this report incorporates elements from both Level 1 and Level 2 analyses, the method relies mostly on Level 2 quantitative results in developing relations for rapid estimation of scour. Scour-depth prediction has important implications for public safety; therefore, an envelope-curve approach was used to ensure that estimates from the rapid-estimation method are likely to be conservatively larger than those from Level 2 analyses.

DESCRIPTION OF THE LEVEL 2 ANALYSES

The results from Level 2 analyses were important in developing the rapid-estimation method. Even though detailed documentation describing the Level 2 method exists, use of scour-prediction equations can involve considerable judgment and interpretation of scour variables. Thus, the interpretation of Level 2 equations and variables for this study is explained in subsequent sections.

GENERAL CONSIDERATIONS

The Level 2 method commonly is used in the hydraulic analysis and design of new bridges and in the evaluation of scour susceptibility of existing bridges that were not designed according to current criteria. An important feature of the Level 2 method is that estimates of scour depth for flood discharges of specified magnitude are provided. A computer model based on one-dimensional open-channel flow is used along with site-specific information on the hydrology, hydraulics, channel geometry, and pertinent bridge-related structural features to determine the water-surface profile through the bridge opening for flood discharges having 100-year and 500-year recurrence intervals. In some situations, a flood discharge smaller than the 100-year peak discharge may be used if the smaller discharge produces greater scour as a result of unique hydraulic conditions. For example, bridge velocities and scour might be less for larger discharges if the downstream water-surface elevation (tailwater) is greatly increased. Resultant hydraulic information from the water-surface profile calculations is then applied to define variables used in scour-prediction equations recommended by the FHWA for determining contraction, pier, and abutment scour depths. Scour-depth information can then be used with design drawings to plot a scour prism based on scour depth and the angle of repose of typical streambed material to show depth of scour in relation to pier and abutment footings. The Level 2 method is considered to be a basic engineering analysis, involving eight steps that are generally applicable to most stream stability problems (Lagasse and others, 1991, p. 73-80):

1. Evaluation of flood hydrology.
2. Determination of hydraulic conditions by water-surface profile analysis.
3. Analyses of bed- and bank-material composition.
4. Assessment of watershed sediment yield.
5. Incipient-motion analysis of streambed material.
6. Determination of armoring potential of streambed.
7. Inspection and evaluation of rating curve shifts.
8. Use of scour-prediction equations.

Although the relative importance of each of the above steps can vary from one site to another, water-surface profile analysis (step 2) and the use of scour-prediction equations (step 8) are important to all sites. Further discussion of these two topics is given in the following sections.

WATER-SURFACE PROFILE ANALYSIS

The computer model WSPRO (Shearman, 1990) commonly is used to determine the water-surface profile through a bridge opening for a specified discharge and to obtain hydraulic variables used in the scour-prediction equations. Flow through the bridge may be free-surface flow or pressure flow (unsubmerged or submerged) and may include road overflow. Surveyed cross-section data are obtained for the downstream face of the bridge opening and for the approach and exit sections, normally located at a distance equal to one bridge-width upstream and downstream, respectively, from the bridge. An important feature of WSPRO is that user-specified subsections within any cross section provide hydraulic variables, such as velocity, flow area, discharge, and conveyance--a hydraulic variable described on page 20 and given by equation 11. Subsections can be defined on the basis of conveyance and roughness considerations and also can be defined by a model option that subdivides a section into 20 subsections, generally termed stream tubes, having equal conveyance (conveyance tubes). Hydraulic variables are obtained from WSPRO according to suggested methods (L.A. Arneson, J.O. Shearman, J.S. Jones, Federal Highway Administration, written commun., 1992, and Resource Consultants, Inc., Fort Collins, Colo., written commun., 1992) consistent with FHWA criteria (Richardson and others, 1993).

Selection of the appropriate scour equation first requires a determination of whether scour conditions are live-bed or clear-water at the specified discharge. This determination typically is based on a comparison of average velocity from the WSPRO analysis with critical velocity determined from equation 1. In some instances, however, general knowledge of stream stability during past flooding and observed scour can also be used to select the appropriate scour-prediction equations.

SCOUR-PREDICTION EQUATIONS

Equations for calculating contraction, pier, and abutment scour are derived mainly from studies in laboratory flumes and are primarily functions of such hydraulic variables as velocity and flow depth. Although equations for calculating different types of scour are numerous, the FHWA has limited the choice of equations for the Level 2 method to those discussed here. To maintain consistency, hydraulic and scour variables used in this report are the same as those used by Richardson and others (1993), with a few minor modifications added for clarification. Because certain Level 2 variables are only generally defined, resulting in some latitude for interpretation, variables may be defined or interpreted differently from one State or group of studies to another. Definitions and interpretations that are described herein are those that were applied to Level 2 studies in Montana.

CONTRACTION SCOUR

The estimation of contraction scour is complicated by the many possible configurations of highway abutments and flood-plain conditions that can result in flow contraction and scour. The problem is further complicated by the fact that both live-bed and clear-water scour conditions can exist at a single cross section. For example, clear-water scour conditions can occur on the vegetated flood plain, while live-bed scour conditions can exist in the main channel.

To simplify contraction-scour calculations, Richardson and others (1993) defined four general cases of contraction scour based on abutment and flood-plain conditions:

Case 1. Flood-plain flow exists at the approach section, and highway abutments force flood-plain flow back to the main channel at the bridge.

Case 2. All flow at the approach section is confined to the main channel. Flow contraction occurs at the bridge as a result of a natural narrowing of the channel (Case 2a) or abutment encroachment on the channel (Case 2b).

Case 3. Flood-plain flow exists at the approach section, and a relief bridge conveys a portion of the flood-plain flow under clear-water scour conditions.

Case 4. Flood-plain flow exists at the approach section, and a relief bridge over a secondary channel conveys a portion of the flood-plain flow under live-bed scour conditions.

Case 1 probably is the most common case of contraction scour. Richardson and others (1993) further subdivided Case 1 contraction scour into three subclasses on the basis of degree of abutment encroachment and main-channel contraction:

Case 1a. The main channel is contracted due to abutments projecting into the main channel, and flood-plain flow at the approach is forced back to the main channel at the bridge.

Case 1b. The main channel at the bridge is not contracted, but the abutments block all flood-plain flow.

Case 1c. The abutments are set back from the channel so that flow is conveyed in both flood-plain and main-channel portions of the bridge opening.

The three subclasses for Case 1 contraction scour and the other three general cases of contraction scour are illustrated in figure 4. As noted by Richardson and others (1993, p. 32), Case 1c contraction scour is very complex because the scour condition in the setback area is clear-water, whereas the condition in the main-channel portion can be either clear-water or live-bed. Case 1c depends upon such factors as (1) the degree of abutment setback from the main channel, (2) the potential for streambank erosion into the setback area, and (3) flow distribution in the bridge section.

The determination of contraction scour for all cases is based on two fundamental contraction-scour equations—one for live-bed scour conditions and one for clear-water scour conditions. Those equations and some discussion about their application are presented next.

The recommended equation for calculating live-bed contraction scour, developed by Laursen (1960) and modified by Richardson and others (1993), is

$$y_s = y_1\left[\left(\frac{Q_2}{Q_1}\right)^{\frac{6}{7}}\left(\frac{W_1}{W_2}\right)^{k_1}\right] - y_1 \qquad (2)$$

where

y_s is scour depth, in feet;

y_1 is the average depth in the main channel at the approach section, in feet;

Q_1 is the discharge in the main-channel portion of the approach section that is transporting sediment, in cubic feet per second;

Q_2 is the discharge in the main-channel portion of the contracted section that is transporting sediment, in cubic feet per second;

W_1 is the width of the main-channel portion of the approach section that is transporting sediment, in feet;

W_2 is the width of the main-channel portion of contracted section that is transporting sediment, in feet; and

k_1 is a coefficient that depends on whether the material transported is mostly contact bed material (k_1= 0.59), contains some suspended material (k_1= 0.64), or is mostly suspended bed material (k_1= 0.69).

As used by Richardson and others (1993), y_s is a general term used to denote scour depth calculated by Level 2 equations for each of the three scour components (contraction, pier, and abutment scour). Scour depth calculated by equation 2 theoretically is the difference between the maximum flow depth at the bridge contraction once maximum scour has been attained (y_{max}) and the flow depth that existed before any scour occurred (y_0). Unfortunately, estimation of y_0 is usually complicated by the fact that existing bridge-contraction geometry typically reflects some degree of contraction scour due to past floods. Equation 2 thus is based on the assumption that the main-channel flow depth at the approach (y_1) approximates y_0, and that the product of y_1 and the bracketed term in equation 2 approximates the value of y_{max}, so that the difference (y_{max} - y_1) equals scour depth (y_s).

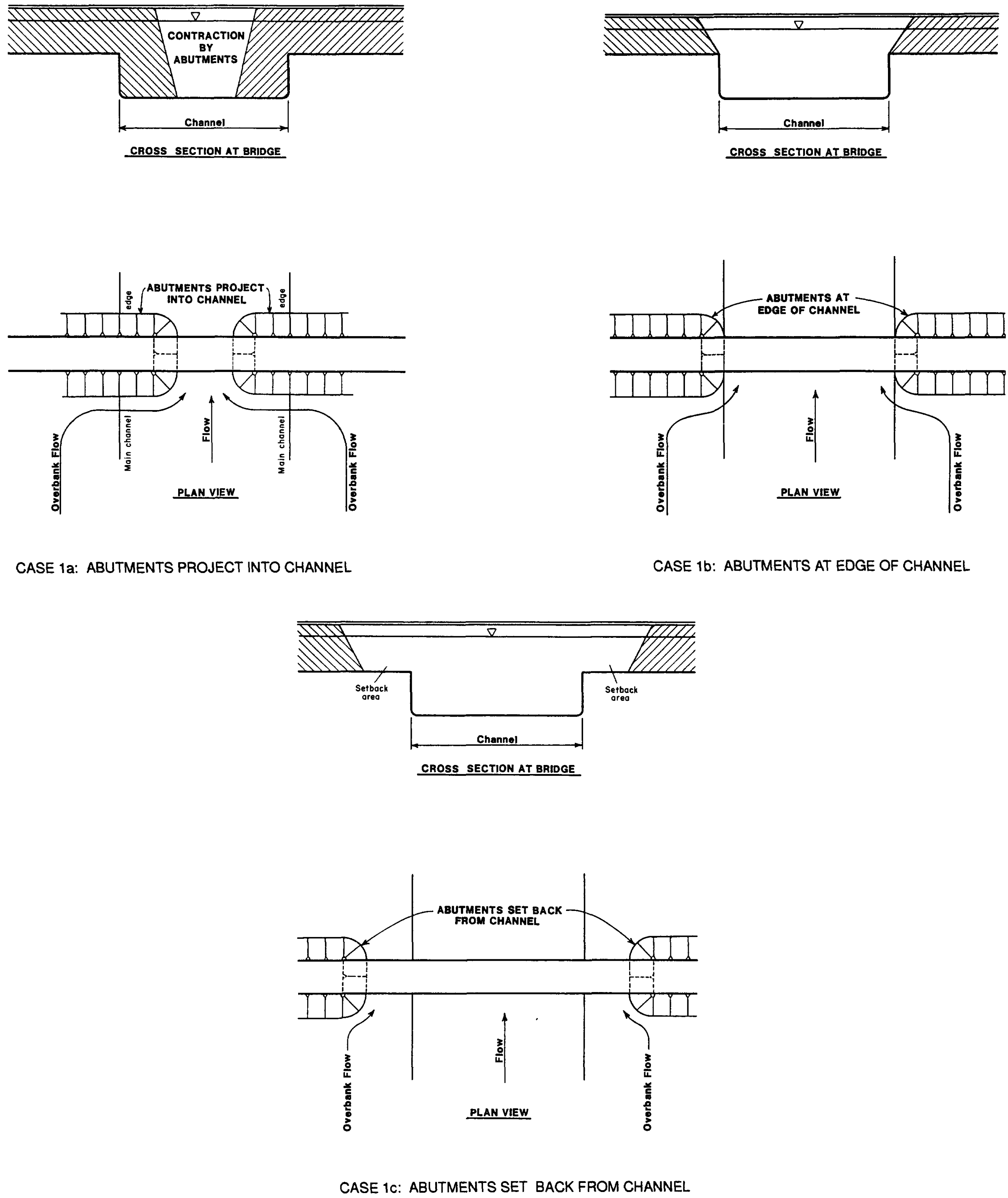
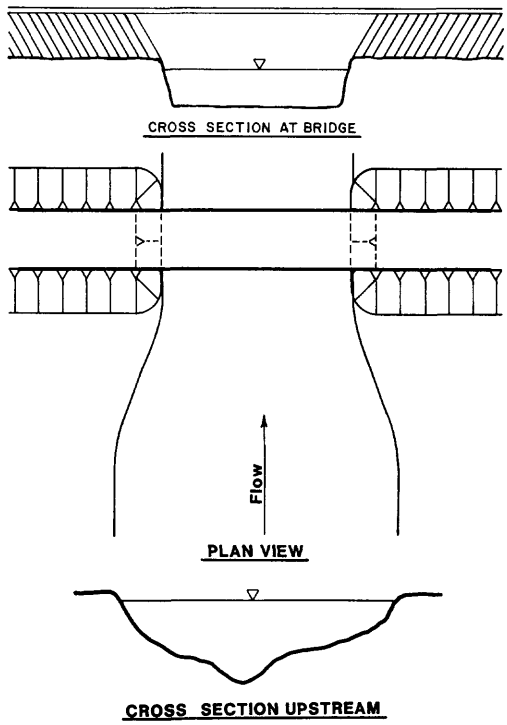
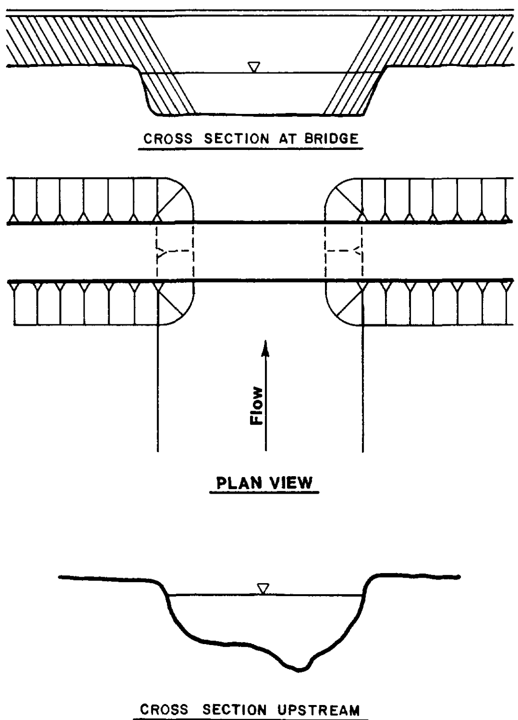


Figure 4. Cases of contraction scour (modified from Richardson and others, 1993).

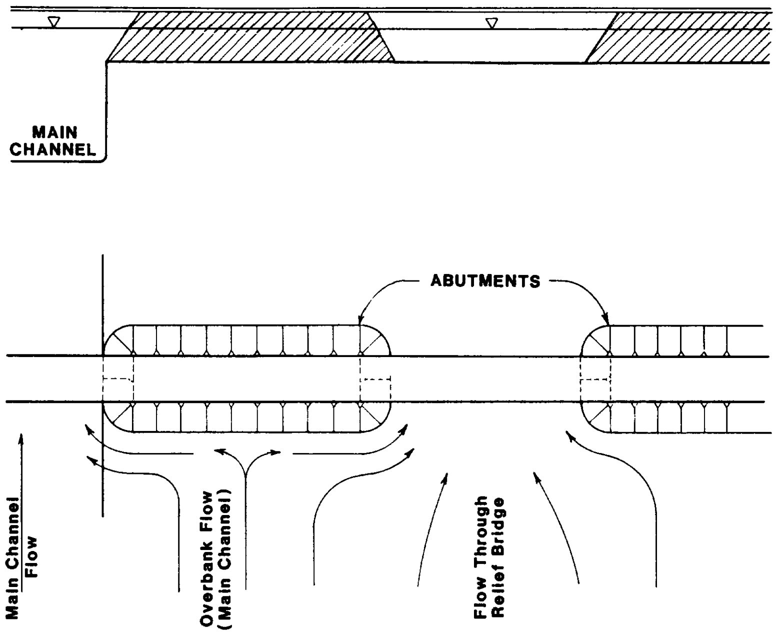


CASE 2a: RIVER NARROWS

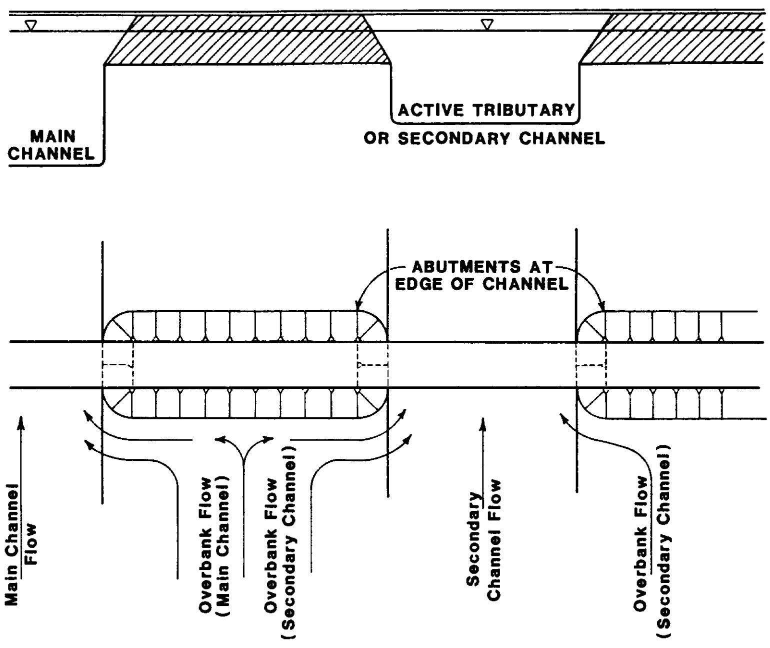


CASE 2b: BRIDGE ABUTMENTS CONTRACT FLOW

Figure 4. Cases of contraction scour (modified from Richardson and others, 1993)--continued.



CASE 3: RELIEF BRIDGE OVER FLOOD PLAIN



CASE 4: RELIEF BRIDGE OVER SECONDARY STREAM

Figure 4. Cases of contraction scour (modified from Richardson and others, 1993)--continued.

Although main-channel bottom width was originally used by Laursen (1960) to define the variables W_1 and W_2, the width of flow at the water surface generally is easier to define and commonly is used instead. Whether measured at the bottom or top, the main channel width needs to be determined consistently at the approach and contracted sections. For Cases 1a, 1b, and 2a and 2b contraction scour, Q_2 is the total flood discharge. For all other cases of contraction scour, Q_2 is the portion of total flood discharge that passes through the main channel at the bridge. In practice, use of equation 2 to calculate contraction scour sometimes results in unreasonably large scour depth when flood-plain widths are very large and conveyance on the flood plain may be overstated. In such instances, judgment needs to be applied in limiting the outer boundaries of the approach section, to minimize the effect that large, ineffective flow areas on the flood plain may have on results. Although not rigorously based, one method for minimizing the problem of very wide flood plains at the approach section is to survey the main channel of the approach section parallel to the bridge and to survey the flood plains at the approach section at an angle to the bridge such that each end of the cross section terminates at the highway embankment (fig. 5). A second method is to limit the approach-section width to some multiple of the main-channel width at the contraction.

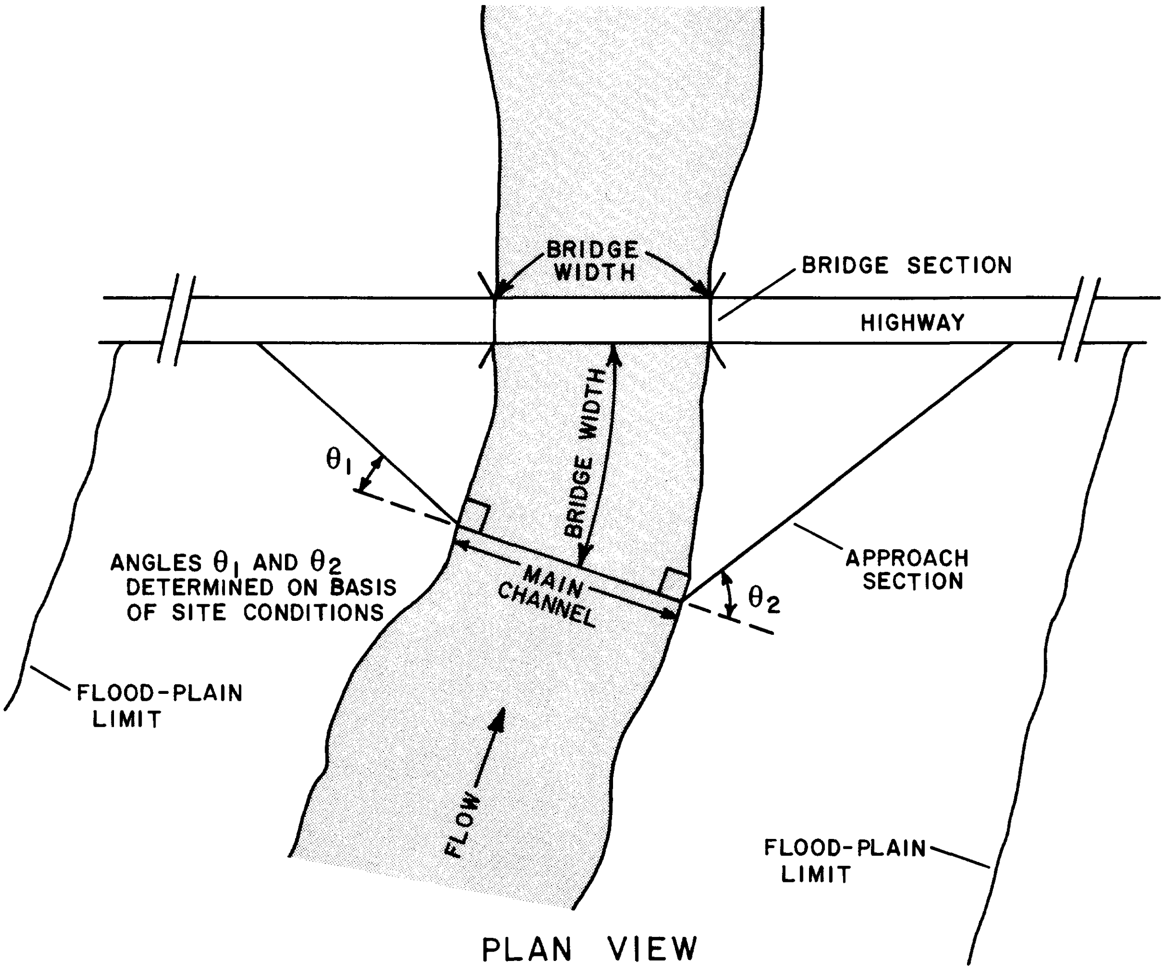


Figure 5. Locating approach section to limit flood-plain widths.

For clear-water conditions, the following equation based on Laursen (1963) and modified by Richardson and others (1993) is used to determine scour in a contracted section:

$$y_s = 0.13y\left[\frac{Q}{D_m^{\frac{1}{3}}y^{\frac{7}{6}}W}\right]^{\frac{6}{7}} - y \qquad (3)$$

where

- y_s is scour depth, in feet;
- y is the average depth of flow in the main channel at the contracted section before clear-water scour has occurred, (Cases 1a, 1b, 2, 3, and 4) or in the setback area at the bridge section (Case 1c), in feet;
- Q is the discharge through the bridge (Cases 1a, 1b, 2, 3, and 4) or in the setback area at the bridge section (Case 1c), in cubic feet per second;
- D_m is the effective mean diameter of bed material (1.25 D_{50}) in the bridge section, in feet; and
- W is the width of bridge opening adjusted for any skewness to flow and for effective pier width (Cases 1a, 1b, 2, 3, and 4) or setback distance (Case 1c), in feet.

For clear-water scour in the main channel, y can be determined from existing channel geometry at the contracted section or the approach section. Also, y can be determined from a subsection of either location based on site-specific conditions and judgment in the field.

Equation 3 is the form of Laursen's equation derived for bed material ranging from about medium to coarse sand (Richardson and Davis, 1995, p. 10-11). Although the coefficient in equation 3 (0.13) generally varies with the particle-size distribution and the Froude number ($F_r = V/(gy)^{0.5}$), most Level 2 scour analyses are based on the version of equation 3 shown above.

The complexity of Case 1c contraction scour requires separate calculations of scour depth for the main channel and for the bridge setback area. Thus, either equation 2 or equation 3 is required for contraction-scour calculations in the main channel, depending upon whether main-channel velocity exceeds critical velocity. Equation 3 is required to compute contraction-scour depths in the setback area.

Although none of the Level 2 scour analyses completed in Montana or Colorado had Case 1c contraction scour, those completed in other States showed that Case 1c contraction scour was common. In a few Level 2 analyses in Montana, the distinction between Case 1b and Case 1c contraction scour could not clearly be made because of uncertainty about the boundary, if any, between the main channel and the setback area. In these instances, Case 1b conditions were assumed to be applicable, and W_2 was set equal to the bridge opening or W_1, whichever was smaller.

PIER SCOUR

The following equation developed by Colorado State University (CSU) and later modified by Richardson and others (1993) is used for calculating pier scour:

$$y_s = 2.0K_1K_2K_3\left(\frac{a}{y_p}\right)^{0.65}(F_p)^{0.43}y_p \qquad (4)$$

where

- y_s is scour depth, in feet;
- K_1 is a correction factor for pier-nose shape;
- K_2 is a correction factor for flow angle of attack on the pier and the ratio of pier length to pier width, L/a, where L and a are measured respectively along the major axis and minor axis of the pier (Richardson and others, 1993, p. 40);
- K_3 is a correction factor for bed form condition;
- a is the pier width, in feet;
- y_p is the flow depth just upstream from the pier, in feet; and
- F_p is the Froude number just upstream from the pier.

Scour depth determined by the modified CSU equation is particularly sensitive to the flow angle of attack on the pier and the ratio of pier length to pier width, *L/a*, as shown in table 1. Pier width and length refer to the structural dimensions unadjusted for any flow angle of attack. For tapered piers or other piers having non-uniform shapes, an average width reflecting the submerged portion of the pier commonly is used, although site-specific conditions require judgment in determining what is reasonably representative for scour-calculation purposes. For Level 2 analyses in Montana and most other States, the greatest velocity and depth in the bridge section as determined from the conveyance tubes in the WSPRO analysis were used to determine F_p for calculating pier scour. Although pier stationing did not necessarily correspond with conveyance tube stationing, lateral migration of the "worst-case" conveyance tube to a position in front of a pier was considered to be a likely possibility.

Table 1. Correction factor, K_2, for selected flow angles of attack on pier (modified from Richardson and others, 1993)

Flow angle of attack (θ)	K_2 for indicated length to width ratio (*L/a*) of pier						
	L/a = 1	*L/a* = 2	*L/a* = 4	*L/a* = 6	*L/a* = 8	*L/a* = 10	[1]*L/a* = 12
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
5	1.0	1.1	1.2	1.3	1.3	1.4	1.5
10	1.0	1.1	1.3	1.5	1.7	1.8	2.0
15	1.0	1.2	1.5	1.8	2.0	2.3	2.5
20	1.0	1.2	1.6	1.9	2.2	2.5	2.8
25	1.0	1.3	1.8	2.1	2.5	2.8	3.1
30	1.0	1.3	2.0	2.4	2.8	3.1	3.5
35	1.0	1.4	2.1	2.5	2.9	3.4	3.8
40	1.0	1.4	2.2	2.7	3.1	3.6	4.0
45	1.0	1.4	2.3	2.8	3.3	3.8	4.3
90	1.0	1.5	2.5	3.2	3.9	4.5	5.0

[1]For *L/a* greater than 12, use tabulated values for *L/a* equal to 12.

ABUTMENT SCOUR

The equation generally used for calculating abutment scour, developed by Froehlich (Richardson and others, 1993, p. 49), is

$$y_s = \left[2.27\, K_1\, K_2 \left(\frac{a'}{y_a}\right)^{0.43} (F_a)^{0.61} + 1.0\right] y_a \qquad (5)$$

where

- y_s is scour depth, in feet;
- K_1 is a coefficient for abutment shape given in table 2;
- K_2 is a coefficient for angle of embankment to the flow;
- a' is the length of flood-plain flow obstructed by bridge abutment (embankment) normal to the flow, in feet;
- y_a is flow depth at the abutment, in feet; and
- F_a is the Froude number of the flow upstream from the embankment.

Although equation 5 was developed for live-bed scour conditions, the FHWA recommends that it be used for both live-bed and clear-water scour conditions. The following equation, commonly referred to as the HIRE equation (Richardson and others, 1993, p. 50), was developed using field data from the U.S. Army Corps of Engineers and can be used to calculate abutment scour when the ratio of flow length (a') to flow depth (y_a) exceeds a value of about 25:

$$y_s = 4.0 (F_a)^{0.33} y_a \qquad (6)$$

where

- y_s is scour depth, in feet;
- F_a is the Froude number of the flow upstream from the abutment; and
- y_a is the flow depth at the abutment, in feet.

Results from equation 6 need to be adjusted using coefficients to account for abutment shape (K_1) and skew of abutment to flow (K_2) in accordance with Richardson and others (1993, p. 50-51). Although Richardson and others (1993, p. 50) define y_a in equation 5 differently from y_a in equation 6, and distinguish between the two by using the variables y_a and y_1, respectively, y_a defined above is presumed to generally apply in both equations 5 and 6 for the rapid-estimation method. Flow depth at the abutment, y_a, is further discussed in subsequent sections of the report.

Table 2. Coefficient, K_1, for abutment shape (from Richardson and others, 1993)

Abutment shape description	K_1
Vertical-wall abutment	1.00
Vertical-wall abutment with wing walls	.82
Spill-through abutment	.55

Equations 5 and 6 are applied separately to the left and right abutments, which are defined to include any concrete retaining-wall structure within or near the main channel together with the road embankments that extend laterally away from the stream. As shown in figure 6, depth at the abutment, y_a, can be interpreted as the depth of flow at the toe of the abutment or as the average depth of flow in the area blocked by the abutment. For Level 2 analyses in Montana and many other States, bridges commonly had spill-through abutments with poorly defined abutment toes, and y_a was considered to be the average depth of flow blocked by the abutment. To determine a Froude number for use in equation 5 or 6, the average velocity in the overbank area blocked by the abutment was first determined from the following equation:

$$V_e = \frac{Q_e}{A_e} \qquad (7)$$

where

- V_e is the average effective velocity in the overbank area blocked by the abutment, in feet per second;
- Q_e is the effective discharge in the overbank area blocked by the abutment, in cubic feet per second; and
- A_e is the effective overbank area blocked by the abutment, in square feet.

The term "effective" is used because portions of some overbank areas may have very small velocities and negligible effect on scour; consequently, those portions are not included in computations for A_e and V_e.

Once V_e and y_a were determined, the average Froude number (F_a) was then obtained for use in either equation 5 or equation 6 according to

$$F_a = \frac{V_e}{\sqrt{g y_a}} \qquad (8)$$

where

- g is the constant for acceleration due to gravity, in feet per second squared, and all other terms are as previously defined.

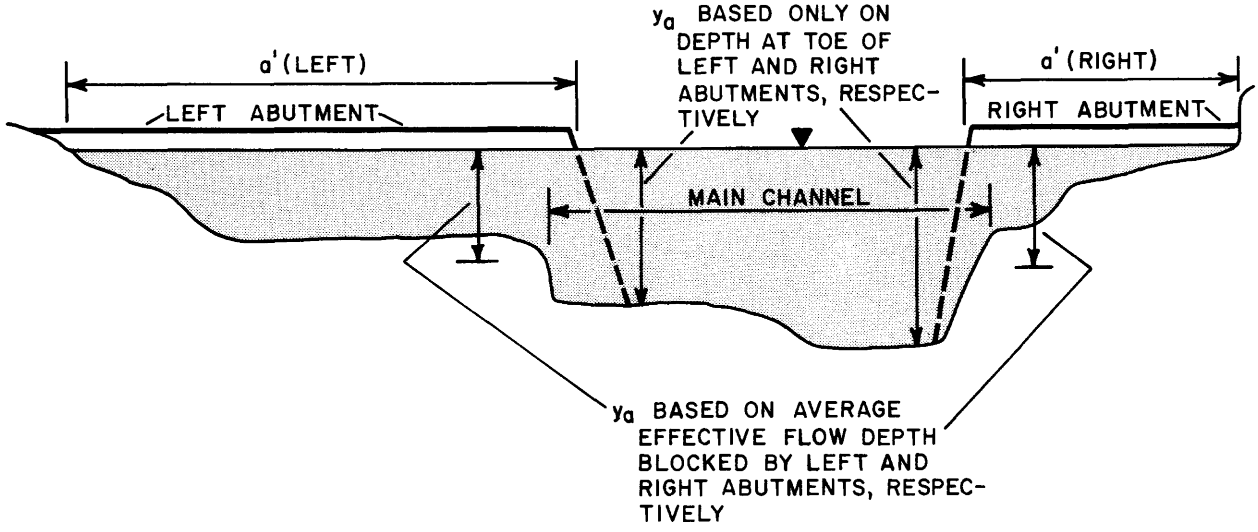


Figure 6. Two choices for defining flow depth at the abutment (y_a) for determining abutment scour.

Hydraulic variables V_e, Q_e, and A_e were determined either manually from WSPRO output, or by using the computer program BSAW (Mueller, 1993, p. 1714-1719). Use of equation 6 rather than equation 5 whenever the ratio a'/y_a in equation 5 exceeded 25 always resulted in a smaller calculated abutment scour in the Level 2 analyses for Montana.

DEVELOPMENT OF RAPID-ESTIMATION METHOD

Calculated scour-depth and hydraulic data from Level 2 scour analyses were used to develop a method for the rapid estimation of scour based on limited data that can be easily measured or estimated from a site visit. To help ensure that the rapid-estimation method would be applicable to a wide range of geographic and hydrologic conditions, data from ten States were used. Although most Level 2 analyses use both the 100-year and 500-year flood discharges to estimate and report scour depths, the rapid-estimation method in Montana is based on the 100-year discharge only for purposes of expediency. Other discharges could be used in the rapid-estimation method, so long as variables that are based on discharge, such as depth and area of flow, can reasonably be estimated and are within the range of variables used in the study.

Although scour depths can be explicitly calculated using the Level 2 equations previously described, some of the hydraulic variables in the equations cannot be easily measured or estimated in the field. Surrogate variables that were considered to be easier to determine were used in place of some process-based Level 2 variables, and simpler forms of the scour equations were used to develop relations between scour depths and the surrogate variables. To help ensure that the rapid-estimation method would tend to overestimate rather than underestimate scour depths, relations between scour depths and the selected surrogate variables were based on envelope curves rather than best-fit curves.

LEVEL 2 SCOUR-ANALYSIS DATA USED

Level 2 scour-analysis data from 51 sites analyzed by the USGS and MDT in Montana and 71 sites analyzed by the USGS in 9 other States (table 5 at back of report) were used to develop the method for rapid estimation of scour. The States for which data from Level 2 analyses were used and the number of Level 2 analyses are shown in figure 7. The data were obtained from published reports for Iowa (Fischer, 1995), Indiana (Mueller and others, 1994) and Colorado (Vaill and others, 1995), and from unpublished analyses documenting scour investigations in the remaining States. Hydraulic and scour data not shown in table 5 are in project files in the USGS Montana District office in Helena.

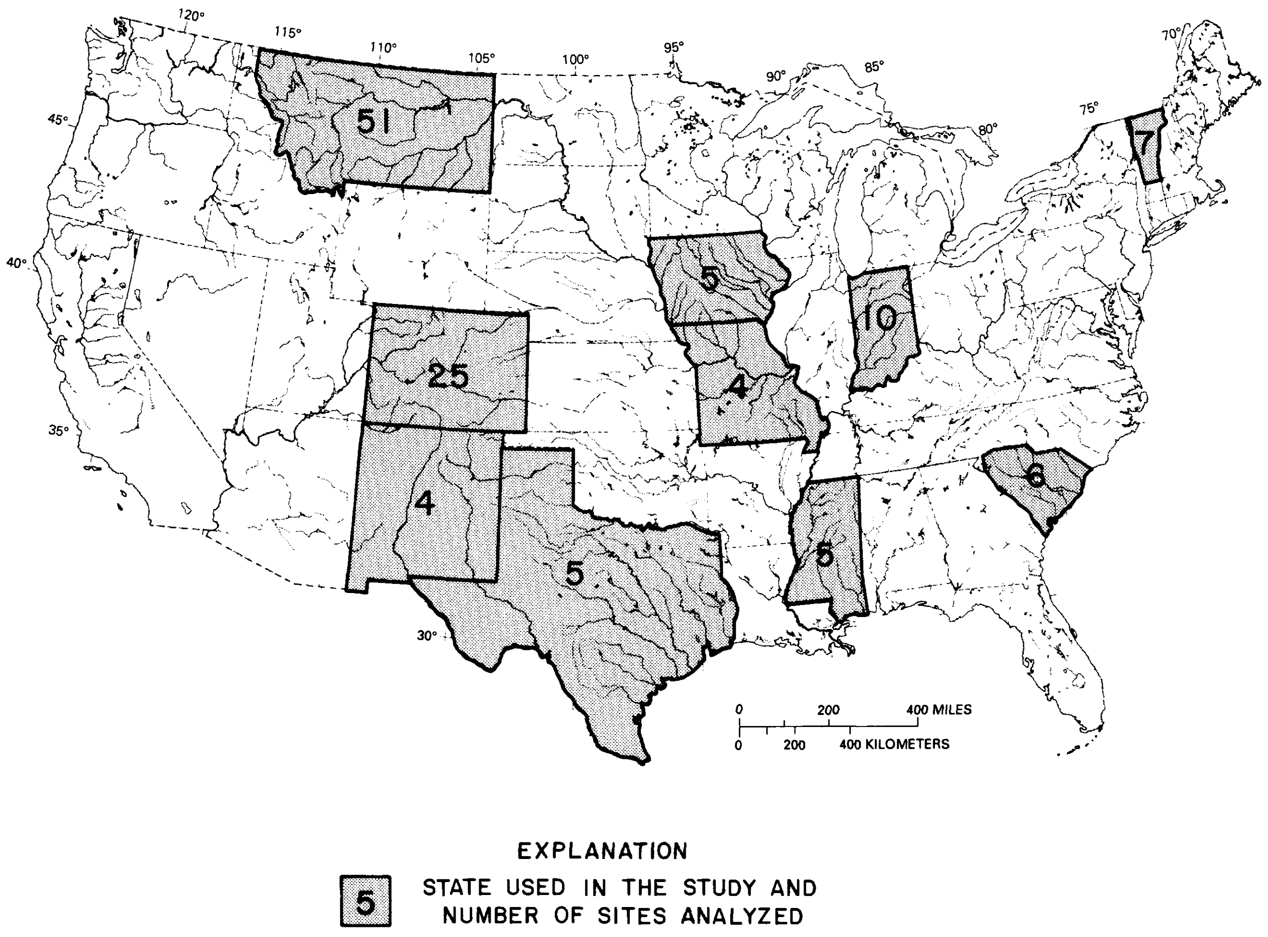


Figure 7. States for which bridge-scour data from Level 2 analyses were used.

Even though efforts to maintain consistency between data bases were made, analyses based on the first edition of the report by Richardson and others (1991) were not necessarily adjusted to reflect subsequent criteria in the second edition (Richardson and others, 1993), nor were results modified to account for more recent changes based on the third edition by Richardson and Davis (1995). For example, the modified CSU equation was revised in the second edition to include a correction factor for bedform (K_3), which can increase calculated scour over results from the equation in the first edition. All sites analyzed by USGS in Montana that initially had no K_3 term were later adjusted; however, no effort was made to determine if the adjustment was needed for other sites. The third edition, furthermore, includes a correction factor for armoring (K_4), which can decrease calculated scour over results from the equation in either the first or second editions. Differences between the three editions of the report by Richardson and others generally resulted in relatively minor differences in scour results for Level 2 scour analyses in Montana and are presumed to have negligible effect on the method for rapid estimation of scour.

Contraction scour and pier scour results generally were found to be consistent among States, although some minor differences of interpretation were found. In all instances of Case 1c contraction scour, which was common in Level 2 analyses of States other than Montana and Colorado, clear-water scour conditions were assumed for the setback area whereas live-bed or clear-water scour conditions were used for the main channel. Abutment scour results did vary among the States, depending upon which of the two prediction equations were used and how the variables in the equations were interpreted. In one group of States, including Montana, the Level 2 abutment scour analyses by the HIRE equation included the use of an average flow depth blocked by the abutment for y_a and an average effective velocity, V_e, in the overbank area to calculate the average Froude number, F_a. In the second group of States, y_a , V_e, and F_a were determined at the abutment toe, which generally resulted in larger predicted scour depths. Furthermore, in States like Iowa and Indiana where a significant portion of flood flow was frequently conveyed on the flood plain under relatively shallow flow conditions, current methods are believed to overpredict scour in such instances due to the inability to accurately account for ineffective flow areas on the flood plain (David S. Mueller, U.S. Geological Survey, written commun., 1996). Because of these differences of interpretation and problematic issues, some data from the second group, notably Indiana and Iowa, were not used to develop the envelope curve for abutment scour.

VARIABLES RELATING TO LEVEL 2 SCOUR DEPTHS

A main objective of this study was to relate scour depths from Level 2 analyses to hydraulic variables on the basis of readily measured site data; consequently, some of the process-based variables in the Level 2 equations were not used or were simplified. For example, variables based on detailed delineation of subsection properties from WSPRO for calculation of pier scour and abutment scour cannot easily be measured or estimated so they were not considered for the rapid-estimation method. Variables considered for use in the rapid-estimation method, therefore, were limited to those from the Level 2 analyses that could be measured or estimated rapidly in the field and which appeared to make physical sense in terms of scour processes.

Variables used in Level 2 analyses, either directly or indirectly, that can be measured or estimated rapidly in the field are pier width and length, flow angle of attack on the piers, Manning's roughness coefficients for channels and flood plains, bed-particle size, and abutment type. A readily measured variable, which is not used directly in Level 2 analyses but is important in the estimation of flow depths and velocities in the rapid-estimation method, is bridge length. Bridge length, together with the estimated 100-year flood discharge, is used in a multi-step procedure described later in the report to first estimate unit discharge, which is 100-year flood discharge divided by width of flow at the bridge, then to estimate flow depth, velocity, and an average Froude number in the main channel at the bridge section and 100-year flow depth in the main channel at the approach section. Once the 100-year flood depth has been determined, other variables that can be measured or estimated in the field are main-channel widths at the bridge and approach sections, flood depths on the overbank or setback areas, and widths of flow areas on the overbank or setback areas. Relations between these variables and scour depths determined from the Level 2 analyses were developed by making some simplifications and adjustments to the Level 2 scour equations or by making trial-and-error plots of different variables versus scour depths.

CONTRACTION SCOUR

The equation for live-bed contraction scour, equation 2, is repeated here for easy reference as:

$$y_s = y_1\left[\left(\frac{Q_2}{Q_1}\right)^{\frac{6}{7}}\left(\frac{W_1}{W_2}\right)^{k_1}\right] - y_1 \tag{9}$$

Equation 9 is based on variables only for main-channel discharge (Q_1 and Q_2), depth (y_1), and widths of channel transporting sediment (W_1 and W_2). The only variables which generally cannot be readily estimated or measured in the field are main-channel discharges.

To develop an equation for live-bed contraction scour that does not directly require estimates for discharge, equation 9 is first simplified by assuming that the 6/7 exponent is approximately equal to 1.0 so that equation 9 becomes:

$$\chi = y_1\left[\left(\frac{Q_2}{Q_1}\right)\left(\frac{W_1}{W_2}\right)^{k_1}\right] - y_1 \tag{10}$$

where χ is the contraction scour variable calculated from the simplified equation, in feet, and all other terms are as previously defined. The function χ is distinguished from scour depth calculated from the Level 2 equation, y_s, so that an envelope-curve relation can later be developed between scour depths calculated from the simplified equation and from the Level 2 analyses. The expression for χ can further be simplified by assuming that the exponent k_1 ($0.59 < k_1 < 0.69$) is a constant that is also equal to 1.0. This simplification is considered acceptable because the width ratio (W_1/W_2) is almost always larger than 1.0, and χ thus will be conservatively larger than the contraction scour calculated from the more precise Level 2 equation. To eliminate discharge terms from equation 10, an analagous variable termed conveyance is used. Conveyance, a hydraulic variable proportional to discharge and a component of the Manning uniform-flow equation, is defined as

$$K = \frac{1.49}{n}AR^{2/3} \tag{11}$$

where

- K is conveyance of the section, in cubic feet per second;
- n is Manning's roughness coefficient;
- A is cross-sectional area of the section, in square feet; and
- R is hydraulic radius, in feet.

Because conveyance is proportional to discharge, discharge in the main-channel portion of a flood-plain cross section can be expressed in terms of total discharge at the section by using the ratio of conveyance in the main channel to conveyance in the total cross section. This relation is shown in the following expression for discharge in the main channel at the bridge section:

$$Q_2 = \left(\frac{K_2}{K_{2tot}}\right)Q_{2tot} \tag{12}$$

where

- Q_2 is the discharge in the main channel at the bridge, in cubic feet per second;
- K_2 is the conveyance of the main channel at the bridge, in cubic feet per second;
- K_{2tot} is the conveyance of the total cross section at the bridge, in cubic feet per second; and
- Q_{2tot} is the total discharge at the bridge section, in cubic feet per second.

Discharge in the main channel at the approach section can be expressed in a similar manner as

$$Q_1 = \left(\frac{K_1}{K_{1tot}}\right)Q_{1tot} \tag{13}$$

where

- Q_1 is the discharge in the main channel at the approach section, in cubic feet per second;
- K_1 is the conveyance of the main channel at the approach, in cubic feet per second;
- K_{1tot} is the conveyance of the total cross section at the approach, in cubic feet per second; and
- Q_{1tot} is the total discharge at the approach section, in cubic feet per second.

Using the expressions for main-channel discharge in equations 12 and 13, the ratio of main-channel discharges in equation 10 can be expressed as

$$\frac{Q_2}{Q_1} = \left[\frac{(K_2/K_{2tot})}{(K_1/K_{1tot})}\right]\left(\frac{Q_{2tot}}{Q_{1tot}}\right) \tag{14}$$

where all terms are as previously defined.

For bridge crossings where no flow overtops the bridge or roadway and where no relief bridges convey part of the flood discharge, the total discharge at the approach section equals the total discharge at the bridge section, and the ratio of the discharge terms on the right-hand side of equation 14 becomes 1 so that

$$\frac{Q_2}{Q_1} = \frac{(K_2/K_{2tot})}{(K_1/K_{1tot})} \tag{15}$$

where all terms are as previously defined. Total conveyance in a cross section is the sum of the conveyances for main-channel and overbank flows. Thus, total conveyance at the bridge section can be expressed as

$$K_{2tot} = K_2 + K_{lsb} + K_{rsb} \tag{16}$$

where K_{lsb} and K_{rsb} are the conveyances in the left and right setback areas, respectively, of the bridge section (Case 1c), in cubic feet per second, and all other terms are as previously defined.

Likewise, total conveyance at the approach section can be expressed as

$$K_{1tot} = K_1 + K_{lob} + K_{rob} \tag{17}$$

where K_{lob} and K_{rob} are the conveyances in the left and right overbank areas, respectively, at the approach section, in cubic feet per second, and all other terms are as previously defined.

Substituting the expressions for conveyance in equations 16 and 17 back into equation 15 and rearranging yields

$$\frac{Q_2}{Q_1} = \frac{1 + (K_{lob} + K_{rob})/K_1}{1 + (K_{lsb} + K_{rsb})/K_2} \tag{18}$$

where all terms are as previously defined.

Substitution of the hydraulic variables in equation 11 into the conveyance ratio $(K_{lob} + K_{rob})/K_1$ yields

$$\frac{K_{lob} + K_{rob}}{K_1} = \frac{n_1}{A_1 R_1^{2/3}}\left(\frac{A_{lob}R_{lob}^{\;\;2/3}}{n_{lob}} + \frac{A_{rob}R_{rob}^{\;\;2/3}}{n_{rob}}\right) \tag{19}$$

where

- n_1 is the Manning roughness coefficient for the main channel at the approach section;
- A_1 is the flow area in the main channel at the approach section, in square feet;
- R_1 is the hydraulic radius for the main channel at the approach section, in feet;
- A_{lob} is the flow area in the left overbank area at the approach section, in square feet;
- R_{lob} is the hydraulic radius for the left overbank flow area at the approach section, in feet;
- n_{lob} is the Manning roughness coefficient for the left overbank area at the approach section;

A_{rob} is the flow area in the right overbank area at the approach section, in square feet;

R_{rob} is the hydraulic radius for the right overbank flow area at the approach section, in feet; and

n_{rob} is the Manning roughness coefficient for the right overbank area at the approach section.

For cross sections that are approximately rectangular, flow area can be approximated as average depth times average width. Also, for most natural cross sections where widths are much greater than depths, hydraulic radius can be approximated by depth. Making those approximations to equation 19 yields

$$\frac{K_{lob}+K_{rob}}{K_1} = \frac{n_1}{W_1 y_1^{5/3}}\left(\frac{W_{lob} y_{lob}^{5/3}}{n_{lob}} + \frac{W_{rob} y_{rob}^{5/3}}{n_{rob}}\right) \qquad (20)$$

where

W_{lob} is the width of flow on the left overbank at the approach section, in feet;

y_{lob} is the average depth on the left overbank at the approach section, in feet;

W_{rob} is the width of flow on the right overbank at the approach section, in feet;

y_{rob} is the average depth on the right overbank at the approach section, in feet; and all other terms are as previously defined.

Following the same steps outlined above, an expression similar to equation 20 can be derived for the conveyance ratio, $(K_{lsb} + K_{rsb})/K_2)$. Because this conveyance ratio has a value greater than 0 only for Case 1c contraction scour, for clarity the ratio is set equal to a new variable, β, that can be expressed as

$$\frac{K_{lsb}+K_{rsb}}{K_2} = \beta = \frac{n_2}{W_2 y_2^{5/3}}\left(\frac{W_{lsb} y_{lsb}^{5/3}}{n_{lsb}} + \frac{W_{rsb} y_{rsb}^{5/3}}{n_{rsb}}\right) \qquad (21)$$

where

n_2 is the Manning roughness coefficient for the main channel at the bridge section;

W_{lsb} is the width of flow on the left setback area at the bridge section, in feet;

y_{lsb} is the average depth on the left setback area at the bridge section, in feet;

n_{lsb} is the Manning roughness coefficient for the left setback area at the bridge section;

W_{rsb} is the width of flow on the right setback area at the bridge section, in feet;

y_{rsb} is the average depth on the right setback area at the bridge section, in feet;

n_{rsb} is the Manning roughness coefficient for the right setback area at the bridge section, and all other terms are as previously defined.

Substituting the right-hand side of equations 20 and 21 back into equation 18, and the resultant expression from equation 18 back into equation 10 yields the following general expression for live-bed contraction scour

$$\chi = y_1\left[\frac{1.0+\left(\frac{n_1}{W_1 y_1^{5/3}}\right)\left\{\frac{W_{lob} y_{lob}^{5/3}}{n_{lob}} + \frac{W_{rob} y_{rob}^{5/3}}{n_{rob}}\right\}}{1.0+\left(\frac{n_2}{W_2 y_2^{5/3}}\right)\left\{\frac{W_{lsb} y_{lsb}^{5/3}}{n_{lsb}} + \frac{W_{rsb} y_{rsb}^{5/3}}{n_{rsb}}\right\}}\right]\left(\frac{W_1}{W_2}\right) - y_1 \qquad (22)$$

where all terms are as previously defined. If the conveyance-ratio term for the setback area is replaced by β, equation 22 can be rewritten in simpler form as

$$\chi = y_1 \left[\frac{1.0 + \left(\frac{n_1}{W_1 y_1^{5/3}} \right) \left\{ \frac{W_{lob} y_{lob}^{5/3}}{n_{lob}} + \frac{W_{rob} y_{rob}^{5/3}}{n_{rob}} \right\}}{1.0 + \beta} \right] \left(\frac{W_1}{W_2} \right) - y_1 \quad (23)$$

where all terms are as previously defined.

Although equation 23 is seemingly more complex than the equation for Level 2 live-bed contraction scour, equation 23 contains only variables that can be readily determined in the field. The width and depth variables for a typical approach and bridge section are illustrated in figure 8. Equation 23 also is a general equation that can be applied to all cases of live-bed contraction scour. The variable β has a value greater than 0 only if a setback flow area is present (Case 1c). For all other cases, β equals 0 and the denominator in equation 23 reduces to 1. Thus, for cases other than Case 1c, equation 23 can be simplified to

$$\chi = \left[y_1 \left(\frac{W_1}{W_2} \right) - y_1 \right] + \left[\left(\frac{n_1}{W_2 y_1^{2/3}} \right) \left\{ \frac{W_{lob} y_{lob}^{5/3}}{n_{lob}} + \frac{W_{rob} y_{rob}^{5/3}}{n_{rob}} \right\} \right] \quad (24)$$

where all terms are as previously defined.

The first term in brackets in equation 24 represents the contraction scour that results from a contraction in main-channel widths only (Case 2). The second term in brackets in equation 24 represents contraction scour that results from overbank flow being forced through the bridge opening (Case 1b). The sum of the two bracketed terms of equation 24 represents total contraction scour resulting from the combined effects of channel-width contraction and overbank flows being forced through the bridge (Case 1a).

Equations 23 and 24 were derived on the assumption that total discharge at the approach section is equal to total discharge at the bridge. Where overtopping of the bridge or roadway occurs, equation 23 or 24 can still be used if one of the following techniques is applied. One technique would be to assume that the total discharge at the approach section will be conveyed through the bridge, resulting in a conservatively larger estimate of scour than if flow was apportioned between the road and the bridge. However, where the overtopping discharge is a large portion of the total discharge, contraction scour estimates based on total discharge may be unreasonably large. In this instance, an alternate technique would be to estimate the overtopping discharge and to reduce the 100-year discharge by that amount. Equation 23 or 24 could then be applied on the basis of the reduced discharge used for both the approach and bridge sections.

Equation 23 or 24 also can be used for relief bridges if the approach section is considered to be composed of two separate subsections, one for the relief bridge and one for the main bridge. The demarcation between that part of the approach section used for relief-bridge scour calculation and that part used for main-bridge scour calculation will necessarily be somewhat arbitrary for the rapid-estimation method. Some relief bridges are so far separated from the main bridges that separate approach sections and separate estimates of total discharge through each bridge are needed. Apportioning total 100-year discharge between a main bridge and a widely separated relief bridge also is somewhat arbitrary and will need to be done on the basis of cross-sectional area of the two bridge openings, estimated conveyances in the two approach sections, or some other basis that seems reasonable for each site.

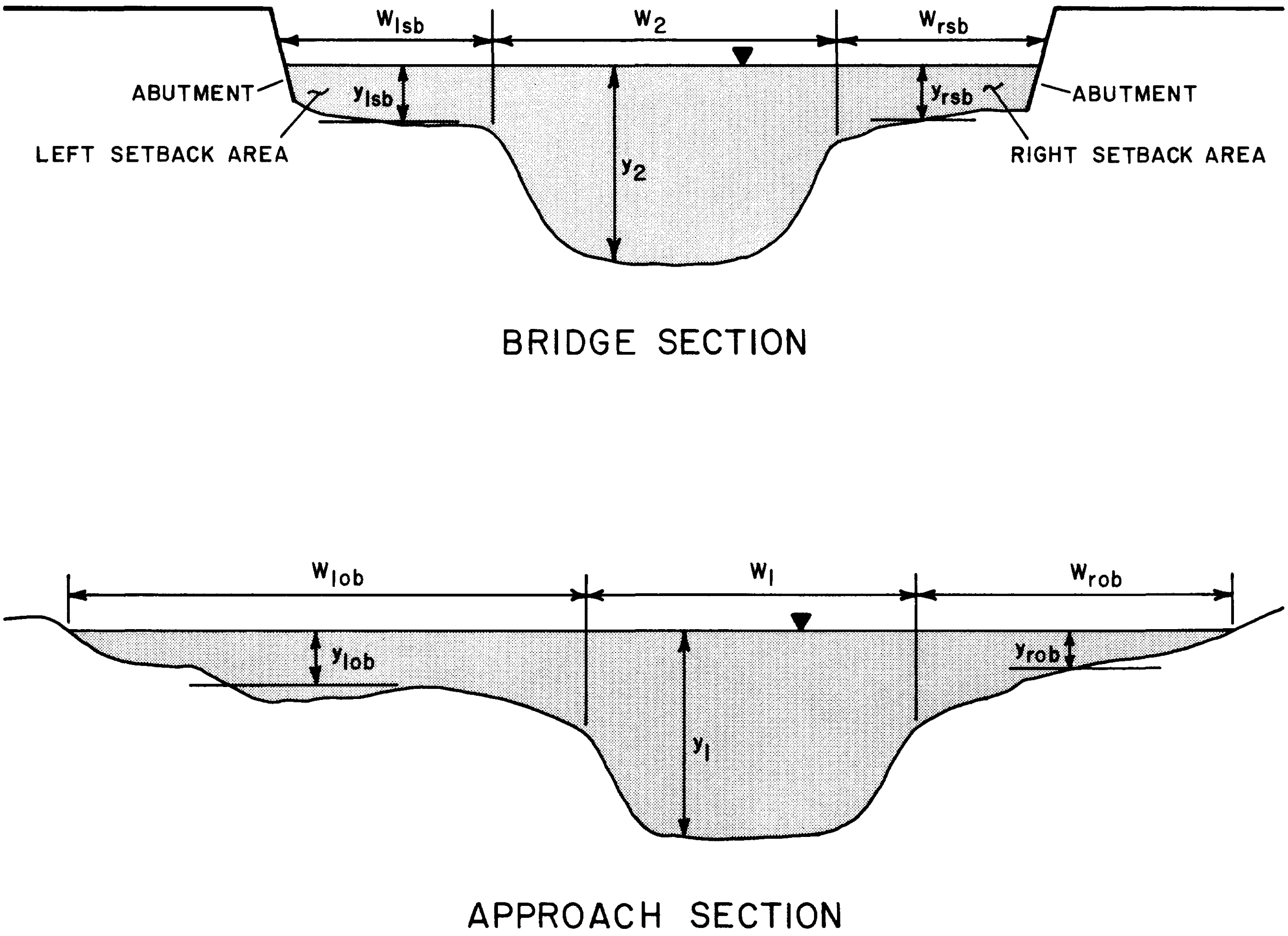


Figure 8. Width and depth variables needed for rapid estimation of live-bed contraction scour at typical approach and bridge sections.

When the main-channel width at the approach (W_1) is less than at the bridge contraction (W_2), the first half of the expression in equation 24 will be negative, and if added algebraically to the second half of the expression, will result in a reduced value of χ. To eliminate the possibility of negative results due to an expanding reach between the approach and bridge sections, the value of W_2 was limited to the value of W_1 for all cases of live-bed scour except Case 1c. The limitation on values of W_2 was not applied to the more complex equation 23 used to calculate χ for Case 1c.

To develop an equation for clear-water contraction scour for general use in the rapid-estimation method, the Level 2 equation for clear-water scour (equation 3) is repeated here for easy reference as

$$y_s = 0.13y\left[\frac{Q}{D_m^{\frac{1}{3}} y^{\frac{7}{6}} W}\right]^{\frac{6}{7}} - y \qquad (25)$$

Using $D_m = 1.25\ D_{50}$, equation 25 can be expressed in terms of median particle size as

$$y_s = 0.122y\left[\frac{Q}{D_{50}^{\frac{1}{3}}y^{\frac{7}{6}}W}\right]^{\frac{6}{7}} - y \qquad (26)$$

For clear-water scour conditions in the main channel (excluding Case 1c) where the discharge term is total discharge (Q_{2tot}), equation 26 can be rewritten as

$$\chi = 0.122y\left[\frac{Q_{2tot}}{D_{50}^{\frac{1}{3}}y^{\frac{7}{6}}W_2}\right]^{\frac{6}{7}} - y \qquad (27)$$

where χ is contraction scour estimated from the rapid-estimation method, in feet, and all other terms are as previously defined.

Thus, for computation of clear-water contraction scour in the main channel, all terms in equation 27 can be readily estimated in the field, and equation 27 can be used to directly estimate contraction scour for the rapid-estimation method. For Case 1c contraction scour, equation 27 can be used to calculate clear-water scour in either the left or right setback area of the bridge if all variables are specified for the proper flow area. Thus, equation 27 can be rewritten to estimate contraction scour in the left setback area as

$$\chi_{lsb} = 0.122y_{lsb}\left[\frac{Q_{lsb}}{D_{50,\,lsb}^{\frac{1}{3}}y_{lsb}^{\frac{7}{6}}W_{lsb}}\right]^{\frac{6}{7}} - y_{lsb} \qquad (28)$$

where

χ_{lsb}	is the clear-water contraction scour in the left setback area, in feet;
y_{lsb}	is the average depth of flow in the left setback area, in feet;
Q_{lsb}	is the discharge in the left setback area, in cubic feet per second;
$D_{50,lsb}$	is the median particle size in the left setback area, in feet; and
W_{lsb}	is the width of flow in the left setback area, in feet.

A similar expression would apply for contraction scour in the right setback area, except that all subscripts would be for the right setback area rather than the left. Unfortunately, equation 28 cannot be applied directly to estimate contraction scour in the setback area using the rapid-estimation method because Q_{lsb} and Q_{rsb} are unknown. Expressions for Q_{lsb} and Q_{rsb} can be developed in terms of conveyance ratios and total discharge as was done for the live-bed scour equation. Thus, Q_{lsb} and Q_{rsb} can be expressed as follows

$$Q_{lsb} = \left(\frac{K_{lsb}}{K_{2tot}}\right)Q_{2tot} \qquad (29)$$

and

$$Q_{rsb} = \left(\frac{K_{rsb}}{K_{2tot}}\right)Q_{2tot} \qquad (30)$$

where

K_{lsb} and K_{rsb} are the conveyances in the left and right setback areas, respectively, in cubic feet per second;

K_{2tot} is the total conveyance in the bridge section, in cubic feet per second; and all other terms are as previously defined.

As shown in equation 16, total conveyance in the bridge section can be expressed as the sum of conveyances in each subsection as

$$K_{2tot} = K_2 + K_{lsb} + K_{rsb} \tag{31}$$

where all terms are as previously defined. Substituting the expression for K_{2tot} in equation 31 back into the expressions for Q_{lsb} and Q_{rsb} (equations 29 and 30) and rearranging terms yields the following expressions:

$$Q_{lsb} = \left(\frac{1}{1 + \frac{K_2}{K_{lsb}} + \frac{K_{rsb}}{K_{lsb}}}\right) Q_{2tot} \tag{32}$$

and

$$Q_{rsb} = \left(\frac{1}{1 + \frac{K_2}{K_{rsb}} + \frac{K_{lsb}}{K_{rsb}}}\right) Q_{2tot} \tag{33}$$

The expression for Q_{lsb} can be substituted back into equation 28 and that for Q_{rsb} can be substituted into a similar equation for the right setback area to produce equations for the estimation of clear-water contraction scour in the setback areas as follows:

$$\chi_{lsb} = 0.122 y_{lsb} \left[\frac{Q_{2tot}}{\left(1.0 + \frac{K_2}{K_{lsb}} + \frac{K_{rsb}}{K_{lsb}}\right)\left(D_{50,\,lsb}^{\frac{1}{3}}\, y_{lsb}^{\frac{7}{6}}\, W_{lsb}\right)}\right]^{\frac{6}{7}} - y_{lsb} \tag{34}$$

and

$$\chi_{rsb} = 0.122 y_{rsb} \left[\frac{Q_{2tot}}{\left(1.0 + \frac{K_2}{K_{rsb}} + \frac{K_{lsb}}{K_{rsb}}\right)\left(D_{50,\,rsb}^{\frac{1}{3}}\, y_{rsb}^{\frac{7}{6}}\, W_{rsb}\right)}\right]^{\frac{6}{7}} - y_{rsb} \tag{35}$$

For clarity and to avoid the use of longer equations, the equations for calculation of clear-water scour in setback areas for the rapid-estimation method are left in terms of conveyance rather than the component variables of conveyance (Manning's n, area, and hydraulic radius). Variables defining conveyance, however, would be based on the same simplifying assumptions used to derive the live-bed equation.

With the derivation of equations for calculation of clear-water contraction scour, equations for all contraction-scour conditions and cases have been determined for the rapid-estimation method. As with the Level 2 analyses for the main-channel, comparisons of critical and actual channel velocities need to be made and judgment applied to determine whether live-bed or clear-water conditions predominate.

In Montana, Level 2 analyses for Cases 1a and 1b indicated that clear-water scour generally was unlikely for streambeds having gravel or finer composition, because shear stresses generally exceeded the critical value. For the nine sites investigated in Montana where bed-material gradation data in combination with comparisons of critical and mean channel velocities indicated clear-water scour conditions, subsequent calculations showed zero scour. For these sites, the D_{50} ranged from about 17 mm to about 180 mm, and more than half of the sites had a D_{50} greater than about 64 mm, which is the lower limit for small cobbles (table 3). To conclude on the basis of the data examined, however, that scour would always be zero might be misleading, because sites analyzed under clear-water conditions represented a limited range of bed-material sizes and hydraulic conditions. Conclusions on the basis of the data, therefore, were expanded by modifying equation 3 by setting scour depth (y_s) equal to zero, substituting 1.25 D_{50} for D_m, and solving for the critical median particle size, D_{c50}, that would result in zero contraction scour ($y_s = 0$) according to

$$D_{c50} = 0.0006\left(\frac{q_2}{y_1^{7/6}}\right)^3 \qquad (36)$$

where

D_{c50} is the critical median bed material particle size that will result in zero clear-water contraction scour, in feet;

q_2 is the unit discharge, (Q_2/W_2), in cubic feet per second per foot-width of main channel at the contracted section; and

y_1 is the average depth in the main channel at the approach section that is assumed to equal average flow depth at the contracted section before any scour occurs, in feet.

Thus, for the rapid-estimation method in Montana excluding Case 1c, if the D_{50} of streambed material estimated in the field is $\geq$ 64 mm and $\geq D_{c50}$, zero contraction scour can be concluded. Where D_{50} is greater than or equal to 64 mm but less than D_{c50}, clear-water scour is presumed, and scour needs to be calculated. For ease of calculation, equation 27 is redefined below in terms of unit discharge as

$$\chi = 0.122y_1\left[\frac{q_2}{D_{50}^{\frac{1}{3}}\,y_1^{\frac{7}{6}}}\right]^{\frac{6}{7}} - y_1 \qquad (37)$$

where q is unit discharge as previously defined, in cubic feet per second per foot-width.

In States where stream slopes are much flatter and bed material much finer than in the Rocky Mountain region, the criterion used here for determining when clear-water scour might occur ($D_{50} \geq$ 64 mm) may need to be modified.

Table 3. Gradation scale for sediment classes

[Modified from Mueller and others, 1994, p. 4. Symbols: <, less than; --, not applicable]

Particle-size range		Class
Millimeters	Inches	
4,100 - 2,000	160 - 80	Very large boulders
<2,000 - 1,000	80 - 40	Large boulders
<1,000 - 500	40 - 20	Medium boulders
<500 - 250	20 - 10	Small boulders
<250 - 130	10 - 5	Large cobbles
<130 - 64	5 - 2.5	Small cobbles
<64 - 32	2.5 - 1.3	Very coarse gravel
<32 - 16	1.3 - .6	Coarse gravel
<16 - 8	.6 - .3	Medium gravel
<8 - 4	.3 - .16	Fine gravel
<4 - 2	.16 - .08	Very fine gravel
<2.00 - 1.00	--	Very coarse sand
<1.00 - .50	--	Coarse sand
<.50 - .25	--	Medium sand
<.25 - .125	--	Fine sand
<.125 - .062	--	Very fine sand
<.062 - .031	--	Coarse silt
<.031 - .016	--	Medium silt
<.016 - .008	--	Fine silt
<.008 - .004	--	Very fine silt
<.004 - .0020	--	Coarse clay
<.0020 - .0010	--	Medium clay
<.0010 - .0005	--	Fine clay
<.0005 - .0002	--	Very fine clay

Figure 9 is the envelope curve relating the contraction-scour variable (χ) to Level 2 calculated live-bed contraction scour for 103 bridge sites in various States. To estimate contraction scour, y_{cs}, χ is first determined by the appropriate equation, and the value is then entered on the abscissa (horizontal axis) of figure 9 to determine the corresponding value of the ordinate (vertical axis) equal to y_{cs}.

To obtain variables used to calculate χ for use in figure 9, y_1 was determined from WSPRO results by dividing the main-channel flow area at the approach by the main-channel top width of flow at approach. Widths W_1 and W_2 were determined either as the bottom widths identified in the field where sediment transport was judged to occur, or from WSPRO results for the main-channel top widths of flow defined on the basis of conveyance requirements for the water-surface profile analysis (Davidian, 1984). The widths W_1 and W_2 were adjusted for any skewness to flow, and W_2 was further reduced for effective width of any piers. Values of y_{lob} and y_{rob} were determined by dividing flow area (A_e) blocked by the abutment by the corresponding flow distance (a') measured normal to the flood plain by superimposing the surveyed approach section against the bridge section. Distances W_{lob} and W_{rob} were based on hydraulic properties obtained at the approach section from WSPRO.

For clear-water scour in the main channel for Case 1a or 1b, the equation for χ (equation 27) is essentially the same equation used for calculation of Level 2 contraction scour, and χ equals Level 2 contraction scour. For clear-water scour in the setback areas of bridges and main channel for Case 1c, equations for χ (equation 34 and 35) are based on conveyance ratios as is the equation for χ for live-bed scour (equation 23). Comparisons between χ and Level 2 contraction scour for clear-water scour in bridge setback areas and main channels involving Case 1c are shown in figure 10. Results in figure 10 have the same general agreement as comparisons for live-bed scour in main channels, but result in a more conservative (larger) prediction of scour depth for a given value of χ.

Although most of the 103 sites used to develop figure 9 were for Cases 1a and 1b, 17 of the sites in the data set involved Case 1c live-bed scour. For the Case 1c sites, scour calculations were complicated by the fact that very wide flood plains were sometimes defined, resulting in large ratios of total flood width at the approach (main channel and flood plain) to main-channel width at the bridge contraction. Because such large ratios can lead to unreasonably large calculated scour depth, limiting the width ratio to some multiple of the main-channel width at the bridge opening may be warranted when using the rapid-estimation method for Case 1c contraction scour.

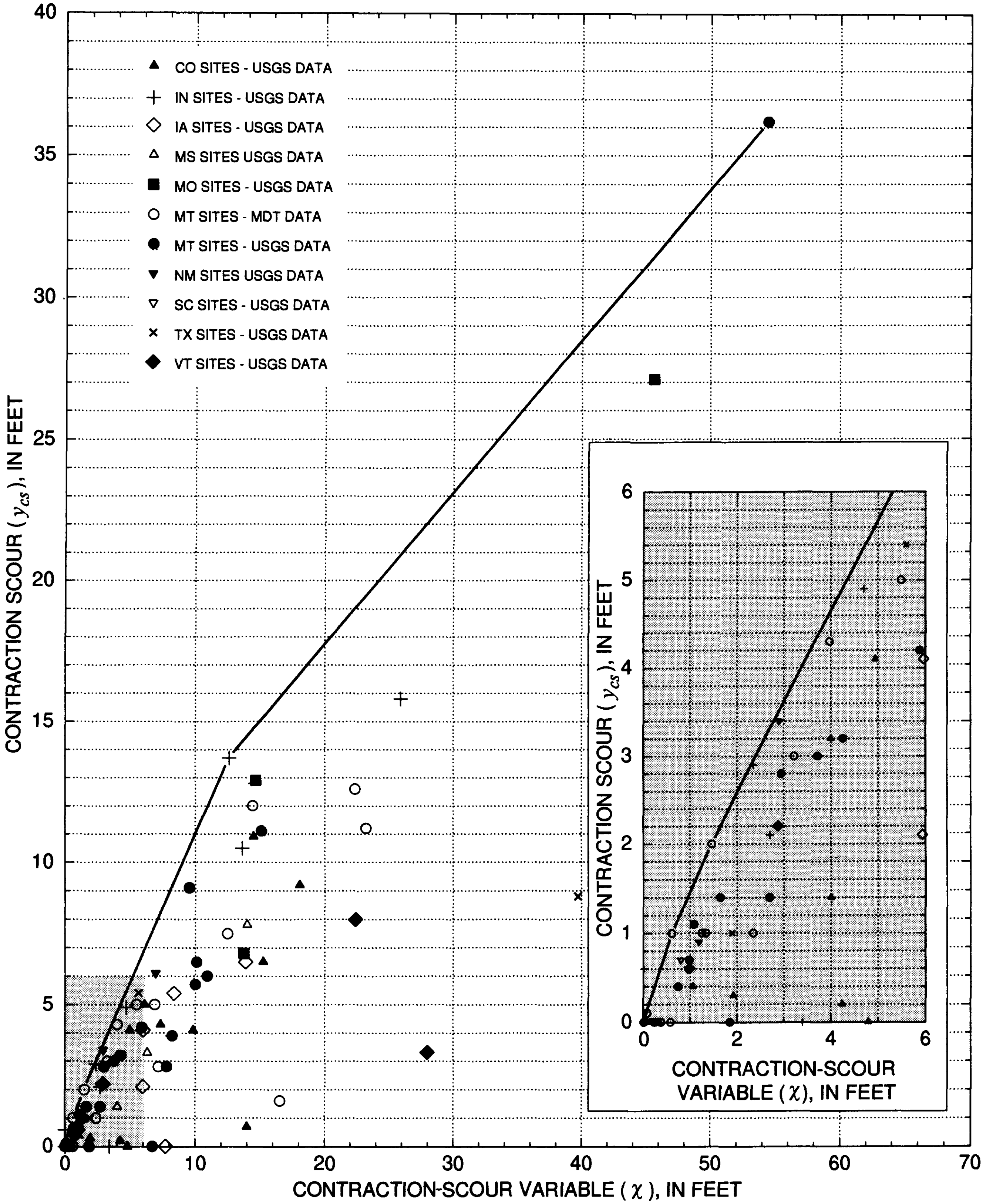


Figure 9. Envelope curve for estimation of live-bed contraction scour.

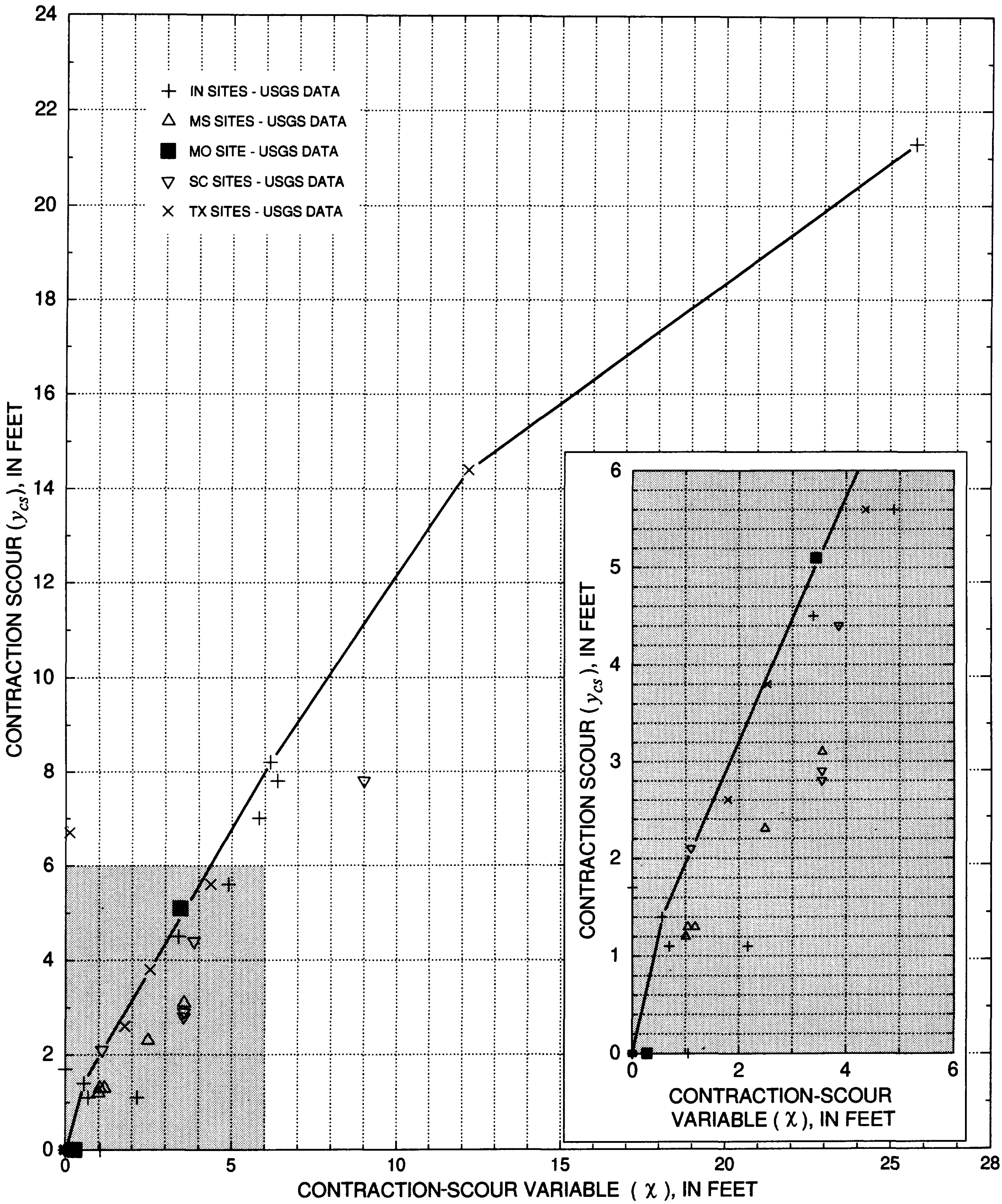


Figure 10. Envelope curve for estimation of Case 1c clear-water contraction scour.

To summarize the calculation of contraction scour by the rapid-estimation method, the following procedures are followed:

1. For all cases involving determination of live-bed scour, the contraction scour variable χ is first calculated using equation 23 or 24, and the value is then entered on the x-axis of the envelope curve (fig. 9) to obtain the estimated value of contraction scour (y_{cs}) on the y-axis.
2. When equation 23 is used to calculate χ, no limitation on the value of W_2 is applied. When equation 24 is used to calculate χ, the value of W_2 is limited to the value of W_1.
3. For the determination of clear-water scour in the setback areas (Case 1c), χ is first calculated using equations 34 and 35 for left and right setbacks, respectively, and the values of χ are then entered on the abscissa of the envelope curve (fig. 10) to obtain y_{cs} on the ordinate.
4. For all other cases of clear-water scour except Case 1c, the value of χ is calculated by equation 27 or the equivalent form given by equation 37, and the value obtained is used directly to equal y_{cs}.

PIER SCOUR

The modified CSU equation for calculating Level 2 pier scour (equation 4), which indicates that scour is a function of pier width, depth just upstream from the pier, Froude number just upstream from the pier, and 3 correction factors, is repeated below for reference:

$$y_s = 2.0K_1K_2K_3\left(\frac{a}{y_p}\right)^{0.65}(F_p)^{0.43}y_p \qquad (38)$$

Equation 38 was used to develop an envelope-curve relation for scour-depth estimation by first rearranging the terms on the right hand side of the equation as follows:

$$y_s = \left[2.0K_1K_3y_p^{\;0.35}\right][K_2]\left[F_p^{\;0.43}\right]\left[a^{0.65}\right] \qquad (39)$$

Within the first set of brackets in equation 39, the two correction factors for pier-nose shape (K_1) and bed form (K_3) have only a small range in values and, when multiplied with the term $y_p^{0.35}$, form a product considered to be essentially a constant, designated α, for purposes of the rapid-estimation method. For use in the rapid-estimation method, the Froude number just upstream from the pier can be approximated by the Froude number, F_2, based on average velocity and flow depth in the main channel at the bridge section. Use of the average Froude number means that the exponent on the Froude number shown in equation 39 may no longer be applicable and needs to be replaced by a generally unknown value, λ. Finally, equation 39 can be further simplified for application to the rapid-estimation method by assuming that the 0.65 exponent on the pier-width term (a) can be approximated by 1.0. Making these adjustments to equation 39 yields:

$$y_s = \alpha[K_2]\left[F_2^{\;\lambda}\right][a] \qquad (40)$$

To provide an envelope curve that was based on a single, physically based, readily measurable variable, both sides of equation 40 were divided by $[K_2]$ $[F_2^{\;\lambda}]$ to yield a pier scour function, ξ, that is directly proportional to pier width, a:

$$\frac{y_s}{\left[K_2 F_2^{\lambda}\right]} = [\alpha]\,[a] = \xi \tag{41}$$

The average Froude number in the bridge section (F_2) used to develop the envelope curve is not the value reported in any of the WSPRO output. Rather, F_2 was calculated using the average velocity and hydraulic depth obtained by dividing flow area by the difference in stationing between the right and left edges of water in the main channel (adjusted for any skew angle to flow) from WSPRO results at the bridge section.

The exponent (λ) used in equation 41 was arrived at by a trial-and-error procedure in which the exponent was varied from zero to about 0.45 in steps of about 0.1. Using the calculated pier scour from Level 2 studies, correction factor for flow angle of attack (K_2), average Froude number at the bridge contraction (F_2), and a trial value for λ, values of the pier scour function (ξ) were calculated and used with corresponding values of pier width (a) to construct a trial envelope curve. The constant term, α, in equation 41 was implicitly eliminated from consideration in the location of the envelope curve. The average difference between calculated Level 2 scour and scour from the trial envelope curve for Montana and Colorado sites was calculated for each trial value of the exponent. The exponent value (λ) that resulted in the minimum value of average difference between Level 2 scour and scour from the envelope curve was 0.15. Substituting $\lambda = 0.15$ into equation 41 yields the final form of equation for pier scour function (ξ) used in the rapid-estimation method equal to

$$\xi = \frac{y_{ps}}{K_2 F_2^{0.15}} \tag{42}$$

where

ξ is the pier scour function, in feet; and

y_{ps} is pier scour depth determined by the rapid-estimation method, in feet, and other terms are as previously defined.

On the basis of equation 42, the final envelope curve relation was developed by plotting values of ξ on the ordinate and pier width on the abscissa (fig. 11). To determine scour depth, pier width is entered on the x-axis of figure 11 to obtain the corresponding value of the pier scour function (ξ) on the ordinate. The correction factor, K_2, is determined on the basis of pier width (a), pier length (L), and flow angle of attack (θ) determined in the field, as shown in table 1. Equation 42 is then solved for pier scour, y_{ps}.

Because the pier scour function (ξ) depends in part on K_2, which is also a function of pier width (a), the potential for introducing spurious or artificial correlation was evaluated. The evaluation of data used to develop figure 11 showed that, although a weak relation between a and K_2 existed ($r^2 = 0.30$), the predominant factor affecting K_2 was the flow angle of attack (θ). Furthermore, when the pier-scour function was redrawn with K_2 and a grouped together in an alternative pier-scour function, the results generally replicated those shown in figure 11.

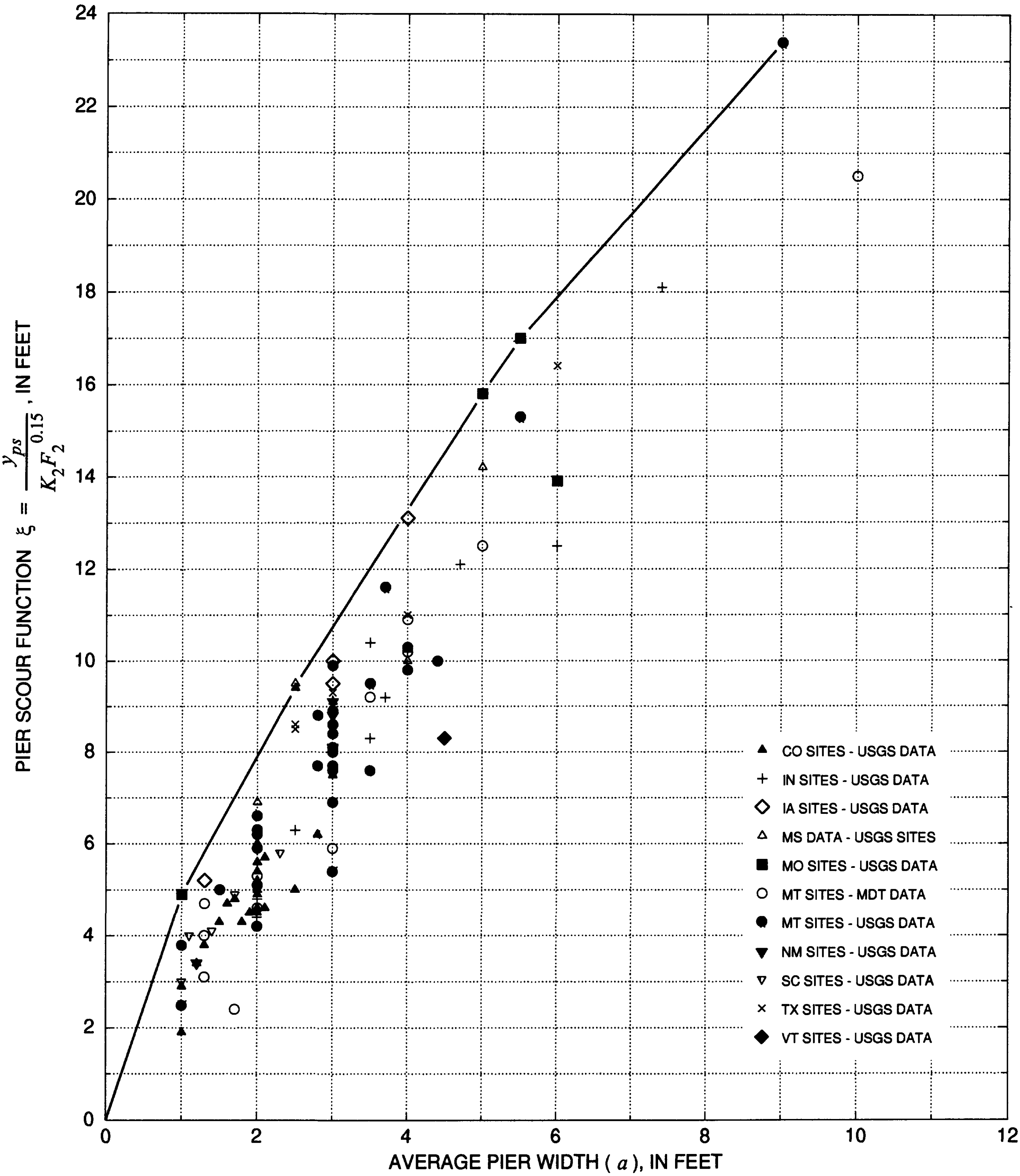


Figure 11. Envelope curve for estimation of pier scour.

ABUTMENT SCOUR

The standard Level 2 equation for abutment scour (equation 5), which indicates that abutment scour is a function of flow depth at the abutment (y_a), two coefficients (K_1 and K_2), length of flood-plain flow blocked by the abutment (a'), and Froude number of flow upstream from the abutment (F_a), is repeated as follows:

$$y_s = \left[2.27\ K_1\ K_2 \left(\frac{a'}{y_a}\right)^{0.43} (F_a)^{0.61} + 1.0\right] y_a \tag{43}$$

The HIRE equation (equation 6), indicates that abutment scour determined by the Level 2 method is a function of flow depth at the abutment (y_a) and Froude number of flow upstream from the abutment, with further adjustments for K_1 and K_2 as previously described, and is equal to

$$y_s = 4.0\,(F_a)^{0.33}\,y_a \tag{44}$$

Although equations 43 and 44 contain the same general variables, the equations are of different form, and one cannot be derived from the other. Because Level 2 analyses in different States were based on different interpretations about the use of the two equations, the development of a single equation for use in the rapid-estimation method, based on all Level 2 analyses, was considered essential. To develop an equation for the rapid-estimation method the general, functional form of either equation 43 or 44 can be expressed as:

$$y_s = f\left(K_1, K_2, a', y_a, F_a\right) \tag{45}$$

where all variables have been previously defined. Because K_2 has a small range in values for most practical situations, this coefficient was eliminated. In addition, because flow velocities generally are very low upstream of abutments, the Froude number also is considered to have a small range of very low values and also was eliminated. Thus, equation 45 can be rewritten in terms of significant variables as

$$y_s = f\left(K_1, a', y_a\right) \tag{46}$$

Various trial combinations of K_1 , a', and y_a plotted against y_s indicated that the inclusion of a' did not improve the plots, and a' was subsequently eliminated. The final functional form of the rapid-estimation method equation for calculation of abutment scour thus is

$$y_s = f(K_1, y_a) \tag{47}$$

To develop an envelope curve with a single, physically based variable on the abscissa, both sides of equation 47 can be divided by K_1 as follows:

$$\frac{y_s}{K_1} = f(y_a) \tag{48}$$

Because the most common abutment shape in Montana is the spill-through abutment having a K_1 equal to 0.55, equation 48 can be rewritten in the following form so that the coefficient for abutment shape will, for most situations, reduce to 1.00:

$$\frac{0.55}{K_1}y_s = f(y_a) \qquad (49)$$

Equation 49 was used to define an abutment scour function, Ψ, that is directly proportional to y_a as follows:

$$\Psi = \frac{0.55}{K_1}y_{as} \qquad (50)$$

where

Ψ is the abutment scour function, in feet; and

y_{as} is the abutment scour depth determined by the rapid-estimation method, in feet, and all other terms are as previously defined.

Thus, fitting an envelope line to plotted values of $(0.55/K_1)y_s$ versus y_a from Level 2 investigations enables abutment scour depth by the rapid-estimation method (y_{as}) to be determined from measured values of y_a and K_1 in a manner similar to that for pier scour. The final envelope curve for abutment scour is shown on figure 12.

FIELD TESTING OF METHOD

To determine how well the rapid-estimation method is likely to perform when actually applied in the field, two different sources of error need to be considered. One is the error due to the limitations of the method as compared to the more rigorous Level 2 scour analysis, and the other is the error or variability in estimates made from the rapid-estimation method by different individuals. To estimate the effects of these two kinds of error, two different tests were made. Data for both tests were obtained by having 3 to 5 highly experienced individuals in the USGS Montana District office independently visit bridge sites for which Level 2 scour analyses had been completed and use the rapid-estimation method to estimate scour depths. For the first test, the individual estimates for each of the three scour components (contraction scour, pier scour, and abutment scour at each abutment) at each site were averaged, and the average value of scour depth was compared to the value determined from the Level 2 analysis. Use of the average value of scour from each individual application of the rapid-estimation method was intended to minimize the effects of variability between individuals. On that basis, comparison of an average value of scour depth from the rapid-estimation method with the value from a Level 2 analysis was considered to be a fair test of the overall difference between the two methods. Results of the first test are compared graphically in figure 13.

Results in figure 13 show that the rapid-estimation method generally performs well in replicating Level 2 scour-depth estimates for contraction, pier, and abutment scour components and generally produces more-conservative (larger) scour-depth estimates than the Level 2 method. Overall, estimates from the rapid-estimation method most closely match those from Level 2 analyses for pier scour and differ most from Level 2 analyses for abutment scour. On the basis of the limited comparison of the two methods, the authors generally believe that the rapid-estimation method meets the desired objective of providing scour-depth estimates that are reasonably close to, and yet are conservatively larger than, those from Level 2 scour analyses.

Determination of the estimation error due to variability among individuals is difficult because of the small sample size (only 3-5 individual scour estimates at each site) and the fact that individuals had different amounts of experience with the rapid-estimation method at the time the estimates were made. In addition, the scour estimates at the test sites were made over a several month period so that each individual gained varying amounts of experience over the course of the test. For these reasons, a strict statistical evaluation of the estimation error due to variability among individuals is not possible. Nonetheless, the test results are presented in terms of commonly used statistics for comparison purposes. Conclusions about the test results necessarily are heuristic rather than statistical, however.

For the second test, the results of the individual estimates of scour depth at each site from the rapid-estimation method were used to calculate the standard deviation of estimated scour depth. The standard deviation, a measure of spread or variability in data, provides an indication of estimation error due to variability among individuals (table 4).

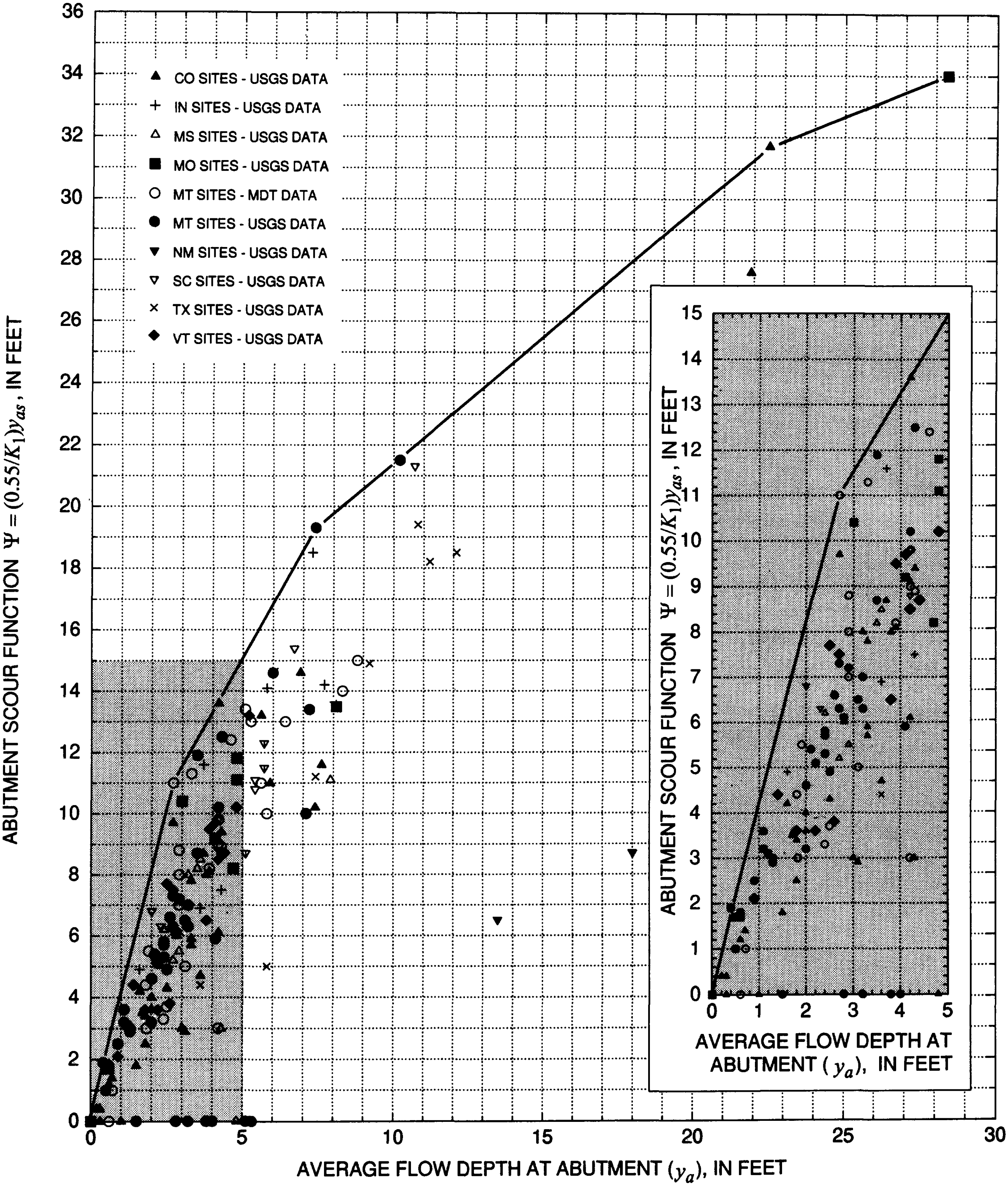


Figure 12. Envelope curve for estimation of abutment scour.

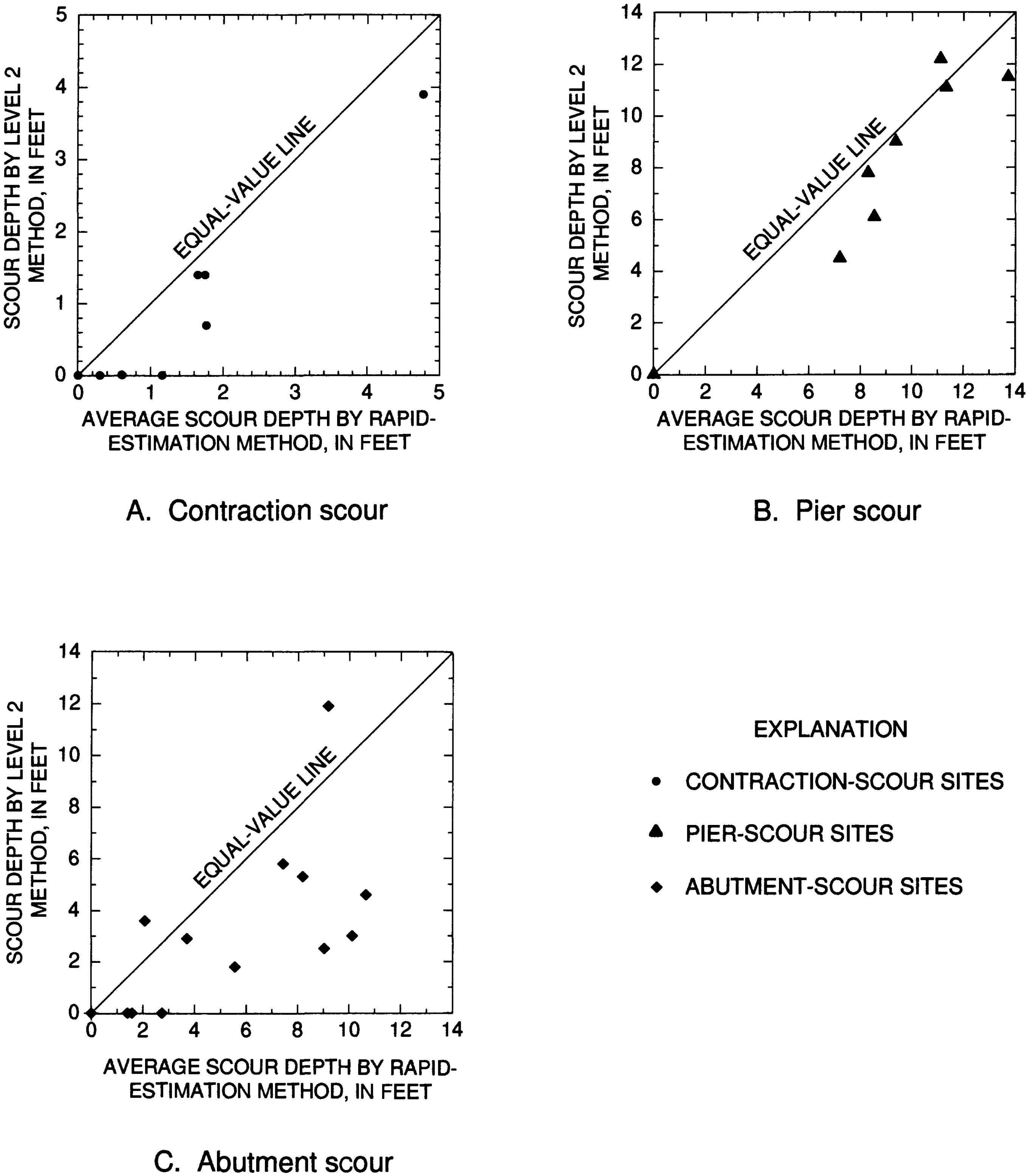


Figure 13. Comparison of average scour depths determined by rapid-estimation method with those determined by Level 2 method. A. Contraction scour. B. Pier scour. C. Abutment scour.

Table 4. Results from application of rapid-estimation method at selected Level 2 scour-analysis sites in Montana

[$\bar{x}$ is the mean scour depth, in feet, obtained for a site where the rapid-estimation method was applied by individuals from the USGS Montana District; σ is the standard deviation of the mean scour depth ($\bar{x}$), in feet, obtained for a site where the rapid-estimation method was applied by individuals from the USGS Montana District; and n is the number of individuals who independently applied the rapid-estimation method at the indicated site. Abbreviation: ft, feet]

Site number	Bridge site name and location	Level 2 scour depth (ft)	Rapid-estimation method		
			Mean scour depth ($\bar{x}$) (ft)	Standard deviation (σ) (ft)	No. of Individuals (n)
	CONTRACTION SCOUR RESULTS				
56	Boulder River at S 69 at Boulder, Montana	3.9	4.8	1.4	4
64	Gallatin River at U.S. 191, 5 miles south of Gallatin Gateway, Montana	0	.6	.7	3
65	Indian Creek at U.S. 287, 7 miles south of Cameron, Montana	0	0	0	3
66	Jefferson River at U.S. 10, 2 miles west of Three Forks, Montana	.7	1.8	2.0	3
68	Little Blackfoot River at U.S. 12 and Burlington Northern Railroad, 5 miles east of Garrison, Montana	0	.3	.5	4
69	Little Blackfoot River at U.S. 12 near Garrison, Montana	1.4	1.7	1.0	4
71	Prickly Pear Creek at U.S. 12 near East Helena, Montana	1.4	1.8	1.5	4
76	Tenmile Creek at U.S. 12, 5 miles west of Helena, Montana	0	1.2	.9	5
80	Yellowstone River at U.S. 89, 11 miles southwest of Emigrant, Montana	0	.3	.4	3
	PIER SCOUR RESULTS				
56	Boulder River at S 69 at Boulder, Montana	11.1	11.3	3.1	4
64	Gallatin River at U.S. 191, 5 miles south of Gallatin Gateway, Montana	12.2	11.1	2.7	3
65	Indian Creek at U.S. 287, 7 miles south of Cameron, Montana	4.5	7.2	.2	3
66	Jefferson River at U.S. 10, 2 miles west of Three Forks, Montana	9.0	9.4	.5	3
68	Little Blackfoot River at U.S. 12 and Burlington Northern Railroad, 5 miles east of Garrison, Montana	11.5	13.7	4.9	4
69	Little Blackfoot River at U.S. 12 near Garrison, Montana	6.1	8.5	.1	4
71	Prickly Pear Creek at U.S. 12 near East Helena, Montana	[1]0	[1]0	[1]0	4
76	Tenmile Creek at U.S. 12, 5 miles west of Helena, Montana	[1]0	[1]0	[1]0	5
80	Yellowstone River at U.S. 89, 11 miles southwest of Emigrant, Montana	7.8	8.3	1.2	3
	ABUTMENT SCOUR RESULTS				
56	Boulder River at S 69 at Boulder, Montana				
	Left abutment	2.9	3.7	1.8	4
	Right abutment	3.6	2.1	2.4	4
64	Gallatin River at U.S. 191, 5 miles south of Gallatin Gateway, Montana				
	Left abutment	5.8	7.4	3.1	3
	Right abutment	0	1.4	1.2	3
65	Indian Creek at U.S. 287, 7 miles south of Cameron, Montana				
	Left abutment	4.6	10.7	2.3	3
	Right abutment	0	0	0	3
66	Jefferson River at U.S. 10, 2 miles west of Three Forks, Montana				
	Left abutment	0	0	0	3
	Right abutment	11.9	9.2	4.5	3
68	Little Blackfoot River at U.S. 12 and Burlington Northern Railroad, 5 miles east of Garrison, Montana				
	Left abutment	0	1.6	3.2	4
	Right abutment	0	0	0	4
69	Little Blackfoot River at U.S. 12 near Garrison, Montana				
	Left abutment	0	0	0	4
	Right abutment	5.3	8.2	2.9	4
71	Prickly Pear Creek at U.S. 12 near East Helena, Montana				
	Left abutment	0	0	0	4
	Right abutment	0	0	0	4
76	Tenmile Creek at U.S. 12, 5 miles west of Helena, Montana				
	Left abutment	3.0	10.1	5.7	5
	Right abutment	1.8	5.6	5.3	5
80	Yellowstone River at U.S. 89, 11 miles southwest of Emigrant, Montana				
	Left abutment	0	2.7	2.4	3
	Right abutment	2.5	9.0	1.3	3

[1]Scour is zero because bridge structure does not involve any piers.

The results in table 4 generally indicate that estimation error due to variability among individuals was least for contraction scour and greatest for abutment scour. The values of standard deviation shown in table 4 also need to be considered in light of the mean values of estimated scour. A large estimation error due to variability among individuals may not be significant if the mean value of scour depth is relatively small. For example, the standard deviation of estimated scour depth at the left abutment of site 68 in table 4 is 3.2 feet, but the mean value of estimated scour depth is only 1.6 feet. Whether the "true" value of abutment scour is 0 feet or 1.6 + 3.2 = 4.8 feet is inconsequential if the abutment footing is, for example, 15 feet lower than the channel bottom and contraction scour (normally added to abutment scour to obtain total scour) at the left abutment is negligible.

Although figure 13 and table 4 are attempts to determine the two sources of error, it is also of interest to note that for contraction scour, 28 of 33 scour-depth estimates by the rapid-estimation method equaled or exceeded corresponding depths calculated by the Level 2 method; for pier scour, 17 of 24 estimates by the method equaled or exceeded corresponding Level 2 depths; and for abutment scour, 55 of 66 estimates by the method equaled or exceeded corresponding Level 2 depths.

The ability to apply the method in a time-effective manner was also demonstrated in the field-testing efforts. On the basis of 123 separate investigations conducted by five individuals, no more than about two hours was required to conduct and report scour-depth estimates for each bridge site.

For those sites where the variability of measurements among individuals was large, most of the variability could be attributed to differences in interpretation of variables that had a large effect on estimated scour depths. For example, a difference in interpretation of the approach section location may result in a difference in estimated flow depth at the abutment of 2 feet that could, on the basis of the lower end of the envelope curve for abutment scour (fig. 12), result in a difference in estimated abutment scour of 8 feet. In some instances, the degree of variability demonstrated would have been similar had Level 2 analyses been performed, because many variables important to the estimation of scour are common to both methods and therefore would have similar impact on results. Such an example is the flow angle of attack (θ) for estimation of pier scour. Overall, the authors believe that the variability of estimated scour depths among individuals applying the rapid-estimation method generally diminished over the course of the field testing as individuals gained more experience and confidence in the method. The error due to variability among individuals thus is considered to be acceptable so long as use of the rapid-estimation method is limited to individuals having experience in the subjects of bridge scour, hydraulics, and flood hydrology and some training in use of the method.

APPLICATION OF RAPID-ESTIMATION METHOD

This section discusses the application of the method to obtain scour-depth estimates at a site. The discussion places particular emphasis on estimation of scour depths for Montana sites; however, the methods and concepts generally are applicable anywhere. Discussion is also given here on the reporting of scour estimates, use of the standardized form, and practical considerations that apply to virtually all sites. Limitations of the method also are discussed.

USE OF LIMITED SITE DATA TO ESTIMATE SCOUR

Although envelope-curves developed from Level 2 studies demonstrate that readily measured variables can be used to estimate scour depth, accurate estimation of these variables on the basis of limited site data is the key to applying the rapid-estimation method. A discussion therefore follows describing how limited site data can be determined for use with envelope curves for estimation of scour.

ESTIMATING IMPORTANT HYDRAULIC VARIABLES

Estimation of important hydraulic variables such as flow depths and velocity for the rapid-estimation method first requires an estimate of the 100-year peak discharge for a site. The 100-year peak discharge can be estimated in one of three general ways: (1) using flood-frequency data from a nearby streamflow-gaging station, (2) using flood-frequency data from a more distant gaging station on the stream and adjusting the data for application to the site, or (3) applying regionalized flood-frequency equations that use basin characteristics or channel-geometry measurements as variables for estimating discharge.

100-Year Peak Discharge

Because gaging-station data typically are not available at sites of interest, most estimates of discharge will need to be obtained from regionalized flood-frequency equations. Regionalized basin-characteristics equations have been developed by the USGS for ungaged sites across the United States (Jennings and others, 1994). For major streams in Montana, Omang (1992) also provides graphs relating flood discharge to drainage area. The 100-year flood discharge for any bridge site on those major streams can be interpolated from the graphs. For many applications in Montana, timely estimates of 100-year flood discharge were required onsite without the benefit of detailed maps and measuring devices used in the office. For these applications, a previous regional flood-frequency report (Omang and others, 1986) that had graphs relating 100-year flood discharge to drainage area alone was used.

Regional channel-geometry equations also have been developed for application at ungaged sites in many western States including Montana (Parrett and others, 1987). Use of the channel-geometry equations does not require detailed maps and complex measuring devices; however, measurement of active or bankfull-channel widths for use in channel-geometry equations can be difficult for ephemeral streams in the prairie regions of the West where poorly defined geometry is common. Furthermore, construction activities and hydraulic conditions at bridge structures often alter the natural channel geometry in the bridge vicinity, requiring that measurements be made some distance upstream or downstream from the actual site. Finally, other factors that can limit use of channel-geometry equations include problems of access to private land for measuring, complications due to intervening drainage at the measurement location, and upstream flood-control regulation resulting in significant alteration to the natural flood hydrograph. Despite such limitations, channel-geometry equations generally are considered to be the best estimators of peak discharge in Montana for streams west of the Continental Divide and for streams in the foothill regions with mountain headwaters. In contrast, equations based only on drainage area are considered to be generally better for streams in the plains regions of Montana, where channel geometry commonly is poorly defined.

Velocity

Once an estimate of the 100-year peak discharge has been made for a site, the next step is to determine average main-channel flow velocity at the bridge. WSPRO hydraulic data from Level 2 analyses were used to develop a step-wise procedure for estimating depth. A similar approach could be used in other areas of the United States where the relations may be different. To enable comparison of widely varying ranges of bridge span and discharge, 100-year peak discharge at the bridge was first converted to a unit discharge

$$q_2 = \frac{Q_2}{W_2} \qquad (51)$$

where

q_2 is the unit discharge in cubic feet per second per foot-width of main channel at the contracted section;

Q_2 is the 100-year peak discharge through the bridge opening, in cubic feet per second; and

W_2 is the estimated top width of flow at the downstream face of the bridge opening, adjusted for any skewness to flow and for effective pier width, in feet.

The logarithm of unit discharge determined by equation 51 was then related to the logarithm of average main-channel velocity at the bridge contraction, V_2 , at the downstream bridge opening using data for 76 Level 2 sites in Montana and Colorado (fig. 14) to develop the following best-fit regression equation

$$V_2 = 2.07 q_2^{0.322} \qquad (52)$$

where all variables are as previously defined.

Equation 52 has a coefficient of determination (r^2) of 0.38 and a standard error of estimate of 0.14 log units. A similar approach could be used in other States where the unit-discharge versus velocity relation might be different.

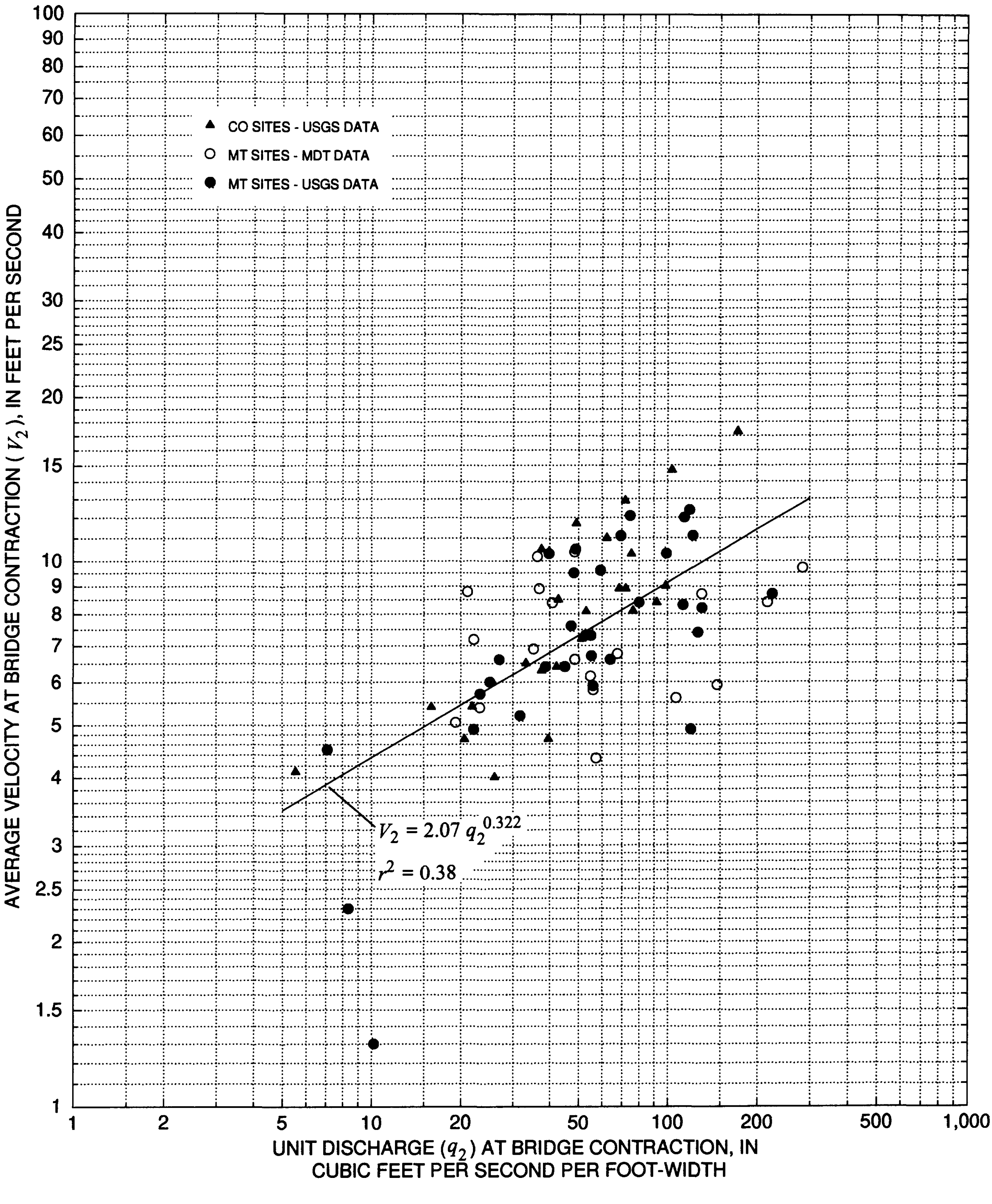


Figure 14. Relation between unit discharge (q) and average velocity at bridge contraction (V_2) for selected sites in Montana and Colorado.

Flow Depths

Equation 52 can thus be used together with unit discharge from equation 51 to estimate flow depth (y_2) at the bridge contraction as follows.

1. Obtain span of bridge opening either by pacing or measuring the distance in the field, or from bridge-design documentation. Estimate or measure with a protractor the skew angle of bridge to flow, and adjust the span by the cosine of the angle to obtain the variable *SPANADJ*1, which is the initial estimate of the top width of flow at the bridge.

2. Use *SPANADJ*1 in place of W_2, along with a value of Q_2, to estimate q_2 using equation 51.

3. Use the regression relation in figure 14 to obtain estimated average velocity at bridge contraction, V_2.

4. Estimate average depth of flow (y_2) by dividing unit discharge by average velocity at the bridge contraction (q_2/V_2).

For spill-through bridge abutments, *SPANADJ*1 might be greater than the actual flow width, and a second or third iteration might be required to improve the estimated depth of flow. To make a second estimate of flow depth ($y_{2,\, i=2}$), use the first estimate ($y_{2,\, i=1}$) and a hand level or some other means to estimate where the water surface corresponding to the estimated depth would intersect the sloping bridge abutments. The estimated intersections of water surface and sloping bridge abutments would determine endpoints for a new, narrower estimate of top width of flow at the bridge, *SPANADJ2* (fig. 15). *SPANADJ2* would then be used to estimate a new depth of flow at the bridge ($y_{2,\, i=2}$). Generally, no more than two iterations would be required to produce estimates of depth of flow within about 1 ft.

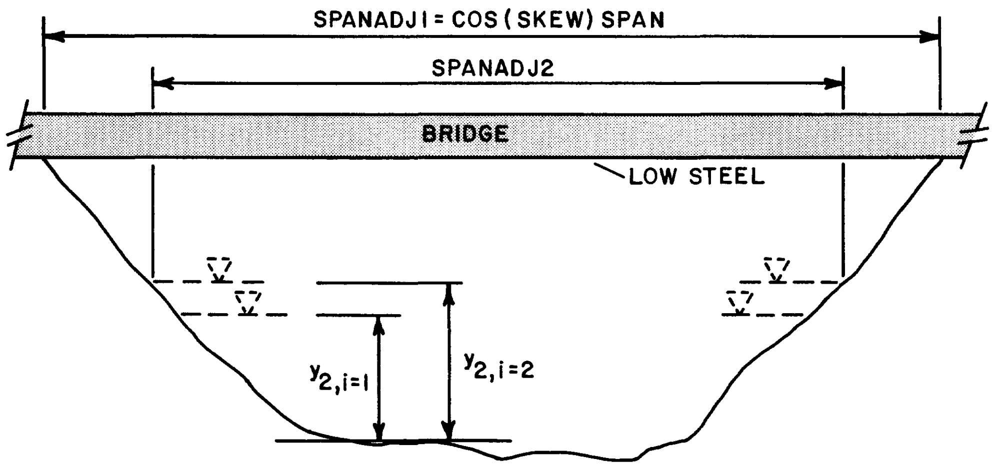


Figure 15. Iterative estimation of top width of flow at bridge section *SPANADJ2*.

Data from 72 Level 2 analyses in Montana and Colorado (fig. 16) were also used to develop a second best-fit relation between V_2^2 and the difference in water-surface elevation from the approach section to the downstream side of the bridge opening, Δh, as follows:

$$\Delta h = 0.025\, V_2^2 + 0.102 \qquad (53)$$

where all variables are as previously described. Equation 53 has a coefficient of determination (r^2) equal to 0.59 and a standard error of estimate of 0.79 ft.

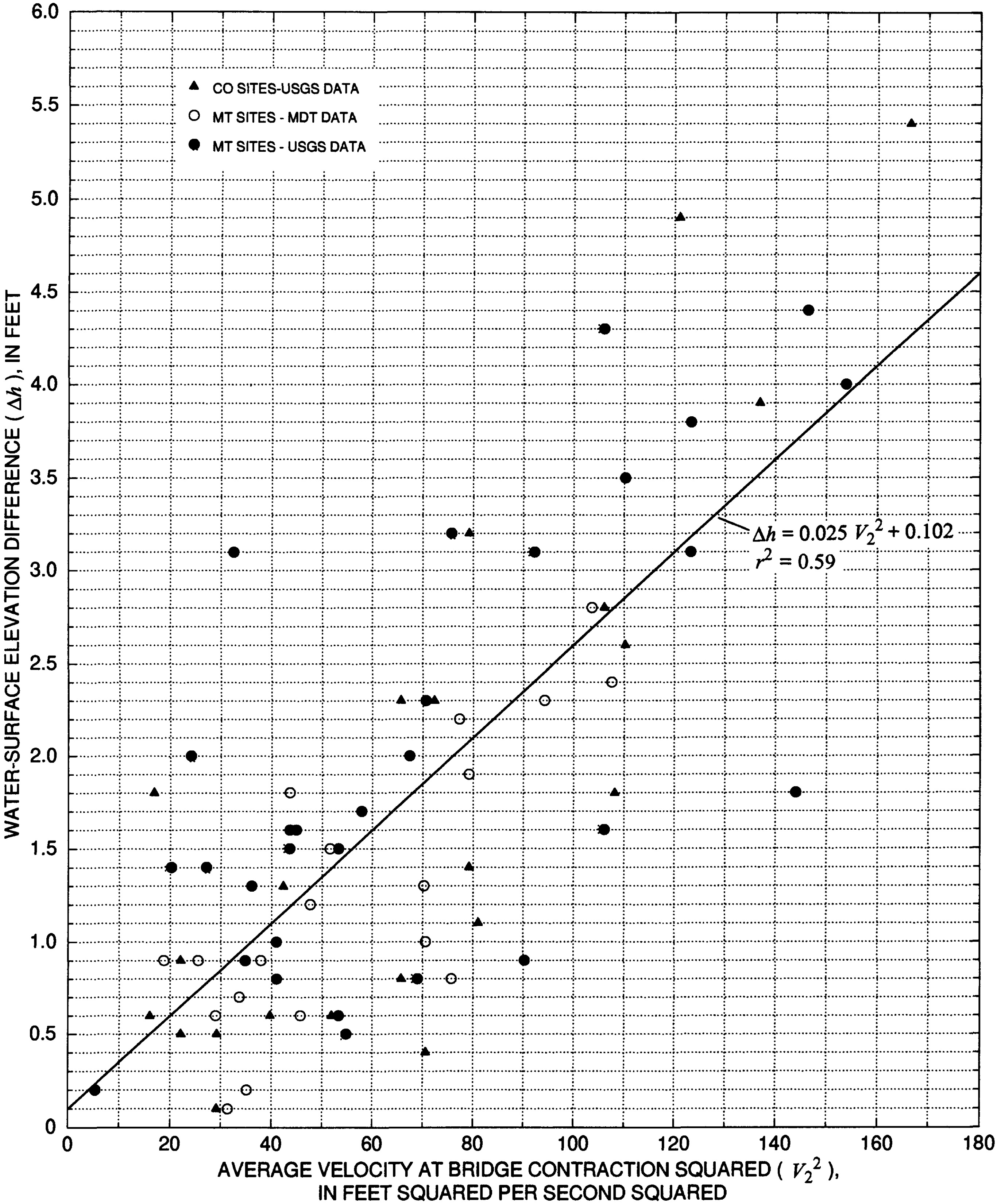


Figure 16. Relation between average velocity at bridge contraction squared (V_2^2) and difference in water- surface elevation between bridge and approach sections (Δh) for selected sites in Montana and Colorado.

The method used here for estimating the difference in water-surface elevation from the approach to the bridge in terms of V_2^2 was not rigorously derived but is similar in form to the basic equation for orifice flow wherein Δh also is a function of V_2^2. The difference in water-surface elevation (Δh) includes the combined effects of channel slope and backwater from bridge to approach sections and enables the estimation of depth at the approach section, y_1, as follows:

$$y_1 = y_2 + \Delta h \tag{54}$$

where all variables are as previously defined and are shown in figure 17.

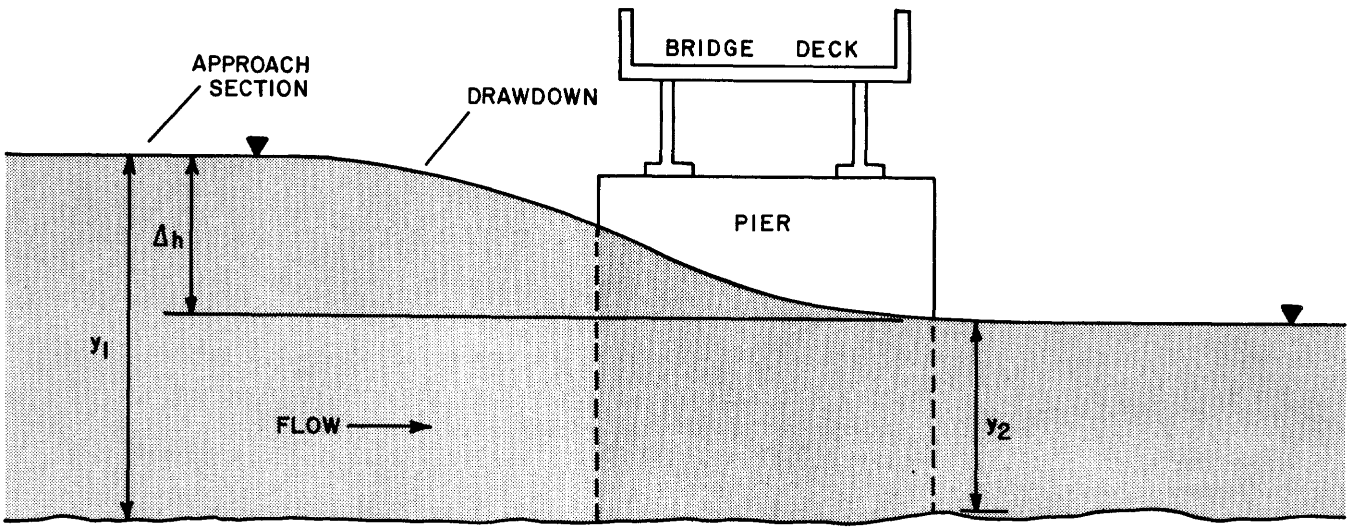


Figure 17. Typical water-surface profile through bridge opening during flood conditions.

Inclusion of the effects of channel slope in the development of equation 53 has the effect of conservatively overpredicting Δh by a margin ranging from less than one-half foot to slightly more than a foot for the range of velocities typically encountered at flood conditions. Where little or no contraction occurs through the bridge section, the term Δh may be omitted from equation 54, and the approach depth can be approximated by y_2. The equations for estimation of V_2 and Δh are intended to provide reasonable approximations for a broad range of conditions. The considerable scatter shown in figures 14 and 16 can be used to adjust estimates upward or downward from values obtained by either equation 52 or equation 53 as field conditions warrant. Alternatives to using the two regression equations to estimate flow depth at the bridge contraction (y_2) and approach (y_1) may include high-water marks, knowledge of past floods, or other site-specific information.

ESTIMATING CONTRACTION SCOUR

To estimate contraction scour using the rapid-estimation method, a determination of whether the scour condition is live-bed or clear-water is first required. Although live-bed scour generally can be presumed for most Montana sites with no rigorous testing, exceptions need to be recognized. The following sections describe how the scour condition is determined and how contraction scour is then estimated.

LIVE-BED SCOUR

As indicated by the results of Level 2 analyses, live-bed scour can generally be presumed for main channels at sites in Montana where streambed material is very coarse gravel or finer (D_{50}<64 mm). Such streambeds can be categorized as generally having very coarse gravel or finer composition by general observation. Qualitative indicators that may help confirm that live-bed scour exists include presence of point bars and chute cutoffs, flood bars, or other indications that the streambed is unstable or has been disturbed such as intermittent, patchy, or alternating deposits of fine- and coarse-grained material. Caution needs to be exercised, however, to ensure that the remnant indications of streambed instability are not the result of a single catastrophic flood that greatly exceeded the particular flood magnitude being used for scour-estimation purposes.

Once live-bed scour has been determined, other variables needed to apply the appropriate live-bed equation with figure 9 can be determined on the basis of y_1, as illustrated in figure 18. If the value of y_1 calculated by equation 54 is greater than the average main-channel approach depth estimated in the field, then overbank flow on the flood plain is indicated. If so, overbank depths y_{lob} and y_{rob} and widths W_{lob} and W_{rob} will need to be estimated, for example, by using a hand level and pacing (fig. 18).

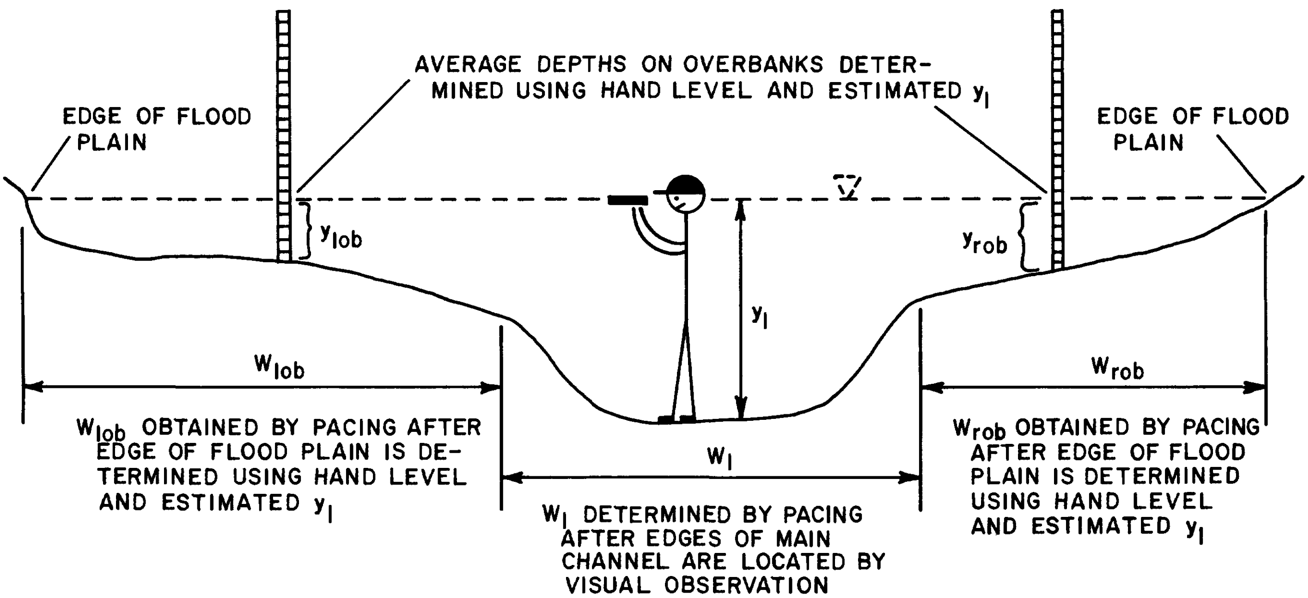


Figure 18. General use of hand level and pacing to estimate overbank depths and widths from y_1.

As previously discussed, Level 2 analyses sometimes indicate unreasonable contraction-scour depths for very wide flood-plain areas unless the flood-plain widths are limited, either somewhat arbitrarily or by surveying overbank areas so that they terminate at the road embankment. For the rapid-estimation method, very wide flood plains also need to be limited. A rule of thumb adopted for use in Montana is to limit values of W_{lob} and W_{rob} to about 3 to 4 times the value of *SPANADJ2*, unless site-specific conditions and judgment indicate otherwise. The multiple of *SPANADJ2* that might be used in a particular instance should, insofar as possible, include all flow area that is reasonably considered to affect bridge scour under 100-year flood conditions.

CLEAR-WATER SCOUR

Clear-water scour conditions are likely for main channels where (1) the natural bed material is very coarse (cobbles to boulders), (2) coarse material or riprap has been intentionally designed and placed in the bridge opening to resist contraction scour, (3) natural armoring of the streambed occurs, or (4) very low velocity in the main channel produces insufficient shear stresses to move relatively fine-grained streambed material. As previously indicated, clear-water scour is also assumed to occur from overbank flows on vegetated bridge setback areas (Case 1c).

For these situations, the general assumption of live-bed scour conditions is not valid, and, for main channels, the scour condition needs to be determined based on additional measurement and calculation. To help confirm the scour condition and calculate contraction scour, the median size of bed material, D_{50} , needs to be estimated. This typically requires a pebble count (Wolman, 1954) where material is in the very fine gravel range or coarser, or a visual inspection and comparison with typical published values for material in the sand range (table 3). Because the calculations to determine the scour condition (live-bed or clear-water) are based on the initiation of motion of streambed material, determination of D_{50} on the basis of the surface layer of streambed material is considered adequate for the rapid-estimation method. A critical-velocity calculation and comparison with main-channel velocity are needed to determine the scour condition and to calculate scour depth as follows:

1. Calculate V_c by equation 1 using the value of y_1 determined from the rapid-estimation method and the field-estimated D_{50} from above.
2. Estimate the mean approach velocity (V_1) in the main channel by dividing the 100-year flood discharge by the product of main channel flow depth (y_1) and width (W_1) determined from the rapid-estimation method. Even though some of the 100-year flood discharge may be conveyed by the flood plain, estimation of V_1 as described will result in a larger, more conservative estimate of V_1. Compare V_1 with V_c to determine the scour condition. If the clear-water condition is indicated ($V_1 < V_c$), use equation 36 to calculate the critical median particle size (D_{c50}) to determine if any contraction scour is likely for the actual D_{50} bed-material size measured in the field and, if so, use equation 37 to calculate χ for use in determining contraction scour.

In some instances where live-bed scour is considered likely, confirmation on the basis of streambed particle size or a critical velocity calculation may not be conclusive. In these instances, both the live-bed and clear-water equations for χ can be used to calculate contraction scour, and the largest value can be reported to ensure that results are conservatively large.

ESTIMATING PIER SCOUR

Site data required to estimate pier scour using the rapid-estimation method include pier width (a) and length (L), flow angle of attack (θ), average main-channel velocity at the bridge contraction (V_2), and average main-channel flow depth at the contraction (y_2). As previously described, values determined for V_2 and y_2 are used to calculate an average Froude number at the contracted section, F_2, according to

$$F_2 = \frac{V_2}{\sqrt{gy_2}} \qquad (55)$$

where all variables are as previously defined.

Pier width and length can be measured at the site or obtained from design drawings. The value for θ needs to be estimated at the site by standing at the upstream side of the bridge deck and using a protractor to determine the angle between the long axis of the pier and the estimated direction of oncoming flow under 100-year flood conditions. As shown by the five hypothetical examples in figure 19, it is important to distinguish between the flow angle of attack for pier scour and the skew angle of flow to the bridge used to determine *SPANADJ*1. As indicated in figure 19, example 1 is the most straightforward situation with no flow angle of attack on the piers and no skew angle of flow to the bridge. All other examples in figure 19 have either a flow angle of attack or a skew angle of flow or both. Where multiple piers are involved, the pier having both the greatest L/a ratio and θ value generally is used for reporting scour by the rapid-estimation method.

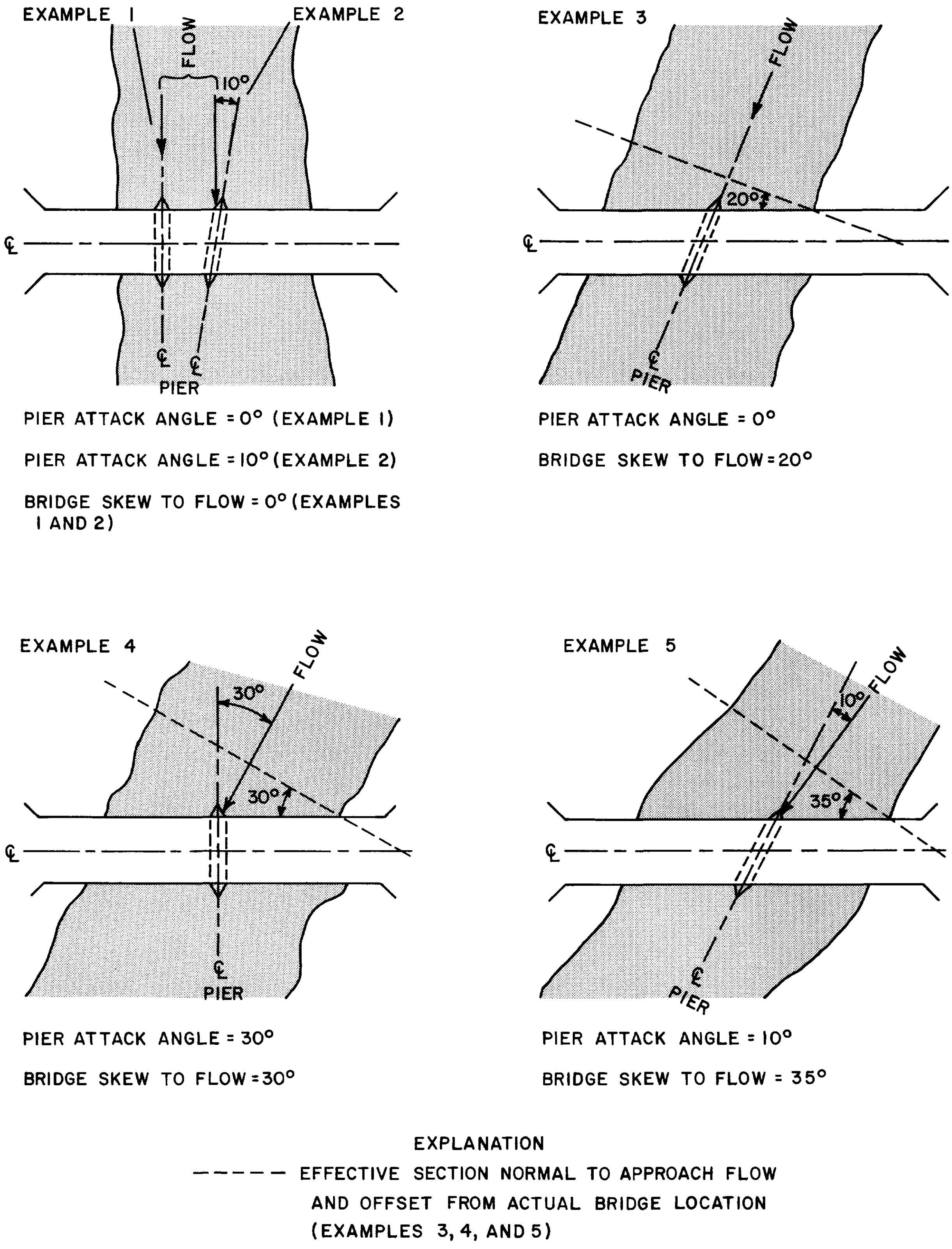


Figure 19. Hypothetical bridge and pier alignments to oncoming flow in the approach section.

Because pier-scour depth determined by both the Level 2 and the rapid-estimation methods is particularly sensitive to flow angle of attack for piers with large *L/a* ratios, careful estimate of flow angle of attack is important. Field determination of the attack angle normally is not difficult. The following conditions can increase the degree of judgment involved:

1. The channel may have migrated laterally over time to the extent that the flow angle of attack has been considerably increased.
2. Base-flow conditions or no streamflow during the site visit make visualization of flood-flow conditions for estimating the flow angle of attack more difficult.
3. Flow curvature at a site located on a river bend commonly results in a tendency towards overestimation of the angle. At flood conditions, flow through bends tend to be straighter than during low-flow conditions.
4. Looking too far upstream, say greater than a bridge width, to reference the direction of approach flow can result in overestimation of the attack angle. Likewise, under low-flow conditions, referencing the direction of flow at a pier by looking straight down at the pier nose from the bridge deck may result in underestimation of the attack angle.
5. An abrupt change in channel alignment and flow direction just upstream of a bridge can result in the tendency to overestimate the angle based on the upstream alignment. In such instances, flow often realigns with the bridge section so that the attack angle at the bridge is greatly diminished.

Although pier-width and length data can usually be obtained from design drawings, K_2 needs to be obtained in the field, particularly for older bridges where significant channel changes and lateral channel migration over time have resulted in an altered flow alignment with the pier. No estimation of θ is required for circular or square piers because the *L/a* ratio is 1.0 for all angles of attack (table 1). Once the pier-scour function (ξ), attack-angle correction factor (K_2), and Froude number (F_2) have been determined, pier scour (y_{ps}) can be solved using equation 42.

ESTIMATING ABUTMENT SCOUR

The only two variables required to estimate abutment scour using the rapid-estimation method are flow depth at the abutment, y_a , and a coefficient for abutment shape, K_1, shown in table 2. Because abutment scour needs to be calculated for both abutments, flow depth at the abutment is hereinafter separately designated as $y_{a\,LT}$ and $y_{a\,RT}$ for the left and right abutments, respectively. As previously discussed, depth of flow at the abutment typically is interpreted as the average depth of flow on each overbank area of the approach section and can be determined from the estimated main-channel depth, y_1, as was described for the estimation of contraction scour. Thus, for most sites, $y_{a\,LT} = y_{lob}$ and $y_{a\,RT} = y_{rob}$, and depth estimates for contraction-scour calculations can be used for abutment-scour calculations. However, abutment scour also may result from abutment encroachment into the main channel. When the abutment encroaches into the main channel, depth of flow at the abutment needs to be based on both the depth of flow on the overbank and the depth of flow at the toe of the abutment. In most instances, a simple average of the two depths is sufficient but, in some instances, the depths may need to be weighted by their respective widths of flow before averaging. Abutment scour also may occur in the absence of flood-plain flow when the abutment encroaches into the main channel, requiring that an estimate of $y_{a\,LT}$ or $y_{a\,RT}$ be made solely on the basis of abutment geometry. Some judgment may be required to determine whether abutments encroach into the main channel and where depth of flow at the toe of abutment needs to be measured. Abutment toes commonly are hard to identify in the field, and depth of flow at the abutment toe may need to be approximated by main-channel depth (y_1).

CONDUCTING AND REPORTING SCOUR ANALYSIS

Even though application of the method involves collection of widely varying site-specific data, similarities in the type of data needed from one site to another have resulted in the development of a standardized scour analysis and reporting form. The following sections describe the form and its use in conducting scour analyses using the rapid-estimation method.

STANDARDIZED SCOUR ANALYSIS AND REPORTING FORM

The standardized form was specifically developed for application in Montana and may require some modification for use in other geographic regions. Hydraulic variables needed to apply the rapid-estimation method can either be obtained on the basis of the procedures previously described and indicated on the front side of the form (fig. 20), or by using other site-specific information. Data required to calculate the three scour components are entered on the form and scour is calculated from the equations previously described. The front side is organized so that flood-hydrology data and general site information are listed first, followed by information and calculations required to determine the hydraulic variables required for scour estimation. Finally, specific information required for calculation of each of the three components of scour are grouped and listed. The equations on the standardized form do not include the components required for Case 1c contraction scour. These components were not included because of the need to limit the form to one page and because Case 1c contraction scour is not common in Montana or Colorado. In general, the form can be filled out in sequence, although some onsite measurements for different scour components are most conveniently made and entered on the form at the same time.

The back side of the form (fig. 21) is a summary of qualitative information about observed hydraulic, simple geomorphic, and scour conditions at the site as well as the estimated scour depths for each scour component and the estimated depth of flow in the main channel at the approach section and depth of flow at the abutments. Information on the back side of the form is intended to help the MDT determine the susceptibility of the bridge to scour on the basis of the estimated scour depths, design characteristics of the bridge, and observed scour and hydraulic characteristics at the site. Because the design drawings show the original channel geometry of the bridge section before any contraction or local scour has taken place, scour depths from the standardized analysis and reporting form can be plotted directly on the design drawings, with no need to adjust the streambed reference level. Referencing scour depths to the original channel geometry should not be done, however, where the general streambed elevation is suspected to have changed over time because of general scour. Total scour depth for plotting purposes on design drawings and for assessment of scour susceptibility is contraction scour plus pier scour for piers and contraction scour plus abutment scour for abutments. For pier scour, the channel bottom at the pier location as shown on design drawings typically is the most convenient reference level for plotting scour depths. Main-channel depth (y_1) and flow depths at the left and right abutments (y_{aLT} and y_{aRT}) are provided so that the intersection of the 100-year peak-discharge water surface with sloping bridge abutments can be properly referenced to plot depth of total scour at abutments on design drawings. In Montana studies, the scour holes at abutments generally are determined by first subtracting calculated flow depth blocked by abutment (y_a) from water surface elevation to obtain a reference point (fig. 22) for measuring total abutment-scour depth. To assess whether pier and abutment footings are susceptible to scour, their locations relative to the plotted scour prism are needed. Scour prisms, based on scour depths and angles of repose for typical streambed materials, can be plotted on the design drawings as described by Richardson and others (1991, p. 56-57) to determine whether scour holes are a threat to pier or abutment footings (fig. 22). For use of the rapid-estimation method in Montana, scour prisms will be plotted and evaluated by the MDT.

To summarize, the front side of the standardized form is a worksheet for scour depth calculations by the USGS, whereas the back side of the standardized form is a summary sheet for reporting scour depths and general hydraulic, geomorphic, and scour conditions to the MDT. Although the form is essentially self-explanatory, the following additional description gives general procedures for conducting scour analysis and reporting results from the rapid-estimation method.

SCOUR ANALYSIS AND REPORTING FORM

Site name: ____________________ Date: __________ Party: __________

Bridge structure no: ____________________ Site no: __________

METHOD USED TO DETERMINE 100-YEAR FLOOD DISCHARGE ESTIMATE

Channel-geometry method ________ Active-channel width, in ft = ________ Bankfull width, in ft = ________

Other method = ________ Flood discharge (Q_{100}), in ft^3/s= ________ Bridge discharge (Q_2), in ft^3/s = ________

ANALYTICAL PROCEDURE FOR ESTIMATING HYDRAULIC VARIABLES NEEDED TO APPLY METHOD

Bridge *SPAN*, in ft = ______ Skew of *SPAN* to flow (degrees)= ______ (*) *SPAN* adjusted for cosine of skew (*SPANADJ*1), in ft = ______

Discharge per ft width of span, in ft^3/s/ft, $q_2 = Q_2 / SPANADJ1$ = ______ Velocity at bridge contraction (figure 14), in ft/s, V_2 = ______

Flow depth at bridge contraction, in ft, $y_2 = q_2 / V_2$ = ______ Froude number at bridge contraction, $F_2 = V_2 / (32.2\, y_2)^{0.5}$ = ______

Water-surface elevation difference from approach to bridge contraction (Δh), (figure 16), in ft = ______

Average main-channel flow depth at approach section, in ft, $y_1 = y_2 + \Delta h$ = ______

(*) NOTE: Repeat procedure using only top width of wetted section at bridge contraction (*SPANADJ2*) based on y_2. Replace *SPANADJ*1 w/*SPANADJ2*.

CONTRACTION SCOUR CALCULATIONS (EXCLUDING CASE 1C):

Top width of wetted section at bridge contraction (*SPANADJ*2), in ft = ______ Width of main channel (W_1) at approach, in ft = ______

Width of left overbank flow (W_{lob}) at approach, in ft = ______ Width of right overbank flow (W_{rob}) at approach, in ft = ______

Average left overbank flow depth (y_{lob}), in ft = ______ Average right overbank flow depth (y_{rob}), in ft = ______

METHOD 1 χ, in ft: For live-bed scour in main channel where streambed material is very coarse gravel or finer ($D_{50} < 64$ mm):

$$\chi = \left[y_1 \left(\frac{W_1}{W_2} \right) - y_1 \right] + \left[\left(\frac{n_1}{W_2 y_1^{2/3}} \right) \left\{ \frac{W_{lob} y_{lob}^{5/3}}{n_{lob}} + \frac{W_{rob} y_{rob}^{5/3}}{n_{rob}} \right\} \right]$$

METHOD 2 χ, in ft : Where streambed material is small cobbles or coarser ($D_{50} \geq 64$ mm) and clear-water scour conditions are likely:

Average approach velocity (V_1), in ft/s = $Q_{100} / (y_1 W_1)$ = ______ Estimated bed material D_{50}, in ft = ______

Critical approach velocity (V_c), in ft/s, $V_c = 11.52\, y_1^{1/6} D_{50}^{1/3}$ = ______ **Use method 2 if $V_1 < V_c$ and $D_{50} \geq 0.2$ ft, otherwise use method 1.**

D_{c50}, in ft = $0.0006\, (q_2 / y_1^{7/6})^3$ = ______ If $D_{50} \geq D_{c50}$, $\chi = 0.0$

If $D_{50} < D_{c50}$, $\chi = 0.122 y_1 \,[q_2 / (D_{50}^{1/3} y_1^{7/6})]^{6/7} - y_1$ = ______

CONTRACTION SCOUR (y_{cs}): Determined by either method 1 (from figure 9) or method 2, ($y_{cs} = \chi$), in ft = ______

PIER SCOUR CALCULATIONS:

Average pier width (a), in ft = ______ Total pier length (L), in ft = ______ L/a ratio = ______

Flow angle of attack on pier(s), in degrees = ______ Correction factor for flow angle of attack (K_2 from table 1) = ______

$[y_{ps} / (K_2 F_2^{0.15})] = \xi$, from figure 11 = ______ **PIER SCOUR** (y_{ps}), in ft = $(K_2 F_2^{0.15}) \cdot \xi$ = ______

ABUTMENT SCOUR CALCULATIONS:

Average flow depths blocked by left and right abutments, in ft: y_{aLT} ______ y_{aRT} ______ Shape coeff. (K_1) (table 2) ______

$y_{as}\,(0.55/K_1) = \psi$, from figure 12: **SCOUR-LEFT** (y_{as}), in ft = $\psi\,(K_1/0.55)$ = ______ ; **SCOUR-RIGHT** (y_{as}), in ft = $\psi\,(K_1/0.55)$ = ______

Figure 20. Front side of standardized scour analysis and reporting form for Montana.

SCOUR ANALYSIS AND REPORTING FORM

Site name: ______________________ Date: ____________

Bridge structure no: ______________________ Site no. ____________

MISCELLANEOUS CONSIDERATIONS:

Chance of overtopping?	________Yes	________No	______Possibly
Chance of pressure flow?	________Yes	________No	______Possibly
Armored appearance to channel?	________Yes	________No	______Possibly
Lateral instability of channel?	________Yes	________No	______Possibly
Riprap at abutments?	________Yes	________No	______Marginal
Evidence of past scour?	________Yes	________No	______Don't know
Debris potential	________High	________Medium	______Low

Comments:

Does scour countermeasure(s) appear to have been designed?

Riprap:	______Yes	______No	_______Don't know	________NA
Spur Dike:	______Yes	______No	_______Don't know	________NA
Other:	______Yes	______No	_______Don't know	________NA

Comments:

BED MATERIAL CLASSIFICATION BASED ON MEDIAN PARTICLE SIZE (D_{50}):

Material:	Silt/Clay______	Sand______	Gravel______	Cobbles______	Boulders______
Size range, in mm	<0.062	0.062-2.00	2.00-64	64-250	>250

Other comments:

SUMMARY OF RESULTS:

Main channel depth (y_1), in ft	____________
Flow depth at left abutment (y_{aLT}), in ft	____________
Flow depth at right abutment (y_{aRT}), in ft	____________
Contraction scour depth (y_{cs}), in ft	____________
Pier scour depth (y_{ps}), in ft	____________
Left abutment scour depth (y_{as}), in ft	____________
Right abutment scour depth (y_{as}), in ft	____________

Figure 21. Back side of standardized scour analysis and reporting form for Montana.

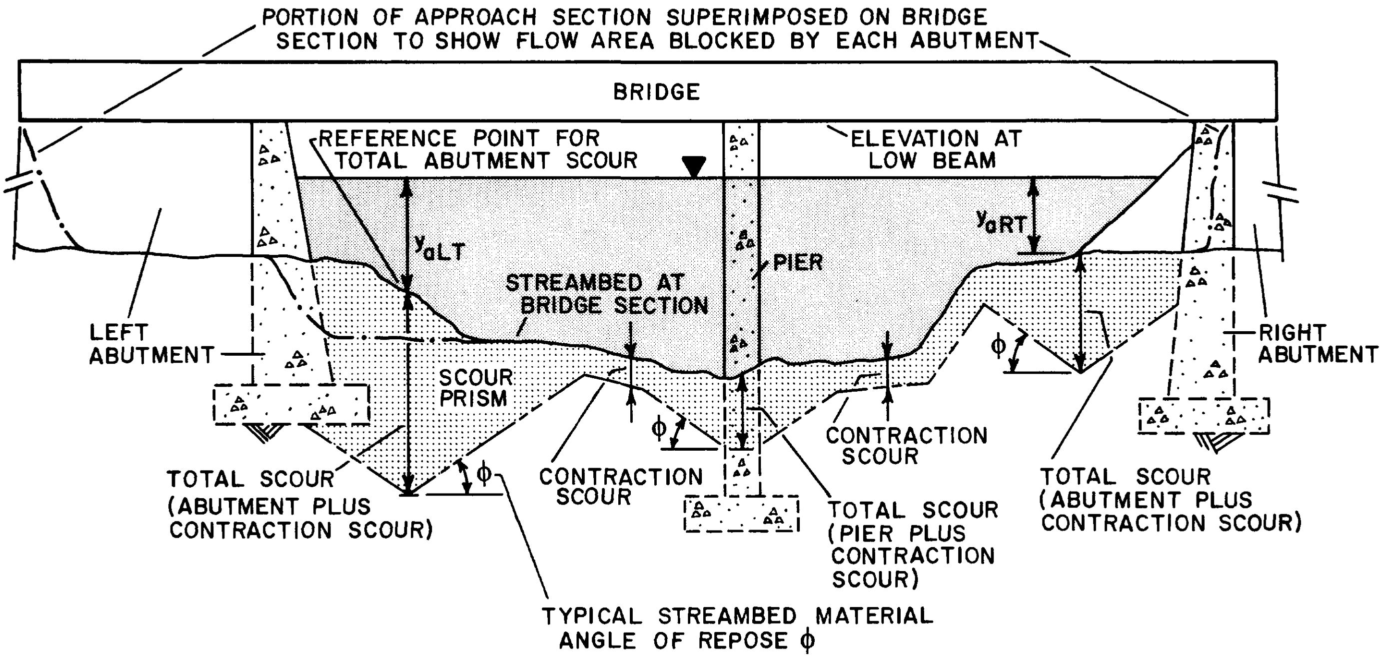


Figure 22. Scour prism plotted on a typical bridge section.

GENERAL PROCEDURES FOR SCOUR ANALYSIS

The method of scour analysis is primarily field-oriented; however, advance planning and completion of some office work will be helpful in the field. The first step typically is to inspect maps in the office to identify sites along a particular portion of highway route or stream where analyses can be conducted efficiently and in a progressive manner. The method is intended to be applied by one person for most situations. In some instances, bridges spanning larger rivers may require two people using slightly more sophisticated approaches to obtain the required site data. Other bridge locations that may warrant the use of two people to collect site data are those having (1) deeply incised main channels, (2) dense vegetation blocking the line of sight, or (3) other conditions involving the use of conventional level and stadia-rod surveying instruments that might be needed to measure horizontal and vertical distances.

Selecting the method to estimate the 100-year peak discharge is the next important step and determines whether the calculations must be performed in the office or can be done in the field. For gaged sites, flood-frequency data are obtained from project files or published reports in the office. For ungaged sites where adjusted flood-frequency data from nearby gaged sites or where regional equations based on basin characteristics are used to estimate 100-year peak discharge, drainage area and other variables need to be delineated on suitable topographic maps and measured. In general, measurement of basin characteristics needs to be done in the office where maps and measuring devices are available. For those applications in Montana where drainage area alone is used to estimate flood discharge, USGS topographic maps having a 1:250,000 scale are of sufficient detail to rapidly determine drainage area. In these instances, drainage area can be estimated in the field by (1) delineating drainages on field maps, (2) overlaying the delineated area with a simple, scaled transparent grid, (3) counting grid intersections within the delineated area, and (4) multiplying the number of grid intersections by the grid scale factor. Maps can also be of significant value in the field to assist in locating access routes, to identify disrupted drainages, and to clarify poorly defined site descriptions. In the western States where channel-geometry equations may be available, estimation of channel width and the subsequent calculation of 100-year peak discharge can be done only in the field.

Once a discharge estimate has been determined in the office or field, the remaining tasks are completed onsite. Upon arriving at the bridge, the person conducting the investigation should be equipped with the following items to assist in measuring or estimating pertinent site data:

1. Clipboard with graphs, envelope curves, and standardized scour analysis and reporting form (figs. 20 and 21).
2. Hand level with stadia-reading capability and stadia rod.
3. Flexible tape measure with an end that can be secured readily to a streambank.
4. Protractor.
5. Hand-held scientific calculator.
6. Camera and film.
7. Master list of bridge sites and important descriptors.

The typical procedure would be to walk to the nearest end of the bridge deck and measure the bridge span (*SPAN* on the standardized form) with a tape or by pacing the distance. Although the actual distance needed for the estimation of unit discharge and subsequent calculations of velocity and depth is the top width of the bridge cross section in contact with and perpendicular to the flood flow, bridge span typically is used as a first approximation. Span usually is measured between abutments, but the distance used could be less if the width of flooding at the bridge is noticeably less than the width between abutments. Documented bridge-design information could also be used to obtain span distance, especially if factors like safety concerns, significant bridge curvature, or an appreciable difference in bridge-deck elevation between abutments makes pacing or measurement by tape difficult.

The skew angle and flow angle of attack next are determined using a protractor and sighting upstream as previously described in the section on pier scour. If the bridge alignment is skewed to the stream, distance based on span will be overstated and will need to be adjusted by multiplying by the cosine of the skew angle. The adjusted top width distance, *SPANADJ*1, can then be used with the discharge estimate to determine unit discharge, q_2. Unit discharge and the general relation between unit discharge and velocity (fig. 14) are then used to estimate average velocity at the downstream face of the bridge, V_2. Depth at the downstream face of the bridge, y_2, is determined by dividing q_2 by V_2. A second estimate for top width, *SPANADJ2*, can be made if the estimated flow depth shows that top width needs to be narrowed. In some instances, high-water marks from previous large floods can be used to estimate flow depth at the bridge and the approach sections or to help verify the depths determined from the velocity versus unit-discharge relation. The use of high-water marks from past floods, together with an assumed velocity, may be especially helpful in apportioning flood discharge between main-channel and relief bridges. For large streams where determining the depth of flow at the time of the site visit might be difficult, determining the discharge and approximate stage for any nearby streamflow-gaging stations before beginning the field trip can be helpful in selecting flood depths at the site. Main-channel flow depth y_2 and main-channel velocity at the bridge V_2 are used to calculate the Froude number for the bridge section using equation 55. Flow depth at the bridge y_2 is used with the curve in figure 16 (or equations 53 and 54) to calculate depth at the approach section main channel y_1.

After top width, skew angle, and flow angle of attack have been measured from the bridge deck, other variables need to be measured under the bridge or at the approach section. Pier width and length generally are measured under the bridge using a tape or stadia rod. Manning's roughness coefficient, n, through the bridge opening also needs to be estimated (Arcement and Schneider, 1989) by observation near the bridge. Pebble counts to determine median bed-particle size can also be made near the bridge if clear-water scour conditions are apparent. For live-bed conditions, main-channel width needs to be measured or paced at the approach section. Average depths on the overbanks are determined from the main-channel depth and from use of a hand level. The ends of the approach section are determined using the hand level to locate points where the ground level rises above the estimated flood elevation. Once the ends of the approach section have been located, the widths of the left and right overbank areas can be measured or paced. For very wide flood plains, the approach section may need to be limited by angling the section to intersect the highway embankments as previously described for Level 2 studies. Manning's roughness coefficients for the approach-section main channel and overbank areas also need to be estimated by observation.

Under certain topographic conditions, the point of intersection between the concrete portions of an abutment and the ground surface might be outside the estimated limits of flooding, but the earthen portions of the abutment and the buried concrete footing might still be susceptible to scour as shown by a plot of the scour prism (fig. 23). Thus, where the visible part of the concrete abutment of a bridge is not subject to flooding, but where some flood flow is blocked by earthen portions of the abutment, abutment scour depth needs to be calculated as previously described. Some judgment is required to determine where flow might still be blocked by bridge abutments having concrete beyond the flood limits.

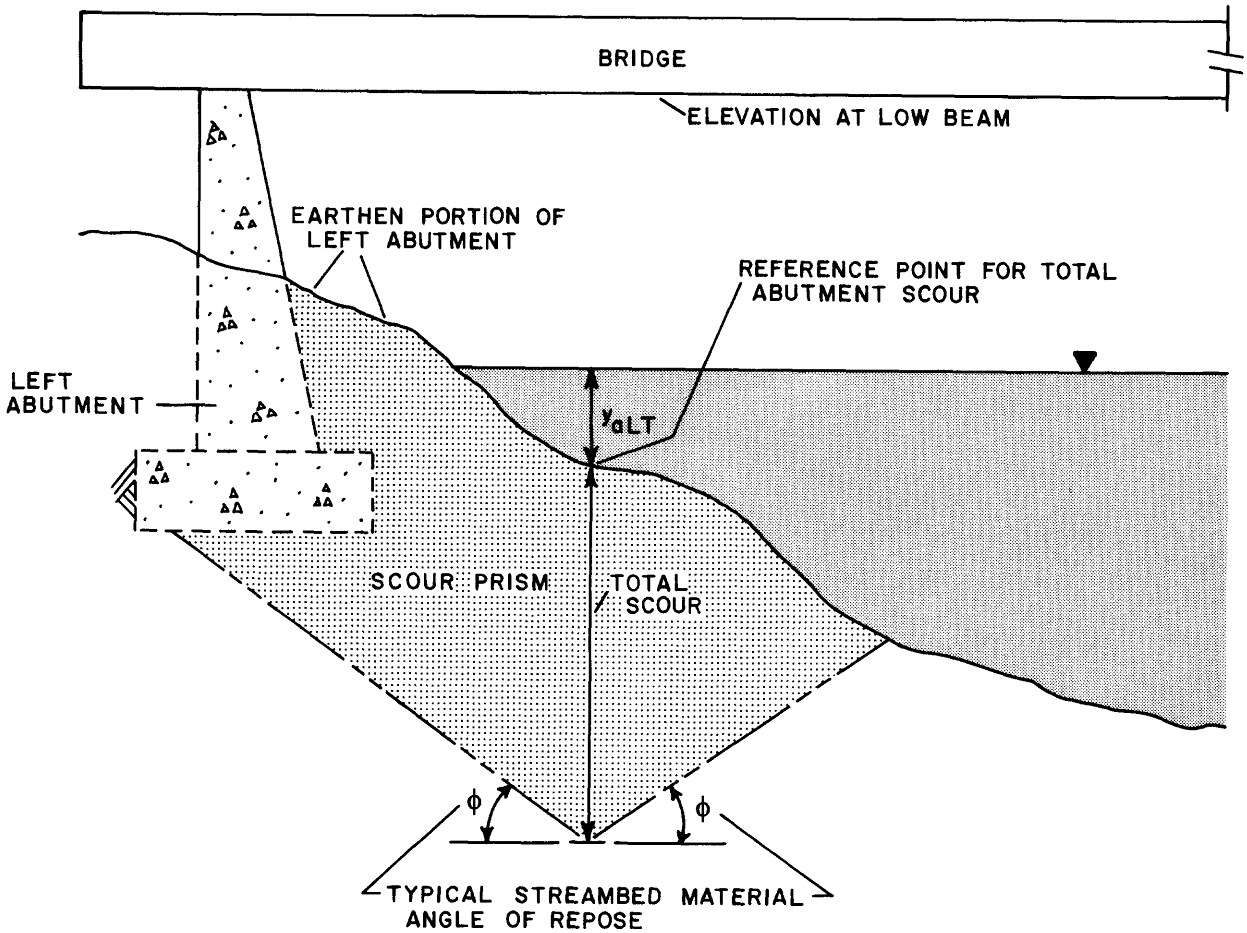


Figure 23. Abutment scour where visible portions of concrete abutments are outside of flood limits.

HYDRAULIC AND GEOMORPHIC CONDITIONS THAT MAY AFFECT SCOUR

After scour-depth calculations have been completed on the front side of the standardized form, results are transferred to the back side, and general hydraulic and geomorphic conditions that may affect scour at the site are noted. Important conditions that can significantly affect scour, but that are difficult to quantify, include:

1. Flow may overtop the bridge or roadway on either side of the bridge. If overtopping is considered likely based on a comparison of y_1 with road-embankment elevation, one of the techniques discussed earlier for dealing with road overflow needs to be applied to estimate the scour components. In many instances, the worst-case condition for maximum scour occurs at the incipient overtopping flood discharge (Richardson and others, 1991, p. 24); thus, the discharge used for scour-determination purposes can be less than the 100-year or other magnitude flood initially considered.

2. Flow may partially submerge the bridge structure so that pressure flow is indicated through the bridge opening based on a comparison of y_1 with the elevation of the upstream side of the bridge. Because pressure flow can produce greater pier-scour depths than non-pressure flow, the possibility of pressure flow needs to be noted on the form (fig. 21).
3. Armored channels may limit calculated scour and need to be noted on the form (fig. 21). If armoring appears to be likely, the clear-water contraction-scour calculations should indicate little or no contraction scour.
4. Lateral instability of the channel may result in significant general scour that is not included in the rapid-estimation method.
5. Riprap at abutments may limit abutment scour if properly designed, but riprap that appears not to conform to typical gradation standards and is sporadically placed may just indicate that abutment scour has been a significant problem in the past.
6. General evidence of past scour, such as remnant scour holes, exposed footings, or non-engineered riprap, indicates scour susceptibility that, in some instances, may not be reflected in the calculated scour depths. For bridges where large floods have historically occurred, lack of scour evidence can be useful information to help determine the reasonableness of calculated scour.
7. Adequately designed scour countermeasures, such as riprap or spur dikes, that conform to such design criteria as indicated in Brown and Clyde (1989), Lagasse and others (1991, p. 83-173), and Richardson and others (1993, p. 115-124) may limit scour depths and need to be noted on the form.
8. Characterization of the streambed material helps support other determinations such as armoring potential, clear-water versus live-bed scour conditions, and other geomorphologically related factors affecting scour.

Other factors that may affect scour but are not listed on the standardized form are eddy currents resulting from abrupt changes in flow direction near the vicinity of piers or abutments, ice jamming, scour effects associated with cohesive-type soils, and abnormally long periods of sustained high flows. Even though some of these factors may be impossible to predict, some may be evident from site conditions or known flood history at the site and need to be indicated on the form.

LIMITATIONS

Although the rapid-estimation method involves only a few graphs, envelope curves, and a standardized form, reliable estimates of such key hydrologic and hydraulic variables as 100-year flood discharge, main-channel and overbank flood depths, flow angle of attack, and Manning's roughness coefficient require considerable field experience and sound judgment regarding bridge scour, flood hydrology, and hydraulics. Even for highly experienced individuals, the results of field testing of the method previously described indicated that some experience with the rapid-estimation method itself is required to produce reliable and generally reproducible results.

The rapid-estimation method is intended to provide estimates of scour that would be reasonably close to those from a Level 2 analysis at the same site. Scour estimates from the rapid-estimation method generally are not as accurate or as reliable as those from Level 2 analyses and tend to be conservative by overestimating scour depths. The method is not intended to be a substitute for more detailed analyses required for design purposes in the rehabilitation or replacement of bridges. Rather, the rapid-estimation method is intended to provide rapid scour assessments at a large number of sites so that most, if not all, bridges in Montana might be inventoried. Further, results from the rapid-estimation method are expected to be used as the basis for deciding where more detailed scour calculations are needed at existing bridges.

Because the rapid-estimation method is based on procedures and results from Level 2 analyses, the rapid-estimation method also is subject to the same limitations as the Level 2 method. Among those limitations are the following:

1. Equations for scour estimation are simplifications of a complex and dynamic process and may not produce reliable estimates under some complex flow conditions. In these instances, a more detailed Level 2 or Level 3 analysis needs to be performed.
2. Equations for scour estimation do not reflect general scour or stream instability that may, under some conditions, compound contraction and local scour or completely erode highway embankments far removed from bridges.
3. Although the equations may sometimes indicate large scour depths, highly erosion-resistant layers may lie a few feet beneath the streambed. Thus, results from hydraulic analyses need to be integrated with geotechnical analyses to fully evaluate scour in some instances.

In addition to limitations common with the Level 2 method, the following also apply:

1. Variables used to develop regression equations of V_2 versus q_2 (fig. 14) and Δh versus V_2^2 (fig. 16) were limited to data from Montana and Colorado for use in the Northern Rocky Mountain region; thus, use of the equations in other regions would first need to be verified and perhaps modified using more region-specific data.
2. Because the rapid-estimation method was developed using only data for inland river systems, the method is not applicable for evaluating scour for bridges in coastal- or marine-type environments affected by tidal conditions.
3. Application of the method outside the range of data used to develop the envelope curves may result in unreliable prediction of scour.
4. Application of the method to complex hydraulic conditions for which reasonable estimates of key hydraulic variables might be difficult, such as some conditions of road overtopping or flow through relief bridges, might also result in unreliable scour-depth estimates. Reliable estimates of scour depth under these conditions can only be provided by Level 2 scour analyses.

SUMMARY AND CONCLUSIONS

To meet the objectives of the national bridge scour program in Montana, the USGS began a study to develop a method for rapid estimation of bridge scour that would (1) require only limited onsite data, (2) provide estimates of scour depth that would be reasonably comparable to estimates from more detailed methods (Level 2 scour analyses), and (3) provide estimates at each site in a few hours or less, so that scour assessments at about 1,600 bridge sites could be completed. The rapid-estimation method was based on results from Level 2 scour analyses completed in 10 States.

Components of bridge scour that are considered in both Level 2 scour analyses and in the rapid-estimation method are contraction scour and local scour at piers and abutments. Where general scour involving long-term degradation or aggradation is a concern, a geomorphic investigation is required. Contraction scour is generally affected by sediment-movement conditions occurring in the reach upstream from and leading into the bridge opening. When sediment supply is incoming to the bridge, the scour condition is termed "live-bed scour." When no sediment supply is incoming to the bridge, the scour condition is termed "clear-water scour." Equations currently recommended for pier scour and abutment scour are mainly a function of localized hydraulic factors like flow depth and velocity and are not dependent on whether conditions are live-bed or clear-water.

Level 2 scour analyses generally are conducted for peak discharges having 100-year and 500-year recurrence intervals. The WSPRO computer program is used to determine the water-surface profile through the bridge reach and to estimate values of various hydraulic variables that are used in Level 2 equations for calculation of contraction and local scour.

Contraction scour is complicated because of the many different configurations of highway abutments and flood-plain conditions that can result in flow contraction and scour. To simplify contraction scour calculations, Richardson and others (1993) defined four general cases of contraction scour. For Cases 1 and 2, all flood discharge passes through a single bridge opening. For Cases 3 and 4, some flood discharge passes through a relief bridge. Case

1, where flood-plain flow occurs at the approach section, is the most common case of contraction scour, and is further subdivided into Cases 1a, 1b, or 1c depending upon whether the main channel at the bridge is contracted (Case 1a) or uncontracted (Case 1b) and whether any flood-plain flow occurs at the bridge section (Case 1c). Case 1c contraction scour is very complex, in part because both live-bed and clear-water contraction scour may occur at the bridge section.

The determination of contraction scour for all classes is based on two fundamental equations: one for live-bed contraction scour and one for clear-water contraction scour. The equation for live-bed contraction scour is based on average depth in the contracted section before any scour occurs (y_0), discharge in the main-channel portion of the contracted section that is transporting sediment, discharge in the main-channel portion of the approach section that is transporting sediment, width of the main-channel portion of the contracted section transporting sediment at the bridge, width of the main-channel portion of the approach section that is transporting sediment, and a coefficient (k_1) that varies from 0.59 to 0.69 depending on whether the sediment transport is mostly bed material (k_1=0.59) or mostly suspended sediment (k_1=0.69). Because y_0 is difficult to determine, the average depth in the main channel at the approach section (y_1) commonly is used in place of y_0.

The equation for calculation of clear-water contraction scour is based on average depth before scour, discharge, width of flow, and the median size of bed material in that part of the cross section (main channel or bridge setback area) where clear-water scour occurs.

The Level 2 equation for calculation of pier scour is based on depth of flow upstream from the pier; correction factors for pier-nose shape, flow angle of attack, and bed-form condition; width of the pier; and Froude number just upstream from the pier. Scour depth calculated by the Level 2 equation is particularly sensitive to flow angle of attack and the ratio of pier length to pier width.

The equation generally used for the estimation of abutment scour is based on coefficients for abutment shape and angle of embankment to flow, the length of flood-plain flow blocked by the abutment, flow depth at the abutment, and Froude number of the flow upstream from the embankment. An alternative equation for the estimation of abutment scour commonly is used when the ratio of length of flood-plain flow blocked by the abutment to depth of flow at the abutment is greater than about 25. The alternative equation is based on Froude number of the flow upstream from the embankment and depth of flow at the abutment.

Hydraulic variables used in Level 2 analyses that can be easily measured in the field for the rapid-estimation method are pier width and length, flow angle of attack on the piers, Manning's roughness coefficients for channels and flood plains, bed-particle size, and abutment shape. An easily measured variable that is important in the rapid-estimation method for calculation of flow depth, velocity, and an average Froude number at the main-channel portion of the bridge section is bridge length.

A form of the Level 2 equation for live-bed contraction scour that is based only on easily measured hydraulic variables was derived for use in the rapid-estimation method. The derived equation is based on estimated flow widths, depths, and Manning's roughness coefficients at the approach and bridge sections.

For clear-water contraction scour in the main channel, the same equation used for Level 2 scour analysis is used for the rapid-estimation method because all variables can be easily measured in the field. For clear-water contraction scour in bridge setback areas (Case 1c), a form of the Level 2 equation based only on easily measured variables was derived for use in the rapid-estimation method. The derived equation is based on total discharge through the bridge section, median particle size of material in the setback area, and estimated conveyances, depths, and flow widths in the left and right setback areas.

For nine Level 2 sites in Montana where clear-water scour conditions were indicated on the basis of bed-material gradation data and calculations of critical velocity, calculated contraction scour was zero. More than half of these nine sites had a D_{50} equal to or greater than about 64 mm, which is characterized as being small cobbles or coarser. The equation used to determine clear-water contraction scour depth for Level 2 analyses was modified and used to determine a critical median bed-particle size that would result in zero contraction scour (D_{c50}). Thus, for application of the rapid-estimation method in Montana, if the D_{50} estimated in the field is equal to or greater than 64 mm and greater than or equal to D_{c50}, contraction scour is presumed to be zero. Where D_{50} is equal to or greater than 64 mm but less than D_{c50}, the scour condition is presumed to be clear-water, and scour depth needs to be calculated using a slightly modified version of the Level 2 equation for clear-water scour adopted for the method.

Two envelope curves relating contraction-scour depth from Level 2 analyses to a contraction-scour variable used in the rapid-estimation method were developed from Level 2 data. The first envelope curve is for live-bed conditions of scour and the second envelope curve is for clear-water conditions involving Case 1c setback areas. The envelope curves were drawn from a plot of Level 2 contraction scour versus the calculated value of the contraction-scour variable obtained on the basis of simplified versions of Level 2 equations.

For the estimation of pier scour using the rapid-estimation method, a pier-scour function based on pier-scour depth, a correction factor for pier width and length and flow angle of attack, and average main-channel Froude number at the bridge contraction was developed from Level 2 data. The envelope curve relation for estimation of pier scour was developed from a plot of pier-scour function versus pier width.

An abutment-scour function based on abutment-scour depth blocked by the abutment and the coefficient for abutment shape was developed for use in the rapid-estimation method from Level 2 scour analysis data. The envelope curve for the estimation of abutment-scour depth was developed from a plot of abutment-scour function versus flow depth at the abutment.

To determine how reliably the rapid-estimation method would perform when actually applied in the field, two different tests were made. Data were obtained by having 3 to 5 highly experienced individuals in the USGS Montana District independently visit bridge sites for which Level 2 scour analyses were completed and use the rapid-estimation method to estimate scour depths. For the first test, individual estimates for contraction, pier, and abutment scour were averaged and compared to the values from the Level 2 analyses. Results of the comparisons indicated that estimates from the rapid-estimation method generally were reasonably close to but conservatively larger than those from the Level 2 analyses.

For the second test, the variability in estimates among individuals was assessed by computing the mean and standard deviation of individual estimates of scour depth at each site. For sites having wide variability among individuals, most of the variability was attributed to differences in interpretation of variables that have a large effect on calculated scour depth common to both the rapid-estimation method and the Level 2 method. Overall, the error due to variability among individuals is considered to be acceptable so long as use of the rapid-estimation method is limited to individuals having experience in bridge scour, hydraulics, and flood hydrology, and some training in use of the method.

Application of the rapid-estimation method requires an estimate of the 100-year peak discharge at the site. Regional basin characteristics equations or channel-geometry equations previously developed can be used to estimate 100-year peak discharge. Channel-geometry equations generally are considered to be the best estimators of peak discharge for mountainous streams and foothills headwaters, whereas the equations based on basin characteristics generally are considered to be the best estimators in the plains regions of Montana.

To estimate the flood depth at the bridge for the 100-year peak discharge, a graph relating unit discharge to velocity was developed from Level 2 hydraulic data in Montana and Colorado. Unit discharge is determined by dividing 100-year peak discharge by estimated width of flow at the downstream face of the bridge, and estimating velocity from the curve. The flood depth is estimated by dividing unit discharge by the estimated velocity. A second graph relating the square of the velocity at the bridge to the difference in water-surface elevation between the bridge and approach section was also developed from Level 2 data in Montana and Colorado. The difference in water-surface elevation is used to estimate flow depth in the main channel of the approach section.

After determination of flow depths for the 100-year peak discharge, variables needed for application of the envelope curves to estimate scour depths are measured or estimated. Although live-bed scour conditions generally can be assumed for main channels in Montana, a determination of the D_{50} for the bed material may be needed to determine the scour condition. In some instances, contraction scour may be calculated using both the live-bed and clear-water equations, and the largest value can be reported to ensure that results are conservatively large. For the estimation of pier scour using the rapid-estimation method, careful measurement of the flow angle of attack on the piers is important. For abutment scour, determination of flow depths blocked by the abutments may require some judgment where abutment toes are hard to identify.

To document the estimation and reporting of scour depths from the rapid-estimation method in Montana, a standardized scour analysis and reporting form was developed. Data required to make scour-depth estimates and the calculations are entered on the front side of the form. Qualitative information about observed hydraulic, geomorphic, and scour conditions at the site and the estimated depths of contraction, pier, and abutment scour and estimated main-channel depth and depths blocked by left and right abutments are entered on the back side of the form for use by the MDT to plot and evaluate the scour prism.

The rapid-estimation method is intended to provide estimates of scour depth that would be reasonably close to those from a Level 2 analysis at the same site. Because key hydrologic and hydraulic variables are only estimated for the rapid-estimation method, results from the rapid-estimation method generally are not as accurate or reliable as those from a Level 2 analysis. In addition, the rapid-estimation method is subject to the same limitations as the Level 2 method.

SELECTED REFERENCES

Arcement, G.J., and Schneider, V.R., 1989, Guide for selecting Manning's roughness coefficients for natural channel and floodplains: U.S. Geological Survey Water-Supply Paper 2339, 38 p.

Brown, S.A., and Clyde, E.S., 1989, Design of riprap revetment: U.S. Department of Transportation No. FHWA-IP-89-016, Hydraulic Engineering Circular 11, 156 p.

Davidian, Jacob, 1984, Computation of water-surface profiles in open channels: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A15, 48 p.

Fischer, E.E., 1995, Potential-scour assessments and estimates of maximum scour at selected bridges in Iowa: U.S. Geological Survey Water-Resources Investigations Report 95-4051, 75 p.

Jennings, M.E., Thomas, W.O., and Riggs, H.C., 1994, Nationwide summary of U.S. Geological Survey regional regression equations for estimating magnitude and frequency of floods for ungaged sites, 1993: U.S. Geological Survey Water-Resources Investigations Report 94-4002, 196 p.

Lagasse, P.F., Schall, J.D., Johnson, F., Richardson, E.V., Richardson, J.R., Chang, F., 1991, Stream stability at highway structures: U.S. Department of Transportation No. FHWA-IP-90-014 Hydraulic Engineering Circular 20, 195 p.

Laursen, E.M., 1960, Scour at bridge crossings: American Society of Civil Engineers, Journal of Hydraulic Engineering, v. 86, no. 2, p. 39-55.

______1963, Analysis of relief bridge scour: American Society of Civil Engineers, Journal of Hydraulic Engineering, v. 89, no. HY3, p. 92-116.

Mueller, D.S., 1993, Bridge-scour analysis using the water-surface profile (WSPRO) model, *in* Hydraulic Engineering '93, vol. 2, Proceedings of the 1993 Conference, San Francisco, Calif., July 25-30, 1993: New York, American Society of Civil Engineers, p. 1714-1719.

Mueller, D.S., Miller, R.L., and Wilson, J.T., 1994, Historical and potential scour around bridge piers and abutments of selected stream crossings in Indiana: U.S. Geological Survey Water-Resources Investigations Report 93-4066, 109 p.

Neill, C.R., 1968, Note on initial movement of coarse uniform bed material: Journal of Hydraulic Research, vol. 17, no. 2, p. 247-249.

Omang, R.J., 1992, Analysis of the magnitude and frequency of floods and the peak-flow gaging network in Montana: U.S. Geological Survey Water-Resources Investigations Report 92-4048, 70 p.

Omang, R.J., Parrett, Charles, and Hull, J.A., 1986, Methods for estimating magnitude and frequency of floods in Montana based on data through 1983: U.S. Geological Survey Water-Resources Investigations Report 86-4027, 85 p.

Parrett, Charles, Hull, J.A., and Omang, R.J., 1987, Revised techniques for estimating peak discharges from channel width in Montana: U.S. Geological Survey Water-Resources Investigations Report 87-4121, 34 p.

Richardson, E.V., and Davis, S.R., 1995, Evaluating scour at bridges (3d ed.): U.S. Department of Transportation, Hydraulic Engineering Circular 18, 204 p.

Richardson, E.V., Harrison, L.J., and Davis, S.R., 1991, Evaluating scour at bridges: U.S. Department of Transportation Hydraulic Engineering Circular 18, 105 p.

Richardson, E.V., Harrison, L.J., Richardson, J.R., and Davis, S.R., 1993, Evaluating scour at bridges (2d ed.): U.S. Department of Transportation Hydraulic Engineering Circular 18, 132 p.

Richardson, E.V., and Richardson, J.R., 1994, Practical method for calculating contraction scour, *in* Hydraulic Engineering '94, vol. 1, Proceedings of the 1994 Conference, Buffalo, N.Y., August 1-5, 1994: New York, American Society of Civil Engineers, p. 6-10.

Richardson, E.V., Simons, D.B., and Julien, P., 1990, Highways in the river environment: U.S. Department of Transportation No. FHWA-HI-90-016, variously paged.

Shearman, J.O., 1990, User's manual for WSPRO--A computer model for water surface profile computations: U.S. Department of Transportation Publication No. FHWA-IP-89-027 Hydraulic Computer Program HY-7, 177 p.

Shearman, J.O., Kirby, W.H., Schneider, V.R., and Flippo, H.N., 1986, Bridge waterways analysis model-research report: U.S. Department of Transportation Publication No. FHWA/RD-86/108, 112 p.

Vaill, J.E., Kuzmiak, J.M., Stevens, M.R., and Montoya, Peter, 1995, Summary of bridge scour analyses at selected sites in Colorado, 1991-93: U.S. Geological Survey Open-File Report 95-296, 51 p.

Wolman, M.G., 1954, A method of sampling coarse river-bed material: American Geophysical Union Transactions, v. 35, no. 6, p. 951-956.

Table 5. Summary of Level 2 bridge scour investigation data used in the study

Bridge length--distance or span measured between left and right main abutments, excluding any relief bridges having distinctly separate pier and abutment systems, in feet.

Bridge-opening type--defined according to Shearman (1990, p. 50).

Type 1, for vertical embankments and vertical abutments, with or without wingwalls;
Type 2, for sloping embankments and vertical abutments, without wingwalls;
Type 3, for sloping embankments and sloping spillthrough abutments;
Type 4, for sloping embankments and vertical abutments with wingwalls.

Flow class through bridge--defined according to Shearman (1990, p. 170).

Class 1 flow, if free-surface flow occurs through bridge with no road overflow;
Class 2 flow, if unsubmerged pressure flow occurs through bridge with no road overflow;
Class 3 flow, if submerged pressure flow occurs through bridge with no road overflow;
Class 4 flow, if free-surface flow occurs through bridge with road overflow;
Class 5 flow, if unsubmerged pressure flow occurs through bridge with road overflow;
Class 6 flow, if submerged pressure flow occurs through bridge with road overflow.

Main channel slope--slope in vicinity of the bridge crossing based on topographic information, channel-section data, or slope of energy grade line, in feet per mile.

Q_{100} --peak discharge at the 100-year recurrence interval, in cubic feet per second.

Q_{brg} --discharge conveyed through the bridge opening, in cubic feet per second.

D_{50} --median bed-material particle size obtained by a sieve analysis, pebble count, or visual inspection in the field, in millimeters.

Predominant streambed material--streambed material classified by sediment grade scale in Mueller (1994, p. 4) if D_{50} is given. Otherwise, material classification obtained from unpublished documentation or published reports summarizing Level 2 analyses.

Contraction-scour variables--

Scour type:

LB, live-bed scour,
CW, clear-water scour.
ab, either Case 1a, 1b, 2a, or 2b;
c, Case 1c;
d, Case 3 or Case 4 for which envelope curves were not explicitly developed.

χ, variable derived for use in the rapid-estimation method, in feet; for sites where up to three values of χ are shown, the first value applies to the main channel while the second and third values apply to the left and right setback areas, respectively.

Pier-scour variables--

Pier width, a, width of the pier producing the worst-case scour in the Level 2 analysis, in feet.
K_2, correction factor for flow angle of attack on pier (modified from Richardson and others, 1993)
F_2, average Froude number for main-channel portion of the contracted opening based on an average flow depth and velocity.

Abutment-scour variables--

K_1, abutment shape coefficient (from Richardson and others, 1993).
y_{aLT}, average flow depth blocked by the left abutment, in feet.
y_{aRT}, average flow depth blocked by the right abutment, in feet.

Symbol: --, data not available or not applicable; ( ), data not used to develop envelope curve because of differences in interpretation or because data were considered to be anomalous.

Abbreviations: ft^3/s, cubic foot per second; ft, foot; ft/mi, foot per mile; mm, millimeter; mi^2, square mile.

Table 5. Summary of Level 2 bridge scour investigation data used in the study (Continued)

Site no.	Bridge site name and location	Bridge structure identification number	Bridge length (ft)	Bridge-opening type	Flow class through bridge	Drainage area (mi^2)	Main channel slope (ft/mi)	Q_{100} (ft^3/s)	Q_{brg} (ft^3/s)	D_{50} (mm)	Predominant streambed material
Data from Colorado USGS (Vaill and others, 1995; J.E.Vaill, U.S. Geological Survey, written commun., 1995-1996)											
1	Alamosa Creek at Route 371 near Capulin, Colo.	O-12-AD	91	3	1	142	9.2	1,750	1,750	--	Sand/gravel
2	Beaver Creek at Route 50 near Penrose, Colo.	K-17-H	205	3	1	209	37.5	20,100	20,100	--	Gravel/cobble
3	Big Sandy Creek at Route 96 near Chivington, Colo.	K-26-A	327	3	1	1,749	13.5	71,300	[1]13,200	--	Sand/gravel
4	Clay Creek at Route 50 near Lamar, Colo.	L-26-F	299	2	1	230	7.4	28,400	[1]21,500	--	Gravel/silt
5	Clear Creek at Route 6 near Golden, Colo.	E-16-EF	200	3	1	392	68.6	7,380	7,380	--	Cobble
6	Clear Creek at Route 70 near Idaho Springs, Colo.	F-15-BM	106	2	1	270	63.4	3,240	3,240	--	Cobble/ boulder
7	Colorado River at Route 340 near Fruita, Colo.	H-02-GA	605	3	1	54,400	6.3	54,400	54,400	--	Gravel/cobble
8	Colorado River at Route 70 near Silt, Colo.	F-06-Y	450	3	1	6,640	14.8	27,200	27,200	--	Gravel/cobble
9	Cucharas River at Route 10 near Walsenburg, Colo.	N-18-AC	248	3	1	530	39.6	43,800	[1]16,900	--	Gravel/cobble
10	Devil Creek at Route 160 at Chimney Rock, Colo.	P-07-B	87	3	1	67	63.4	2,230	2,230	--	Cobble/ boulder
11	Dolores River at Route 141 at Gateway, Colo.	J-01-C	234	3	1	4,188	6.3	29,700	[1]21,500	--	Gravel/cobble
12	Dry Creek at Route 40 near Hayden, Colo.	C-07-D	44	4	1	80	28.0	963	963	--	Gravel
13	Gunnison River at Route 50 at Delta, Colo.	I-04-K	307	3	1	5,500	9.5	23,200	23,200	--	Gravel/cobble
14	Kiowa Creek at Route 86 near Kiowa, Colo.	G-19-B	198	4	1	106	30.1	20,500	20,500	--	Sand
15	[2]Lone Tree Creek at Route 25 near Cheyenne, Wyo.	A-17-AD	120	3	1	132	26.4	24,300	[1]5,250	--	Gravel/sand
16	McElmo Creek at Route 160 at Cortez, Colo.	O-02-I	100	3	1	119	14.8	2,700	2,700	--	Cobble
17	Plateau Creek at Route 330 near Mesa, Colo.	H-04-S	156	3	1	484	52.8	3,860	3,860	--	Cobble/ boulder
18	Rio Grande River at Route 149 at Creede, Colo.	M-09-R	221	3	1	566	13.7	4,180	4,180	--	Gravel/cobble

Table 5. Summary of Level 2 bridge scour investigation data used in the study (Continued)

Data from Level 2 bridge-scour investigations												
	Contraction-scour variables			Pier-scour variables				Abutment-scour variables				
Site no.	Scour type	χ (ft)	Contraction scour (ft)	Pier width, *a* (ft)	K_2	F_2	Pier scour (ft)	K_1	y_{aLT} (ft)	y_{aRT} (ft)	Left abutment scour (ft)	Right abutment scour (ft)
Data from Colorado USGS (Vaill and others, 1995; J.E.Vaill, U.S. Geological Survey, written commun., 1995-1996)												
1	*LB,ab*	18.0	9.2	2.0	1.0	0.40	4.5	0.55	3.3	2.5	5.9	4.3
2	*LB,ab*	117.8	50.7	2.5	1.0	.97	9.4	.55	21.9	22.5	27.6	31.7
3	*LB,ab*	14.0	.7	1.6	1.0	.67	4.4	.55	3.9	2.8	8.1	6.0
4	*LB,ab*	14.5	10.9	1.7	1.0	.55	4.4	1.00	3.6	7.4	8.6	18.5
5	*LB,ab*	4.8	0	3.0	1.0	.67	7.1	.55	4.2	6.9	13.6	14.6
6	*LB,ab*	15.2	6.5	2.8	1.0	.81	6.0	1.00	0	0	0	0
7	*LB,ab*	0	0	2.0	1.0	.48	5.0	.55	0	0	0	0
8	*LB,ab*	0	0	2.0	1.0	.56	5.5	.55	0	3.3	0	5.7
9	*LB,ab*	7.3	4.3	2.0	1.0	.95	5.4	.55	5.6	.6	13.2	1.2
10	*LB,ab*	.1	0	2.0	1.0	.93	4.6	.55	1.6	1.0	4.2	0
11	*LB,ab*	.3	0	2.0	1.0	.45	5.2	.55	5.9	2.0	11.0	3.6
12	*LB,ab*	.2	0	1.9	1.0	.47	4.0	.82	1.7	.7	5.2	2.1
13	*LB,ab*	.3	0	2.1	1.0	.46	5.1	.55	4.3	3.7	9.4	8.7
14	*LB,ab*	4.9	4.1	3.0	1.0	.98	9.1	.82	4.2	7.6	9.1	17.3
15	*LB,ab*	9.8	4.1	1.5	1.0	.56	3.9	.55	4.2	3.8	9.1	8.0
16	*LB,ab*	.1	0	2.0	1.0	.45	4.4	.55	1.8	0	3.4	0
17	*LB,ab*	0	0	2.0	1.0	.98	4.5	.55	0	0	0	0
18	*LB,ab*	1.0	.4	2.5	1.0	.51	4.5	.55	3.3	0	7.8	0

Table 5. Summary of Level 2 bridge scour investigation data used in the study (Continued)

Site no.	Bridge site name and location	Bridge structure identification number	Bridge length (ft)	Bridge-opening type	Flow class through bridge	Drainage area (mi^2)	Main channel slope (ft/mi)	Q_{100} (ft^3/s)	Q_{brg} (ft^3/s)	D_{50} (mm)	Predominant streambed material
Data from Colorado USGS (Vaill and others, 1995; J.E. Vaill, U.S. Geological Survey, written commun., 1995-1996)--continued											
19	Rio San Antonio at Route 142 near Manassa, Colo.	P-13-D	118	4	1	341	1.3	3,070	3,070	--	Sand/gravel
20	South Fork Rio Grande River at Route 160 at South Fork, Colo.	N-10-V	80	2	1	216	42.2	5,160	5,160	--	Gravel/cobble
21	South Fork South Platte River at Route 285 near Fairplay, Colo.	H-13-G	71	4	1	90	18.5	906	906	--	Sand
22	Spring Creek at Route 64 near Rangely, Colo.	D-02-A	101	2	1	34	47.5	310	310	--	Sand
23	Spring Creek at Route 70 near Vona, Colo.	G-26-T	120	3	1	62	3.2	15,300	[1]4,750	--	Sand
24	Uncompahgre River at Route 348 near Olathe, Colo.	J-05-X	88	3	1	920	24.8	4,450	4,450	--	Gravel/cobble
25	Unnamed Draw at Route 86 near Limon, Colo.	G-20-C	89	3	1	10	31.7	8,320	[1]3,750	--	Fine sand
Data from Indiana USGS (Mueller and others, 1994; D.S. Mueller, U.S. Geological Survey, written commun., 1995-1996)											
26	Big Blue River at Interstate 74 near Shelbyville, Ind.	I-74-114-4192B	462.8	3	1	314	4.8	17,300	17,300	.49	Medium sand
27	Buck Creek at State Road 32 at Yorktown, Ind.	32-18-5441A	134	[3]--	[3]--	100	5.8	7,000	7,000	4.0	Fine gravel
28	East Fork White River at U.S. Route 231 near Haysville, Ind.	45-19-995D	800	3	1	5,558	.84	116,000	116,000	.20	Fine sand
29	East Fork White River at U.S. Route 258 near Seymour, Ind.	258-36-4912	775	[4]--	[4]--	2,347	1.9	98,000	39,100	1.0	Very coarse sand
30	Kankakee River at U.S. Route 231 near Hebron, Ind.	231-37-4980	318.5	[3]--	[3]--	1,445	1.1	6,800	6,800	1.0	Very coarse sand
31	Tippecanoe River at U.S. Route 24 at Monticello, Ind.	24-91-3731A	469.5	2	1	1,768	2.6	25,000	25,000	4.0	Fine gravel
32	Tippecanoe River at State Road 331 at Old Tip Town, Ind.	331-50-6627	223.5	3	1	390	1.1	3,850	3,850	1.0	Very coarse sand
33	White River at State Road 358 near Edwardsport, Ind.	358-42-6779	499.5	[4]--	[4]--	5,013	3.2	110,000	63,600	.40	Medium sand
34	White River at U.S. Route 41 near Hazelton, Ind.	41-26-3917C	2,400	3	1	11,305	.53	186,000	186,000	.50	Coarse sand

Site no.	Scour type	χ (ft)	Contraction scour (ft)	Pier width, *a* (ft)	K_2	F_2	Pier scour (ft)	K_1	y_{aLT} (ft)	y_{aRT} (ft)	Left abutment scour (ft)	Right abutment scour (ft)
Data from Level 2 bridge-scour investigations												
Contraction-scour variables				Pier-scour variables				Abutment-scour variables				
Data from Colorado USGS (Vaill and others, 1995; J.E. Vaill, U.S. Geological Survey, written commun., 1995-1996)--continued												
19	*LB,ab*	6.1	5.0	1.0	1.0	.27	2.4	.82	3.1	3.0	4.3	4.5
20	*LB,ab*	0	0	1.8	1.0	1.01	4.3	1.00	1.5	.3	3.2	0
21	*LB,ab*	0	0	1.0	1.0	.55	3.5	.82	0	0	0	0
22	*LB,ab*	.1	0	1.0	1.0	.61	1.8	1.00	.2	.3	.8	.7
23	*LB,ab*	4.2	.2	2.1	1.0	.28	3.8	.55	1.8	2.7	2.5	9.7
24	*LB,ab*	.1	0	1.3	1.0	.48	3.4	.55	0	0	0	0
25	*LB,ab*	1.9	.3	2.0	1.0	.44	4.3	.55	2.0	2.0	4.6	4.0
Data from Indiana USGS (Mueller and others, 1994; D.S. Mueller, U.S. Geological Survey, written commun., 1995-1996)												
26	*LB,c*	0	0	3.5	1.0	.27	6.8	.55	4.3	3.6	7.5	6.9
	CW,c	4.9	5.6									
	CW,c	3.4	4.5									
27	*LB,c*	3.4	0	3.7	1.0	.30	7.7	.82	0	0	0	0
	CW,c	2.2	1.1									
	CW,c	.7	1.1									
28	*LB,c*	25.9	15.8	7.4	2.0	.22	28.8	.55	(12.4)	7.7	(31.6)	14.2
	CW,c	(7.7)	(11.1)									
	CW,c	(20.9)	(25.7)									
29	*LB,c*	12.6	13.7	2.5	1.0	.81	6.1	.55	(3.0)	(3.9)	(13.7)	(11.5)
	CW,c	1.1	0									
	CW,c	.6	1.4									
30	*LB,ab*	(0)	(.6)	2.0	1.0	.21	3.8	--	0	0	0	0
31	*LB,ab*	2.4	2.9	6.0	1.0	.33	10.6	--	0	0	0	0
32	*LB,ab*	2.7	2.1	2.0	1.0	.19	3.4	.55	1.6	5.8	4.9	14.1
33	*LB,c*	0	0	3.5	1.0	.32	8.8	.55	7.3	(6.2)	18.5	(24.4)
	CW,c	25.7	21.3									
	CW,c	0	0									
34	*LB,c*	13.6	10.5	4.7	1.0	.19	9.4	.55	3.7	(12.5)	11.6	(48.9)
	CW,c	6.2	8.2									
	CW,c	6.4	7.8									

Table 5. Summary of Level 2 bridge scour investigation data used in the study (Continued)

Site no.	Bridge site name and location	Bridge structure identification number	Bridge length (ft)	Bridge-opening type	Flow class through bridge	Drainage area (mi²)	Main channel slope (ft/mi)	Q_{100} (ft³/s)	Q_{brg} (ft³/s)	D_{50} (mm)	Predominant streambed material
Data from Indiana USGS (Mueller and others, 1994; D.S. Mueller, U.S. Geological Survey, written commun., 1995-1996)--continued											
35	[5]Whitewater River at Interstate 74 near Harrison, Ohio	I-74-170-4684A and 4684JA	968	3	1	1,344	5.3	62,200	62,200	.50	Coarse sand
Data from Iowa USGS (Fischer, 1995; E.E. Fischer, U.S. Geological Survey, written commun., 1995-1996)											
36	Maple River at State Highway 175 near Mapleton, Iowa	036911	241	1	3	669	4.8	26,200	26,200	.39	Medium sand
37	Middle Raccoon River at State Highway 25 near Bayard, Iowa	026131	240	1	3	375	4.2	18,800	18,800	.34	Medium sand
38	Nodaway River at Clarinda, Iowa	--	312	1	3	762	2.1	42,700	42,700	.34	Medium sand
39	Platte River near Diagonal, Iowa	--	178	4	3	217	3.1	10,000	[1]9,800	.47	Medium sand
40	West Nishnabotna River at State Highway 184 near Randolph, Iowa	025531	383	4	3	609	2.2	49,500	[1]32,600	.41	Medium sand
Data from Mississippi USGS (W.T. Baldwin, U.S. Geological Survey, written commun., 1995-1996)											
41	Allbritton Creek at U.S. Interstate Highway 55 near Norfield, Miss.	26.4 A and B	160	3	1	5.52	15.0	2,880	2,880	.34	Medium sand
42	Bahala Creek at State Highway 27 near Oma, Miss.	55.5	560	3	1	150	3.5	23,800	23,800	.88	Coarse sand
43	Buffalo River at State Highway 563 at Wilkinson, Miss.	7.2	700	3	4	142	4.6	54,200	51,700	.30	Medium sand
44	Hays Creek at State Highway 407 at Winona, Miss.	39.3	186	3	1	25.1	7.3	13,000	13,000	.30	Medium sand
45	Tonacana Creek at U.S. Highway 80 at Chunky, Miss.	121.4	98	3	1	8.65	15.0	3,640	3,640	.34	Medium sand
Data from Missouri USGS (R.J. Huizinga, U.S. Geological Survey, written commun., 1995-1996)											
46	Honey Creek at State Route 81 in Clark County, Mo.	A-2497	145	3	1	21.4	4.5	5,600	5,600	.13	Fine sand
47	Platte River at U.S. Route 136 in Nodaway County, Mo.	J-376	445	3	1	486	3.8	33,200	33,200	16	Coarse gravel
48	South Wyaconda River at U.S. Route 136 in Scotland County, Mo.-- main bridge	J-780	220	3	1	106	3.8	13,800	[6]12,803	.57	Coarse sand
48	Do -- relief bridge	J-780	135	2	1	106	3.8	13,800	[6]997	.57	Coarse sand

Data from Level 2 bridge-scour investigations												
	Contraction-scour variables			Pier-scour variables				Abutment-scour variables				
Site no.	Scour type	χ (ft)	Contraction scour (ft)	Pier width, a (ft)	K_2	F_2	Pier scour (ft)	K_1	y_{aLT} (ft)	y_{aRT} (ft)	Left abutment scour (ft)	Right abutment scour (ft)
Data from Indiana USGS (Mueller and others, 1994; D.S. Mueller, U.S. Geological Survey, written commun., 1995-1996)--continued												
35	*LB,c*	4.7	4.9	4.0	1.0	.37	8.8	.55	(4.6)	0	(29.3)	0
	CW,c	(0)	(1.7)									
	CW,c	5.8	7.0									
Data from Iowa USGS (Fischer, 1995; E.E. Fischer, U.S. Geological Survey, written commun., 1995-1996)												
36	*LB,ab*	8.3	5.4	3.0	1.0	.42	8.8	.55	(5.6)	(2.0)	(14.0)	(15.8)
37	*LB,ab*	5.9	2.1	3.0	1.3	.35	10.5	.55	(5.7)	(6.8)	(11.9)	(14.1)
38	*LB,ab*	6.0	4.1	4.0	2.0	.38	22.6	.55	(3.1)	(4.1)	(12.5)	(15.5)
39	*LB,ab*	13.9	6.5	1.3	1.0	.23	4.2	.55	(1.3)	(2.7)	(8.6)	(15.0)
40	*LB,ab*	7.7	0	3.0	1.0	.33	8.5	.55	(0)	(0)	(0)	(0)
Data from Mississippi USGS (W.T. Baldwin, U.S. Geological Survey, written commun., 1995-1996)												
41	*LB,c*	6.3	3.3	1.2	1.0	.32	2.9	.55	3.5	3.6	8.2	8.5
	CW,c	1.0	1.2									
	CW,c	1.2	1.3									
42	*LB,c*	14.0	7.8	4.0	1.0	.33	8.5	.55	7.9	0.0	11.1	0
	CW,c	0	0									
	CW,c	0	0									
43	*LB,c*	0	0	5.0	1.0	.42	12.5	.55	4.3	4.8	3.0	0
	CW,c	0	0									
	CW,c	3.6	3.1									
44	*LB,c*	4.0	1.4	2.5	1.0	.31	8.0	.55	2.9	2.7	5.5	5.2
	CW,c	0	0									
	CW,c	0	0									
45	*LB,c*	4.0	3.2	2.0	1.2	.39	7.2	.55	3.2	2.4	8.0	6.2
	CW,c	1.0	1.3									
	CW,c	2.5	2.3									
Data from Missouri USGS (R.J. Huizinga, U.S. Geological Survey, written commun., 1995-1996)												
46	*LB,ab*	45.6	27.1	1.0	2.0	.64	9.1	.55	4.8	3.0	11.1	10.4
47	*LB,c*	16.7	10.8	5.5	1.4	.33	20.2	.55	28.4	4.7	34.0	8.2
	CW,c	.3	0									
	CW,c	3.4	5.1									
48	*LB,ab*	14.6	12.9	6.0	1.1	.23	12.3	.55	4.8	4.1	11.8	9.2
48	*CW,d*	--	2.7	1.5	2.0	.51	5.9	.82	.5	.6	2.6	2.5

Table 5. Summary of Level 2 bridge scour investigation data used in the study (Continued)

Site no.	Bridge site name and location	Bridge structure identification number	Bridge length (ft)	Bridge-opening type	Flow class through bridge	Drainage area (mi^2)	Main channel slope (ft/mi)	Q_{100} (ft^3/s)	Q_{brg} (ft^3/s)	D_{50} (mm)	Predominant streambed material
	Data from Missouri USGS (R.J. Huizinga, U.S. Geological Survey, written commun., 1995-1996)--continued										
49	West Fork Grand River at State Route 46 in Worth County, Mo.	J-795	288	3	1	229	4.4	25,100	25,100	.13	Fine sand
	Data from Montana USGS										
50	Badger Creek at U.S. 89, 15 mile southeast of Browning, Mont.	P00003096+05771	303	3	4	239	20.5	13,000	5,666	8	Medium gravel
51	Beaver Creek at U.S. 2, 6 miles west of Saco, Mont.	P00001492+07001	148	3	1	1,327	.26	13,500	[7]6,750	--	Fine sand/silt
52	Beaver Creek overflow at U.S. 2, 7 miles west of Saco, Mont.	P00001491+08241	89	3	2	1,327	.05	13,500	[7]4,570	[8]180	Grassland flood plain
53	Beaver Creek overflow at U.S. 2, 9 miles west of Saco, Mont.	P00001490+05771	88	3	1	1,327	.53	13,500	[7]2,180	[8]180	Grassland flood plain
54	Big Timber Creek at U.S. 191, 2 miles north of Big Timber, Mont.	P00045001+07641	126	3	4	119	37.0	5,750	5,340	5	Fine gravel
55	Bitterroot River at U.S. 12 near Missoula, Mont.	P00007090+01161 and 62	344	3	1	2,842	13.7	31,800	31,800	--	Coarse sand to medium gravel
56	Boulder River at S 69 at Boulder, Mont.	P00069037+02861	105	3	1	346	13.7	4,440	4,400	73	Small cobbles
57	Boulder Creek at State Route 1, near Maxville, Mont.	P00019049+00211	77	3	2	71.3	125.3	1,350	1,350	60	Very coarse gravel
58	Cherry Creek at U.S. 2, 1 mile north of Glasgow, Mont.	P00001540+03401	113	3	4	146	6.9	6,570	4,100	--	Silty, clayey gravel
59	Clark Fork at U.S. 12 at Missoula, Mont.	P00007095+00581	571	3	1	6,084	5.8	43,100	43,100	--	Gravel
60	Clarks Fork Yellowstone River at U.S. 310, 2 miles south of Bridger, Mont.	P00004023+07461	288	3	1	1,809	37.0	13,800	13,800	39	Very coarse gravel
61	Cutbank Creek at U.S. 2 at Cut Bank, Mont.	P00001254+01521	263	3	1	1,065	16.9	15,900	15,900	9	Medium gravel
62	Dearborn River at State Route 200, 25 miles southwest of Simms, Mont.	P00024102+05011	177	3	1	235	26.4	12,100	12,100	2	Very fine gravel
63	East Rosebud River at State Route 78, 6 miles south of Absarokee, Mont.	P00078026+02021	151	3	1	145	51.2	4,210	4,210	58	Very coarse gravel

Data from Level 2 bridge-scour investigations												
	Contraction-scour variables			Pier-scour variables				Abutment-scour variables				
Site no.	Scour type	χ (ft)	Contraction scour (ft)	Pier width, *a* (ft)	K_2	F_2	Pier scour (ft)	K_1	y_{aLT} (ft)	y_{aRT} (ft)	Left abutment scour (ft)	Right abutment scour (ft)
Data from Missouri USGS (R.J. Huizinga, U.S. Geological Survey, written commun., 1995-1996)--continued												
49	*LB,ab*	13.7	6.8	5.0	1.9	.41	26.3	.55	(18.4)	8.1	(36.4)	13.5
Data from Montana USGS												
50	*LB,ab*	6.7	0	3.5	1.0	.42	6.7	.55	2.9	3.5	7.2	8.7
51	*LB,ab*	7.8	2.8	3.0	1.0	.49	6.9	.55	2.6	3.2	6.6	7.0
52	*CW,ab*	--	0	2.0	1.0	.49	5.6	.55	5.3	5.1	0	0
53	*CW,ab*	--	0	2.0	1.0	.60	4.7	.55	3.8	4.0	0	0
54	*LB,ab*	10.1	6.5	2.0	1.0	.72	6.3	.55	4.1	4.2	5.9	10.2
55	*LB,ab*	0	0	4.0	1.0	.41	9.0	.55	0	0	0	0
56	*LB,ab*	8.2	3.9	2.0	1.8	.89	11.1	.55	1.3	1.1	2.9	3.6
57	*CW,ab*	--	0	--	--	--	--	.55	0	.4	0	1.9
58	*LB,ab*	0	0	2.0	1.0	.56	5.4	.55	0	2.7	0	7.3
59	*LB,ab*	.2	0	3.7	1.7	.35	16.8	.55	0	0	0	0
60	*CW,ab*	--	0	4.4	1.5	.90	14.8	.55	0	1.1	0	3.2
61	*LB,ab*	5.9	4.2	5.5	1.7	.65	24.4	.55	4.8	6.0	11.1	14.6
62	*LB,ab*	10.0	5.7	3.0	3.3	.77	31.5	.55	10.2	0	21.5	0
63	*LB,ab*	.2	0	3.0	1.2	.78	9.9	.55	0	0	0	0

Table 5. Summary of Level 2 bridge scour investigation data used in the study (Continued)

Site no.	Bridge site name and location	Bridge structure identification number	Bridge length (ft)	Bridge-opening type	Flow class through bridge	Drainage area (mi^2)	Main channel slope (ft/mi)	Q_{100} (ft^3/s)	Q_{brg} (ft^3/s)	D_{50} (mm)	Predominant streambed material
	Data from Montana USGS--continued										
64	Gallatin River at U.S. 191, 5 miles south of Gallatin Gateway, Mont.	P00050070+04611	252	3	1	825	33.5	10,700	10,700	95	Small cobbles
65	Indian Creek at U.S. 287, 7 miles south of Cameron, Mont.	P00013030+08711	81	3	1	65.3	47.7	1,820	1,820	135	Large cobbles
66	Jefferson River at U.S. 10, 2 miles west of Three Forks, Mont.	P00013093+06931	246	3	4	9,532	14.8	23,600	23,350	19	Coarse gravel
67	Lang Creek at U.S. 2, 19 miles southwest of Marion, Mont.	P00001080+04821	35	3	1	7.09	45.4	149	149	--	Fine sand to coarse gravel
68	Little Blackfoot River at U.S. 12 and Burlington Northern Railroad, 5 miles east of Garrison, Mont.	P00008006+02301	303	3	1	398	27.4	6,170	6,170	26	Coarse gravel
69	Little Blackfoot River at U.S. 12 near Garrison, Mont.	P00088001+00271	138	3	4	407	34.3	6,580	4,900	4	Fine gravel
70	Pole Creek at U.S. 12, 3 miles southwest of Roundup, Mont.	P00014165+07861	71	3	1	389	22.7	4,800	[1]3,700	2	Very fine gravel
71	Prickly Pear Creek at U.S. 12, near East Helena, Mont.	P00008049+03341	74	3	1	251	34.3	2,160	2,160	5	Fine gravel
72	Sage Creek at U.S. 2, near Gildford, Mont.	P00001353+08951	116	3	4	701	2.7	9,820	8,730	.09	Very fine sand
73	Sandstone Creek at U.S. 12, near Plevna, Mont.	P00002070+07611	129	3	1	149	10.4	4,350	4,350	.15	Fine sand
74	Spring Creek at State Route 35 1 mile east of Kalispell, Mont.	P00052050+04871	94	3	1	36.9	13.8	414	414	17	Coarse gravel
75	Sweetgrass Creek at U.S. 191, 2 miles south of Melville, Mont.	P00045018+02631	184	3	1	89.0	22.2	3,420	3,420	4.5	Fine gravel
76	Tenmile Creek at U.S. 12, 5 miles west of Helena, Mont.	P00008036+09441	100	[3]--	4	83.3	58.1	2,130	1,820	50	Very coarse gravel
77	Tule Creek at U.S. 2, 10 miles east of Wolf Point, Mont.	P00001601+03641	116	3	1	144	5.8	6,650	6,650	.10	Very fine sand
78	West Fork Willow Creek at U.S. 2, 2 miles east of Devon, Mont.	P00001300+01071	55	3	4	226	6.3	4,740	[1]2,050	.15	Fine sand

Data from Level 2 bridge-scour investigations												
	Contraction-scour variables			Pier-scour variables				Abutment-scour variables				
Site no.	Scour type	χ (ft)	Contraction scour (ft)	Pier width, *a* (ft)	K_2	F_2	Pier scour (ft)	K_1	y_{aLT} (ft)	y_{aRT} (ft)	Left abutment scour (ft)	Right abutment scour (ft)
Data from Montana USGS--continued												
64	*CW,ab*	--	0	4.0	1.3	.77	12.2	.55	2.4	0	5.8	0
65	*CW,ab*	--	0	1.5	1.0	.49	4.5	.55	2.0	3.2	4.6	0
66	*LB,ab*	1.0	.7	3.5	1.0	.70	9.0	.55	0	3.5	0	11.9
67	*LB,ab*	.7	.4	1.0	1.0	.65	2.3	.55	0	0	0	0
68	*LB,ab*	1.8	0	3.0	1.7	.41	11.5	.55	2.8	0	0	0
69	*LB,ab*	1.6	1.4	3.0	1.0	.44	6.1	.55	1.5	2.4	0	5.3
70	*LB,ab*	10.9	6.0	2.8	1.0	.35	7.5	.55	3.1	2.8	6.5	6.1
71	*LB,ab*	2.7	1.4	--	--	--	--	.55	0	0	0	0
72	*LB,ab*	54.4	36.2	3.0	3.8	.43	29.9	.55	7.2	7.1	13.4	10.0
73	*LB,ab*	2.9	2.8	3.0	1.2	.40	8.4	.55	2.0	4.3	3.2	12.5
74	*CW,ab*	--	0	3.0	1.0	.22	4.3	.55	.5	1.2	1.0	3.1
75	*LB,ab*	3.7	3.0	3.0	2.5	.41	16.7	.55	2.5	2.2	4.9	5.1
76	*CW,ab*	--	0	--	--	--	--	.55	1.3	.6	3.0	1.8
77	*LB,ab*	15.1	11.1	2.8	1.0	.50	7.0	.55	2.4	2.7	5.7	6.3
78	*LB,ab*	4.3	3.2	1.0	1.0	.46	3.4	.55	3.2	2.1	6.3	5.4

Table 5. Summary of Level 2 bridge scour investigation data used in the study (Continued)

Site no.	Bridge site name and location	Bridge structure identification number	Bridge length (ft)	Bridge-opening type	Flow class through bridge	Drainage area (mi^2)	Main channel slope (ft/mi)	Q_{100} (ft^3/s)	Q_{brg} (ft^3/s)	D_{50} (mm)	Predominant streambed material
					Data from Montana USGS--continued						
79	Whitefish River at U.S. 93 at Whitefish, Mont.	P00005128+00531	171	3	1	126	1.1	1,290	1,290	--	Clay to very fine sand
80	Yellowstone River at U.S. 89, 11 miles southwest of Emigrant, Mont.	P00011020+04171	450	3	1	2,810	11.6	31,900	31,900	73	Small cobbles
81	Yellowstone River at State Route 23, 2 miles south of Sydney, Mont.	P00026001+02341	1,244	3	1	69,103	.50	154,600	154,600	--	Silt
	Data from Montana MDT (D.R. McIntyre and M.A. Goodman, Montana Department of Transportation, written commun., 1995-1996)										
82	Assiniboine Creek at MT 242, 6 miles north of Malta, Mont.	S00242006+0.0	114	1	1	119	21.1	4,200	4,200	--	--
83	Beaverhead River near Barretts, Mont.	BR9001(15)	97	3	1	2,737	16.9	3,100	3,100	--	Sand to gravel
84	Big Hole River at county road west of Melrose, Mont.	BR9047(13)	210	3	1	2,476	16.9	16,524	[6]4,000	--	Gravel
85	Clark Fork at State Route 200 near Paradise, Mont.	P00006082+0.759	986	3	1	19,958	1.2	142,310	142,310	--	Sand to medium gravel
86	Clarks Fork Yellowstone River 1 mile east of Silesia, Mont.	L05304005+0.0	236	3	1	2,731	10.6	14,130	14,130	--	--
87	Judith River 6 miles northwest of Moore, Mont.	L14303007+0.7	74	3	1	533	16.9	2,250	2,250	--	--
88	Little Bighorn River 11 miles southwest of Wyola, Mont.	L02202012+0.2	86	3	1	221	35.9	3,200	3,200	--	--
89	Little Bighorn River 3 miles southwest of Wyola, Mont.	L02269000+0.1	102	3	4	270	26.4	3,620	2,780	--	Gravel
90	Madison River - Montana Rail Link at Interstate 90, 1 mile east of Three Forks, Mont.	I00090278+0.857	336	2	1	2,551	4.8	10,700	10,700	--	Silty sand
91	Milk River 1 mile north of Lohman, Mont.	BR9003(16)	184	3	4	6,166	2.1	17,000	10,600	--	Silt/sand
92	Mill Coulee near Sun River, Mont.	F24-4(11)138	60	3	1	23.1	23.8	2,330	2,330	--	Sand/gravel
93	Missouri River 8 miles southeast of Wolf Point, Mont.	P00025045+0.0	600	3	1	82,290	2.6	53,400	53,400	--	--

Data from Level 2 bridge-scour investigations													
	Contraction-scour variables			Pier-scour variables				Abutment-scour variables					
Site no.	Scour type	χ (ft)	Contraction scour (ft)	Pier width, a (ft)	K_2	F_2	Pier scour (ft)	K_1	y_{aLT} (ft)	y_{aRT} (ft)	Left abutment scour (ft)	Right abutment scour (ft)
Data from Montana USGS--continued												
79	*LB,ab*	1.1	.7	2.0	1.0	.08	2.9	.55	0	0	0	0
80	*CW,ab*	--	0	3.0	1.0	.59	7.8	.55	0	.9	0	2.5
81	*LB,ab*	9.5	9.1	9.0	2.4	.34	47.8	.55	7.4	0	19.3	0
Data from Montana MDT (D.R. McIntyre,and M.A. Goodman, Montana Department of Transportation, written commun., 1995-1996)												
82	*LB,ab*	5.5	5.0	2.0	1.0	.71	5.0	1.00	2.4	2.5	6.0	6.7
83	*LB,ab*	1.3	1.0	1.3	1.0	.75	3.0	.55	0	0	0	0
84	*LB,ab*	.1	.1	3.0	2.3	.46	12.0	.55	0	.6	0	0
85	*LB,ab*	12.5	7.5	10.0	1.7	.29	29.0	.55	0	0	0	0
86	*LB,ab*	.6	1.0	3.5	1.0	.40	8.0	.55	2.9	2.7	8.0	11.0
87	*LB,ab*	2.3	1.0	1.3	1.0	.95	4.0	.55	3.1	1.8	5.0	3.0
88	*LB,ab*	1.3	1.0	--	--	--	--	.55	0	5.3	0	13.0
89	*LB,ab*	7.1	2.8	--	--	--	--	.55	1.9	3.3	5.5	11.3
90	*LB,ab*	3.2	3.0	5.0	1.0	.42	11.0	.55	0	0	0	0
91	*LB,ab*	16.5	1.6	3.0	1.0	.21	6.4	.55	2.9	4.2	7.0	9.8
92	*LB,ab*	23.2	11.2	--	--	--	--	.55	3.9	4.3	8.2	8.9
93	*LB,ab*	.4	0	4.0	1.0	.43	9.0	.55	0	4.2	0	3.0

Table 5. Summary of Level 2 bridge scour investigation data used in the study (Continued)

Site no.	Bridge site name and location	Bridge structure identification number	Bridge length (ft)	Bridge-opening type	Flow class through bridge	Drainage area (mi^2)	Main channel slope (ft/mi)	Q_{100} (ft^3/s)	Q_{brg} (ft^3/s)	D_{50} (mm)	Predominant streambed material
Data from Montana MDT (D.R. McIntyre and M.A. Goodman, Montana Department of Transportation, written commun., 1995-1996)--continued											
94	Musselshell River on NH 16, 2 miles southwest of Roundup, Mont.	P00016047+0.55	273	3	1	4,023	3.5	12,500	12,500	--	--
95	North Fork Canyon Creek on STPS 401, 8 miles northwest of Laurel, Mont.	S00401001+0.468	72	3	1	12.7	52.8	779	779	--	--
96	O'Fallon Creek 20 miles northwest of Ekalaka, Mont.	BR9006(5)	71	3	6	118	7.4	4,255	2,325	--	--
97	South Fork Smith River south of White Sulphur Springs, Mont.	P00014033+0.554	66	3	1	75	6.9	1,625	1,625	--	Sandy clay
98	Teton River southwest of Collins, Mont.	BR9050(5)	134	3	4	813	4.8	22,380	13,342	--	Silty sand to gravel
99	Timber Creek 2 miles east of Powderville, Mont.	Off System	127.5	3	2	132	3.2	3,925	3,925	--	Silt to silty clay
100	Warm Springs Creek - Cedar Street in Anaconda, Mont.	BR9012(5)	59.5	3	5	162	58.1	1,430	1,216	--	Silty sand to gravel
Data from New Mexico USGS (S.D. Waltemeyer, U.S. Geological Survey, written commun., 1995)											
101	Cuchillo Negro at Interstate 25 at Truth or Consequences, N.M.	--	520	3	1	[9]341.6	51.3	6,290	6,290	4.6	Fine gravel
102	Manuelito Canyon at Interstate 40 near Manuelito, N.M.	--	170	3	1	78.4	31.7	13,900	13,900	--	Mostly sand and silt
103	Tesuque River at U.S. 285 at Tesuque, N.M.	--	198	3	1	33.4	264	5,935	5,935	--	Sand and silt
104	Unnamed Tributary to Lordsburg Draw at Interstate 10 near Lordsburg, N.M.	--	210	3	1	678	47.5	21,300	[1]18,000	--	Silt/clay
Data from South Carolina USGS (S.T. Benedict, U.S. Geological Survey, written commun., 1995-1996)											
105	Big Swamp at Route 51 in Florence County, S.C.	214005100200	100	3	1	16.6	4.3	1,710	1,710	.21	Fine sand
106	Cypress Creek at Route 3 in Jasper County, S.C.	274000300200	210	3	1	53.0	4.9	3,350	3,350	.17	Fine sand
107	Eighteen Mile Creek at Route 229 in Anderson County, S.C.	047022900100	150	3	1	47.0	7.4	5,360	5,360	.76	Coarse sand

Data from Level 2 bridge-scour investigations												
	Contraction-scour variables			Pier-scour variables				Abutment-scour variables				
Site no.	Scour type	χ (ft)	Contraction scour (ft)	Pier width, a (ft)	K_2	F_2	Pier scour (ft)	K_1	y_{aLT} (ft)	y_{aRT} (ft)	Left abutment scour (ft)	Right abutment scour (ft)
Data from Montana MDT (D.R. McIntyre and M.A. Goodman, Montana Department of Transportation, written commun., 1995-1996)--continued												
94	*LB,ab*	6.9	5.0	1.3	1.0	.35	4.0	.55	4.2	5.6	9.0	11.0
95	*LB,ab*	1.5	2.0	--	--	--	--	.55	0	.7	0	1.0
96	*LB,ab*	14.4	12.0	--	--	--	--	.55	8.3	8.8	14.0	15.0
97	*LB,ab*	4.0	4.3	--	--	--	--	.55	2.9	1.8	8.8	4.4
98	*LB,ab*	22.4	12.6	4.0	1.0	.28	9.0	.55	4.6	5.1	12.4	13.4
99	*LB,ab*	(9.5)	(15.0)	2.0	1.0	.41	4.0	.55	6.4	5.8	13.0	10.0
100	*LB,ab*	.6	0	1.7	1.0	.72	2.3	.55	0	0	0	0
Data from New Mexico USGS (S.D. Waltemeyer, U.S. Geological Survey, written commun., 1995)												
101	*LB,ab*	1.2	.9	1.2	1.0	.53	3.1	--	(0)	(0)	(0)	(0)
102	*LB,ab*	6.9	6.1	3.0	3.5	.47	28.3	--	(0)	(0)	(0)	(0)
103	*LB,ab*	.9	.6	3.0	2.8	1.16	25.3	--	(0)	(0)	(0)	(0)
104	*LB,ab*	2.9	3.4	3.0	1.0	.95	8.0	1.00	13.5	18.0	11.8	15.8
Data from South Carolina USGS (S.T. Benedict, U.S. Geological Survey, written commun., 1995-1996)												
105	*CW,ab*	--	11.1	1.0	1.0	.31	2.5	.55	4.2	4.2	8.8	9.8
106	*CW,ab*	--	6.6	1.4	1.0	.16	3.1	.55	5.7	5.7	11.5	12.3
107	*LB,c*	.8	.7	1.1	1.0	.42	3.5	.55	2.3	2.0	6.3	6.8
	CW,c	3.5	2.9									
	CW,c	3.5	2.8									

Table 5. Summary of Level 2 bridge scour investigation data used in the study (Continued)

Site no.	Bridge site name and location	Bridge structure identification number	Bridge length (ft)	Bridge-opening type	Flow class through bridge	Drainage area (mi^2)	Main channel slope (ft/mi)	Q_{100} (ft^3/s)	Q_{brg} (ft^3/s)	D_{50} (mm)	Predominant streambed material
Data from South Carolina USGS (S.T. Benedict, U.S. Geological Survey, written commun., 1995-1996)--continued											
108	Ox Swamp at Route 521 in Clarendon County, S.C.	142052100300	175	3	1	32.7	4.0	2,530	2,530	.18	Fine sand
109	South Tyger River at Route 85 in Spartanburg, S.C.	421008530100	320	3	3	96.2	3.5	7,940	7,940	.60	Coarse sand
110	Tools Fork Creek at Route 322 in York County, S.C.	464032200500	150	3	1	13.4	9.0	3,820	3,820	.92	Coarse sand
Data from Texas USGS (D.D. Dunn, U.S. Geological Survey, written commun., 1995-1996)											
111	Brazos River at State Highway 159 near Hempstead, Tex.	--	972	3	1	34,400	6.3	166,500	166,500	.35	Medium sand
112	Colorado River at State Highway 71 near Columbus, Tex.	--	873	3	1	[10]41,640	1.6	114,600	[6]109,926	.50	Coarse sand
113	Guadalupe River at State Highway 80 near Belmont, Tex.	--	1,136	3	1	2,036	1.1	60,300	60,300	.22	Fine sand
114	Guadalupe River at U.S. 183 near Hochheim, Tex.	--	758	3	[4]4	4,094	2.6	152,000	83,240	.60	Coarse sand
115	Trinity River at State Highway 7 near Crockett, Tex.	--	687	3	1	13,911	.5	116,500	[6]74,117	.20	Fine sand
Data from Vermont USGS (J.D. Ayotte and S.A. Olson, U.S. Geological Survey, written commun., 1995-1996)											
116	Ayers Brook at Town Highway 023, Braintree, Vt.	BRAITH00230012	28	1	5	18.8	15.8	1,670	970	3.3	Very fine gravel
117	Black River at Town Highway 005, Irasburg, Vt.	IRASTH00050006	70	1	1	91.1	79	3,530	3,530	171	Large cobbles
118	Black River at Town Highway 008, Irasburg, Vt.	IRASTH00080020	88	1	1	110	11	3,800	3,800	35	Very coarse gravel
119	North Bridgewater Brook at Town Highway 018, Woodstock, Vt.	WODSTH00180022	40	1	1	4.34	180	1,100	1,100	44	Very coarse gravel
120	Ompompanoosuc River at Town Highway 003 (VT132), Norwich, Vt.	NORWTH00030046	100	1	1	135	15.8	2,600	2,600	.50	Coarse sand
121	Second Branch White River at Town Highway 066, Randolph, Vt.	RANDTH00660034	57	1	6	51.3	10	7,660	3,490	.67	Coarse sand

Site no.	Scour type	χ (ft)	Contraction scour (ft)	Pier width, a (ft)	K_2	F_2	Pier scour (ft)	K_1	y_{aLT} (ft)	y_{aRT} (ft)	Left abutment scour (ft)	Right abutment scour (ft)
Data from Level 2 bridge-scour investigations												
Contraction-scour variables				Pier-scour variables				Abutment-scour variables				
Data from South Carolina USGS (S.T. Benedict, U.S. Geological Survey, written commun., 1995-1996)--continued												
108	*CW,ab*	--	6.9	2.0	1.0	.20	4.0	.55	5.4	5.4	11.1	10.8
109	*LB,c*	(.4)	(2.8)	1.7	1.0	.18	3.8	.55	0	10.7	0	21.3
	CW,c	1.1	2.1									
	CW,c	0	0									
110	*CW,c*	9.0	7.8	2.3	1.3	.28	6.2	.55	5.1	6.7	8.7	15.4
	CW,c	3.9	4.4									
	CW,c	(4.6)	(7.7)									
Data from Texas USGS (D.D. Dunn, U.S. Geological Survey, written commun., 1995-1996)												
111	*LB,c*	0	0	6.0	2.5	.22	32.7	.55	(0)	(0)	(0)	(0)
	CW,c	1.8	2.6									
	CW,c	0	0									
112	*LB,c*	1.9	1.0	2.5	1.0	.19	6.6	[11].55,1.0	9.2	5.8	14.9	9.0
	CW,c	2.5	3.8									
	CW,c	0	0									
113	*LB,c*	5.6	5.4	2.5	1.1	.20	7.4	.55	10.8	0	19.4	0
	CW,c	12.2	14.4									
	CW,c	4.4	5.6									
114	*LB,c*	(3.6)	(5.5)	3.0	1.0	.28	7.7	.55	12.1	11.2	18.5	18.2
	CW,c	0	0									
	CW,c	(.1)	(6.7)									
115	*LB,c*	39.7	8.8	4.0	1.0	.12	8.0	.55	7.4	3.6	11.2	4.4
	CW,c	0	0									
	CW,c	0	0									
Data from Vermont USGS (J.D. Ayotte and S.A. Olson, U.S. Geological Survey, written commun., 1995-1996)												
116	*CW,ab*	--	5.4	--	--	--	--	[11]1.0,.82	1.8	4.8	6.5	15.2
117	*CW,ab*	--	0	--	--	--	--	.82	2.5	4.1	11.5	14.4
118	*CW,ab*	--	0	--	--	--	--	[11]1.0,.82	4.4	4.2	15.9	12.7
119	*LB,ab*	1.0	.6	--	--	--	--	.82	2.2	2.6	5.3	5.6
120	*LB,ab*	2.9	2.2	4.5	1.7	.57	13.0	.82	.9	3.8	3.1	9.7
121	*LB,ab*	22.4	8.0	--	--	--	--	[11].82,1.0	2.7	3.9	11.2	17.2

Table 5. Summary of Level 2 bridge scour investigation data used in the study (Continued)

Site no.	Bridge site name and location	Bridge structure identification number	Bridge length (ft)	Bridge-opening type	Flow class through bridge	Drainage area (mi²)	Main channel slope (ft/mi)	Q_{100} (ft³/s)	Q_{brg} (ft³/s)	D_{50} (mm)	Predominant streambed material
	Data from Vermont USGS (J.D. Ayotte and S.A. Olson, U.S. Geological Survey, written commun., 1995-1996)--continued										
122	Second Branch White River at Town Highway 073, Randolph, Vt.	RANDTH00730039	42	1	6	53.7	50.4	7,910	2,407	.44	Medium sand

[1]Because methods for analyzing scour resulting from pressure-flow conditions were unavailable when the site was investigated, discharge was limited to maximum discharge for free-surface flow conditions.

[2]Site is in Colorado, but reference location is in Wyoming.

[3]Because the bridge does not contract the flow, bridge section was analyzed as a non-bridge open-channel flow section in the WSPRO water-surface profile analysis.

[4]Water-surface profile analysis was performed using the "composite-section method" (Shearman and others, 1986, p. 39-40) with WSPRO. Flow class was free-surface flow through the bridge and may also include flow through a relief bridge, or over a road, or both for the given site.

[5]Site is in Indiana, but reference location is in Ohio.

[6]Portion of the 100-year discharge conveyed through the indicated bridge and the remainder was conveyed by one or more other nearby bridges.

[7]Values equal the portion of the 100-year peak discharge conveyed through the indicated bridge, with the combined discharges of sites 51, 52, and 53 equalling the 100-year discharge.

[8]While the channel upstream and downstream of the bridge is characterized as grassland flood plain, the channel within the bridge opening is comprised of randomly placed riprap having a D_{50} as indicated.

[9]Total drainage area includes 325 mi² regulated by Cuchillo Negro Dam, N.M., and 16.6 mi² unregulated below dam.

[10]Although drainage area is 41,640 mi², about 11,403 mi² probably are non-contributing.

[11]Values indicate coefficients for left and right abutments, respectively.

Data from Level 2 bridge-scour investigations												
	Contraction-scour variables			Pier-scour variables				Abutment-scour variables				
Site no.	Scour type	χ (ft)	Contraction scour (ft)	Pier width, *a* (ft)	K_2	F_2	Pier scour (ft)	K_1	y_{aLT} (ft)	y_{aRT} (ft)	Left abutment scour (ft)	Right abutment scour (ft)
Data from Vermont USGS (J.D. Ayotte, and S.A. Olson, U.S. Geological Survey, written commun., 1995-1996)--continued												
122	*LB,ab*	28.0	3.3	--	--	--	--	.82	1.4	5.2	6.6	19.7