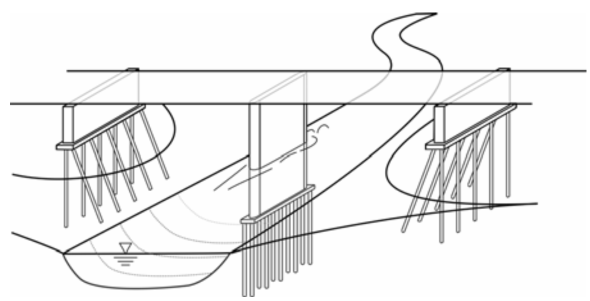
AN ILLUSTRATED GUIDE FOR MONITORING AND PROTECTING BRIDGE WATERWAYS AGAINST SCOUR

Iowa Highway Research Board
Project TR-515
Final Report



IIHR Technical Report No. 449

Prepared for:
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March 2006

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SUMMARY

This report is a well illustrated and practical Guide intended to aid engineers and engineering technicians in monitoring, maintaining, and protecting bridge waterways so as to mitigate or prevent scour from adversely affecting the structural performance of bridge abutments, piers, and approach road embankments. Described and illustrated here are the scour processes affecting the stability of these components of bridge waterways. Also described and illustrated are methods for monitoring waterways, and the various methods for repairing scour damage and protecting bridge waterways against scour.

The Guide focuses on smaller bridges, especially those in Iowa. Scour processes at small bridges are complicated by the close proximity of abutments, piers, and waterway banks, such that scour processes interact in ways difficult to predict and for which reliable design relationships do not exist. Additionally, blockage by woody debris or by ice, along with changes in approach channel alignment, can have greater effects on pier and abutment scour for smaller bridges. These considerations tend to cause greater reliance on monitoring for smaller bridges.

The Guide is intended to augment and support, as a source of information, existing procedures for monitoring bridge waterways. It also may prompt some adjustments of existing forms and reports used for bridge monitoring. In accord with increasing emphasis on effective management of public facilities like bridges, the Guide ventures to include an example report format for quantitative risk assessment applied to bridge waterways. Quantitative risk assessment is useful when many bridges have to be evaluated for scour risk and damage, and priorities need to be determined for repair and protection work. Such risk assessment aids comparison of bridges at risk.

It is expected that bridge inspectors will implement the Guide as a concise, handy reference available back at the office. The Guide also likely may be implemented as an educational primer for new inspectors who have yet to become acquainted with waterway scour. Additionally, the Guide may be implemented as a part of process to check whether existing bridge-inspection forms or reports adequately encompass bridge-waterway scour.

ACKNOWLEDGEMENTS

Preparation of the Guide was funded by the Iowa Highway Research Board, as Research Project TR-515.

An Advisory Panel, confirmed by the Board provided advice and recommendations as to the content and format of the Guide. The members of the Panel and their affiliations are listed below:

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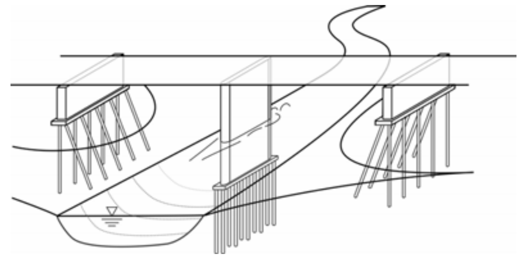


1.1 The Need for Monitoring

The sketch, shown just above, views a bridge in a way not ordinarily seen by the public who use the bridge. It is an important view, one that emphasizes the critical role played by the foundation underpinnings of a bridge. Scour-induced collapse of those underpinnings, however, is a common cause of bridge failure.

Few situations in bridge engineering are potentially more complex, or more in need of monitoring, than are bridge waterways in which bridge foundations are placed. Indeed, an old saying reputedly holds that "person who overlooks water under bridge will find bridge under water." Of concern is scour of the sediments and soils that form the boundaries of bridge waterways. Water flow approaching and passing through the bridge opening, as well as flow immediately downstream of the bridge opening, may erode and remove (scour) these sediment and soils, and, thereby, imperil a bridge.

The need for monitoring increases for smaller bridge-waterways, because the scour processes at waterway components (abutments, piers, channel banks) are complicated by increasing interactions with each other, and thereby, cause scour depths to be estimated inaccurately. Design relationships for scour at piers and abutments typically are derived from laboratory tests of piers and abutments simulated in simplified conditions that do not replicate the complexities of actual bridge sites. To date, laboratory tests have not taken into account the interactions of scour processes occurring at components of a bridge waterway. Therefore, there is on-going need to monitor small bridges to ensure that their foundations and approach embankments are not imperiled by the various scour processes that may occur in bridge waterways.

This Guide considers bridges to be "small" when they span a small river, stream or creek whose watershed upstream of the bridge encompasses about 100 square miles or less. It is common for such bridges to have one, two, or perhaps, three spans. Though the Guide focuses on small bridges, it also addresses the monitoring of bridge waterways generally.

The term “bridge waterway” here encompasses the bridged stream or river bed along with banks and embankments in the vicinity of the bridge. A bridge waterway should include the channel immediately upstream of the bridge opening as well as the channel immediately downstream of the bridge opening. A key assumption is that the waterway length of concern depends on the channel factors influencing flow alignment through the bridge opening. Accordingly, it is important to assess the condition of the channel approach to the bridge, the channel immediately downstream of the bridge, as well as the channel within the bridge waterway.

Figure 1-1 depicts the common features of a bridged waterway, and gives a quick sense of the flow field (including the various levels of flow field) and the boundary-soil complexities involved in a waterway. Besides the natural course of the stream or river, flow passes by the piers and abutments, as well as approach embankments, of a bridge. As indicated, flow may occur at a range of discharges and commensurate water levels.

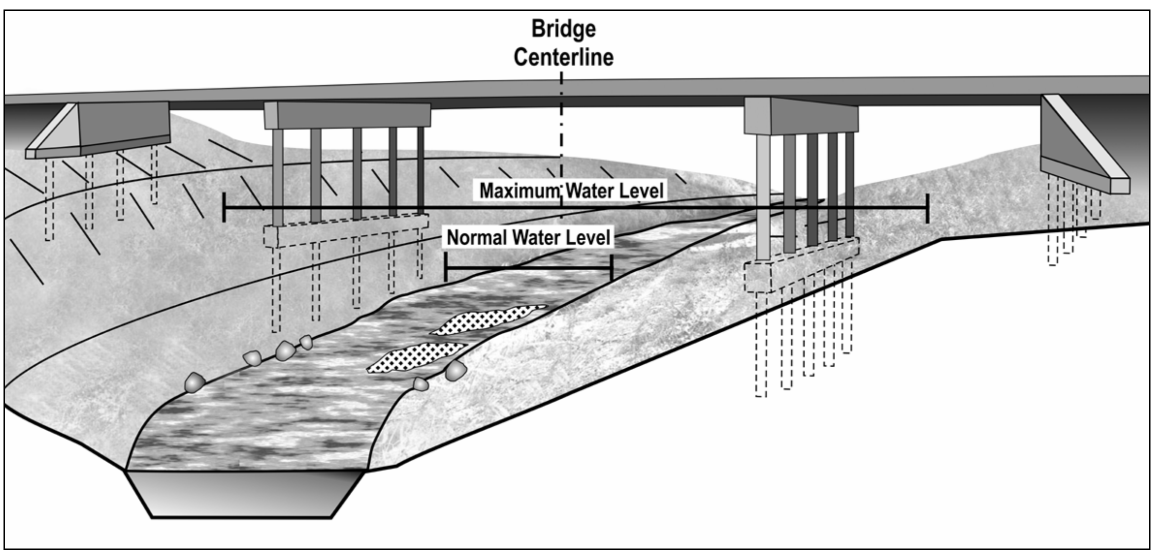


Figure 1-1. A common layout of a bridge over a small stream

The complexities of scour arise from considerations of bridge shape and construction; the variability of flow under local channel conditions over time; the flow field generated at the bridge opening; the diverse sediments and soils bounding the waterway; and, the mix of scour and erosion processes that may occur at bridge sites. The complexities inevitably are difficult, or impracticable, to investigate fully by means of laboratory experiments or computer simulations. Consequently, much reliance has to be placed on the monitoring of waterways at individual bridge sites, and then, necessarily, on protecting those sites against scour, should scour become a threat.

State, county, and city engineering offices expend considerable effort monitoring bridge waterways. Monitoring efforts, like that shown in Figure 1-2, are common. Though each engineering office has its own checklist procedure for waterway monitoring, the incidence of scour failures at small bridges suggests that there are substantial potential benefits in having a well illustrated guide to help bridge-inspection personnel recognize the range of scour situations and processes that can occur at bridge waterways, particularly those at small bridges. The Guide is not intended to replace the existing procedures used by bridge inspection offices, but rather to augment them with illustrations and explanations.

Figure 1-2. Bridge-inspection personnel checking for scour beneath the pile cap of a vertical-wall abutment

1.2 Purpose and Scope of this Guide

This Guide to bridge monitoring is written to provide a well illustrated and practical aid for technicians and engineers monitoring, maintaining, and protecting bridge waterways. Of particular concern is management or mitigation of scour occurring at the components of bridge waterways, especially for bridges in Iowa and surrounding regions. Accordingly, it focuses especially on the bridge conditions (e.g., abutment and pier designs) commonly found in Iowa. Though the Guide Companion is useful for all bridges over waterways, it focuses especially on small and mid-size bridges, such as a typically used for the many smaller rivers and streams in Iowa.

The Guide is intended to provide insightful information, without an overburdening amount of detail, about the flow and erosion processes that may occur at bridges waterways. Specifically, the Guide aims to –

1. Explain scour and erosion processes that may occur at bridge waterways, such as the one depicted in Figure 1-3;
2. Indicate how past, present, and possible future changes in river or stream dynamics may affect bridge-waterway stability;
3. Aid in identifying and prioritizing "at-risk" sites, and thereby avoid potential safety and asset risks;
4. Encourage a rational and consistent approach to evaluation of scour risk; and,
5. Assist in ensuring the repairs or mitigation works related to scour are appropriately applied.

Figure 1-3. Collapse of a road embankment at a small bridge in western Iowa

The term "Guide" is applied in the sense of providing background descriptions about scour processes, things to look for when monitoring bridge waterways, and suggestions on monitoring instrumentation for possible use. The Guide serves to accompany the usual checklist reporting procedure customarily used when monitoring bridge waterways. Nonetheless, this Guide does include (in Appendix C) a reporting format offered as an approach to quantitative risk assessment of scour at bridge waterways. Good management of infrastructure is increasingly reliant on quantitative methods for evaluating priorities for investing in infrastructure maintenance, repair, and upgrade.

This Guide focuses mainly on bridges in Iowa and surrounding states, though it draws illustrations of scour from a broad area. Iowa has about 25,000 bridges, the majority of them spanning a river, stream, creek, or small water-drainage course. It is common for floods of such waterways to result in scour-related bridge damage or even failure. By virtue of there being many more smaller bridges over smaller waterways, the majority of scour-related failures tend, consequently, to involve small bridges, such as those typical of the numerous smaller rivers and streams in Iowa. Not only are small bridges much more numerous than large bridges in Iowa and the Midwest, small bridges may not receive the extensive hydraulic-engineering attention during their design that large bridges commonly receive. Additionally, the variability of local site conditions, and small changes in those conditions, can play a greater role in waterway flow, and thereby more greatly complicate estimation of scour at small bridges. For instance, debris accumulation at a small bridge potentially can pose a major scour concern, as illustrated by Figure 1-4.

Information input was sought from Iowa civil engineers and engineering technicians engaged in bridge monitoring to identify different features in the approach reach of a bridge structure and the structure itself that lead to increased scour at the bridge piers and abutments. That input also was used to define the scope and format for the Guide. A draft of the Guide was reviewed by the members of a Panel of engineers assembled to oversee the preparation of the Guide. The Panel members are mentioned in the Acknowledgement section of the Guide.

So as to be readily available to engineers during field monitoring, the Guide is available also on CD and can be downloaded, in pdf format, from the website of the Iowa Highway Research Board.

Figure 1-4. Debris accumulation at a small bridge results in abutment scour and flooding; Wild Rice River, Minnesota

1.3 Relationship to Inspection Reports or Manuals

The Guide Companion goes with, and elaborates, the manual "Bridge Inspector's Reference Manual," published by the U.S. Federal Highway Administration (FHWA 2002). The FHWA Manual is comprehensive, covering most aspects of all bridges (structural, traffic, as well as waterway). The following features distinguish the Guide from the FHWA Manual: the Guide ~

1. Focuses on monitoring of waterway scour;
2. Provides more complete and accurate descriptions of the scour processes;
3. Introduces more recent instrumentation options for monitoring;
4. Suggests a broader range of scour protection methods; and,
5. Overall, is somewhat more portable than the FHWA Manual.

The Guide also serves to accompany the bridge-inspection reports used by the Iowa DOT, county engineers and city engineers when monitoring bridges. To a certain extent, the Companion partners with the manual recently completed for IHRB Project TR-429, "Evaluation of Appropriate Maintenance, Repair and

Rehabilitation Methods for Iowa Bridges" (Wipf et al. 2003)[1]. Whereas that manual focuses on the superstructure of bridges, the Guide focuses on the condition of the waterway spanned by bridges.

There are numerous existing manuals and procedures for monitoring bridge waterways. Several of them are listed in Section 10.3 of the Guide's Bibliography. No existing manual or procedure is as well illustrated, or contains as much scour-process explanation, as does the present Guide.

The Guide's monitoring procedures apply to common designs of bridges, especially smaller bridges, in Iowa. Accordingly, the drawings shown in the guide are taken to be reasonably representative of bridges in Iowa and surrounding states.

1.4 Monitoring Purposes

There are several specific purposes for waterway monitoring:

1. ***Identify bridge waterway vulnerability or damage***. Waterway monitoring is needed to identify conditions where a pier, abutment, or approach embankment are potentially vulnerable to failure, or already have suffered damage;

2. ***Record existing waterway conditions***. Waterway monitoring is conducted to create a record of the existing channel conditions adjacent to a particular bridge;

3. ***Check for waterway changes***. Current waterway observations and data should be compared to previous observations and data in order to identify channel changes. This "tracking" of channel change over time is a very important monitoring step for ensuring the safety of a bridge; and,

4. ***Select appropriate maintenance or repair actions***. The diagnostic insights from monitoring, along with options for effective maintenance and repair, should facilitate use of the bridge through its full design life.

The present Guide seeks to keep these considerations forefront in the mind of personnel conducting bridge inspections.

[1] Wipf, T.J., Fanous, F.S., Klaiber, F.W., and Eapen, A.S., (2003), "Evaluation of Appropriate Maintenance, Repair and Rehabilitations Methods for Iowa Bridges," Report for Iowa DOT Project 429, Iowa State University, Ames, IA.

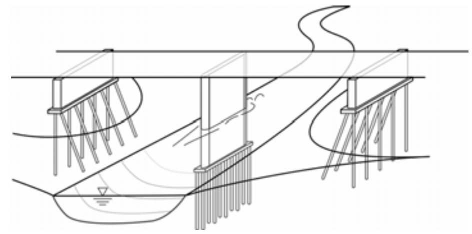
1.5 Implementation of the Guide

In accordance with the Guide's objectives, the following implementation outcomes are –

1. To serve as a concise, well-illustrated reference on scour processes, the sort of reference that gets consulted back at the office. Such a reference is useful for people already conducting inspections of bridge waterways, or for people who are new to bridge-waterway inspection; and,

2. To indicate how existing bridge-inspection forms or reports might be adjusted so as to enhance monitoring for waterway scour. As monitoring technologies evolve, it becomes increasingly feasible to acquire quantitative information about bridge-waterway conditions and to track waterway changes over time.

2
STRUCTURE OF THE GUIDE



2.1 Introduction

To serve as a well illustrated aid for personnel engaged in bridge-waterway monitoring, maintenance, and bridge rehabilitation, this Guide describes and illustrates the following aspects of bridge waterways:

1. The main components of a bridge waterway (*Chapter 3*);
2. River and stream-channel types, along with the variables affecting channel shape and stability (*Chapter 3*);
3. The scour types that may occur at bridge waterways (*Chapter 4 - Appendix A gives illustrative examples of waterway scour and waterway situations prone to scour*);
4. Instrumentation and methods for bridge-waterway monitoring (*Chapter 5*);
5. Options for protecting and repairing bridge waterways in response to scour (*Chapter 6 - Appendix B gives illustrative examples of actions taken to protect bridges*);
6. Procedures for use in monitoring bridges (*Chapter 7 - The procedures presented apply especially to small bridges. A detailed quantitative risk assessment procedure for larger bridge waterways is presented in Appendix C*); and,
7. An extensive bibliography indicating articles that may provide useful further information on aspects of bridge-waterway scour (*Chapter 8*).

Information provided by the Guide is laid out succinctly, and as practicable options for scour protection or repair. It is recognized that it is not feasible herein to detail the options completely, as they usually need to be tailored to individual bridge waterways. Nevertheless, effort has been made to present the monitoring procedures in a practical light so as to illustrate their use.

The Guide is well illustrated. Examples of scour conditions, along with scour-protection and repair methods, are drawn extensively from bridge sites in Iowa and the Midwest. Figures from further away also are used; the Guide's writers offer illustrative photographs from locations as distant as Japan and New Zealand, both being countries with many rivers and thus many well-documented bridge-scour concerns.

In addition, the Guide provides a comprehensive Bibliography of publications that give further, more detailed information on bridge waterways and scour (*Chapter 8*). The Guide also provides extensive explanatory notes covering most of the usual considerations associated with bridge waterway inspection.

In proceeding with their work, bridge inspection personnel commonly follow a concise report format that documents the existing condition of a bridge, and recommends actions to be taken to correct a particular problem. Each agency conducting bridge inspection normally has its own report format and procedures for deciding when maintenance or repair actions need to be carried out for a bridge waterway that has been identified as having experienced scour damage or at risk from scour. The information in the Guide augments these report formats.

Appendix C of the Guide, though, introduces (for consideration only) a quantitative procedure for waterway monitoring. Quantitative procedures are increasingly being used in the risk management of infrastructure components like bridges. Quantitative risk assessment helps in assigning priorities to infrastructure components in need of repair or replacement.

2.2 Guide Preparation

Preparation of the Guide entailed the following sequence of tasks:

1. Establishment of an advisory panel of engineers from the Iowa DOT, Iowa counties, Iowa cities, and bridge-engineering consultants. Soliciting input regarding the structure and content of the manual;

2. Meetings with Iowa DOT engineers, a representative number of Iowa county engineers, a number of city engineers and selected consulting

engineers to discuss the monitoring procedures presently used, and to learn more about their main concerns regarding bridge waterways;

3. Preparation of a preliminary, detailed outline for the Guide. The outline was provided to the Panel, as well as to appropriate engineers in the Iowa DOT, together with selected Iowa counties, Iowa cities and bridge-engineering consultancies. Comment and input regarding the outline was sought and acted upon;

4. Review of the bridge-waterway portions of the monitoring procedures presently in use by Iowa DOT, Iowa counties, and Iowa cities, as well as by state transportation agencies in a cross-section of states across the Midwest (e.g., Illinois, Missouri, and Nebraska). This task entailed the following activities:

    a. Visiting selected engineering offices
    b. Site visits to a representative sample of bridges in Iowa
    c. Viewing existing bridge waterway inspection forms

5. Participation in several bridge inspections conducted by the Iowa DOT;

6. Completion of the Guide;

7. Presentation of the Guide (first edition) to the Panel with the Panel suggesting adjustments to enhance the Guide's utility;

8. Presentation of the Guide to the Iowa Highway Research Board, and then the Board's recommendation regarding publishing and distributing the Guide; and,

9. Presentation of the Guide during two Iowa conferences, one being the annual December Conference of the Iowa County Engineers Association, the other possibly being the biennial Mid-Continent Transportation Conference.

2.3 Training for Monitoring

As reflected in the structure of the example, quantitative inspection report (*Chapter 7*), and also in the various bridge-water monitoring forms used in the

U.S., there is a recognized need for increased understanding of bridge-waterway processes. Based on this need, it is recommended that training of bridge-inspection teams be undertaken in order to ensure that the scour monitoring is effective.

2.4 Background to the Guide

Before proceeding to the ensuing chapters of the Guide, it is useful to elaborate a little further the overall concerns with the waterways of small bridges, and thereby, provide background to the information given in the ensuing chapters.

Small bridges commonly have one to three spans. For such bridges, erosion of the riverbank, approach embankment and bridge abutment is of heightened concern because a shift in riverbank alignment has a greater influence on thalweg alignment (line of deepest flow along a channel) than it would for a wider river. A shift in thalweg toward a riverbank or embankment is a common factor contributing to the scour of the approach embankments at small bridges.

Figures 2-1 and 2-2 depict fairly recent examples of a bridge failure and a bridge at risk. It is common for such bridges to have been in service for many years before becoming prone to a failure situation. Figure 2-1 depicts a bridge where one pier has lost partial foundation support, and then tilted laterally. Figure 2-2 shows a situation where the abutments of a small bridge gradually are becoming exposed as the adjoining riverbanks erode. Further illustrations are given in Chapter 4.

A question that inevitably arises in most cases of bridge failure, such as those in Figures 2-1 and 2-2, is whether scour failure was preventable. Additionally, what monitoring and maintenance activities might have helped to mitigate failure owing to scour? In reviewing cases such as shown in Figures 2-1 and 2-2 (and in other examples illustrated subsequently in the Guide), it becomes evident that the abutment structure itself (i.e., the wingwall or stub abutment) did not fail, but that the approach embankment failed. Alternatively, the riverbank and approach-road embankment failed first; then caused the abutment to fail. Such failures could be detected with monitoring.

Figure 2-1. Pier failure of a bridge; Willow Creek in western Iowa. The creek had experienced channel degradation (drop in bed elevations) associated with head-cutting (see Chapter 3), which critically reduced support for the pier's piles

Figure 2-2. General degradation, associated with stream-bed head-cutting threatens the stability of piers and abutments of a bridge in western Iowa

In attempting to answer these questions, further questions soon arise as to what exactly should be scrutinized during monitoring, and what protective measures are needed to inhibit scour. The Iowa Department of Transportation (Iowa DOT), as well as county and city agencies routinely engaged in monitoring bridges, have procedures and checklists for use in monitoring and maintaining bridges. Those procedures and checklists are reasonably effective (see, e.g., http://de.usgs.gov/publications/ofr-96-554/). Yet, they are not as effective as they could be. The writers of this Guide believe that there are some very important processes of which bridge engineers are completely unaware.

Problem situations requiring good monitoring involve considerations of bank conditions, channel-thalweg alignment, abutment-pile or pier-pile exposure, the state of bridge drainage courses, vegetation growth and accumulation. Because conditions at bridge sites are seldom fixed for long periods of time, there is an on-going need to be alert to the potential for such problems to develop, and for ways to protect bridge waterways against unacceptable scour.

Monitoring procedures for bridge waterways would be assisted greatly by the availability of a comprehensive and well-illustrated (ample drawings and photographs) guidebook or manual that describes the many ways whereby bridge waterways can deteriorate, potentially resulting in the failure of bridge foundations and approach embankments, that indicates the potential-problem situations to look for, and that outlines options for means to protect against excessive scour. Such a manual would serve as a practical and useful aid for existing monitoring procedures used by the Iowa DOT and by county and civil engineers, as well as consulting engineers engaged in the design and monitoring of bridge waterways.

A preliminary survey indicates that no up-to-date practical guide manual or handbook exists for bridge waterways. For instance, the Federal Highway Administration's publications HEC-18 and HEC-20 (Richardson and Davis 1995, Lagasse et al. 1995) are inadequate in this respect, as are books such as those by Neill (1973) and Melville and Coleman (2000).

Additionally, because an important feature of waterway monitoring commonly is on minimizing the detrimental effects of bank erosion on small-bridge stability, an emphasis must include guidance on flow control and averting bank erosion. In this regard, the use of hydraulic structures to guide strong currents away from banks near bridges, and grooming flow through bridge waterways, has gained increased support in recent years. In general terms, such structures create a region of comparatively low velocity, low turbulence, and low shear stress along a stream bank immediately upstream of a bridge, thereby creating a protected region for susceptible bridge foundations, as well as guarding weak banks. Further potential considerations for such guidance structures are that they be environmentally acceptable, insofar as they create beneficial, diverse hydraulic conditions for aquatic species and are aesthetically pleasing due to their constructional components of large boulders and river rock. Examples of diversion structures used in Iowa are vanes, spur dikes, and groins.

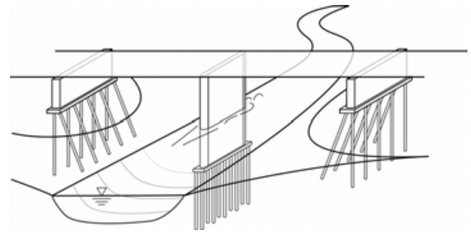
2.5 Units

The Guide uses the customary quantity units adopted by the U.S., but includes as Table 2-1 the basic conversion factors for converting these units to Standard International metric units. From time to time, a bridge inspector may be required to consult publications that use SI units.

Table 2-1. Conversion of Units

Customary U.S. Units	Metric Units
1 foot (ft)	0.305 meter (m)
1 inch (in.)	25.4 millimeter (mm)
1 pound force (lbf)	4.45 Newtons (N)
1 pound per square inch (psi)	6,895 Newtons/square meter (N/m^2), a.k.a. Pascals (Pa)

3
BRIDGE WATERWAYS



3.1. Introduction

Bridge engineers and people involved in bridge design and monitoring often assume that a river or stream channel will maintain its course, its shape, and its dimensions. Contrary to this assumption, and because channels usually have erodible boundaries, most channels may adjust their shape and alignment in response to hydrological events and to land-use changes in their watersheds. Channel changes sometimes have severe consequences for bridge waterways. Therefore, monitoring of bridge waterways requires monitoring of the channel approach to a bridge, as well as the channel immediately downstream of a bridge.

This chapter briefly describes the main features of river channel morphology that are of consequence for bridge waterways, and then focuses on the bridge waterway.

3.2 Bridge Waterway Components

The bridge components of concern for bridge waterway scour are:

1. The upstream approach channel;
2. The bridge opening, which commonly features ~
    - bridge abutments;
    - approach-road embankments;
    - piers; and
    - drainage courses flanking the abutments; and
3. The downstream channel

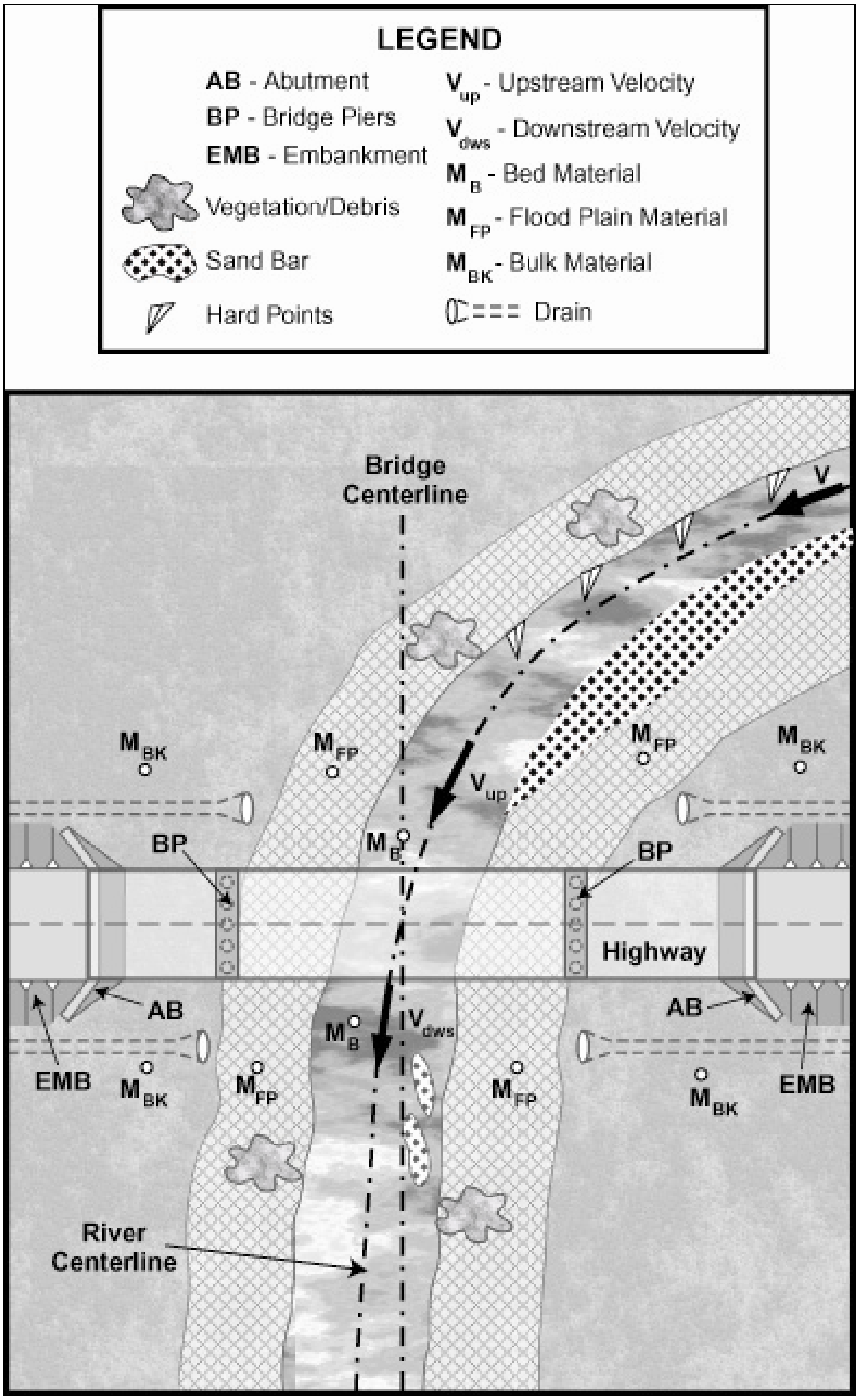


Figure 3-1. Plan-view sketch detailing bridge components and surrounding features of a bridge waterway

These components, shown simply in Figure 2-1 of Chapter 2, are given in more detail in Figure 3-1, which also indicates the variable foundation material conditions associated with the river bed, the floodplain, and the earthfill embankment approaches to the bridge abutments. Foundation material also may vary with depth at a pier or abutment. Additionally, variations in vegetation may occur along a floodplain as well as the banks of the main channel and the floodplain.

To varying extents, most bridge waterways are compound in shape and in boundary roughness. As depicted in Figure 3-1, and illustrated in Figure 3-2, they comprise a central main channel flanked by side portions (floodplains) formed to aid conveyance of larger flows. Channel geometry factors have to be taken into account when monitoring for scour. These factors are discussed below in Section 3.3. Here, in the present section, consideration is briefly given to the components of the bridge opening.

Figure 3-2. A bridge waterway often comprises approach embankments, abutments, piers, and a compound channel formed of a central main channel and floodplains

The geometric factors characterizing the bridge opening are important in evaluating scour conditions at a bridge. The factors include the degree of flow contraction caused by the bridge opening, the foundation geometry, and the location of the bridge relative to channel bends. Flow contraction can be lateral, because of the encroachment of the bridge approach embankments; and, flow contraction can be vertical if the bridge deck becomes submerged for extremely large flows. Complex flow interactions can occur between flow on a floodplain and flow in the main channel of a compound channel. The interactions involve large-scale turbulence and eddies formed in the shear layer developed in the flow region between the channel portions. Chapter 4 further describes the flow field at bridge abutments and piers.

The geometry of bridge abutments is described in terms of abutment type, end shape, length, and alignment, including the approach embankment. Piers, too, can be described in terms of the type, shape, length, width, and alignment with flow. The position of abutments and piers are important. For example, bridge foundations sited in a floodplain may be subject to scour under different channel conditions than piers and abutments sited in the main channel of a stream.

3.3 Channel Morphology: A Brief Primer

In general, river or stream channels are classified into three categories on the basis of the continuity of flow that they convey:

1. Perennial rivers or streams carry some flow continuously. Nearly all streams in Iowa are perennial;
2. Ephemeral streams are dry most of the year except for periods during summer thunderstorms or spring snowmelt season. This type of stream is rare in Iowa and is commonly found in the western states; and,
3. Intermittent streams are located in separated reaches where ground water seasonally intersects the stream bed. Some streams in northwestern and northeastern Iowa are intermittent streams.

In general, the top width (w) and depth of the flow (d), and the mean flow velocity (v) vary with the water discharge (Q) at a channel cross section. The relationships between the water discharge and these three variables are called the hydraulic geometry which differs from the channel geometry that defines the bank-full width and the mean flow depth of a channel cross section. Leopold and Maddock (1953) found that w, d, and v are expressed in terms of the power of Q (average annual water discharge), which indicates that the channel width increases faster than the depth or the velocity as the water discharge increases. Exponents of the power relationships are 0.5, 0.4, and 0.1 for w, d, and v, respectively.

As the water discharge increases, the suspended load (fine-size sediment material transported in suspension) and the bed load (sediment material moving on and near the bed) increase. The suspended load is generally expressed in terms of the power of the water discharge with a power exponent in the range from 2 to 4, approximately, indicating that the suspended load increases more rapidly than w, d, and v as the water discharge increases. The bed load is very difficult to measure, and there is no explicit relationship developed with the water discharge. The sediment load transported by the flow influences both the channel geometry and the longitudinal bed profile. Lane (1955) found the stream power (the water discharge, Q, multiplied by the channel slope, S) as being equal to the bed material load, Q_s, times the median bed material size, d_{50}.

Furthermore, it was found that slope, S, at any point in the channel is approximately proportional to the 0.6 power of the ratio of d_{50} and the drainage area, A, indicating that the stream gradient is greater for the larger bed material size and smaller for the larger drainage area. However, channel slope is strongly influenced by local characteristics of the flows and sediment loads delivered to the system, resulting in aggradation or degradation of the channel bed and significant variations in channel patterns. Channel degradation occurs in a reach where the sediment supply at the upstream boundary becomes smaller than the sediment transport capacity of flow, often observed downstream from a dam where sediment is trapped. Channel aggradation occurs when the sediment supply at the upstream boundary exceeds the sediment transport capacity of flow within a reach.

Channel degradation has been a major issue in western Iowa streams where head cutting progresses upstream at a substantial speed. For example, a knickpoint (the upstream point of the head cutting phenomenon), about 6 ft high, in a small tributary of the Boyer River was reported to have moved upstream by 300 ft in one storm event in Crawford County, Iowa, taking a bridge down. Some preventive schemes used in western Iowa streams for knickpoint migration problems include rock weirs, sheet piling, and concrete weirs (Chapter 6 and Appendix B). Channel aggradation features are typically observed upstream of a dam and a grade control structure, or immediately downstream from a tributary that introduces high sediment loads to the channel.

Besides changes in channel cross section and its slope, channels also form very unique patterns in the downstream direction in a planar view. These patterns are classified into three groups, including straight, meandering, and braided patterns which are formed as a combined effect of the water discharge, the sediment load that the channel can transport, the channel cross section, and the channel slope. These channel patterns are illustrated by Nelson, et al. (1983) in terms of the sediment load in Figure 3.3. Therein, relative stabilities of the channel are also identified in termed of the channel type, sediment load, bed-material size, mean flow velocity, and stream power.

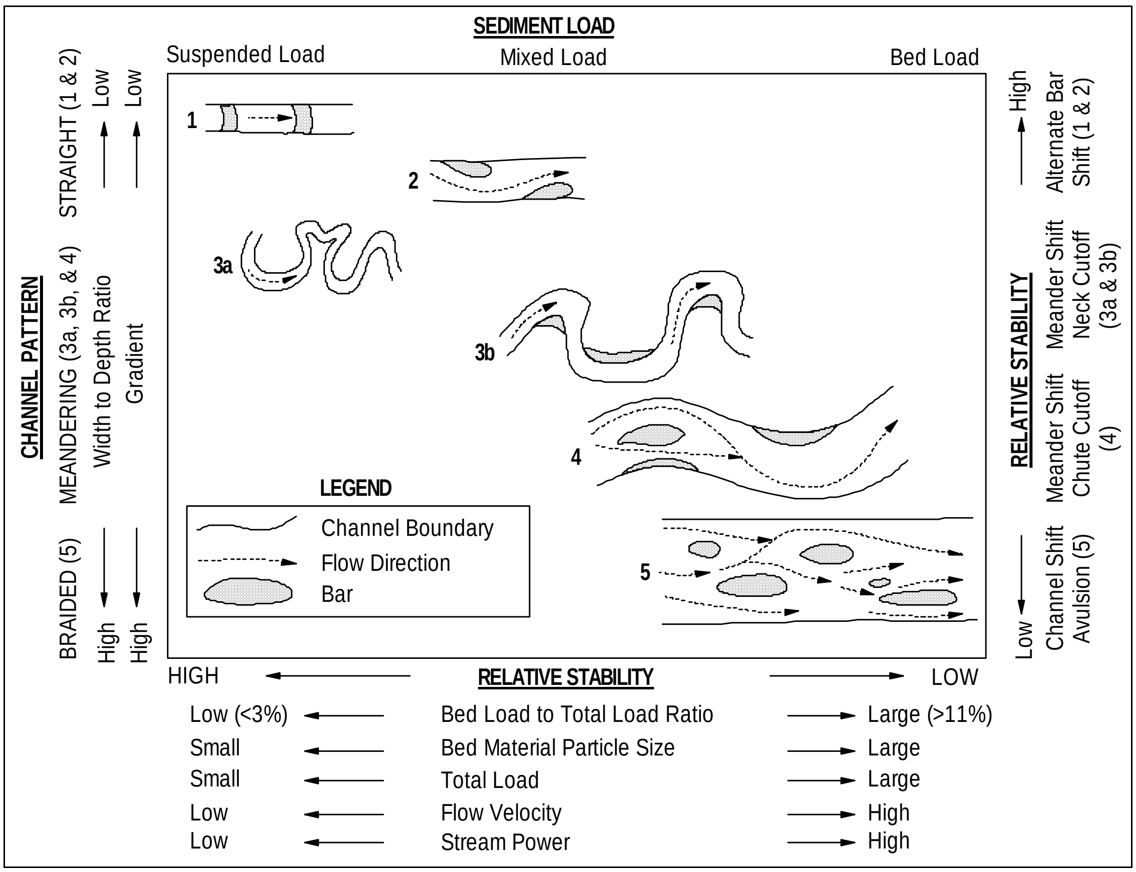


Figure 3-3. Channel classification with relative stability and various channel characteristics associated with each channel pattern (Adapted from Nelson et al., 1983)

Most small or intermediate streams in Iowa are either straight, when seen as a short reach, or meandering. The braided channel pattern is seen only in large rivers, such as in the Mississippi River. Even in a straight channel, a thalweg (deepest part of the channel) tends to shift from bank to bank as the channel migrates laterally, forming bars opposite of the deepest points of the channel.

A reach of the East Nishnabotna River in Cass County, Iowa, and a reach of Walnut Creek in Pottawattamie County, Iowa, present typical straight channel features, as depicted in Figure 3-4.

(a) A small straight channel reach - Walnut Creek on gravel road G66 in Pottawattamie County, Iowa (upstream view; notice the bank failure line along the left bank)

(b) A medium straight channel reach - the East Nishnabotna River on Highway 48 in Cass County, Iowa (upstream view)

Figure 3-4. Samples of straight channel reach

Typical meandering patterns observed in Kleinlein Creek at Highway 13 in Clayton County, Iowa, are shown in Figures 3-5. Point bars developed along the inside (concave) banks and active bank erosion occurring along the outside (convex) bank, as sketched in Figure 3-3, are easily distinguishable in these photographs. Samples of braided channels found in Pool 16 of the Mississippi River between Muscatine and Davenport, Iowa, are shown in Figure 3-6.

(a) A meandering reach – Kleinlein Creek at Highway 13 in Clayton County, Iowa (upstream view)

(b) A meandering reach – Kleinlein Creek on Highway 13 in Clayton County, Iowa (downstream view)

Figure 3-5. Samples of meandering channel reach

(a) A braided channel – Pool 16 of the Mississippi River

(b) A braided channel – Pool 16 of the Mississippi River

Figure 3-6. Samples of braided channel reach, Mississippi River, Iowa

3.4 Erosion Behavior of River or Stream Channels

Very few river or stream channels are stable. Most channels are continuously adjusting their channel patterns following flow and sediment inputs and outputs within their reach boundaries. These morphological changes entail bed and bank erosion, and may be triggered by changes in base-level characteristics (at the channel outlet), land use, or climate. The first two changes are commonly caused by human activities, such as dam construction, bank stabilization work, stream channelization, mining activities, etc. Under these circumstances, part of the channels may become entrenched or filled with sediment, re-adjusting themselves so as to establish locally a new equilibrium slope. The channel entrenchment moves both upstream and downstream.

The effect of climate on channel patterns and erosion must be viewed on a long-term basis because climate changes occur in very subtle ways. Major floods in the Midwest seem to occur on a decade basis. However, localized flash floods seem to occur very frequently on an annual basis, affecting many small bridges in rural areas in Iowa.

General scour is channel-bed erosion attributable to changes that occur irrespective of the existence of a bridge. It is common to differentiate general scour in terms of long-term general scour and short-term general scour.

- ***Long-term general scour*** is scour or erosion that occurs with a time scale of the order of several years or longer, and includes progressive degradation or aggradation of the channel bed, and lateral bank erosion due to channel widening or meander migration.

  Progressive degradation is the almost permanent lowering of the river bed at a bridge site owing to natural changes in the watershed (e.g., meander-bend cutoff, head-cut progression (head-cutting), landslides, fire, climate change) or human activities (e.g., channel straightening, dredging, dam construction, agriculture, urbanization). It is noted here that head-cutting of channel beds and channel migration are two types of channel degradation that are of major concern for bridges in Iowa. Head-cutting along a channel bed is a chronic problem for streams in western and southern Iowa.

Progressive aggradation is the general raising of the riverbed at the bridge site (e.g., owing to dam construction downstream).

- ***Short-term general scour*** is scour or erosion that develops during a single or several closely spaced floods, and includes scour at a confluence, a shift in channel thalweg, shifts in bends, and scour arising from bed-form (dune or bar) migration. The changes are not long-term, as the channel re-adjusts during subsequent flow events, as illustrated in Figure 3-7.

Figure 3-7. The alignment of alluvial channels continually vary with time. This channel reach of the Upper Missouri River, Montana, is shifting sideways, eroding one bank, while depositing sediment along the opposite bank.

When a main-stem channel experiences bed degradation for some reason, the overall bed slope of a tributary channel then becomes steeper, the erosion causing the steepening beginning at the downstream end (or base level) of the tributary channel. The steepening process forms a so-called knickpoint along the bed of the tributary channel, the knickpoint being the location where there is a discontinuity in the channel bed of the tributary. As the downstream extent of the bed of the tributary channel erodes, the knickpoint is moved upstream. For a bed composed of sandy alluvium, bed erosion and knickpoint movement occur relatively quickly. This process of knickpoint upstream migration is illustrated in Figure 3-8. For a bed formed of cohesive sediment (clay) or soft sedimentary rock, knickpoint movement can be relatively slow.

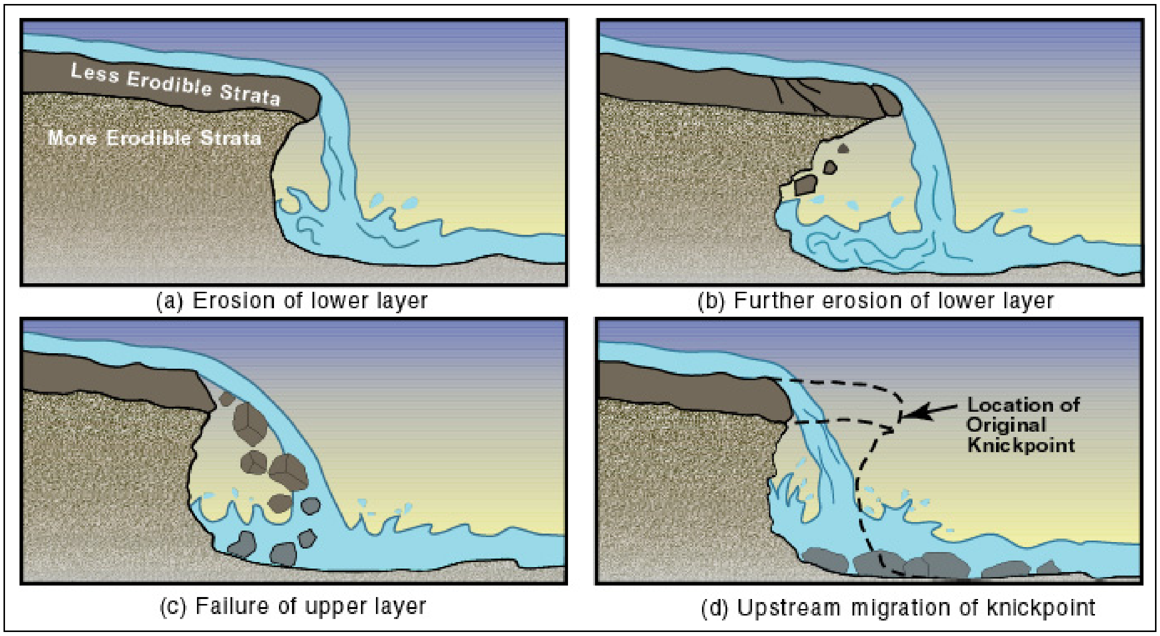


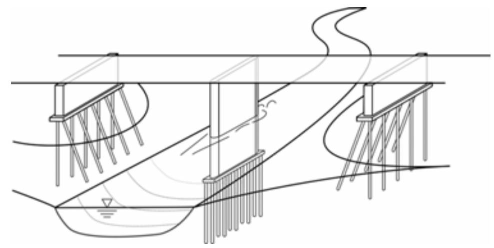
Figure 3-8. Sketches showing a knickpoint migration process

For channel beds formed from sediment that is extensively cohesive, or from rock, the upstream movement of the knickpoint occurs by means of a process called headcutting. A headcut is a vertical or near-vertical drop in the channel bed. Flow plunges over a headcut face, striking the bed downstream and eroding a scour hole. The scour hole deepens until the face of the head-cut becomes unstable geotechnically, then fails into the scour hole; and the head-cut progresses upstream.

The upstream migration of a headcut induces channel bed and bank instabilities, worsens erosion, and increases the sediment load delivered to downstream reaches. The mass failure is determined by a time-averaged model that treats the discontinuous event as a continuous mass wasting process. The knickpoint migration and associated headcutting are very common in west central Iowa in small tributary streams along the Boyer River, in particular, in Harrison, Crawford, and surrounding counties, causing severe damage to state and county bridges. A severe headcut occurring in the Fox River in Missouri is shown in Figure 3-9. The "grandfather" of headcuts in North America is the Niagara Falls.

Figure 3-9. Headcut progression up the Fox River, Missouri. This river flows also through Van Buren County, Iowa. Note the cohesive (clayey) nature of the sediment forming the river's bed

4
SCOUR TYPES



4.1 Introduction

Bridge scour potentially involves all forms of waterway erosion occurring near and within bridge waterways. The main concerns are that scour can reduce the capacity of a bridge's foundations (pier and abutment) to support the bridge's deck, and that scour may erode a bridge's approach-road embankments, possibly causing them to collapse.

The types of scour that can occur at a bridge waterway are commonly referred to as

- General scour; and,
- Localized scour

The scour types are identified in Figure 4-1, and pertinent scour terminology is described below in Section 4.2. The main features of general scour of channels are covered in Chapter 3, which described channel morphology responses to changes in flow and sediment conditions.

This present chapter describes the main features of scour at bridge piers and abutments. It is important to point out that abutment scour is an especially complex set of processes involving hydraulic erosion of sediment from the bed of a channel or floodplain at the abutment, and that the erosion then may trigger the geotechnical slope failure of the earthfill forming the approach embankment approach to the abutment. As is explained below, several abutment failure modes are possible.

Additionally, as illustrated at the end of this chapter, for small bridges the interaction of scour features complicates scour and scour-depth estimation. Consequently, for smaller bridges, reliable waterway performance entails greater reliance for bridge-waterway monitoring.

4.2 Scour Terminology

It is useful to define certain common terms of scour terminology. As noted above, the types of scour that can occur are typically referred to as general scour and localized scour, which is a combination of contraction scour and local scour. The scour types classified in Figure 4-1 can be defined as follow:

- ***Total scour*** refers to the total depth of scour at the particular bridge foundation (for a pier or abutment). It includes general plus localized scour.
- ***General scour*** is scour that occurs irrespective of the existence of the bridge, and includes long-term general scour and short-term general scour.
- ***Long-term scour*** is scour that occurs with a time scale of the order of several years or longer, and includes progressive degradation or aggradation and lateral bank erosion due to channel widening or meander migration.
- ***Progressive degradation*** is the almost permanent lowering of the river bed at a bridge site owing to natural changes in the watershed [e.g., meander-bend cutoff, head-cut progression (head-cutting), landslides, fire, climate change or human activities (e.g., channel straightening, dredging, dam construction, agriculture, urbanization)]. It is noted here that head-cutting of channel beds and channel migration are two types of channel degradation that are of major concern for bridges in Iowa. Head-cutting along a channel bed is a chronic problem for streams in western Iowa.
- ***Progressive aggradation*** is the general raising of the riverbed at the bridge site (e.g., owing to dam construction downstream).
- ***Short-term general scour*** is scour that develops during a single or several closely spaced floods, and includes scour at a confluence; a shift in channel thalweg, shifts in bends, and scour arising from bed-form (dune or bar) migration.
- ***Localized scour*** is scour that is directly attributable to the existence of the bridge, and includes scour owing to flow contraction and the local flow field developed at a pier or abutment.
- ***Contraction scour*** is scour that occurs because the flow is constricted by the bridge and its approaches.
- ***Local scour*** is scour caused by the flow field formed at a bridge pier or abutment. The terms pier scour and abutment scour are commonly used.

- ***Jet scour*** is the scour that occurs when a road drain discharges into the river along the flank of an abutment.

At any bridge waterway, any or all of these types of scour may occur simultaneously. It is necessary to ensure that the total scour for design includes an appropriate combination of the scour types. Figure 4-2 is a simple illustration of the scour types often observed with the bridge opening. Scour depths normally are greatest close to piers and abutments, because of the flow fields generated by those components of a bridge.

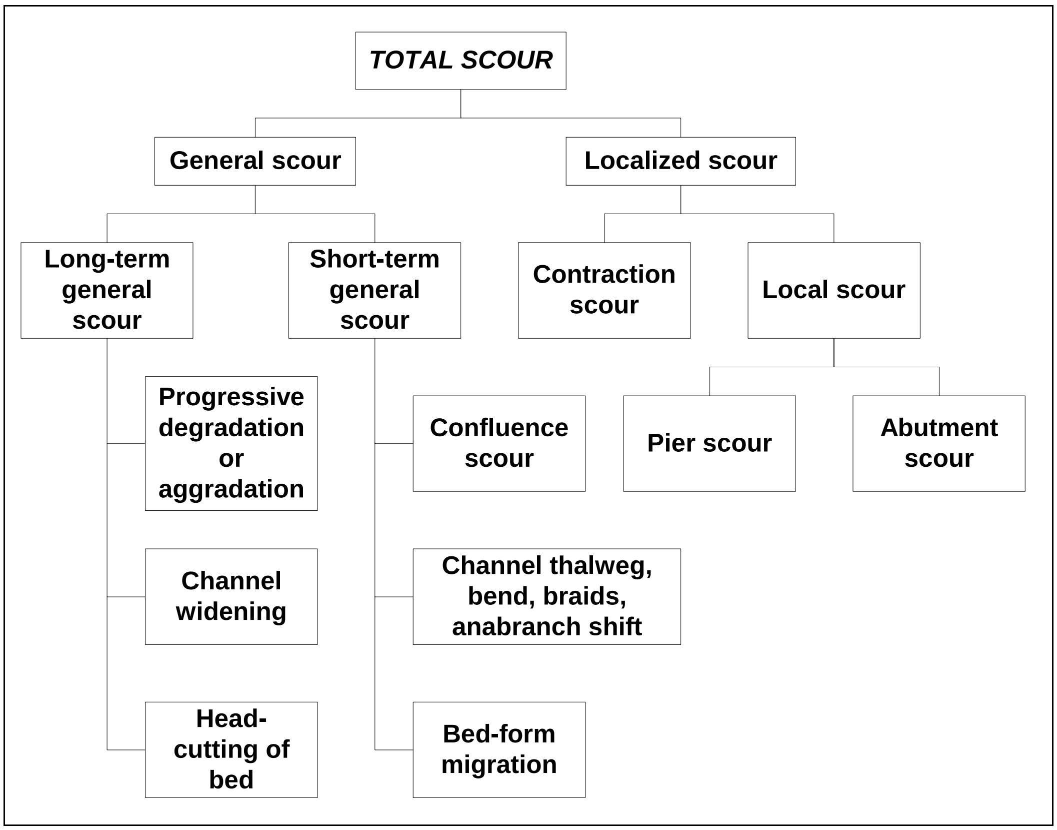


Figure 4-1. Scour types at bridge waterways

Note that Chapter 3, which describes the natural behavior of natural rivers and streams, briefly covers the main aspects of general scour.

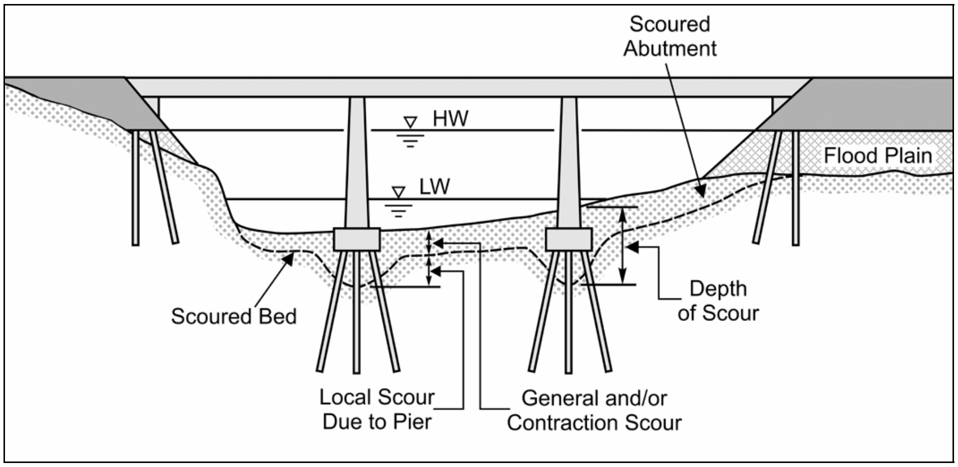


Figure 4-2. Scour types at a bridge opening

This chapter gives a concise description of the flow fields and the localized scour processes that they cause at piers and abutments. Contraction scour, being an important component of abutment scour, is discussed here in the context of abutment scour. Pier scour, though affected by contraction scour, is discussed in terms of the flow field generated by a pier.

4.3 Pier Scour

Scour of the foundation material around a pier may occur because of two processes:

1. For piers founded in the embankment around an abutment, erosion of the embankment may expose piles; and,
2. For piers founded in a river or stream bed, the local flow field generated by the pier may cause what is called local scour at a pier.

Pier scour is common, and leads to several modes of bridge pier failure, as sketched in Figures 4-3a-d. It is common for an initially stable bridge-pier (Figure 4-3a) to settle vertically (Figure 4-3b) or collapse completely. Scour also may reduce the streamwise longitudinal support of a pier, causing the pier to tilt, or the bridge to lose support in the streamwise direction. Depending on the hydrodynamic loading against the pier, as well as the sideways strength of the connection between the pier and the bridge deck, flow pressure may push the pier backwards or it may push the support piles backwards (Figures 4-3c, d). Example photographs of these cases are given in Chapter 5.

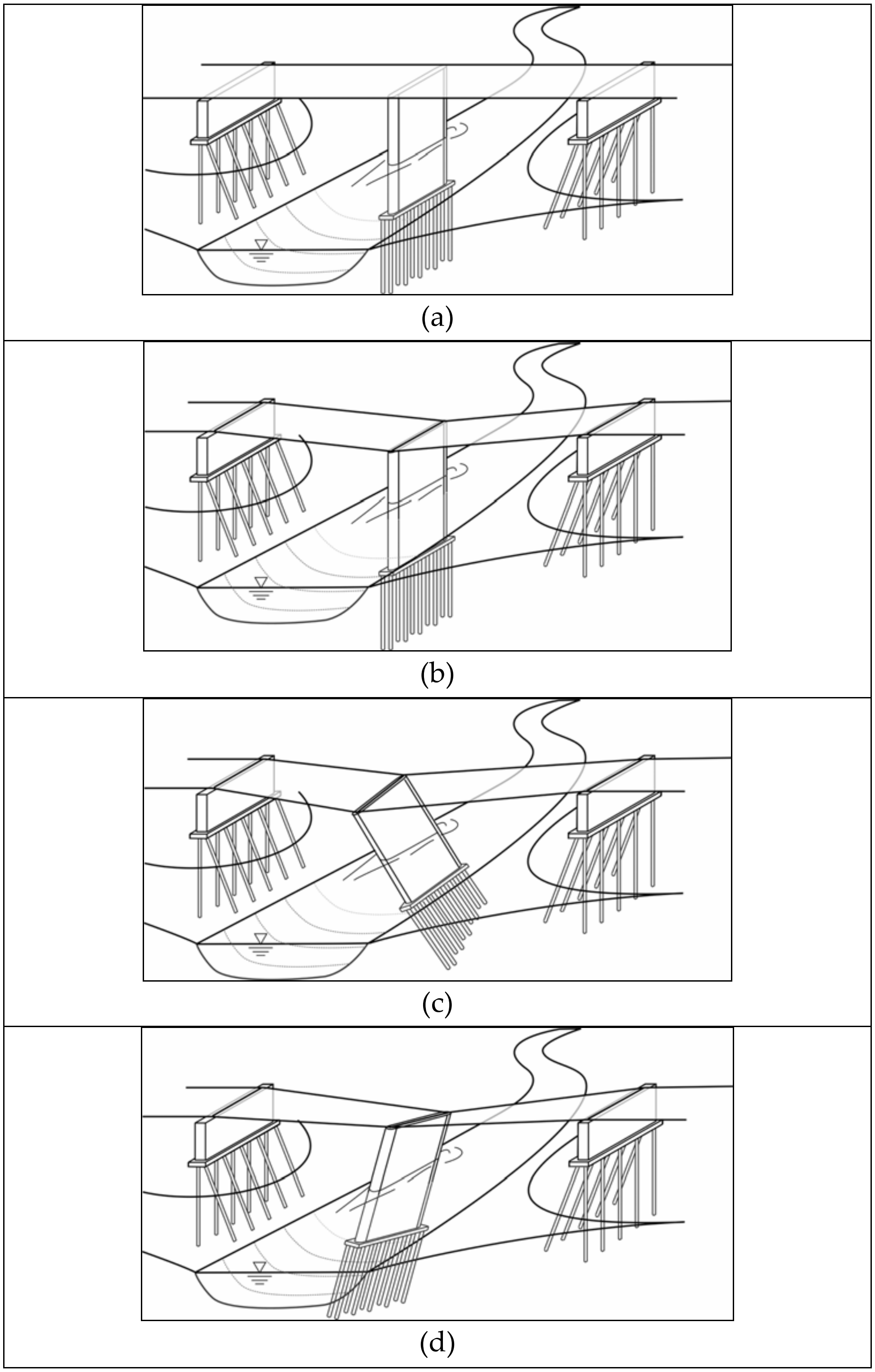


Figure 4-3. Scour reduces pier support, causing pier settlement (a) → (b), bottom rotation of pier (a) → (c), and top rotation of pier (a) → (d)

4.3.1 Scour Location

Local scour develops as a hole around the pier, and involves a complex local flow field causing sediment erosion. Usually, the scour hole is deepest at the leading edge of the pier, because of downflow into the scour hole and the formation of a vortex that in plan looks horseshoe-shaped. The form of the scour hole shown in Figure 4-4 occurs in sandy bed streams. The upstream side of the scour hole usually is at the angle of repose of the bed sediment. In gravel bed streams, the scouring strength of the vortex may not be sufficient to move gravel stones, and conditions may occur where the moving bedload of stones even piles up against the pier like a bow wave. In clay beds, the scour hole has more of the shape of a pot hole, its upstream side being near vertical.

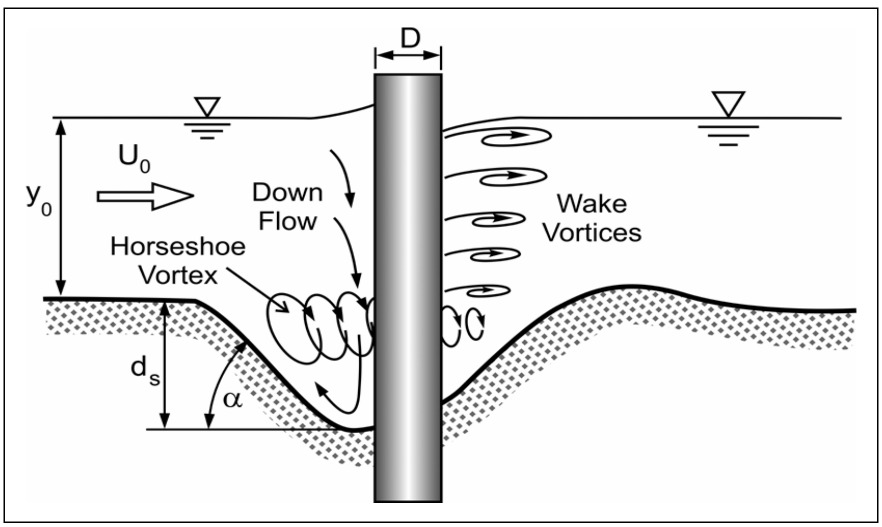


Figure 4-4. The local flow field around a cylindrical pile or pier

4.3.2 Scour Processes

The pier locally blocks the approach flow, inducing a pressure field that leads to a three-dimensional separation of the flow close to the pier. The pressure field produces a strong downwards flow in front of the pier (Figure 4-4). Flow near the riverbed rolls up and forms a horseshoe-shaped vortex wrapped around the pier. The ends of the horseshoe vortex stretch downstream around the pier. As the vortex stretches, the rotational velocities in its core increase. Finally the vortex breaks up and diffuses into the flow. The horseshoe vortex also sheds periodically, and in the laboratory is observed as the pulsating movement of bed sediment around the pier.

An additional vortex system is formed by flow separation from the sides of the pier. The flow forms shear layers that roll up into concentrated vortices with vertical axes. On being shed from the pier, these vortices form a clearly visible vortex trail downstream of the pier. These vortices increase the scouring action along the line of their movement, and act like little vacuum cleaners by sucking bed sediment into their lower pressure core. Relatively little scour is observed in the wake of the pier, however. Instead, at some short distance downstream as the wake vortices break up, the sediment is deposited to form a low mound.

In the developing process of local scouring, the wake vortices pick up bed sediment and transport it in the downstream direction. A sediment mound forms due to the side scouring and the re-circulating influence of wake vortices. Wake vortices cause bursts to occur downstream of the cylinder.

4.3.3 Pier-Scour Depth Trends

Local scour can occur when the rest of the river bed is stable and no bed sediment transport occurs. This condition is referred to as *clear-water scour*. Equilibrium between the local flow and the bed is reached when the flow in the scour hole is no longer able to move bed sediment. The process becomes more involved when there is general sediment transport, which is often referred to as *live-bed scour*. The limiting scour then corresponds to the equilibrium between the sediment transport into the scour hole and out of the scour hole. For this condition, the scour depth may fluctuate with time as dunes pass by the scour hole.

Figure 4-5 shows the relationship between equilibrium scour depth, d_{se}, and average flow velocity and with time, for a constant pier and bed-sediment size. The equilibrium scour depth increases with flow velocity, V, until eventually (at velocity V^*) bed sediment begins to be moved by the flow; then a maximum equilibrium scour depth, d_{se}^*, occurs. Thereafter, for larger flow velocities, sediment flows into the scour from upstream, and equilibrium scour depth is based on consideration of sediment inflow rate equaling outflow rate.

The time, t_e^*, required to reach equilibrium scour depth below the bed level for given flow conditions depends on bed material, and is less for live-bed scour, as is indicated in Figure 4-6. In other words, scour may reach its maximum depth quicker at a pier in a streambed than at a pier on a floodplain. For clear-water scour, equilibrium scour depth is approached asymptotically over a period of days of flow. For scour with bed sediment transport in the channel, equilibrium scour can be attained in a matter of a few hours. The time to equilibrium scour depth depends on pier size.

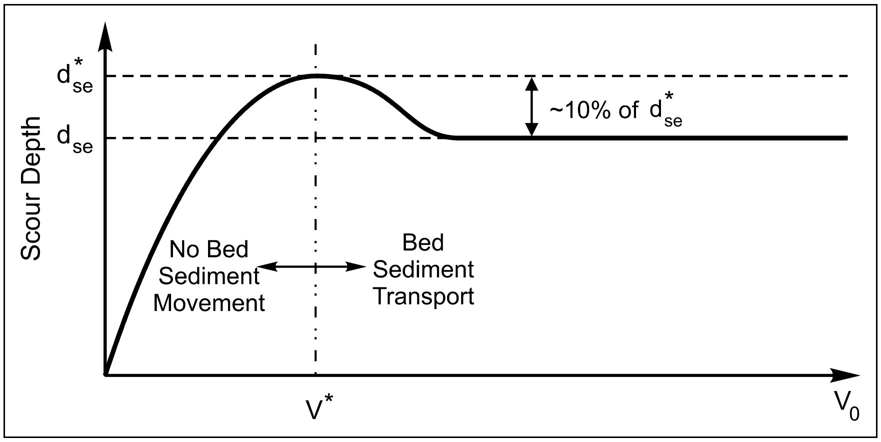


Figure 4-5. The variation of maximum pier-scour depth with flow velocity and bed sediment transport

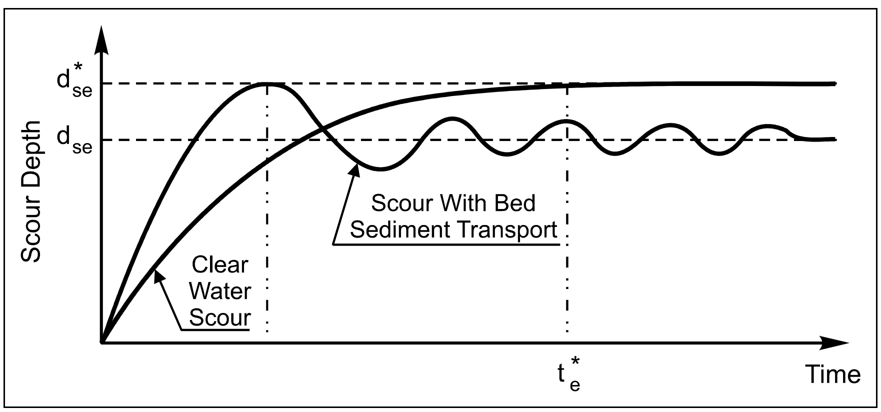


Figure 4-6. The time development of pier scour for clear-water conditions (e.g., pier on a floodplain) and for conditions when the waterway transports bed sediment

Scour at piers founded in clay beds typically develop as clear-water scour, because eroded clay usually goes directly into suspension in the flow, and is not transported along the channel bed. It may take a long time for scour in clay to reach eventual equilibrium scour depth. It is usual for several flood events to occur before attaining an equilibrium, maximum scour depth.

Piers located close to an abutment need extra attention, because they can experience deeper scour owing to flow acceleration around abutments, and to erosion of the river bank and embankment slope around an abutment; illustrative examples are shown in Chapter 5. Also, piers located in, and near the edge of, a main channel can experience significant lateral flow and be prone to deeper scour owing to the skewness of the pier to the local flow orientation.

4.4 Abutment Scour

Described here are the flow field and the scour processes leading to abutment scour. Given that several processes contribute to abutment failure, it is useful to first mention the several boundary materials forming the bridge waterway, and then to indicate the locations where abutment scour can be deepest. Figure 4-7 indicates the usual soil and sediment dispositions in the vicinity of a bridge abutment, in this case for an abutment on a floodplain. The soils and sediments can have different erosion resistance and behavior.

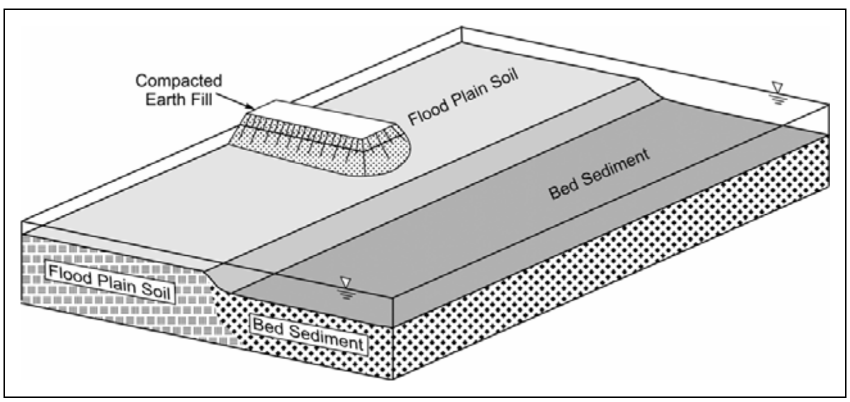


Figure 4-7. Boundary soils and sediments forming the waterway at an abutment

4.4.1 Locations of Abutment Scour

Abutment layout, flow field, along with the erodibility of sediment and soil at bridge sites, may cause the deepest scour to occur at any, or all, of three locations near an abutment; as indicated in Figure 4-8:

1. In the main channel near the abutment;
2. A short distance downstream of the abutment; and,
3. At the abutment itself.

Scour at these locations occurs at different rates, and can differ in the maximum depth attained, in accordance with flow-field and soil conditions. If sufficiently deep, scour at each location can cause the slope-stability failure of the embankment adjoining the abutment.

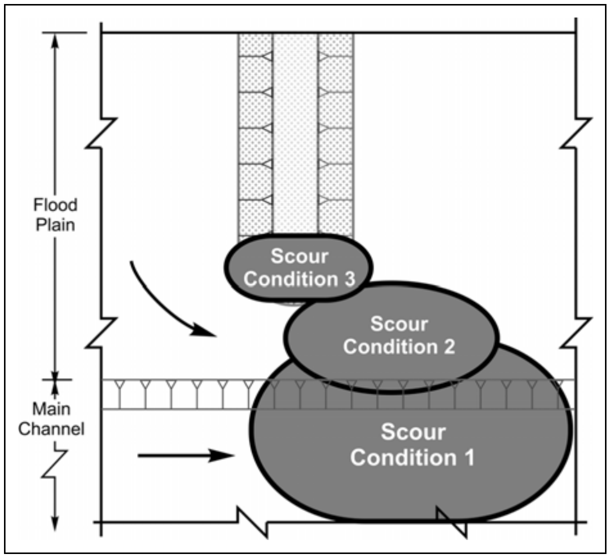


Figure 4-8. Three main regions of abutment scour (spill-through abutments in compound channel); plan view of scour locations

4.4.2 Flow Field

In its effect on flow in a channel, a bridge abutment may be likened to a short contraction, such as indicated in Figure 4-9 for flow through a simple orifice. Two flow features are directly evident in the flow field through a contraction:

1. Flow contraction; and,
2. The generation and shedding of large-scale turbulence structures from the boundaries of the contraction.

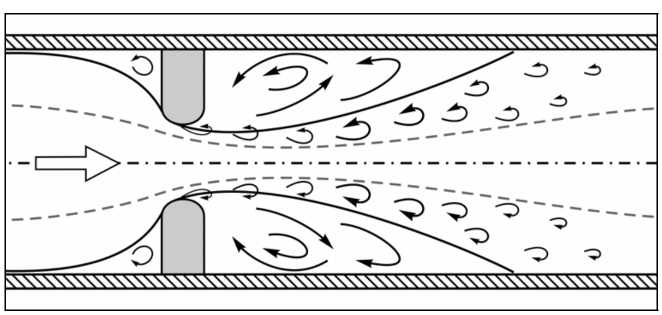


Figure 4-9. Flow through a bridge opening is analogous to flow through an orifice contraction; the flow contracts and turbulence structures develop

As shown schematically in Figure 4-10, the flow field at an abutment typically comprises an acceleration of flow from the upstream approach to the most contracted cross section somewhere at, or just downstream, of the head of the abutment, followed by a deceleration of flow. A flow-separation region forms immediately downstream of the abutment, and flow expands around the flow separation region until it fully re-establishes across the compound channel. Just upstream of the abutment, a flow-separation point and a small eddy may develop (Figure 4-10). The size of the upstream eddy depends on the length and alignment of the abutment. The curvature of the flow along the interface between the stagnation region and the flow causes a secondary current that, together with the flow, leads to a spiral motion or vortex motion like flow through a channel bend. The vortex in flow around an abutment head is more localized and it has a strong scouring action. The vortex erodes a groove along its path, and it also induces a complex system of secondary vortices. At abutments with wing walls (Figure 4-11), the flow impinging on the wall may create a downflow (similar to at a bridge pier), which excavates a locally deepened scour hole at the wall. The downflow is much higher for spill-through abutments, because of their sloped face.

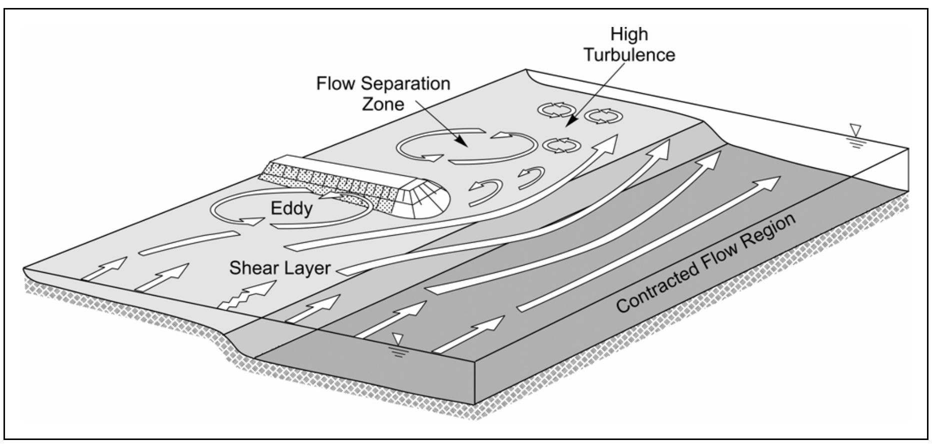


Figure 4-10. Schematic of near-field flow around a spill-through abutment

The two features are related and difficult to separate in the flow field. The region of flow contraction is influenced by the area ratio of the approach flow and the contracted flow, as well as by the form and roughness of the contraction. The large-scale turbulence structures also are influenced by the contraction's form and roughness. The orifice analogy is somewhat simplistic, but an important point to be made from it is that the flow field through a bridge waterway, like the flow field through an orifice, is not readily delineated as a contraction flow field and local flow field limited to the near zone of the abutment. For the purpose of characterizing flow through an orifice, the effect of flow contraction on velocity through the contraction can be explained in terms of a contraction coefficient, C, as used in calibrating flow through an orifice. For fully turbulent flow, C is a function of orifice geometry. Likewise, for abutments, the extent of flow contraction and the turbulence generated by the contracting flow depends on abutment shape.

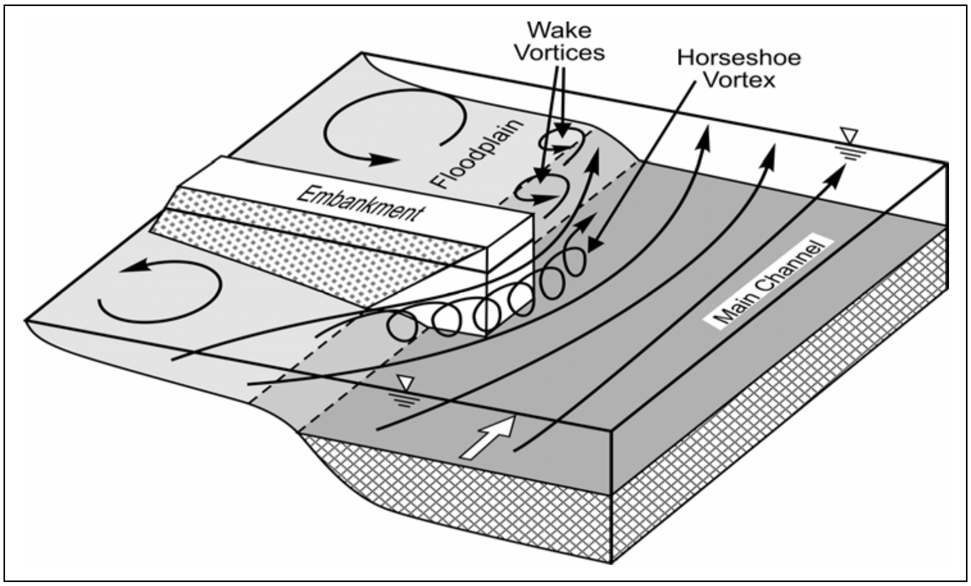


Figure 4-11. The flow field passed a wing-wall abutment

Either of the flow features may become more pronounced, depending on the extent of flow contraction. When an abutment barely constricts flow through the waterway, scour at the abutment may develop largely in consequence of the local flow field generated by the abutment. In the other extreme situation, flow contraction may dominate the flow field when the flow is severely constricted such that a substantial backwater rise in water level occurs. In this case, the approach flow slows as it approaches the upstream side of the bridge, then it accelerates to high speed as it passes through the bridge waterway. Except for bridges whose spans greatly exceed abutment length, the flow field at a typical bridge waterway will be influenced by the combined effects of flow contraction and flow features generated by the abutment.

4.4.3 Common Scour Conditions Causing Abutment Failure

The foregoing considerations of scour location, based on flow field and boundary susceptibility to erosion, indicate that scour at the locations indicated in Figures 4-12 through 4-17 can lead to the following conditions of abutment failure:

1. Condition 1: Scour destabilization of the main-channel bank near the abutment, which is located close to the bank. The floodplain is relatively resistant to erosion compared to the bed of the main channel. Figures 4-12a,b illustrate the several-stage failure process, which involves scour leading to geotechnical failure of the main-channel bank and the embankment. Hydraulic scour of the main-channel bed causes the channel bank to become geotechnically unstable and to collapse. The collapsing bank undercuts the abutment embankment, which in turn collapses locally. Soil, and possibly riprap, from the collapsed bank and embankment slide into the scour hole.

   For wing-wall abutments, located within the bank of the main channel, several erosion processes in addition to flow contraction can result in failure of the main-channel bank and the approach embankment (Figures 4-13a,b);

   - the local flow field generated at the corners of the abutment can cause local scour at those locations; and,
   - exposure of the piles beneath the abutment pile cap can cause river-banks and embankment soil to be eroded out from beneath the pile cap (Figure 4-14a-c).

2. Condition 2: Scour of the floodplain around an abutment well set back from the main channel. The floodplain scours near and slightly downstream of the abutment (scour location 2). The scour hole locally destabilizes the embankment side-slope, causing embankment soil, and possibly riprap, to slide into the scour hole (Figure 4-15a,b);

3. Condition 3: Scour at locations 1 or 2, just mentioned, may eventually cause the approach embankment to be washed out near the abutment, thereby fully exposing the abutment. In this condition, scour at the exposed stub or wing-wall abutment essentially then occurs as if the

abutment were in the form of a pier. Figure 4-16 illustrates this scour condition;

4. Scour may occur at the embankment approach some distance from an abutment, as is shown in Figure 4-17. The embankment intercepts and deflects flow on the floodplain, but the unprotected floodplain near the embankment may experience eroding velocities that cause a local side-slope failure of the embankment. This scour mechanism differs from those shown in Figures 4-12 through 4-16 insofar that scour does not occur at the bridge opening. In somewhat extreme cases, flow may erode through the embankment or wash-out the embankment; and,

5. A scour condition not illustrated here can occur when an approach embankment is overtopped by a high flow. Overtopping can occur because the embankment has a comparatively low crest elevation, or because the bridge opening has become clogged with vegetation debris or perhaps (during early spring) with ice. In this condition, flow spilling over the abutment scours the floodplain along the downstream side of the embankment, and then the embankment side-slope may undergo a side-slope failure. This scour condition is akin to dam-breaching, and possibly to the scour form that develops immediately downstream of an unprotected outlet of a culvert.

It is important to realize that a scour event (or series of events) at an abutment, however, may involve a sequence of all three scour conditions. When an abutment is close to the main channel, Condition 1 (Figure 4-12) may develop relatively quickly, with Condition 2 (Figure 4-13) occurring at a slower rate. Either alone, or together, scour Conditions 1 and 2 may eventually cause the approach embankment to undergo a slope-stability failure. If the embankment extensively washes out, so as to expose the abutment structure, scour may then develop at the abutment structure as if the abutment were a form of pier (Condition 3, Figure 4-15). The combination of scour conditions is suggested earlier in Figure 4-8.

To describe how flow through a bridge opening induces scour, and to relate scour depth to flow, it is useful to refer to Figure 4-18, which shows how approach flow (section 1) is contracted through a general bridge opening, and how flow sweeping past an abutment generates turbulence. A streamtube of flow attains its greatest contraction a short distance downstream of the bridge access (at section 2), and it receives turbulence dispersed into the flow (Figure 4-18). The contracted and more turbulent flow at section 2 has increased erosion power compared to flow approaching the bridge opening (section 1).

Figure 4-19 illustrates scour of the main-channel bed or the floodplain, which may result in the slope failure or scour of the abutment embankment that are illustrated in Figure 4-12. Various modes of slope failure may occur, depending on the strength behaviors of the floodplain soil and/or embankment soil. Note that, for many small bridges, the floodplain may be narrow and sloped, or non-existent. Several scour depths are indicated in Figure 4-19: Y_1 is the approach-flow depth at section 1; Y_F is flow depth on the floodplain at section 1; Y_C is the flow depth adjusted by assuming a uniform contraction of flow; Y_{MAX} is the maximum flow depth at the scour hole.

The trend in scour depth (perhaps better described as flow depth) around an abutment is sketched in Figures 4-20a-c. Figures 4-20b,c help in explaining the trend. When flow is not much contracted around an abutment, scour is largely attributable to the local flow field around the abutment (e.g., as in Figure 4-20a). When the bridge opening is highly contracted, flow contraction dominates scour, and the local flow field generated by the abutment plays a minor role; this latter case is similar to scour caused by flow exiting a culvert. In these figures, "q" is unit discharge (flow depth times average velocity over depth).

The scour conditions described in this section may occur for pile-supported or spread-footing-supported abutments, and are of practical importance for the design and monitoring of bridge abutments.

4.4.4 Other Abutment Failure Processes

Other possible scour conditions can be associated with abutments. These processes usually are attributable to shifts in channel or channel-thalweg alignment. They have to be factored into the estimation of scour depth at an abutment that has become fully exposed. Additionally, they may usually be addressed by means of channel control or riverbank protection, such as described earlier in this chapter.

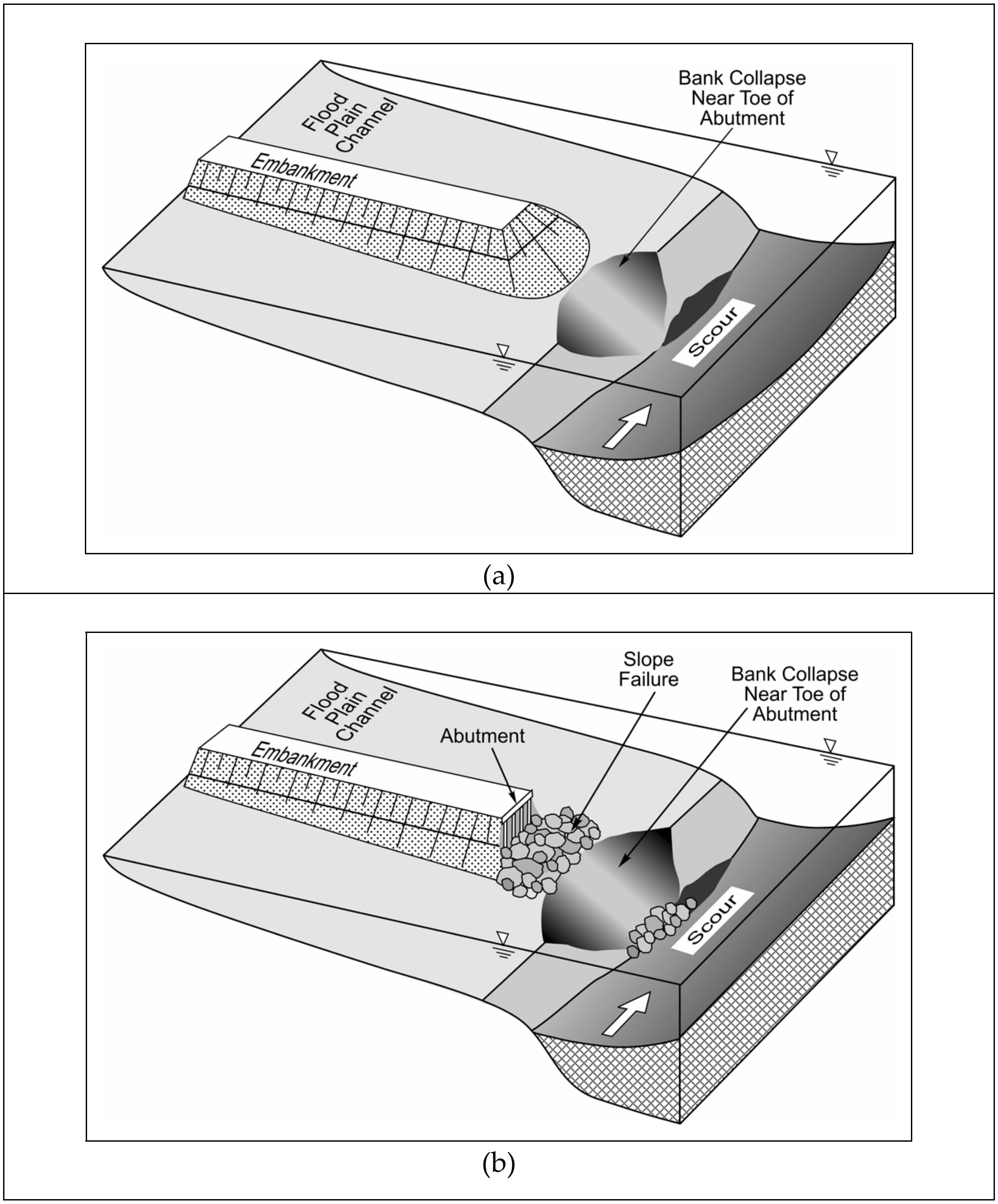


Figure 4-12. The several stage collapse process associated with one common condition of scour at a spill-through abutment in a compound channel: (a) hydraulic scour of the main-channel bed causes riverbank instability and failure, which in turn (b) causes a failure of the face of the abutment embankment. In this condition, the floodplain is much less erodible than is the bed of the main channel

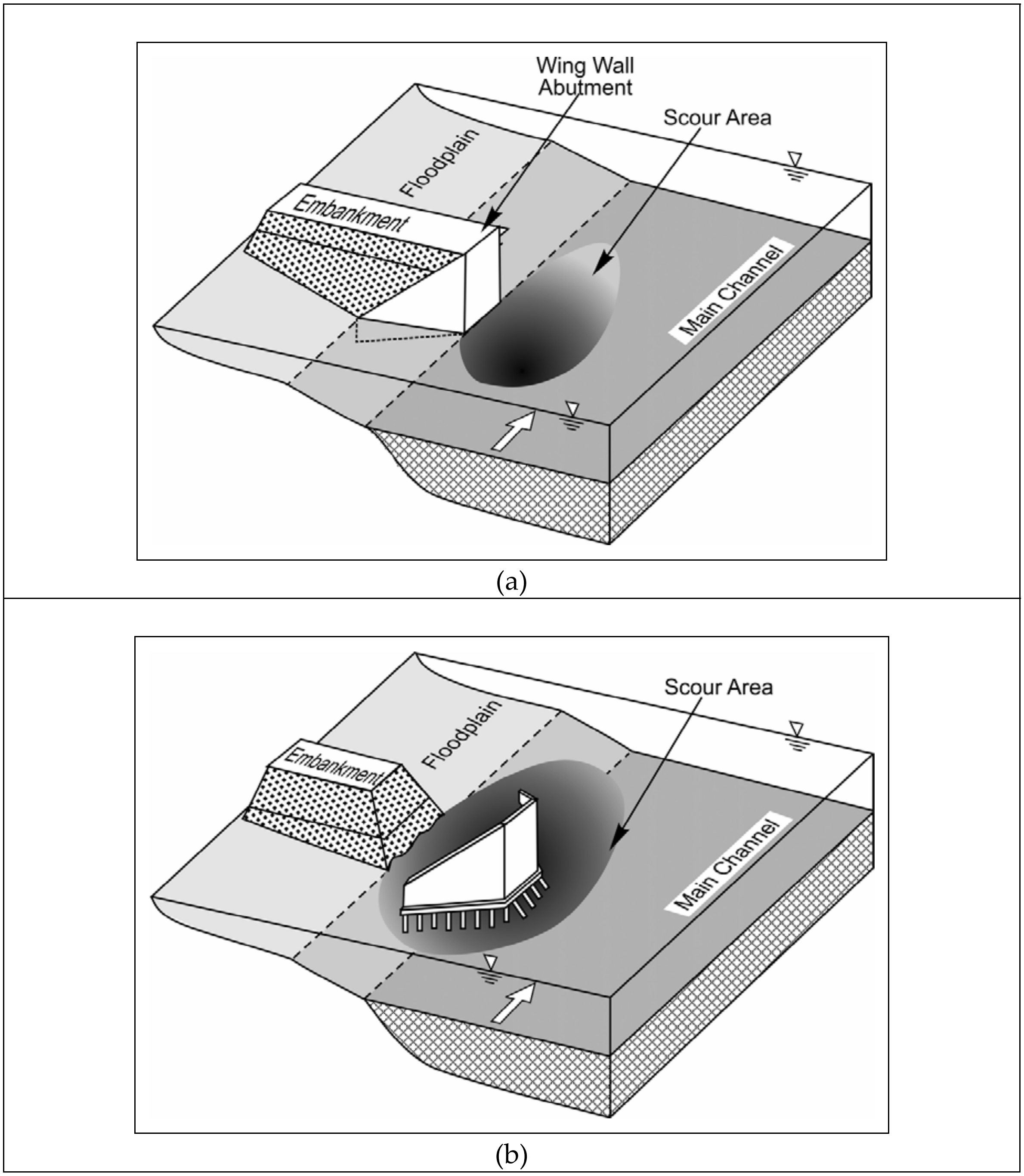


Figure 4-13. The two-stage collapse process associated with one common condition of scour at a wing-wall abutment: (a) hydraulic scour of the main-channel bed causes riverbank instability and failure, which in turn (b) causes a failure of the channel bank and the face of the abutment embankment.

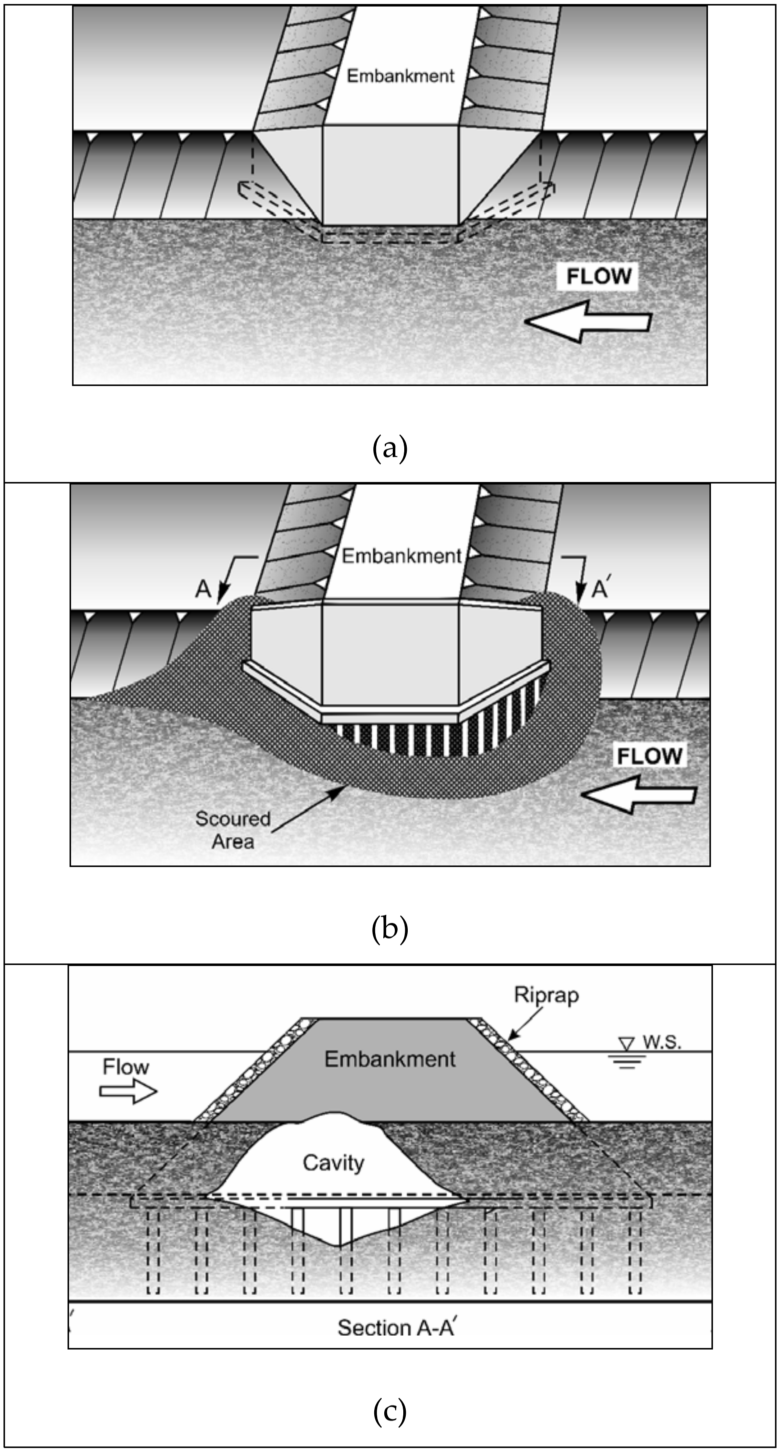


Figure 4-14. Scour development below the pile cap of a wing-wall abutment (a) → (b) can cause embankment soil to be sucked from beneath the pile cap, and form a cavity in the embankment (c), which then may collapse (Figure 4-13b)

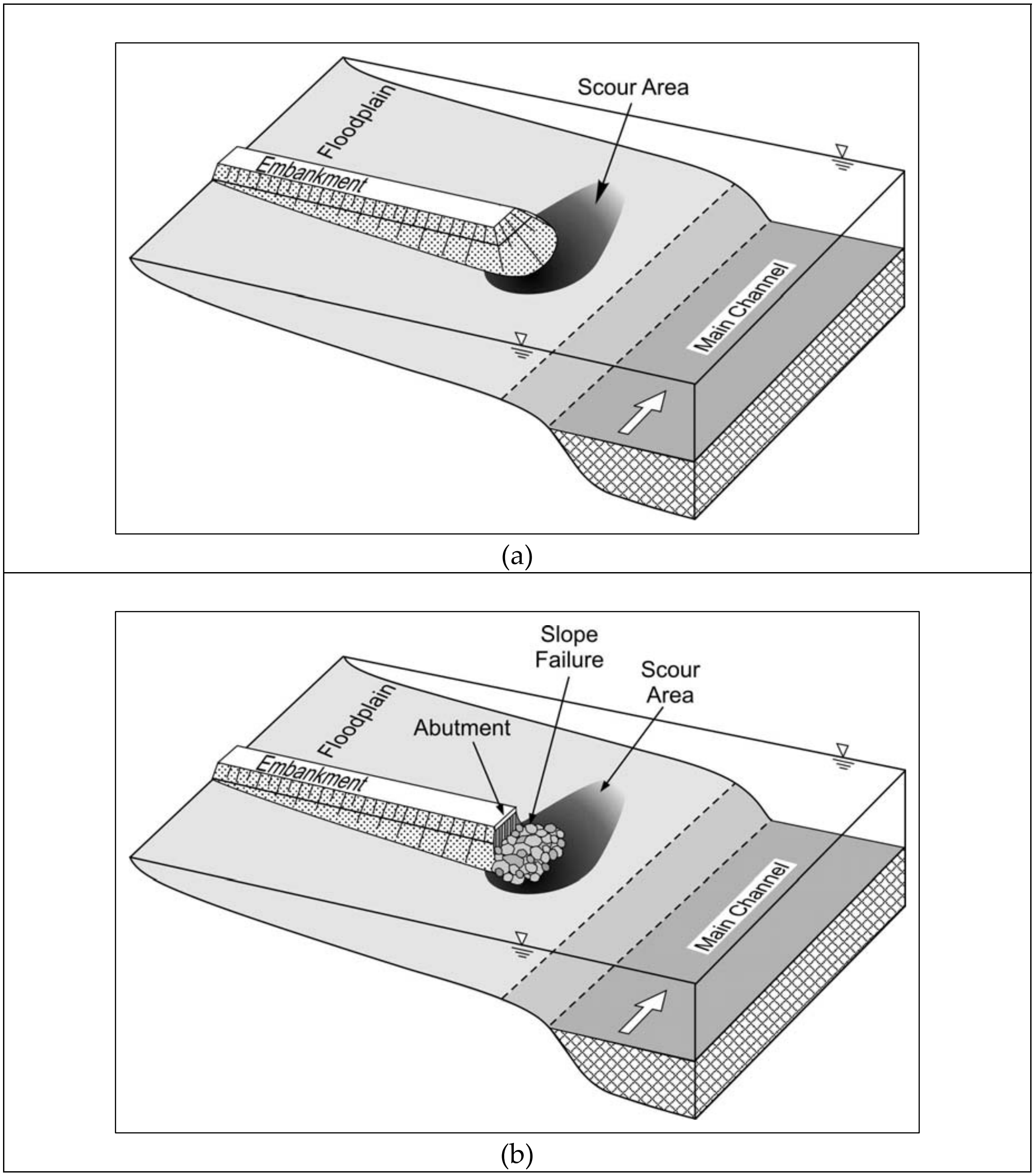


Figure 4-15. The several stage collapse process associated with a further common condition of scour at a spill-through abutment in a compound channel: (a) hydraulic scour of the floodplain causes (b) a failure of the face of the abutment embankment. In this condition, the floodplain is as erodible (more or less) as is the bed of the main channel. The collapse of the embankment soil (and armor protection) into the scour hole modify the scour area.

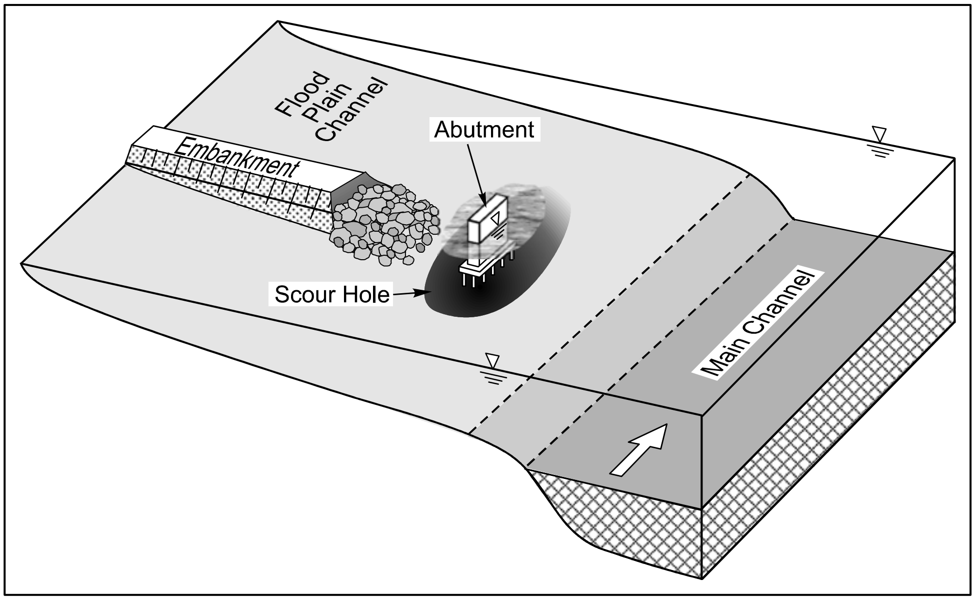


Figure 4-16. Washout of the approach embankment can fully expose the abutment foundation, such that further scour progresses as if the abutment were a form of pier

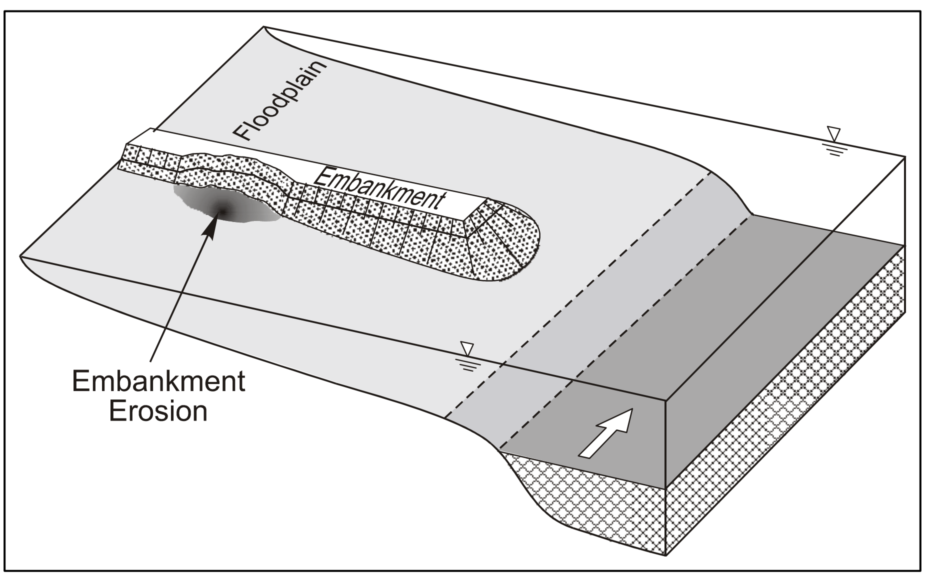


Figure 4-17. Floodplain flow impingement against a long approach embankment can result in erosion of the embankment

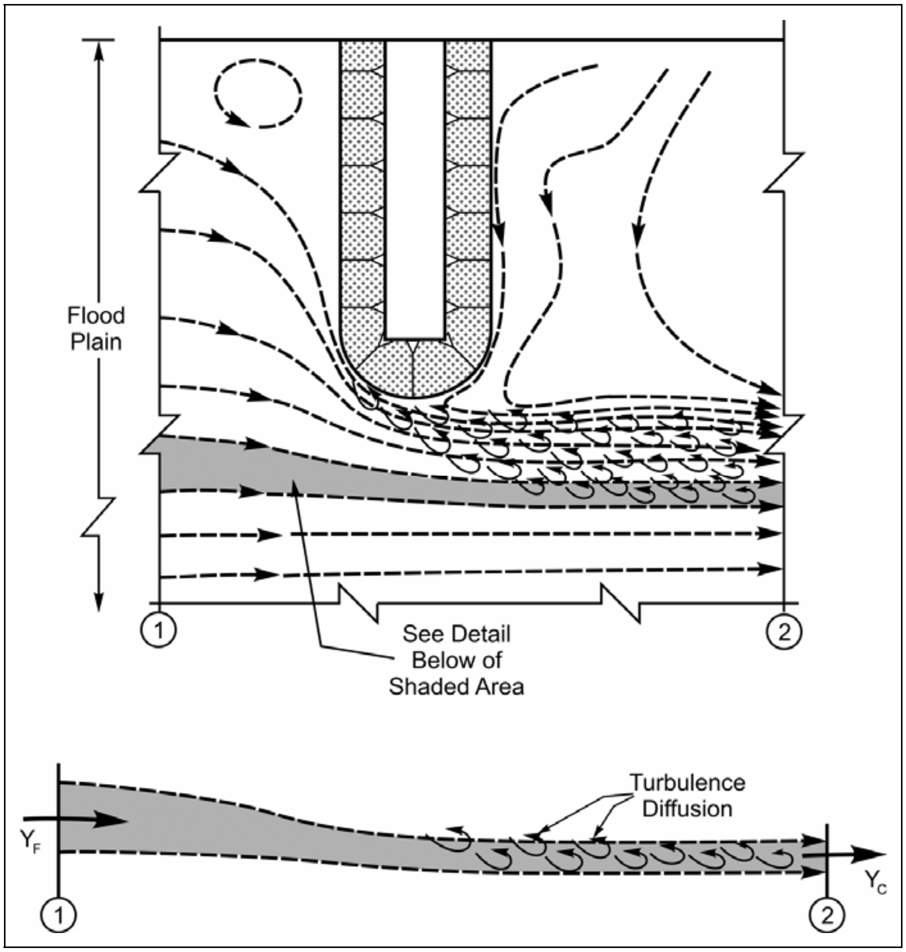


Figure 4-18. Flow contraction around an abutment, and turbulence generation by flow separation from the abutment. The detail streamtube shows how the flow is concentrated, and turbulence introduced, in the scour region

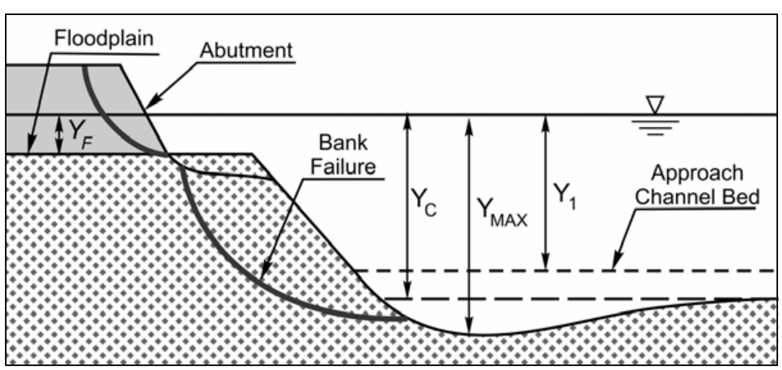
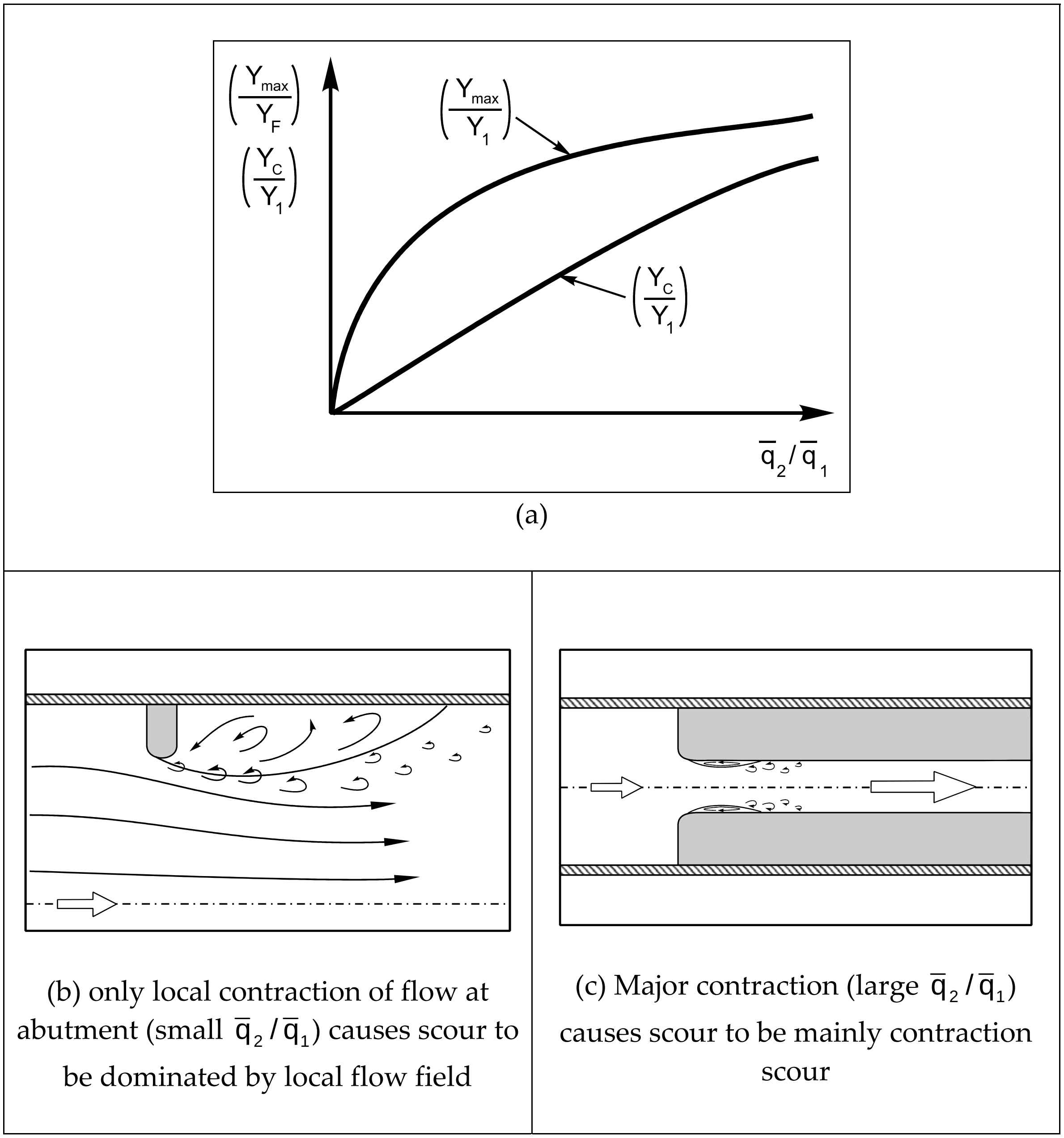


Figure 4-19. Scour of the bed of the main channel, or of the floodplain, can result in the slope instability of the main-channel bank, and the abutment embankment



(a)

(b) only local contraction of flow at abutment (small $\bar{q}_2/\bar{q}_1$) causes scour to be dominated by local flow field

(c) Major contraction (large $\bar{q}_2/\bar{q}_1$) causes scour to be mainly contraction scour

Figure 4-20. Scour depth trend with flow concentration around an abutment (a); With only small flow concentration, the scour is due to combined effects of local contraction of flow around the abutment, and flow turbulence generated by flow at the abutment (b); With large contraction of flow, flow contraction is the major cause of scour (c), this case is similar to scour in a bottomless culvert.

4.5 Narrower Bridges

For the waterways of narrower or smaller bridges (say, of three or less spans), the scour processes described above may occur together and overlap, complicating scour-depth estimation, possibly producing unforeseen scour processes.

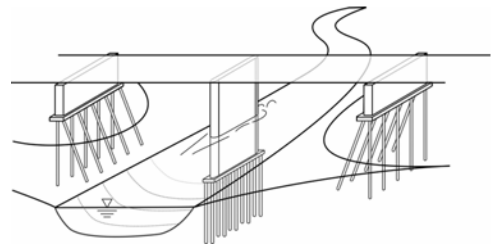
Moreover, shorter bridges are more susceptible to partial blockage by debris: trees and sundry other vegetation. For such bridges, debris accumulation may radically alter waterway geometry, deflecting flow in directions not anticipated in the design of the bridge. This concern is illustrated by two photographs presented as Figures 4-21a and 4-21b. For a long bridge (Figure 4-21a), debris accumulation at a pier remains localized at the pier, and is largely a floating accumulation. However, for a short bridge (Figure 4-21b) over a stream with quite variable water flows, a debris accumulation may block a substantial part of the bridge waterway. Further, an accumulation may become embedded in the waterway, and thus deflect flow adversely toward an abutment or a nearby pier. The debris accumulation may trap bed sediment, and become anchored into the channel bed.

(a)

(b)

Figure 4-21. Debris accumulation at bridge piers may affect flow more significantly through a shorter bridge than a longer bridge [e.g., (a) longer bridge over Miami River, Ohio, develops only a local accumulation, whereas (b) a major blockage could occur at a shorter bridge, such as the one shown unknown Creek]

5
MONITORING INSTRUMENTATION AND METHODS



5.1 Introduction

The essential intent of monitoring is to enable bridge engineers to obtain an accurate assessment of the waterway condition, as well as to detect potential or impending problems with the waterway and the bridge placed in it. Monitoring can be done quite simply, requiring a visual check and, perhaps, a limited amount of data, or it may entail an extensive measurement effort that produces detailed data on waterway bathymetry (flow depths) and on the possible exposure of pier or abutment foundations. Accordingly, there are a variety of methods and instrumentation that can be used for monitoring.

Note that the instrumentation and methods described in this chapter are used for bridges of all sizes. For small bridges, instrumentation emphasis likely is on the use of hand-held devices (such as simple rods) and on visual inspection, since much of a typical small waterway is directly viewable by eye.

5.2 Aspects to be Monitored

Before outlining the instrumentation and methods, it is useful to run briefly through the main aspects of a bridge waterway that need to be monitored:

- Physical characteristics of the waterway (including bed material and bank erosion);
- Physical characteristics of bridge abutments, piers, and approach embankments;
- Geomorphic history of the waterway upstream and downstream (history of changes in the location, shape, and elevation of the channel);
- Hydraulic forces imposed on the bridge components by the waterway, especially force amplifications produced by debris or ice;

- Changes in the river channel or flow due to development projects (such as dams, diversions, and channel stabilization) or natural phenomena;
- Interaction between the abutments, piers, and footings supporting the bridge and the impact of hydraulic conditions on general scour and local scour (i.e., erosion of the channel bed);
- Condition of the riprap, revetments, spurs, and other structural devices that may have been utilized to help protect the bridge and adjacent channel; and,
- Changes in the sediment balance in the stream due to nearby streambed stream gravel mining or landslides can cause streams to aggrade or degrade, and become laterally unstable

Inspecting bridge waterways and monitoring for scour, especially right after high flow events, can provide early indications of waterway stability problems.

5.3 Monitoring Methods

Waterway monitoring typically is accomplished by two basic means:

1. ***Surface or "Wading."*** Exposed foundations can be accessed by foot (Figure 5-1). Submerged substructure, streambeds and embankments are often accessible by inspectors using hip boots or chest waders and probing rods. Additionally, truck-mounted telescopic booms (Figure 5-2) and boats (Figure 5-3) are often used as a surface platform from which to gather waterway data, including channel cross-sections, and pier soundings.

2. ***Underwater Diving.*** Site conditions for larger bridges may require waterway and submerged substructure units to be evaluated using divers, in order to obtain complete, accurate data. This is especially true when water depths are too great for wading inspection, and/or undermining of substructure elements is suspected.

Figure 5-1. Inspecting pile exposure at an abutment after a flood–flow event, Fullmer Creek, New York

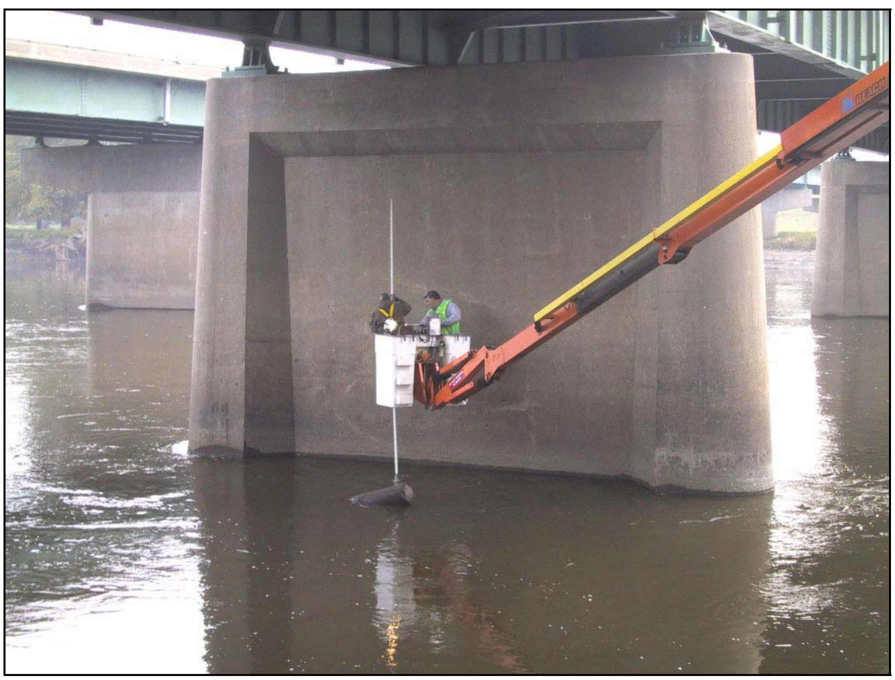


Figure 5-2. Access by means of a truck-mounted telescopic boom. Equipment of this scale usually is used by the Iowa DOT, Highway 151 bridge over Cedar River, Iowa

Figure 5-3. Surface-monitoring of bridge waterway conditions by means of boat; Missouri River, Montana

5.3.1 Monitoring Procedures

The procedures and related instrumentation depend on the purpose of the inspection and can be categorized as follows:

1. ***Visual:*** The primary method used to inspect waterways is visual. The inspector must look at the site in the vicinity of the bridge. The inspector also needs to look at the flood plain. This observation may have to be done during periods of high water flow.

2. ***Probing:*** After the inspector gets the general condition by visually inspecting the bridge site, the next step is to probe for any scour or undermining. Care should be taken to adequately press the probing rod into the soil in the streambed. Sometimes scour holes are loosely filled with silt. This silt may be washed away quickly during the next period of high stream flow velocity, permitting additional scour.

3. ***Measuring/Documentation:*** Measurements to obtain the cross section and profile must be taken. These measurements are used to analyze the area of the hydraulic opening and help determine the need for, and design of, mitigation measures. The cross section under the bridge can be measured with a surveyor's tape or rod. The stream profile is measured with a hand

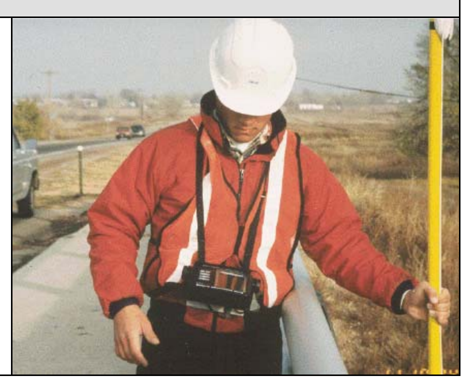
level, survey tape and surveying rod. The streambed profile and hydraulic opening should be compared to previous inspections.

5.3.2 Instrumentation

This section focuses on instrumentation for collecting bathymetry and water-depth data during scour monitoring of bridge waterways. Supplemental measurements during bridge monitoring may include measurements of flow distributions (unit discharge, velocity) across a waterway, and sediment analyses (sediment cores, sediment size distributions, transport rates). There is a wide variety of instrumentation used and vast literature on waterway monitoring (e.g., see Mueller and Landers 1999).

The typical scour monitoring instrumentation can be described as being portable (in that it can be transported, by hand or by vehicle to a bridge site) or fixed (installed at the bridge site, and usually monitoring real-time at the site). Tables 5-1 and 5-2 describe for portable or fixed instrumentation, respectively, the role, principle of operation, advantages, and limitations of the instruments and associated methods.

Table 5-1. Portable instruments for scour monitoring at waterways

<table>
<tr><th colspan="2">PROBING RODS</th></tr>
<tr><td>
• Short pole for checking scour depth
• Advantages: Not affected by air entrainment or high sediment loads.
• Limitations: Not applicable for large depths, high velocities, debris or ice accumulation. Susceptible to bed surface penetration.
</td><td></td></tr>
<tr><th colspan="2">SOUNDING POLE</th></tr>
<tr><td>
• Long pole used to probe the scour depth.
• Advantages: Not affected by air entrainment or high sediment loads.
• Limitations: Not applicable in high velocities, debris or ice accumulation. Weight must be kept low with a large foot in order to not penetrate the river bed and receive incorrect depths.
</td><td></td></tr>
<tr><th colspan="2">SOUNDING WEIGHTS</th></tr>
<tr><td>
• Torpedo shaped weights (45-136 kg) suspended by measurement cable deployed in the stream to measure scour depth. Crane or boom is required to raise and lower the weights.
• Advantages: Not affected by air entrainment or high sediment loads.
• Limitations: Not applicable in high velocities, debris or ice accumulation. The measurement is slow. Susceptible to bed surface penetration.
</td><td></td></tr>
<tr><th colspan="2">SONAR</th></tr>
<tr><td>
• Sound waves are used to measure scour depth.
• Advantages: Salinity has little effect on readings. Can be deployed on floating platforms and operated remotely. Can be coupled with Global Positioning System (GPS).
• Limitations: Affected by high sediment or air entrainment. Operated in depths >2 m and velocities >3 m/s might encounter problems.
</td><td></td></tr>
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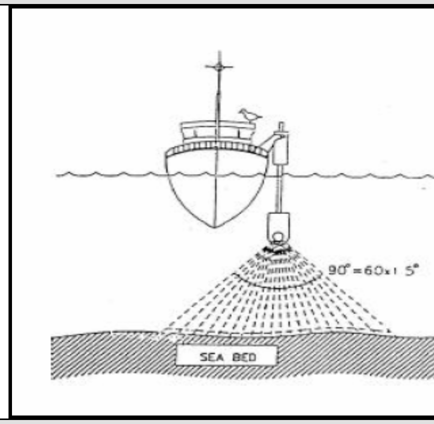
SCANNING SONAR

- Rotating high resolution sonar for **mapping the bathymetry**. Transducer can be suspended (on a crane or boom), mounted on a boat, or fixed.
- **Advantages**: Provides high definition images. Can be used in high water velocity (20 ft/s) and equipped with GPS for mapping.
- **Limitations**: Typically expensive (include instrument, computer for data acquisition, and data storage devices). Stable deployment vessels required or instrumentation to correct for ship's pitch and roll.



GROUND PENETRATING RADAR

- Similar to sonar, it uses electromagnetic waves to detect interfaces between the surveyed layers, hence **bathymetry mapping** can be obtained.
- **Advantages**: Provides high density data.
- **Limitations**: Cannot be used with saltwater or in flows with high suspended sediment. The instrument cost is high and professional data interpretation needed. It is labor intensive.

RANGE-AZIMUTH SYSTEMS

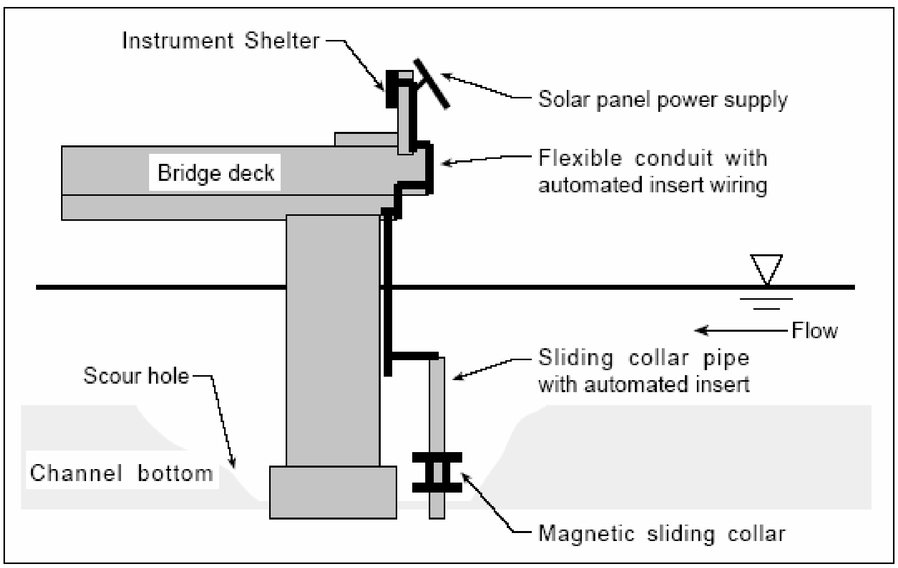
- Range-azimuth systems operate similarly to survey total stations by combining an electronic distance meter (EDM) with a theodolite to document the **change in channel morphology.**
- **Advantages**: Can measure with high accuracy up to 10,000 m (using prisms) with a frequency of 2-10 times per second.
- **Limitations**: The disadvantage of the system is the initial cost, which was from 3 to 5 times the cost of a manual system in 1993.

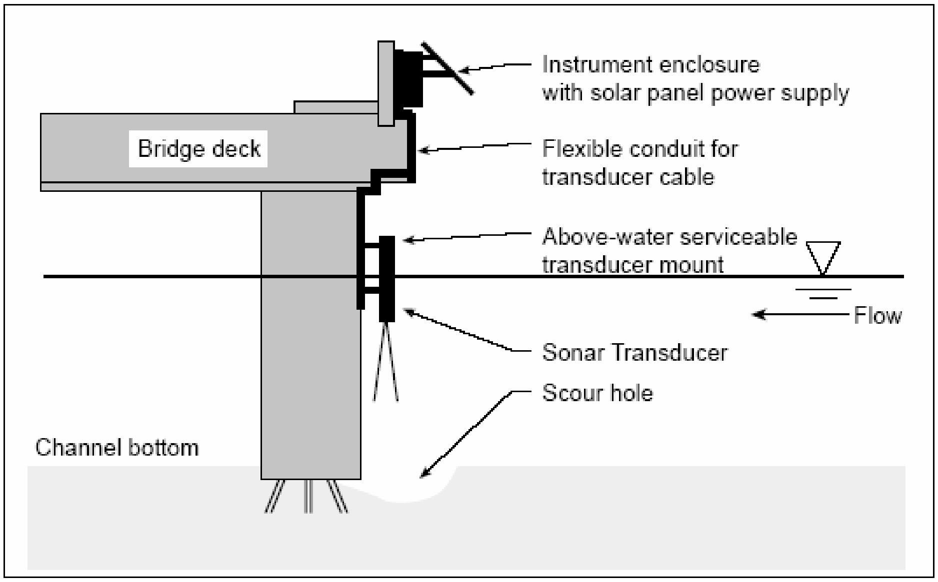
REMOTELY CONTROLLED, UNMANNED BOATS

- Unmanned vessel used to deploy instrument **for bridge inspection** (scour depth, stream velocity, cameras).
- **Advantages**: Unmanned, so no persons could be injured during a storm event.
- **Limitations**: Pitch, roll, and capsizing must all be monitored, and knowledgeable operator must be used.

DIVER, DIVING EQUIPMENT	
• Underwater data collection and documentation is an invaluable source of information about the **structure and extent of the scour.** • **Advantages:** Eliminate uncertainties associated with the measurements with instruments. • **Limitations**: Large depths, high velocities, debris or ice accumulation. Labor intensive.	

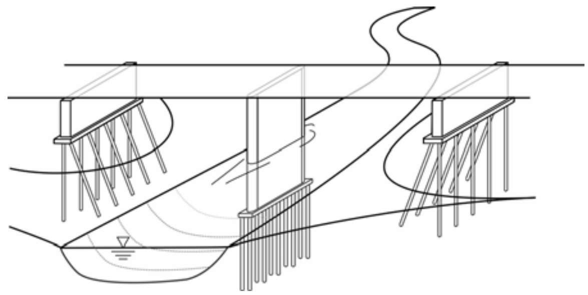
Table 5-2. Fixed instruments for scour monitoring of waterways

DRIVEN/BURIED RODS
• Driven/buried-rod scour monitors derive their name from the fact that a rod must be driven or buried into the streambed to measure the scour depth. The following sensors can be used in conjunction with driven/buried rods: ◦ Horseshoe Collar ◦ Magnetic Collar ◦ Piezo-Electric Probes ◦ Heat Dissipation Gage ◦ Photo-Electric Cells ◦ Trip Switch Probes • **Advantages**: Rods that have a sensor mounted in a collar may be more economical and easier to install than those with sensors mounted on the sides of the rod. The piezo-electric probes, heat-dissipation gage, photo-electric cells, and conductance probes can measure both scour and deposition. • **Limitations**: The instruments utilizing a sliding collar or trip switches can measure only maximum scour and not subsequent deposition. Installation of all driven/buried rod systems can be difficult, and this makes the technology undesirable in streams with coarse or hard bottoms. Damage by ice and debris is also a potential problem.


FATHOMETERS
• Similar to sonar, uses sound waves to measure **scour depth** locally. Usually it is deployed at the location of maximum depth. • **Advantages**: Real-time data acquisition, and operation from the boat. • **Limitations:** Air entrainment, high sediment content can affect readings.


FLOAT-OUT DEVICE
• The device is placed at a desired depth in the rip rap, and when scour reaches that level, the device floats to the surface signaling a **critical level of the scour**. • **Advantages**: Receiver can transmit signal to cell phone or pager when problematical scour depths are reached. • **Limitations**: Needs reinstallation after one signaling event.


6
PROTECTION, MAINTENANCE, AND REPAIR



6.1 Introduction

A point to be emphasized is that effective protection against scour, along with good maintenance and repair of waterways, in concert with regular monitoring, are key considerations for reliable design-life performance of a bridge waterway.

Bridge waterways often are fitted with various scour protection methods that go a long way to mitigate scour concerns. However, it is quite common for bridge waterways to require maintenance and repair because of damage, or possible impending damage, caused by one scour process or another. For example, adjustments in upstream channel alignment owing to changes in land use, the abrasive impacts of large flows, or head-cut advance along the downstream channel, may result in wear and tear of bridge waterways.

The present chapter outlines and illustrates concepts for scour protection and repair of bridge waterways. Case study photographs illustrating specific examples of maintenance and repair activities are provided in Appendix B.

Waterway maintenance and repair entails undertaking one or more of the following remedial actions:

1. ***Approach-channel control***. If the damage is attributable to a troublesome approach flow, such as caused by channel shifting, the approach flow must be controlled so as to realign its passage through the bridge waterway;
2. ***Downstream-channel control***. If the damage is caused by troublesome changes in the condition of the channel downstream of the bridge, these conditions must be mitigated so that the bridge is no longer affected by them. It is usual for some channel-control structure to be placed so as to

ensure that the adverse condition does not affect the bridge waterway. In western Iowa, for example, a common concern in this regard is the movement upstream of a so-called knickpoint (Figure 3-8) or head cut in the channel bed (Figures 3-9). Such knickpoint or head-cut migration may expose the foundations of a bridge and cause embankment failure;

3. ***Armoring of bridge opening***. If the foundation of an abutment or a pier is about to be exposed, or an approach embankment or riverbank to be eroded, these locations need to be armored with riprap stone or some other protective surface;
4. ***Bridge modification***. Sometimes it is necessary to modify a bridge so as to enable better passage of flow through a bridge waterway. The bridge modification may be needed because of a change in the approach channel, or perhaps to improve an inadequate initial design; and,
5. ***Drainage control***. Flow draining along the sides of an approach embankment must be discharged into the waterway without eroding the waterway.

It is to be noted that the protection actions applied to small bridges usually are limited to armoring of the bridge waterway and the approach channel. The comparative narrowness of the waterway and channel makes the use of certain channel control methods infeasible, as is mentioned subsequently.

Nevertheless, it is useful to describe here the full range of repair actions that can be used, and to provide guidance as to the type of protection method likely needed for particular sites. Not included here, though, are the detailed construction considerations associated with each of the remedial actions. In most cases, the layouts of flow-control structures are determined on a site-by-site basis, and sometimes require investigation by means of a hydraulic laboratory model or a two-dimensional numerical model.

Chapter 8, Bibliography, has a section that gives numerous references to articles on the design and performance of specific scour-protection methods. For example, there exist several design guides for determining the layout of riprap blankets, aprons, or side-slopes, and for the sizing of the riprap stone forming them.

6.2 A Cautionary Word

Scour control can be a "tricky" process. When protecting one bridge component (e.g., and abutment) against scour, or protecting the entire bridge, it is possible that the scour problem is simply shifted elsewhere, or that another problem may result. Therefore, when considering possible scour-protection concepts, it is important to evaluate the likely consequences of the protection method. For instance, scour protection of an abutment may concentrate flow locally so as to aggravate scour at an adjacent pier; and, adjustment of the angle at which a channel approaches a bridge opening may result in bank erosion a short distance downstream of the bridge.

James Eads, the civil engineer and river engineer who built the first bridge across the Mississippi River (at St Louis), once remarked that "nature has endowed the river with something wonderfully resembling the instinct for self-preservation that is common to the whole animal kingdom.[2]" What he meant was that river and stream channels seem to have a knack at slipping out of the control intended by engineers. Accordingly, in the context of bridge waterways, it is wise to express a cautionary word. It cannot be assumed that, once set along a prescribed orientation and bed elevation through a bridge waterway, a river or stream channel will hold to its course.

6.3 Upstream-Channel Control

Approach-channel control is intended to guide the approach flow directly through the bridge opening, so that the flow does not expose the bridge's component piers, abutments, and approach embankments to scour. Flow control methods seek to streamline the flow through a bridge waterway; or, in other words, to minimize a bridge's obstruction to flow. It is usual, for example, to reduce the angle between the major horizontal axis of a pier and the approach flow for an approach-channel remediation.

Figures 6-1 through 6-5 illustrate the usual options for flow control. The options vary in accordance with the extent to which the approach flow has to be aligned and guided through the bridge opening.

Flow control can be summarized as typically requiring the use of one or more of the following structures for the purpose indicated:

- ***Guidebanks*** – are fitted to bridge abutments in order to guide flow locally through a bridge opening. Guidebanks are used in situations where a wide flow approaches a bridge opening at an awkward angle or has to be

[2] James Eads' address to merchants at the Cotton Exchange; published in the New Orleans Picayune, Feb. 16, 1878.

"funneled" through the bridge opening. Guidebanks are often used for guiding floodplain flow through an opening, or for guiding flow through bridge openings in broad, braided channels. Figure 6-1 shows a common arrangement of guidebanks;

- ***Hardpoints*** – are short, erosion-resistant outcrops placed to ensure that channel alignment is maintained in situations where the approach channel may otherwise tend to shift laterally. The hardpoints also serve as roughness elements that act to slow flow Figure 6-2 illustrates a typical application of hardpoints. Sometimes, various flow-slowing devices (termed retards) are used to slow flow and reduce erosion near a channel bank;
- ***Spur dikes (also called jetties, wing-dams, groynes) –*** are fitted to force the re-alignment of a channel and/or to increase flow velocities. Channel re-alignment may be needed when an approach channel is shifting laterally. Increased flow velocities may be needed in situations where a channel has widened, flow velocities decreased, and the approach channel is aggrading. Channel aggradation may reduce the flow area of the bridge opening, as shown in Figure 6-3;
- ***Bendway weirs or barbs*** – are fitted to stop lateral shifting of a channel, and, thereby, to re-direct the channel optimally through a bridge opening, as shown in Figure 6-4; and,
- ***Vanes*** – are an alternative to spur dikes, bendway weirs or barbs for use in improving approach channel alignment, as shown in Figure 6-5.

Note that, in progressing from channel-control structures 1 through 5, the repair effort entails dealing with a widening channel, so as to ensure that the channel passes centrally through the bridge waterway.

For smaller channels, channel control normally is limited to the use of hardpoints, though sometimes they might be shaped similarly to short spurs of barbs. In most situations, the narrow or none-existent floodplains at small bridges mean that no control is needed for floodplain flows.

Additional channel control methods include –

1. ***Removal of brush (small/large trees) and sloughed river-bank material*** – this a mundane but very important requirement for ensuring that the bridge opening does not become clogged, and that flow within the waterway does not get deflected adversely towards a pier or abutment; and,

2. ***Bridge widening or shifting*** – is an option when the options for channel control are infeasible. For some bridge sites, and approach channels, a technically and fiscally more feasible option is to add a span to a bridge, as illustrated in Figure 6-6. This option becomes attractive if the bridge opening should be increased in area so as to reduce flow velocities in the opening, and if an abutment has experienced damage to the extent that it has been largely washed-out.

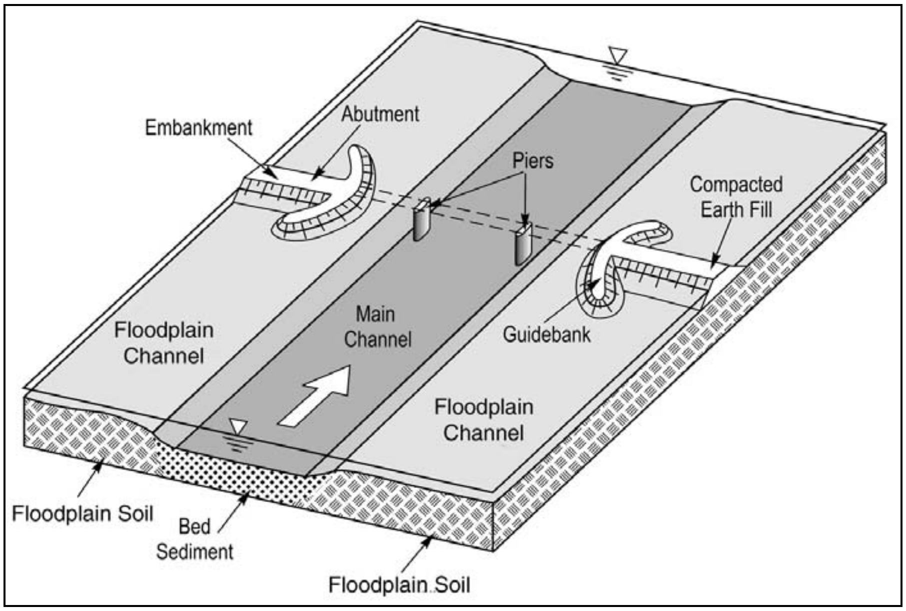


Figure 6-1. Guidebanks placed to guide flow around bridge abutments

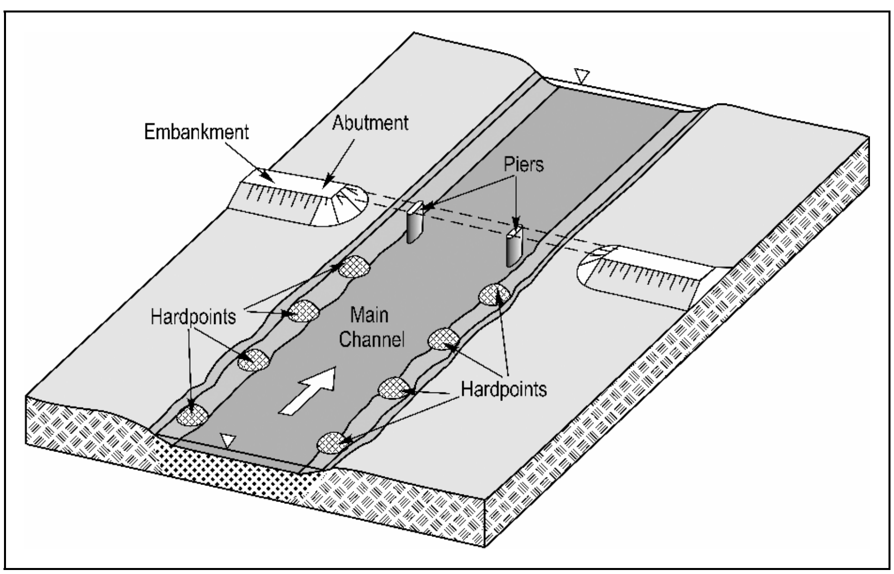


Figure 6-2. Hardpoints placed to keep approach channel in required alignment

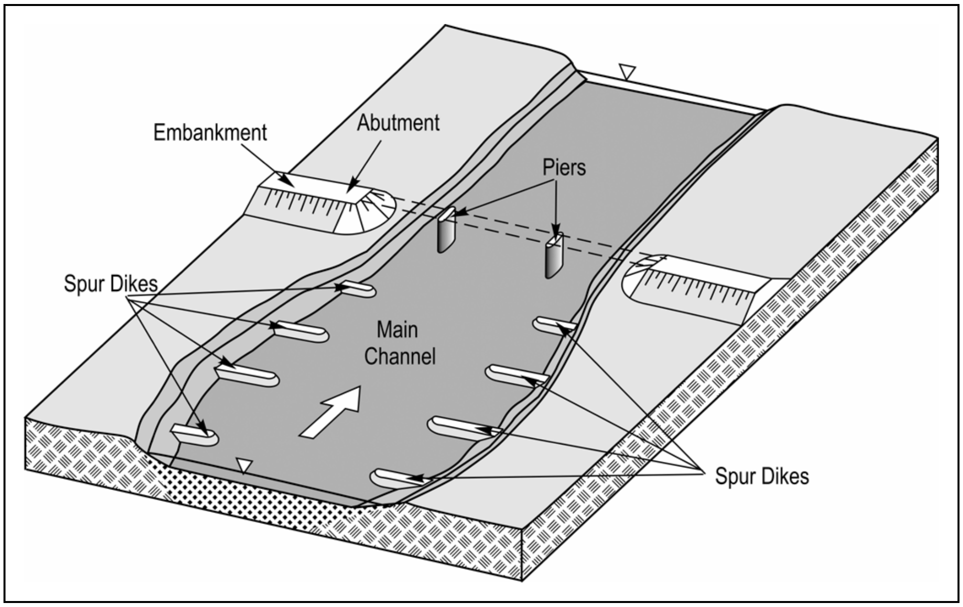


Figure 6-3. Spur dikes placed to narrow a widened approach channel, and to ensure desired alignment of approach channel

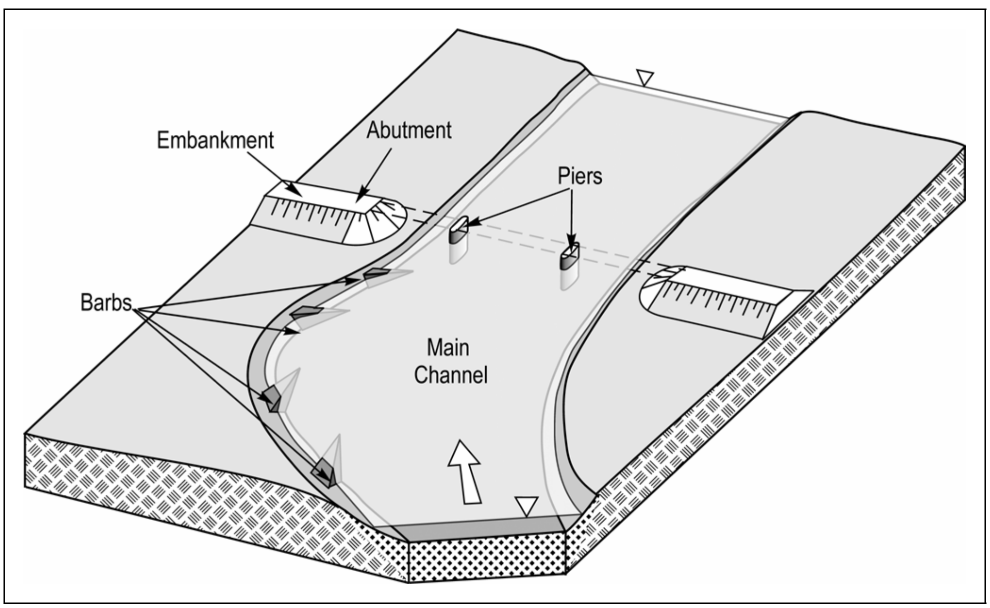


Figure 6-4. Barbs placed to stop lateral migration of an approach channel

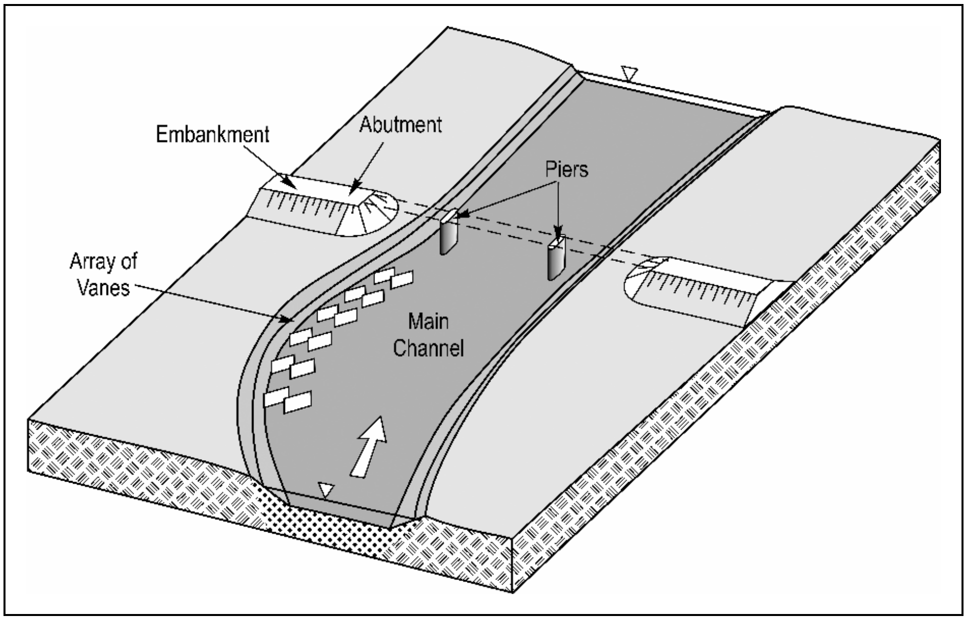


Figure 6-5. An array of vanes placed to stop lateral migration of an approach channel, and to narrow the approach channel to match the width of the bridge opening

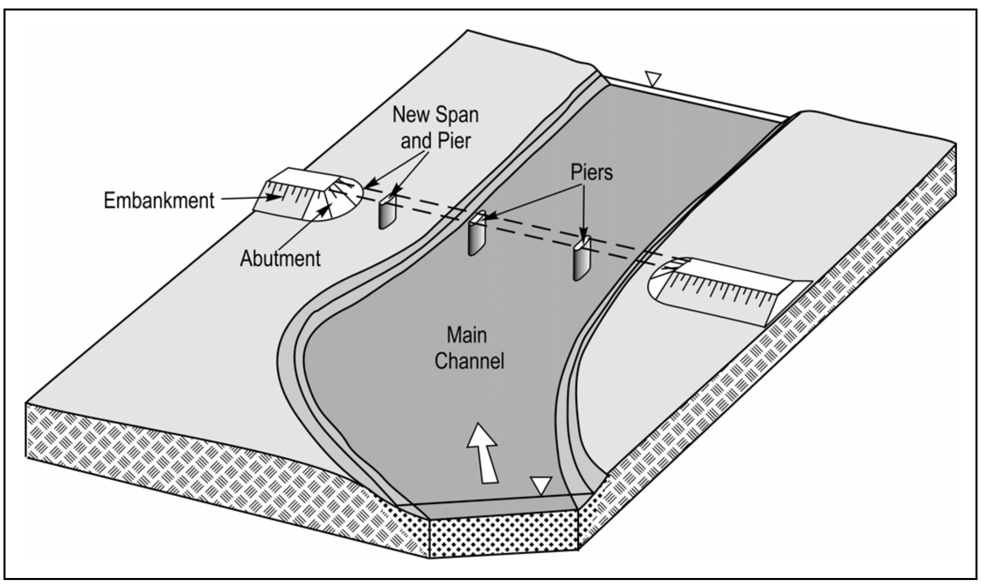


Figure 6-6. Bridge widening to reduce mean flow velocity and bed scour

These flow control structures are used in rather specific applications that often have to be tailored to fit local conditions of channel alignment and morphology, as well as bridge extent and alignment. The references given in Chapter 8 include articles giving further, and more detailed, descriptions and design recommendations. However, as to the use of guidebanks and spurs in one form or another (barbs, bendway weirs, wing-dams), it is useful here to mention briefly a couple of notes regarding their use.

Guidebanks serve to guide flow directly through the bridge opening, especially for bridges placed on floodplains or for bridges crossing channels at locations where the flow approach is awkward. To ensure that guidebanks function as intended, it is important to keep the following points in mind:

1. The guidebanks must extend far enough upstream such that they will not be outflanked by shifts in the main channel. Figure 6-7 illustrates this concern.
2. The guidebanks are best set parallel to each other, so as to maintain steady conveyance of sediment through the bridge opening. They should not converge, whereby they would increase flow velocities through the bridge waterway and, thereby, might aggravate scour; nor should they diverge, so as to decrease velocities through the bridge waterway, and possibly cause excessive scour at the upstream end of the guidebanks and sediment deposition near the upstream side of the bridge opening. Vegetation growth on shoaled regions may be problematic.

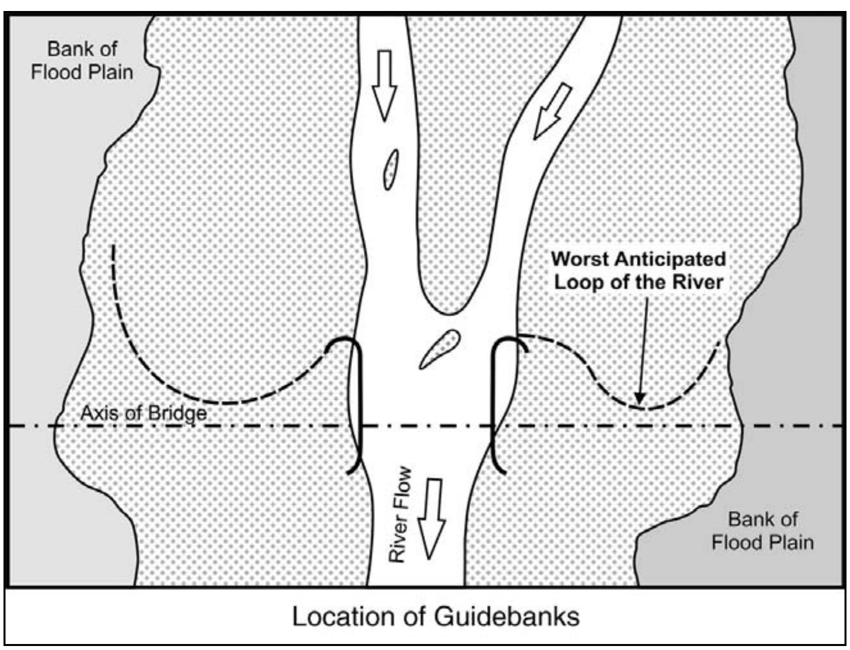


Figure 6-7. The positioning and upstream extent of guidebanks for directing river flow through a bridge opening

There are numerous instances of spur dikes (or variations on spurs) being used to control the approach channel to a bridge opening. There exist design guidelines for impermeable and permeable spurs, guide banks, and riprap stability factor design. The following points are useful to keep in mind:

1. The flow field around a typical spur causes bed scour at the spur's tip, and sediment deposition (siltation) close to where the spur adjoins the river/stream bank, as illustrated in Figure 6-8a. A spur is useful for defining the local path of flow thalweg, as well as providing local bank protection;
2. If the spur points downstream, flow can be drawn to the river/stream bank because the scour hole is moved closer to the river/stream bank. An attracting spur is illustrated in Figure 6-8b;
3. If the spur points upstream, the scour hole is shifted away from the bank, and flow, accordingly, is deflected away from the bank. A deflecting spur is illustrated in Figure 6-8c;
4. Spurs of low crest elevations are sometimes used (barbs or bendway weirs) for sites where concerns exist about excessive depth produced by a spur, spur retarding of higher flow discharges (e.g., bankfull flow), and debris accumulation on spurs. Additionally, flow passage over the submerged spurs reduces the amount of sediment deposition around the spur; and,
5. Spurs in series are spaced so that the space between spurs just accommodates the wake eddy formed by flow around a spur, as illustrated in Figure 6-9. There is no need to space the spurs more closely. The spurs are spaced too widely if flow is drawn in towards the face of the downstream spur.

Spurs and their variants can be built from placed rock or from timber posts driven into a stream/river bed. A great variety of sizes and construction methods have been employed in building spurs.

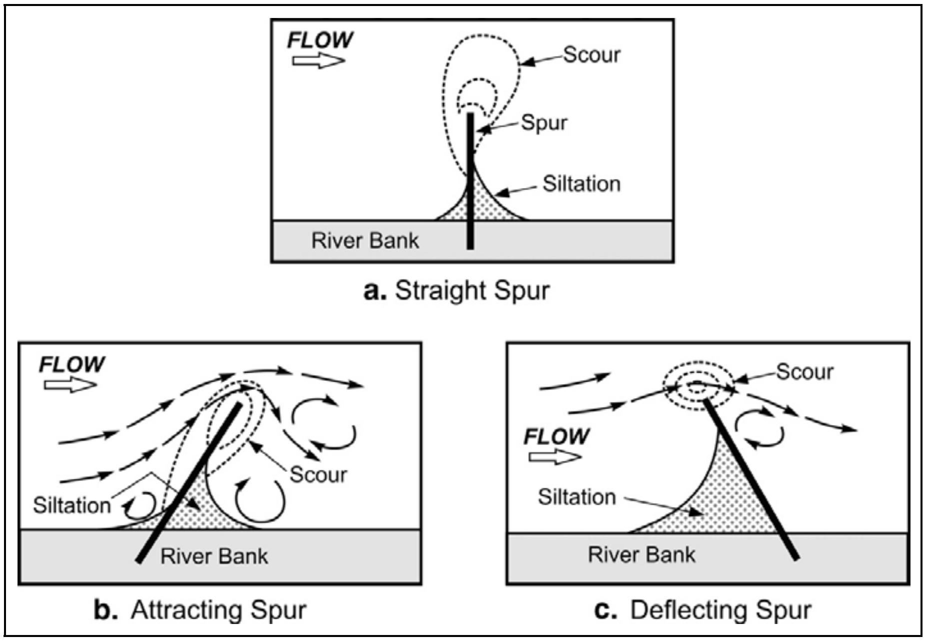


Figure 6-8. Flow, scour and siltation features for spurs (spur dykes, groins, exposed barbs, bendway weirs)

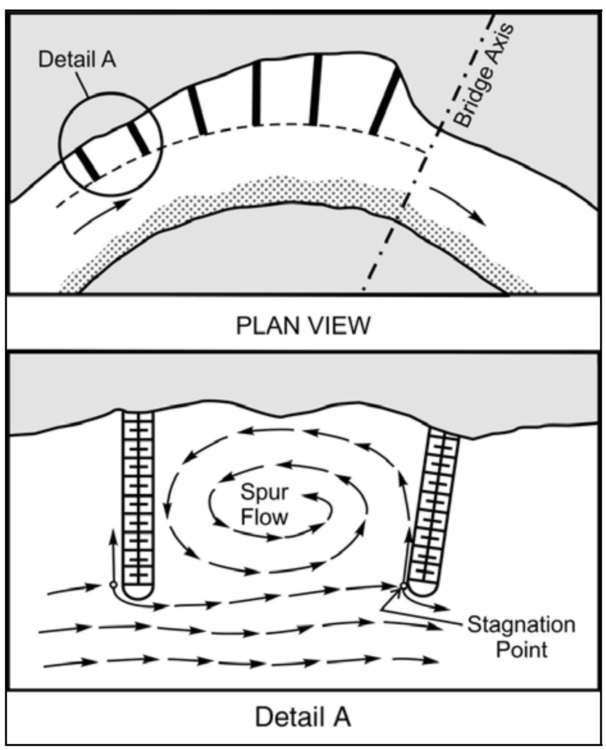


Figure 6-9. Typical spur layout along the convex (curving outward like surface of a sphere) bank

Vanes have been used for erosion reduction on river bends and for stopping river bend migration at a bridge waterway. Vanes are small panels placed in the riverbed at an angle of attack to the flow, which creates a vortex downstream that can be used to manage sediment and alter flow. When placed in an array, vanes deflect water current and bed sediment toward the desired orientation through a bridge waterway. There are several instances where vanes have been used to guide the main channel of rivers in Iowa.

Though spurs usually are employed to guide flow through a comparatively wide (multi-span) bridge opening, they occasionally are used in re-aligning smaller streams whose lateral movement threatens to outflank a bridge. The plan view in Figure 6-9 depicts such a situation.

6.4 Downstream-Channel Control

To stop knickpoint or head-cutting migration upstream, various hydraulic structures have been developed, including sheet-pile weirs, concrete spillways, rock drop-structures, etc. The methods used to halt the upstream advance of a knickpoint have been required to change in recent years, because of concerns that fish and other aquatic species be able to move along a stream or river.

Early work to stop knickpoint migration on small streams requiring single-span bridges sometimes entailed the construction of a bridge waterway as a weir. The resulting bridge was called a Greenwood Bridge, named for the county engineer who developed the concept for this form of bridge waterway. An example is shown in Figure B-38. Sometimes a simple sheet-pile wall was placed across the channel. Such weirs are not well received by environmental biologists because fish migrations upstream are prohibited.

In recent years, considerable effort has been devoted to developing a channel control structure, as illustrated in Figure 6-10, that does not block fish and aquatic creatures from moving along streams. The structures typically have replicated the form and flow features of rock riffles, like small-scale rapids. This type of drop structure is favored by biologists because it resembles a natural rock riffle, and enables fish and aquatic creature migration upstream or downstream. In some instances, grout is applied over the riprap rocks to prevent them from moving during extreme flow events.

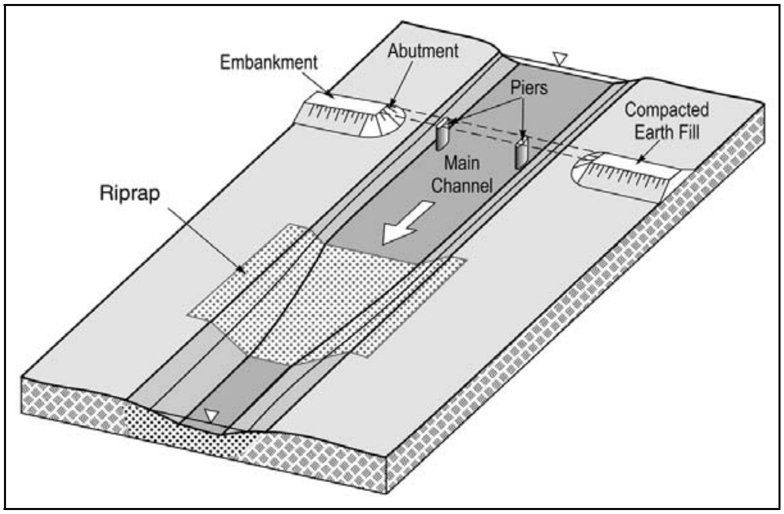


Figure 6-10. A riprap stone riffle placed to arrest head-cut progression upstream towards a bridge waterway. The riffle halts erosion, but enables the passage of aquatic creatures

Appendix B illustrates several successful applications of riprap riffles placed in streams in western Iowa; they have been extensively used in Harrison and Crawford Counties, Iowa.

6.5 Armoring of Abutments

Abutments require several forms of scour protection:

1. Approach-flow guidance, such as discussed above;
2. Armor protection when in contact with water flow; and,
3. Protection against erosion by drainage flow along abutment flanks.

This section focuses on armor protection (item 2).

It is usual for abutments exposed to water flow that some form of armoring be used so that the abutments can resist scour. The most common type of armoring is riprap rock. The placement of riprap rock at the base and side of abutments has been a widely used way to protect abutments. Other armoring methods include cable-tied mats formed of precast concrete blocks tied together as a flexible mat by steel cables; and, on rare occasion, concrete dolos or tetrapods are used. Gabions and geobag containers are sometimes used to retain and armor abutment embankments; geobag containers normally are used as a temporary repair.

6.5.1 Riprap

Riprap is used commonly to protect bridge abutments and bridge approach embankments from scour, as illustrated for the riprap apron in Figure 6-11. The increased weight of the riprap stones enables them to resist the increased turbulence caused by the presence of the abutment in the flow, effectively armoring the underlying sediments. A common layout of riprap stone layer is shown in Figure 6-12 for wing-wall abutments. To protect the layer from various failure mechanisms (discussed below), a skirt of riprap stone is placed in a band around the riprap layer.

Figure 6-12 shows a riprap layer arrangement often used for spill-through abutments. Riprap is placed on the embankment slopes to protect the embankment sediment from scour. However, the riprap can also be placed in a launching apron as a blanket around the toe of the abutment. The stones from the launching apron fall onto the sides of the developing scour hole, reducing the local scour depth, which protects the abutment foundation from being undermined. In many applications, riprap bank protection has traditionally been kept free of vegetation.

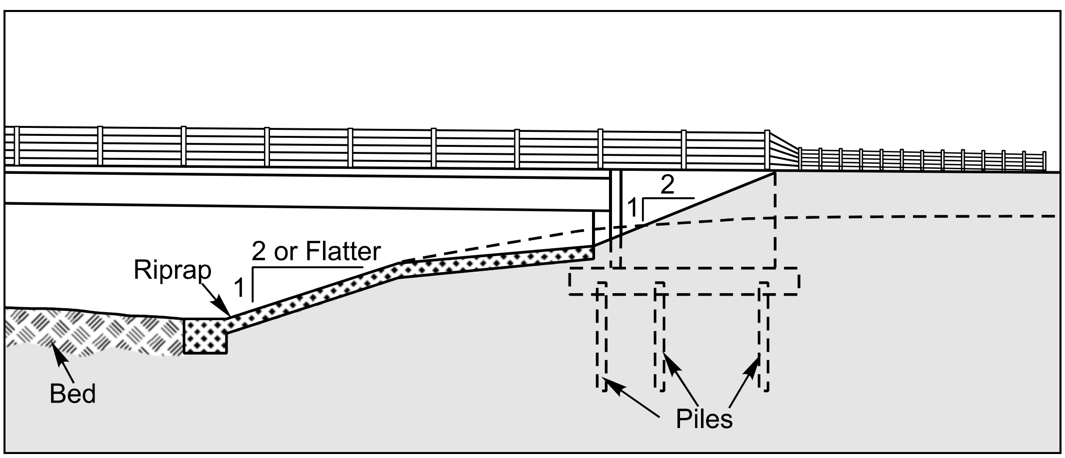


Figure 6-11. A common layout of a riprap apron fitted around a wing-wall abutment with engineering fabric underneath - a toe of riprap stone (about three stones thick) surrounds the apron.

The failure mechanisms of riprap depend on where the riprap is placed in respect to an abutment. Riprap is an effective scour prevention measure, but if incorrectly placed it could initiate scour. Riprap that is placed in an apron is subject to similar failure mechanisms as the riprap that is placed around bridge piers (see below). Whereas riprap placed on the side-slopes of an approach embankment is subject to dislodgment by the flow, it also is subject to slump and slide failures in situations where an embankment fails because of side-slope instability. Launching aprons are recommended to extend about two times the bank-full flow depth out from the abutment toe, as indicated in Figure 6-12.

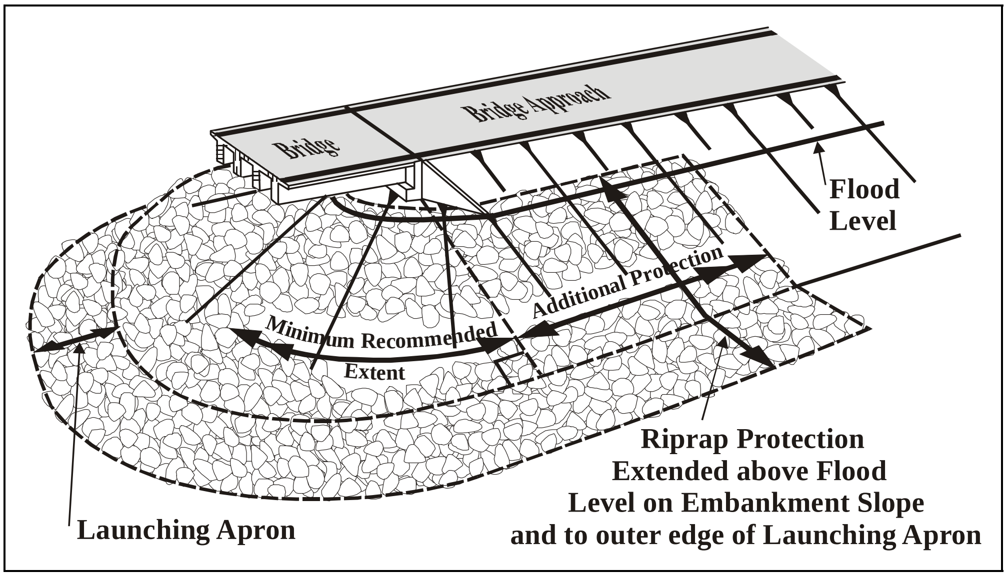


Figure 6-12. Recommended practice for the placement of riprap protection at spill-through abutments (Melville and Coleman, 2000).

There are four main riprap failure mechanisms for riprap placed in an apron around a spill-through abutment on a floodplain, or a wing-wall abutment adjoining a main channel:

1. ***Shear failure*** due to the stones not being large enough to withstand the down flow vortex induced by the flow, resulting in the stones being entrained by the flow;
2. ***Winnowing failure* is** due to the turbulence and seepage flow eroding the underlying bed material through voids between the coarser riprap stones. This process is more likely to occur in sand-bed rivers than in coarser bed materials, such as gravels;

3. ***Edge failure*** where the erosion of the natural bed material at the periphery results in a small scour hole into which the outer stones of riprap apron roll or slide, leading to progressive failure; and,
4. ***Bed-form undermining*** occurs where the migration of the troughs of large dunes past the pier undermines the riprap layer, which settles as a consequence. This is the controlling failure mechanism for riprap placed around bridge piers founded in riverbeds subject to migration of dunes. This failure mechanism would similarly apply to riprap aprons around vertical wing-wall abutments that are situated in the main channel of a river.

There are also four main riprap failure mechanisms for riprap placed on an embankment slope:

1. ***Particle erosion,*** where the hydrodynamic forces of the flowing water are able to dislodge individual riprap stones. Causes are that stones are not large enough; the riprap gradation is too uniform; the embankment side slopes are too steep relative to the angle of repose of the riprap; and the removal of individual stones by impact and abrasion of the flow;
2. ***Translational slide,*** where a translational slide of riprap occurs down the embankment. This may be initiated by channel scour eroding the toe of the riprap blanket, movement along the plane of the filter blanket, excess pore pressures, or embankment slopes that are too steep. This type of failure may be indicated by cracks running parallel to the channel in the upper part of the riprap blanket;
3. ***Modified slump,*** where a mass movement of riprap material occurs along an internal slip surface within the riprap layer. A possible cause is that the slope is near the riprap's angle of repose so that the disturbance of critical matter in the lower levels of the riprap layer results in a slide; and,
4. ***Slump failure,*** where a mass movement of material occurs along a rotational slip surface within the embankment material. Possible causes are excess pore water pressures reducing the resisting shear forces in the embankment material, the use of non-homogeneous base material with layers of impermeable material that can act as fault lines when subjected to excess pore pressure, and side slopes being too steep.

These problems can be avoided by making the riprap rock large enough to resist motion, ensuring the thickness of the riprap layer is adequate and at least greater than one stone thick (this facilitates re-armoring of any scour and eliminates winnowing and edge failure), providing a stone or fabric filter layer to retain the bed material, and ensuring that the riprap extends uniformly over the areas prone to scour. Also decreasing the steepness of embankment side slopes increases the stability of the riprap. Recommendations by various agencies on the use of riprap on side slopes are that riprap should not be used on slopes steeper than 1:2 to 1:1.5 (vertical: horizontal).

It is important that the riprap layer is thick enough and composed of stones of the necessary diameter and gradation to withstand the prevailing conditions. There are many equations that can be used to calculate the required diameter of the riprap. Many of the early equations for riprap stability were based on flat bed conditions. Ishbash (1936) conducted research concerned with the stability of rock dumped in flowing water. Neill (1973) considered the main factors affecting stability to be flow velocity, stone density, rock shape and angularity, depth of flow, degree of turbulence or eddying, curvature of the flow, and slope angle. Maynard (1987) generalized these factors for graded riprap to produce design guides for riprap sizing and placement.

The recommended practice (e.g. Richardson and Davis, 1995; Austroads, 1994) for riprap protection at bridge abutments is to extend the riprap right around the abutment and down to the expected scour depth. This recommended practice assumes the shape and depth of the scour hole are already defined, despite the fact that the protection itself will be a factor in determining scour.

Extending the riprap down to the expected scour depth can be costly and very difficult, especially if it needs to be placed under water. The alternative to extending the riprap down to the expected scour depth is to lay an equivalent blanket of riprap, known as a launching apron, on the existing bed. As the scour hole develops the stones from the launching apron fall onto the side of the scour hole, protecting the side of the scour hole as further erosion occurs. This is seldom practiced, and the riprap rarely extends below the existing riverbed. Partly due to the high cost of riprap, the recommended practice is frequently not adopted, and the riprap barely extends below the existing riverbed.

Richardson et al. (1993) and Lagasse et al. (1997) provide specific guidelines for riprap layout for a launching apron, based on the studies of Pagan-Ortiz (1991) and Atayee (1993). Figure 6-13 illustrates the guidelines. The guidelines are as follows:

- The apron at the toe of the abutment slope should extend along the entire length of the abutment toe, around the curved portions of the abutment to the point of tangency with the plane of the embankment slopes; and,
- The apron should extend from the toe of the abutment into the bridge waterway a distance equal to twice the flow depth in the overbank area near the embankment.

The riprap layer thickness may affect the stability and durability of riprap protection. USACE (1994) specifies a minimum thickness of D_{100} or $1.5D_{50}$, for relatively low-turbulence applications such as bank protection and $1.5D_{100}$ for high-turbulence applications. Maynord (1988) shows that additional thickness above these minima generally results in increased stability. The exact size distribution of the rock riprap is not critical, although it is important that the grading curve should be smooth. Failure to ensure well-graded stone may result in a riprap layer with large voids through which bank or filter material can be winnowed.

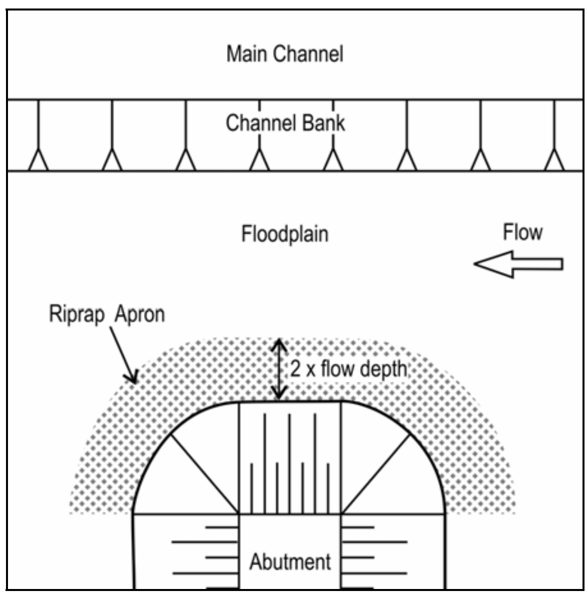


Figure 6-13. Plan view of the recommended extent of rock riprap apron (from Lagasse et al., 1997)

Filters can be used to combat the winnowing effects on abutment slopes. Filters can be granular, making use of the filtering effect of graded sediments, or synthetic commonly known as geotextiles. Filters are placed beneath riprap layers to meet both of the following objectives:

- To prevent the groundwater seepage behind the riprap from transporting the underlying sediment through the riprap, commonly known as piping failure. The filter should be fine enough to prevent the base sediment from passing through it, but more permeable than the base sediment being protected to prevent buildup of any excess pore-water pressures.
- To prevent the high level of turbulence in front of the riprap layer from sucking bank material through the riprap, commonly known as winnowing.

Partially grouted concrete is becoming a popular form of armoring. It entails placing an incomplete filler of grouting amidst riprap stone. The grouted riprap remains porous, but the layer of riprap is strengthened and thus can withstand larger magnitudes of flow velocity and turbulence intensity.

6.5.2 Cable-tied Blocks

Articulated concrete block systems that are held together by cables are commonly known as "cable-tied blocks." Cable-tied blocks comprise precast concrete blocks or slabs that are interconnected to form a continuous protection layer. The cables used can be fabricated from steel, copper, or synthetic materials, such as polypropylene. Another example of cable-tied blocks is given in Figure 6-14.

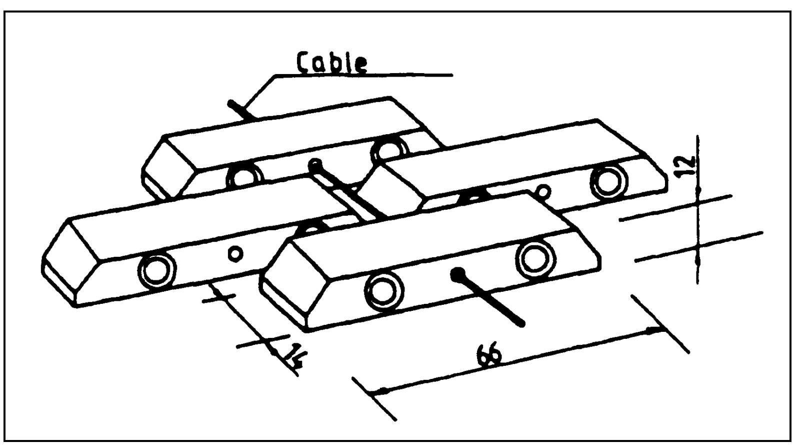


Figure 6-14. Cable-tied blocks used as bank protection (Przedwojski, et al., 1995)

Cable-tied blocks offer an advantage over riprap because the blocks that are subject to the highest dynamic forces (which would probably be unstable as individual blocks), are stabilized by the surrounding blocks so that they act as a system rather than individual blocks.

Cable-tied blocks have been used for a long time in river engineering. However, the application of cable-tied blocks has been limited to river bank protection. There is very little experience with the use of cable-tied blocks as scour protection for bridge abutments. Guidelines for placing cable-tied blocks at bank lines and channels are well documented, and standard specification documents for revetment work using articulated concrete mattresses can be found in U.S. Army Corps of Engineers (1987).

Other methods that have been attempted for abutment scour mitigation are Toskanes, Tetrapods, reinforced soil, and tied mats. These alternative scour countermeasures are used when riprap is not feasible.

6.6 Protection of Piers

Scour of the bed material around the foundations of a pier reduces pier capacity to provide vertical support and lateral, especially streamwise, support. Figures A-11 through A-14 of Appendix A show examples of pier-foundation failure.

The methods used to protect against pier scour are not sophisticated, and can listed in two groups:

1. Flow-altering; and,
2. Armoring.

6.6.1 Flow-Altering

Flow-altering methods seek to substantially weaken the erosive downflow and horseshoe vortex, which are primarily responsible for scour at a pier, as illustrated in Figure 4-3. Flow-altering concepts involve one of the following three methods:

1. Install some form of structure upstream of the pier (e.g., so called "sacrificial piles");
2. Modify the pier's shape; and,
3. Fit on the pier a device that interrupts the downflow or weakens the horseshoe vortex (e.g., a collar).

In practice, however, laboratory tests show that none of these methods works sufficiently well to justify their expense. Also, the addition of an upstream structure, or the placement of a collar on a pier, can aggravate concerns for debris accumulation on a pier, and, thereby, aggravate scour.

To be sure, reducing (or eliminating) pier skewness to approach flow will minimize scour depth. In situations where flow orientation relative to pier axis is difficult to control or maintain (e.g., for piers in wide or braided channels), it is preferable to use piers formed by two circular cylinders rather than solid piers whose axis is long in the streamwise direction.

6.6.2 Armoring

As with armoring of abutments, armoring of the bed around a pier aims to provide a physical barrier against scouring. The barrier is designed to withstand the eroding power of the local flow field formed around the bridge pier. In practice, they are often in the form of large, heavy, rock units that are not easily eroded by the flow, as illustrated in Figure 7-15. Parker et al. (1998) and Melville and Coleman (2000) contain excellent descriptions of examples of these two methods used as pier scour countermeasure.

Bed armoring is used far more extensively than is flow altering. Engels (1929) dates the possible use of riprap at bridge sites as far back as 1893. Besides using riprap as a means to reduce pier scour, there are other alternative armoring devices such as cabled-tied blocks, gabion mattresses, concrete-filled mats and bags, concrete apron, dolos, tetrapods, etc. Some of these methods, such as dolos and tetrapods, are "borrowed" from coastal engineering practices, but their success when used as a pier scour countermeasure is as yet uncertain. Chapter 8 illustrates a couple of applications involving these armor units.

The failure mechanisms that may destabilize riprap stone around a pier, and lead to the breakdown of the riprap layer, are the same as for a riprap mat around an abutment; i.e., shear failure, winnowing failure, edge failure, and bed-form undermining. During a sequence of floods the high velocities and turbulence experienced through the bridge openings can move riprap, so regular monitoring is required. The collapse of the bridge at Schoharie Creek in the USA in 1987, which caused the death of ten people, started with the removal of riprap around the bridge piers (Richardson et al., 1993 and Lagasse et al., 1995).

6.6.3 Streamwise Support for Pier

For situations where scour already has lowered the bed around a pier and has given rise to a load-stability concern for a pier, a special care must be given to resolving the load-stability issues, especially loads exerted in the streamwise direction.

Figure 6-15 illustrates one way of providing additional support. A mound of riprap stones placed around the piles and up to the pile cap may provide the needed support. Alternatively, depending on foundation conditions, additional piles may be driven so as to provide support. The piles may be directly tied to the pier; or, driven to form a containment box around the pier (an example is given in Figure B-3 in Appendix B).

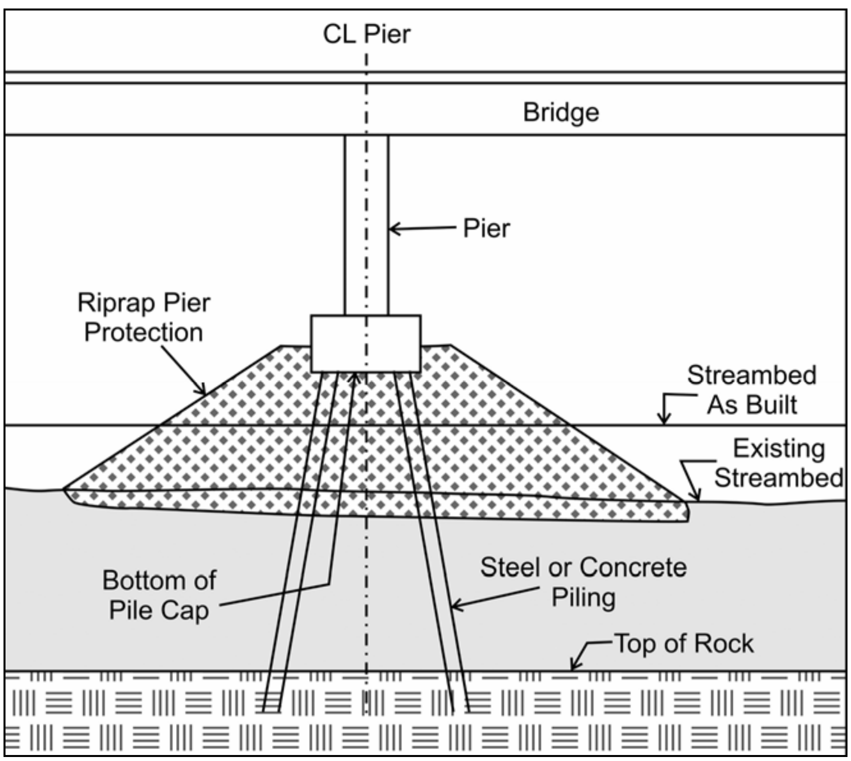
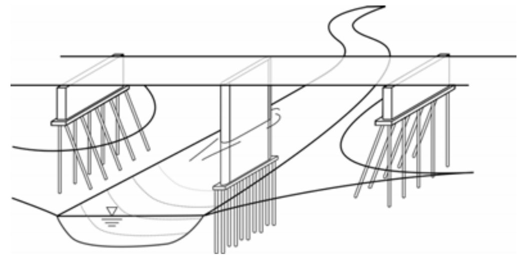


Figure 6-15. Typical riprap protection around a bridge pier

7
SCOUR MONITORING



7.1 Introduction

Several levels of scour monitoring commonly are used for bridge waterways:

1 A basic or preliminary level of monitoring observations. This level is used for bridge waterways known to have no prior scour problems. Additionally, it is used when numerous bridges, especially small bridges, have to be monitored (e.g., Figure 7-1); and,

2 A detailed inspection and site analysis level of monitoring. This level is used for larger bridges, bridge waterways known to be vulnerable to scour (e.g., Figure 7-2); and,

3 A post-flood inspection of bridge waterways that recently have experienced a major flood flow. After, sometimes during, the passage of a major flood flow in a watershed, it is very useful to determine how well bridges withstood the flood flow, and to ascertain whether the flood flow increased bridge vulnerability to scour.

This chapter describes the elements typically included in these levels of monitoring. Examples of these monitoring levels are given at the end of the chapter.

In addition to these monitoring levels a formal, quantitative scour-risk assessment methodology can be implemented, particularly when a rationale is needed for prioritizing bridges in need of repair when repair resources are limited. The methodology is presented in Appendix C as an example that might be considered for adoption (in one form or another) by bridge-inspection authorities seeking a more comprehensive way to evaluate and prioritize bridges for repair or replacement.

Figure 7-1. Basic monitoring of a small bridge entails observing conditions at the site, as well as upstream and downstream of the bridge site

Figure 7-2. Detailed monitoring for scour concerns. In this case, a probing rod is used to measure debris-accumulation thickness at a pier; Verdigris River, Kansas

7.2 Basic Monitoring

The following observations and data are recommended (e.g., by the Federal Highway Administration) to be collected as part of a basic monitoring of bridge waterways:

1. Abutment and pier conditions;
2. Water elevation and discharge at time of monitoring; Cross-section observations and data along the upstream and downstream edges of the bridge crossing;
3. Notes on debris or ice accumulations, surface currents, roughness, and vegetation; and,
4. Observing the stream reaches upstream and downstream.

Table 7-1 lists the itemized properties, procedures, and instrumentation that need to be verified in minimal monitoring.

Table 7-1. Basic level of bridge waterway monitoring

Waterway Aspect	Procedure	Instrumentation
Waterway Channel in Vicinity of Bridge		
Hydraulic opening	Periodic low flow survey and during flood observations. Document freeboard history.	Probing rods, sounding, photos, fathometer, diving equipment.
Structure	Verify drawings or bridge structure (for older bridges).	Visual, diving equipment, tapes, levels, angles.
Control structures in the bridge vicinity	Identify and document existing hydraulic control structures (riprap, spurs, guidebanks, gabions, slope stabilization, channel lining, footing aprons)	Photos and video-recordings
Waterway alignment	Establish observational grid and document history. Check lateral migration of stream.	Visual, photo, aerial photo
Floodplain (if exists)	Check and document accumulations of debris, sediments, and other obstructions (fallen fences)..	Sketch, photos.
Bank condition in the bridge vicinity	Inspect bank stability several hundred feet upstream and downstream the bridge. Keep track of construction activities that might affect stream under the bridge.	Drawings and photos.
Local channel conditions variability	Inspect during low flows and use underwater surveys to check aggradation/degradation within bridge opening and long-term scour due to natural and man-made modifications. Establish observational grids. Estimate maximum scour.	Probing rods, fathometers, sonars, total stations, diving equipment.
Channel vegetation variability	Document vegetation that can obstruct or impact flow within an observational grid and create history track.	Photos and video-recordings.
Abutments		
Shape and orientation	Verify drawings. Inspect during low flows including underwater survey.	Tapes, levels, angles, photos.
Materials defects and damage	Check periodically for defects and damage (undermining, settlement, rotation, failure).	Visual, Probing rods, sounding, photos, diving equipment.
Foundation	Document the type of foundation and level of exposure.	Probing rods, tapes, photos.
Scour variability	Inspect during low flows to check for local scour at abutment and document long-term scour within an observational grid. Estimate the maximum scour and rate the	Probing rods, fathometers, sonars, total stations, diving equipment. Sediment

	abutment condition. Extract bed core samples.	grain analysis.
Piers		
Shape and orientation	Verify drawings. Inspect during low flows including underwater survey.	Tapes, levels, angles, photos.
Materials defects and damage	Check for defects and damage (undermining, settlement, rotation, failure).	Probing rods, sounding, photos.
Foundation	Document the type of foundation and level of exposure.	Probing rods, photos.
Scour variability	Inspect during low flows to check for local scour at pier and document long-term scour within an observational grid. Estimate the maximum scour.	Probing rods, fathometers, sonars.

7.3 Detailed Monitoring

The observations and data collected for the detailed monitoring expands upon the information obtained during basic monitoring. The Federal Highway Administration (e.g., Mueller and Landers 1999) recommends that detailed monitoring should include the following observations and data:

1. Water-discharge hydrograph;
2. Water-surface elevation hydrograph;
3. Water-surface slope;
4. Detailed channel-geometry data at and near the bridge;
5. Channel geometry in the river reach upstream/downstream of the bridge;
6. Flow velocities (magnitude and direction) in the entire study reach;
7. Bed-material samples;
8. Notes on surface currents, channel roughness, and vegetation;
9. Approximate measurements of debris piles present;
10. Photographs of the bridge and stream reaches upstream/downstream;
11. Bridge and pier geometry; and,
12. Soil-boring logs for the bridge crossing.

Table 7-2 lists the itemized properties, procedures, and instrumentation normally considered in the detailed monitoring of bridge waterways, and Figure 7-3 illustrates post-flood monitoring of scour at a bridge abutment.

Table 7-2. Properties, procedures, and instrumentation for detailed monitoring

Location	Procedure	Instrument
Channel Under Bridge		
Substructure	Inspect damage, defects, foundation condition	Visual, photos
	Document foundation exposure and undermining	Sketches, photos, tapes
	Note location of the high water mark on abutments/pier and check for local settlements	Sketches, photos, plumb
	Check for accumulation of debris	Visual, photos
	Document changes in streambed elevation, cross-section, large scour holes	Sketches, photos
	Establish observational grid (first inspection) for depth sounding and make measurements (periodic)	Probing rods, sounding, photos, fathometer, diving equipment.
Superstructure	Check for irregularities in superstructure grade and horizontal alignment	Visual, photos
	Check for lodged debris	Visual
	Check for high water marks, overtopping (verify elevation and frequency in previous inspections)	Visual
Channel protection and scour countermeasures	Examine river training and bank protection devices to determine their stability and condition.	Visual, photos
	Check for separation of slope pavement joints.	Visual, photos
	Check for evidence of protective works slippage	Visual, photos, probing
	Check the evidence, condition, and size of failed riprap in the stream.	Visual, photos
	Check for the proper placement, condition, and function of guidebanks, or spurs.	Visual, photos
	Check if the streamflow is impinging behind the protective devices.	Visual, photos
	Check the streambed in the vicinity of the channel protection for evidence of scour under the device.	Visual, photos, probing, sounding, reflectometer.
	Inspect for steepening of the protective material and the surface upon which these materials are placed.	Visual, photos
Waterway area	Check the hydraulic opening with respect to the floodplain. Determine if the hydraulic opening is causing or has the potential to cause scour under the bridge.	Probing rods, sounding, photos, fathometer, diving equipment.

	Check for contraction scour due to abutment placement, sediment buildup, and vegetation.	Probing rods, sounding, photos, diving equipment
	Determine the streambed material.	Sediment grain analysis.
	Check for local scour around piers and abutments and record data.	Probing rods, sounding, photos, diving equipment
	Check for degradation (inspection during drought conditions recommended).	Visual, diving equipment.
	Check for debris underwater, which may constrict flow or create local scour conditions.	Probing rods, sounding, photos, diving equipment
Upstream Channel		
Banks	Check if banks and slope stabilization procedures are in place and intact. Document unstable banks.	Visual, sketches, photos
Main channel	Record flow velocity.	Floats, velocimeters, video-recordings
	Check for sediment buildup and debris, cattle guards and fences which may alter the direction of stream flow	Visual, sketches, photos
	Determine the streambed material.	Sediment grain analysis.
	Check for aggradation or degradation.	Visual, diving equipment, reflectometer.
	Check the basic alignment of the waterway with respect to the structure and compare it to its original alignment	Visual, total station, tapes
	Record the direction and distribution of flow between piers and abutments.	Floats, acoustic velocimeters,
	Document stream alignment, conditions of bank protection works, and anything that appears unusual at each inspection	Sketches, photos
Floodplain	Check for accumulations of sediments, debris, or significant vegetation growth in the waterway that may impact sufficient waterway adequacy and adversely affect streamflow under the main channel span	Visual, photos
	Check for damage to the approach pavement, shoulders, embankments, and returns to the main channel to flow under the structure.	Visual, photo, sounding, probing
	Check the extent of structures, trees, and other obstructions that could impact stream flow and adversely affect the bridge site.	Visual, photo, sounding, probing
	Check for evidence of embankment	Visual, photo,

	sloughing, undermining, and lateral embankment movement resulting from significant stream flow.	sounding, probing
Other features	Check for streamflow impact of any other features such as tributaries, confluence of another waterway, dams, and substructure units from other bridges	Visual, sketches, photos
	Report any recent construction activity (e.g. causeways, fishing piers, and stranded vessels) which may affect stream flow under the bridge.	Visual, sketches, photos
Downstream Channel		
Banks	Check if banks and slope stabilization procedures are in place and intact. Document unstable banks.	Visual, sketches, photos
Main channel	Check for general alignment and buildup of sediment, which could redirect the stream flow	Floats, velocimeters, videorecordings
	Check for fallen timber in the waterway, boulders or debris, cattle guards and fences that may block or deflect the stream flow.	Visual, sketches, photos
	Determine the streambed material type.	Sediment grain analysis
	Check for aggradation or degradation.	Visual, diving equipment, total station.
	Check the banks for evidence of lateral movement.	Visual, sketches, total station, photos
	Record the location of the waterway with respect to the bridge.	Visual, sketches, photos
	Document stream alignment at each inspection.	Visual, sketches, photos
Floodplain	Check for any obstructions that would prevent constricted flow under the structure from returning to the floodplain.	Visual, sketches, photos
Other features	Note any dams or confluence with larger waterways, which may cause variable tailwater depths.	Visual, sketches, photos

Figure 7-3. Post-flood monitoring of scour at an abutment

7.4 Post-Flood Monitoring

It is useful for the design of repair and protection works for bridge waterways, as well as for the future design of bridge waterways, that scour events and failures be measured and documented during or shortly after the passage of a flood. Information of interest includes scour depths and locations, along with data on the flow conditions associated with the scour event (flow elevations and flow discharge), and observations of the condition of the approach waterway (e.g., whether a channel shift had aggravated scour at the bridge, or whether knick-point migration had exposed piers and abutment supports). These data and observations are useful for developing an information bank on scour failures. Such an information bank is needed in ensuring the sound design of bridge waterways. Figures 7-4 and 7-5, for instance, illustrate post-flood monitoring of embankment failure at an abutment and the measurement of erosion extent behind an abutment, respectively.

A complication in recording scour events is that the deepest scour may have occurred near the peak of a flood flow hydrograph, and that scour depth may have diminished on the waning side of the hydrograph, or it may have become obscured when part of the bridge waterway failed; e.g., when an embankment sloughs into the scour hole. This complication needs to be kept in mind when assessing a scour event at a waterway.

Figure 7-4. Post-flood monitoring of embankment failure at an abutment

Figure 7-5. Measurement of erosion extent behind a wing-wall abutment, Turkey Creek, Iowa

7.5 Examples of Monitoring Reports

Presented here are two examples of the scour-monitoring portions of bridge inspection reports or forms used in Iowa. One form (Table 7-3) is used by a county, and the other form (Table 7-4) is used by the Iowa Department of Transportation. The two examples are illustrative of monitoring reports used elsewhere besides Iowa. An interesting feature of the form used by the county is its procedure to quantify or rank the condition of the components of the bridge being inspected. Appendix A presents a more elaborate and expanded (risk management) version of a quantitative monitoring procedure.

Table 7-3. The main features of inspection form used by a county in Iowa when inspecting bridges biennially

BRIDGE INSPECTION REPORT **Date:**____________

Bridge No.: _________ **Bridge Type:** _____________________ **Inspector:** _______________

Bridge Name: __________ **Crossing Over:** ________________ **Year Built:** ______________

Section: ____ **T** ____ **NR** ____**W Township:** ______________ **County:** _________________

Route Carried: _______________

CONDITION RATINGS: (Use for ISIA Items 60, 61, & 92)

N: **Not Applicable**
9: **New Condition**
8: **Near New Condition** – No problems
7: **Good Condition** – Only minor problems – Normal operating conditions
6: **Generally Good Conditions** – Showing wear, weathering or minor problems. May need minor repairs
5: **Fair Condition** – Problems may affect strength or usability. Problems need repair.
4: **Marginal Conditions** – Problems requiring repair and affecting strength. Load restrictions warranted.
3: **Poor Conditions** – Major problems requiring repair. Load restrictions required.
2: **Critical Conditions** – Major problems present. Load restrictions required. Maybe unsafe for traffic.
1: **Very Critical Condition** – Major problems make bridge unsafe for traffic.
0: **Closed** – Structure is unsafe and closed. Possibly beyond repair.

---

60 Substructure

ITEMS		CONDITION RATING	REMARKS
1. Abutment	Caps	_____	________________________
	Wings	_____	________________________
	Backwall	_____	________________________
	Footing	_____	________________________
	Piles	_____	________________________
	Erosion	_____	________________________
	Settlement	_____	________________________
2. Piers/Bents	Caps	_____	________________________
	Column	_____	________________________
	Footing	_____	________________________
	Piles	_____	________________________
	Scour	_____	________________________
	Settlement	_____	________________________

ITEMS	CONDITION RATING	REMARKS
3. Pile Bents	______	______________________________
4. Concrete Cracking/Spalling	______	______________________________
5. Steel Corrosion	______	______________________________
6. Timber Decay	______	______________________________
7. Debris on Seats	______	______________________________
8. Paint	______	______________________________
9. Collision Damage	______	______________________________

INSPECTOR'S CONDITION RATING

61 CHANNEL AND CHANNEL PROTECTION

ITEMS	CONDITION RATING	REMARKS
1. Channel Scour	______	______________________________
2. Embankment Erosion	______	______________________________
3. Drift	______	______________________________
4. Vegetation	______	______________________________
5. Channel Change	______	______________________________
6. Fender System	______	______________________________
7. Spur Dikes & Jetties	______	______________________________
8. Riprap	______	______________________________
9. Adequacy of Opening	______	______________________________

INSPECTOR'S CONDITION RATING

92 CRITICAL FEATURE INSPECTION

1. Fracture Critical Feature ______________________________

____

2. Scour Critical ______________________________

____

3. Other Special Inspection ______________________________

____

Table 7-4. The main features of inspection form used by the Iowa DOT when inspecting bridges that recently have experienced a major flood flow

Bridge No. ______________________________ **Area No.** ______ **FHWA No.** ___________________

located in ____

and/or ____.____ mi. __________ of ____

Scour Inspection by Team No. ____________ Date inspected: ______________________

Date Received in Office: _________________

This report contains
Comments ____ Yes ____ No
Sketches ____ Yes ____ No
Photos ____ Yes ____ No

Place an "X" by all that apply

1. ____ Is there a significant build-up of debris?

2. ____ Is there a change in the horizontal alignment of the handrail or structure members such as beams?

3. ____ Is there any indication of vertical movement of the superstructure?

4. ____ Is there shifting of the channel alignment or erosion of the stream banks? Also, are there cracks in the soil of the banks parallel to the stream?

5. ____ Is there a significant change in the alignment of the exterior bearings?

6. ____ Are there cracks or other signs of distress in the approach pavement?

7. ____ Is the water currently on the superstructure?

8. ____ Are the berm slopes steeper than **2:1** from the toe of the scour to the roadway?

9. ____ Do scour measurements indicate: (Place an "**X**" by all that apply.)

_____A. that the streambed is two or more feet below the bottom of pier footings which are supported on piles
_____B. scour below the bottom of spread footings?
_____C. scour below the bottom of high abutment footings?
_____D. that the streambed has scoured five feet or more below the original streambed elevation at pier bents?

Note:
Streambed sounding data is to be documented.

A streambed profile should be done on the upstream side of all bridges. If Item #9 is yes, then a profile on the downstream side of the bridge should also be done in the scoured area. If the downstream profile also indicates a problem, then soundings should be made under the bridge if possible.

If "No" is the answer to all of the items in the checklist, no further action will be necessary.

If "Yes" is the answer to any items on the checklist, contact the Office for further instructions.

An "*" indicates the item is not visible.

Comments: ___________________________

____

____

____

Completed on ___________________________ By ____

Reviewed by ___________________________________ Date reviewed _________________________

Is a follow-up inspection recommended? _____ Yes _____ No

Comments/Recommendations:____

____

____

____

ESTIMATED REPAIR COSTS

1. Removal of debris: ………………………………………………… …$______________________
2. Riprap berms &/or banks: ………………………………………… …$______________________
3. Reshape berms &/or banks: ……………………………………..…$______________________
4. Footing/pier protection: ………………………………………………$______________________
5. Channel protection/retards/jetties: ……………………….………..$______________________
6. Other: ………………………………………………………..…..…....$______________________

Total estimated cost: …………………………………………...……$______________________

Total final cost: ……………………………………………………….$______________________

8
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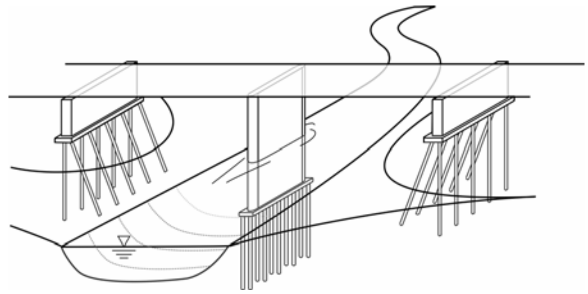

8.1 Introduction

This bibliography lists reference articles (papers and reports) that provide additional detailed information on bridge waterways. The references are grouped in four categories:

1. River behavior;
2. Methods and manuals for scour monitoring of bridges;
3. reports and articles on monitoring instrumentation and field experience;
4. Design for bridge scour; and,
5. Methods for protection against scour.

The reader is encouraged to consult with articles selected from the bibliography in order to obtain further insight into aspects of bridge waterways, as well as to get quantitative information on scour trends and scour-protection methods.

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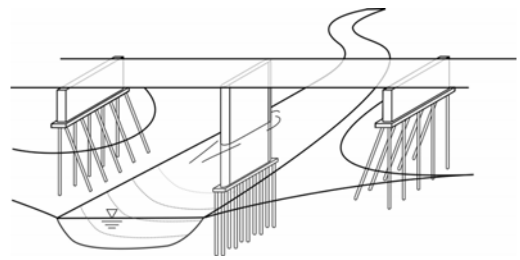
APPENDIX A:
ILLUSTRATIONS OF BRIDGE VULNERABILITY TO SCOUR FAILURE



A.1 Introduction

This appendix contains illustrations of conditions that caused, or may cause, a bridge waterway to be vulnerable to scour that must be kept in mind during monitoring of bridge waterways. The examples coincide with the scour types discussed in Chapter 4. ***In certain respects, by virtue of a "picture being worth a thousand words," this section of the Guide is of great importance, insofar that it directly shows the problems that effective monitoring should detect***.

The examples are arranged in the following way:

1. Upstream approach to the bridge (Table A-1)
    - approach flow angle
    - channel aggradation and flow capacity
    - channel bank stability
    - debris or ice yields
    - construction of a new bridge

2. At the bridge (Table A-2)
    - scour at piers
    - scour at abutments and approach embankments
    - lateral drainage
    - debris or ice accumulation

3. Downstream of the bridge (Table A-3)
    - channel degradation

- channel head-cutting
- effect of bridge on downstream channel

The descriptions comprise photographs or drawings accompanied by brief explanations of the waterway concern.

Table A-1. Upstream Approach to the Bridge

Features in waterway of concern

1. Channel migration
2. Approach bank erosion
3. Aggradation

1. Channel migration

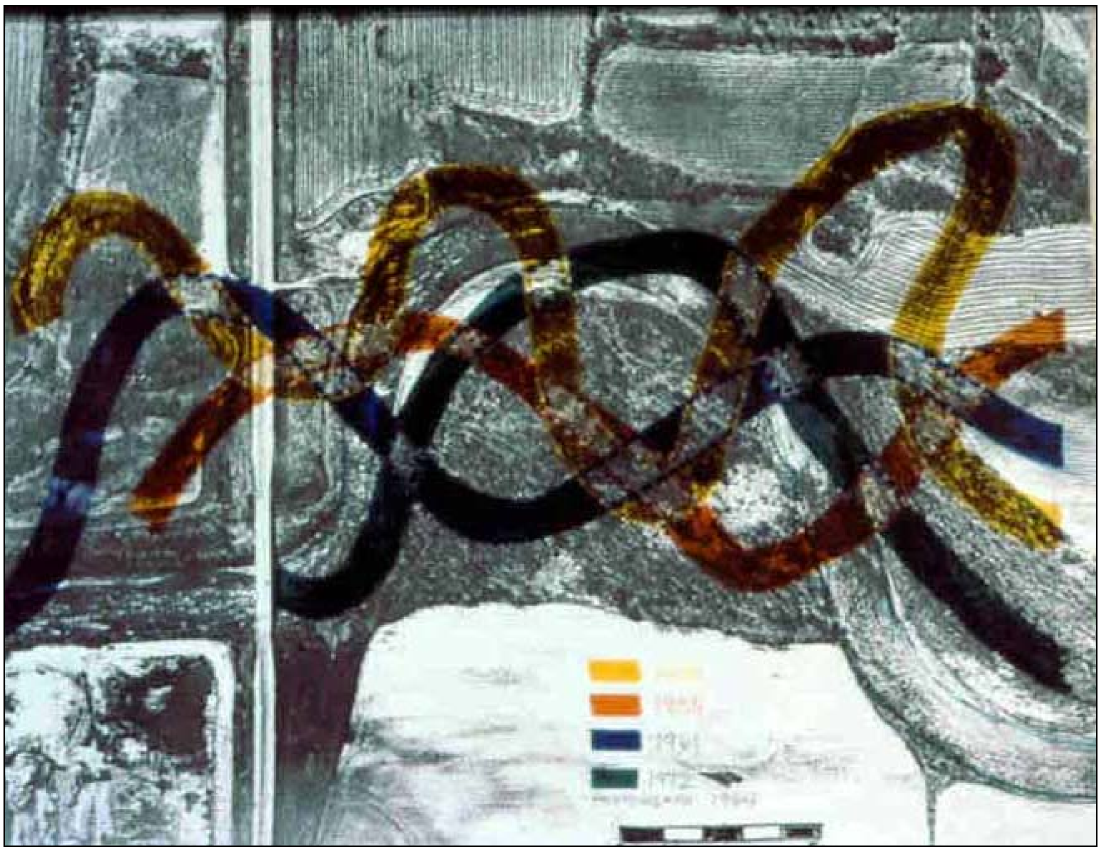


Figure A-1. Channel shifts, East Nishnabotna River, Iowa

Figure A-2. Channel shift, Hewitt Creek in Dyersvuille, Iowa

2. Approach bank erosion

Figure A-3. Eroded left bank – unknown river

Figure A-4. Failed left bank – unknown river, western Iowa

Figure A-5. Failed left and right banks upstream of bridge, Walnut Creek on G66, Iowa

3. Aggradation

Figure A-6. Aggradation of approach channel through cattle ground, East Otter Creek, near Kiron, Iowa

Figure A-7. Aggradation of approach channel, Boundary Creek, New Zealand

Table A-2. At the Bridge

Features in waterway concern

1. Road drainage
2. Pier scour
3. Abutment and embankment scour
4. Woody debris and ice

1. Road drainage

Figure A-8. Flow from side drainage ditch eroding the right bank – unknown river in Iowa

Figure A-9 Head cutting at side drainage upstream from right abutment – unknown river in Iowa

Figure A-10. Improperly designed drainage pipe, aggravating pier scour by contributing to erosion of soil around pier– unknown river in Iowa

2. Pier scour

Figure A-11. Pier scour associated with bed degradation (notice initiation of head cutting of side-drainage ditch) – unknown river in Iowa

Figure A-12. Pier scour around channel margin – unknown river in Iowa

Figure A-13. Pier scour associated with channel degradation – unknown river in Iowa

Figure A-14. Pier scour in floodplain, Asuwa River, Japan (courtesy of Prof. T. Hosoda, Kyoto University)

Figure A-15. Pier settlement due to overloading – unknown river

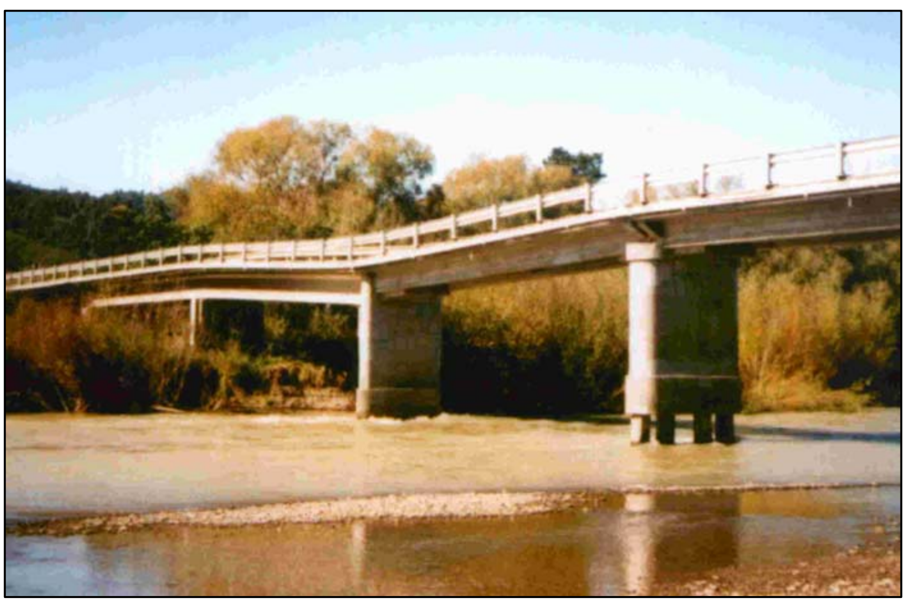


Figure A-16. Pier settlement owing to scour, Whakatane River, New Zealand

Figure A-17. Pier scour, Chikuma River, Japan (courtesy of Prof. T. Hosoda, Kyoto University)

Figure A-18. Pier scour – Abukuma River, Japan (courtesy of Prof. T. Hosoda, Kyoto University)

Figure A-19. Pier scour and eventual loss of pier; Akabane River, Japan (courtesy of Prof. T. Hosoda, Kyoto University)

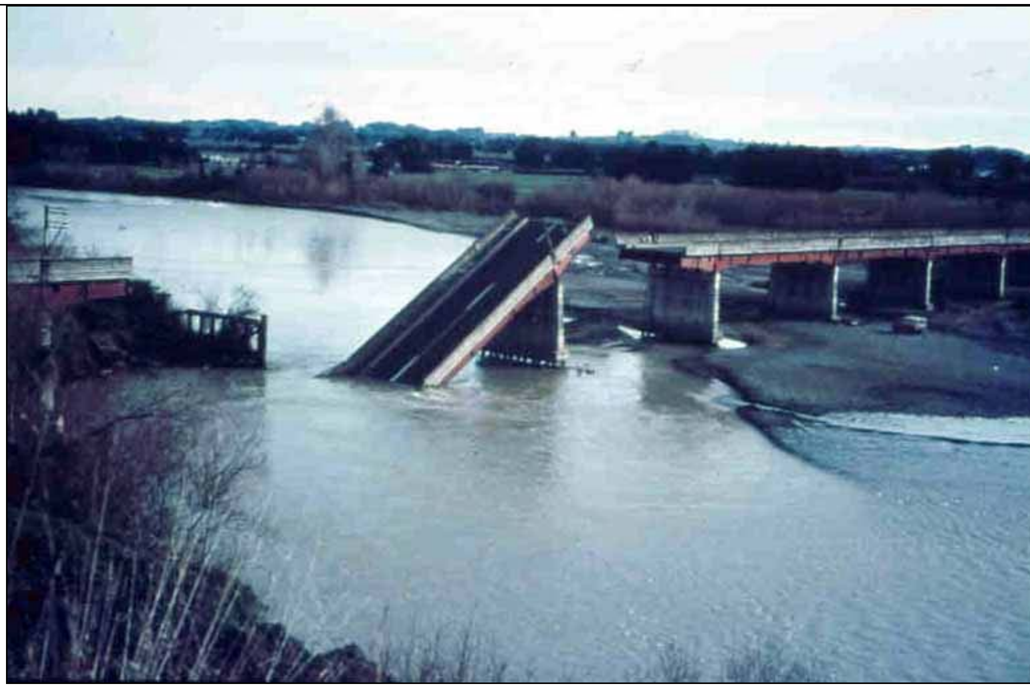


Figure A-20. Pier scour and failure, Bulls River, New Zealand; The poor alignment of the bridge relative to the left bank caused adverse velocities at the failed pier

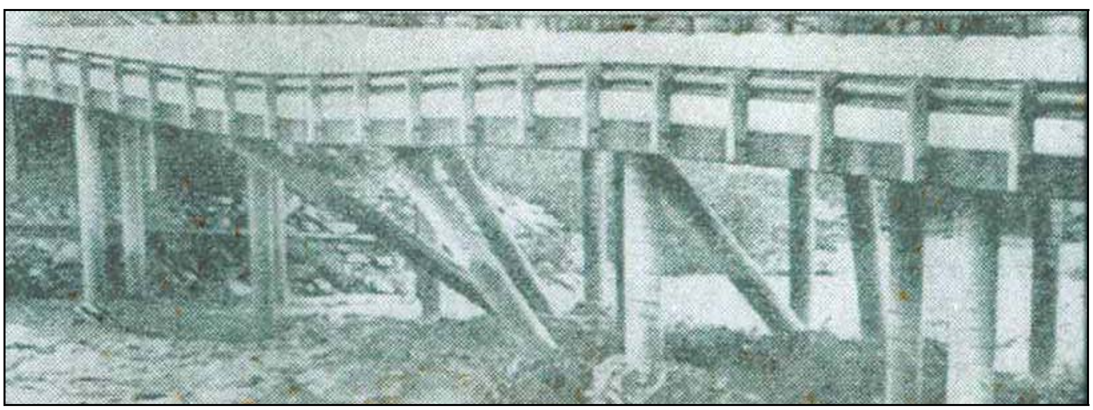


Figure A-21. Loss of piers – unknown river

3. Abutment scour

Figure A-22. Local bank failure around abutment – unknown stream, New Zealand

Figure A-23. Embankment erosion, exposing abutment piling, Boyer River, Iowa

Figure A-24. Abutment scour, unknown river in New Zealand

Figure A-25. Cuspate embankment failure of abutment on rough footing, Shoemaker Creek, New York

Figure A-26. Inspecting undermined abutment footing, Fulmer Creek, New York

Figure A-27. Scour at abutment on floodplain of Missouri River, I-70, Kansas

Figure A-28. Bank failure at abutment, Plate River, New York

Figure A-29. Failure of embankment and exposure of abutment structure, Camerons Creek, New Zealand

Figure A-30. Washed-out embankment, Brushy Creek, Iowa

Figure A-31. Partial embankment failure extending from side drainage outlet along the left bank, Boyer River, Iowa

Figure A-32. A large scour hole formed in the floodplain near an abutment and piers of a bridge over the Des Moines River near Chillicothe, Iowa; a substantial amount of flow over the floodplain was forced to pass through the bridge waterway

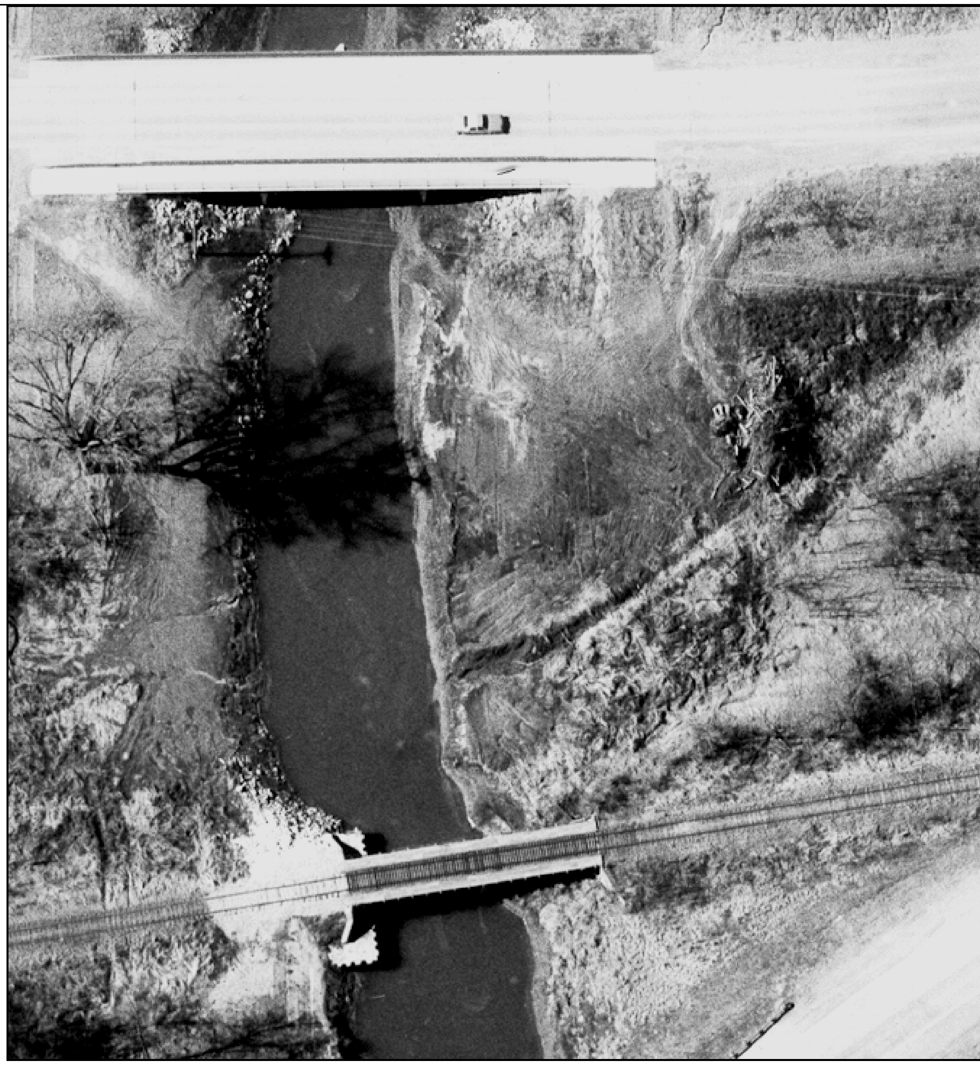


Figure A-33. A rail bridge abutment repaired after scour failure associated with channel bank scour, a creek near Columbus Junction, Iowa; flow is from top to bottom

Figure A-34. Washed-out embankment and exposed abutment, I-70 over a small creek, Illinois

4. Woody debris and ice at bridge opening

Figure A-35. Vegetation growth on debris at bridge opening, East Skokie Ditch, Illinois

Figure A-36. Debris accumulation at piers, Iroquois River, Illinois

Figure A-37. During flood flow, debris blockage led to high side loads and scour resulting in bridge failure, Florida Creek, Missouri

Figure A-38. Debris accumulation at pier and abutment on floodplain of Mississippi River, Quincy, Illinois

Figure A-39. Ice accumulation at piers – Iowa River, Iowa

Figure A-40. Ice accumulation along bridge during Spring thaw – Red River, North Dakota

Table A-3. Downstream of the Bridge

Features in waterway concern
1. Channel degradation 2. Knickpoint migration 3. Scour of downstream channel
1. Channel degradation
 *Figure A-41. Channel degradation owing to knickpoint migration – unknown river in western Iowa*

Figure A-42. Downstream channel degradation, Pigeon Creek on L55, Iowa – notice the sheet-pile weir to stop knickpoint migration

2. Head-cutting and knickpoint migration

Figure A-43. Headcutting; unknown stream in Iowa

Figure A-44. Headcutting beneath a bridge – Wabash Creek, western Iowa

3. Scour of downstream channel

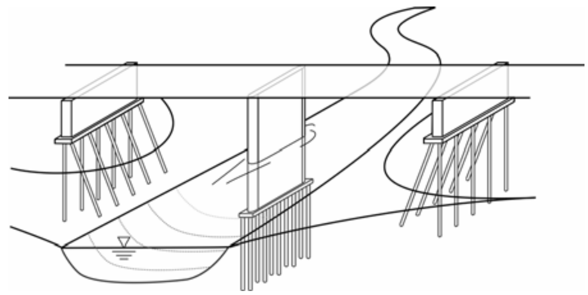
Figure A-45. Local scour at downstream side of vertical-wall abutment due to wake eddies associated with flow separation from abutment, Ralston Creek, Iowa City, Iowa

Figure A-46. Scour of embankment at downstream side of culvert; South Platte River, Nebraska

Figure A-47. Deep scour hole created downstream of culvert outlet – culvert in Iowa

Figure A-48. Large scour hole created downstream from culvert outlet, Walnut Creek on County Road G66, Iowa

APPENDIX B: ILLUSTRATIONS OF PROTECTION AND REPAIR METHODS



B.1 Introduction

This chapter illustrates examples of protection and repair methods applied to ensure that bridge waterways do not fail owing to scour. The examples illustrate the scour protection methods discussed in Chapter 6. The protection and repair examples are arranged in the following way:

1. At the bridge (Table B-1)
    - scour at piers
    - scour at abutments and approach embankments
    - lateral drainage

2. Upstream approach to the bridge (Table B-2)
    - approach flow angle
    - channel aggradation and flow capacity
    - channel bank stability

3. Downstream of the bridge (Table B-3)
    - general degradation of channel
    - channel head-cutting and knickpoint migration
    - effect of bridge on downstream channel

The descriptions comprise photographs or drawings accompanied by brief explanations of the waterway concern.

Table B-1. Protection at Bridges

1. Scour protection at piers

Figure B-1. Heavy riprap protection of low-flow channel and floodplain piers under the bridge on Highway 151 – under construction; Catfish Creek in Dubuque County, Iowa

Figure B-2. Heavy riprap protection under construction around piers and abutments Highway 151 bridge; Catfish Creek in Dubuque County, Iowa

Figure B-3. Sheet piling placed around pile footing of a railway bridge pier in a channel that has lowered by general bed degradation, Iowa River in Iowa City, Iowa, below Coralville Reservoir. The leading edge of the sheet piling is protected with large blocks of stone and concrete.

Figure B-4 Placing rock riprap as a mound around exposed pile supports of a bridge pier in a channel that has experienced general bed degradation; Iowa River in Iowa City, Iowa, below Coralville Reservoir

2. Scour protection at abutments and approach embankments

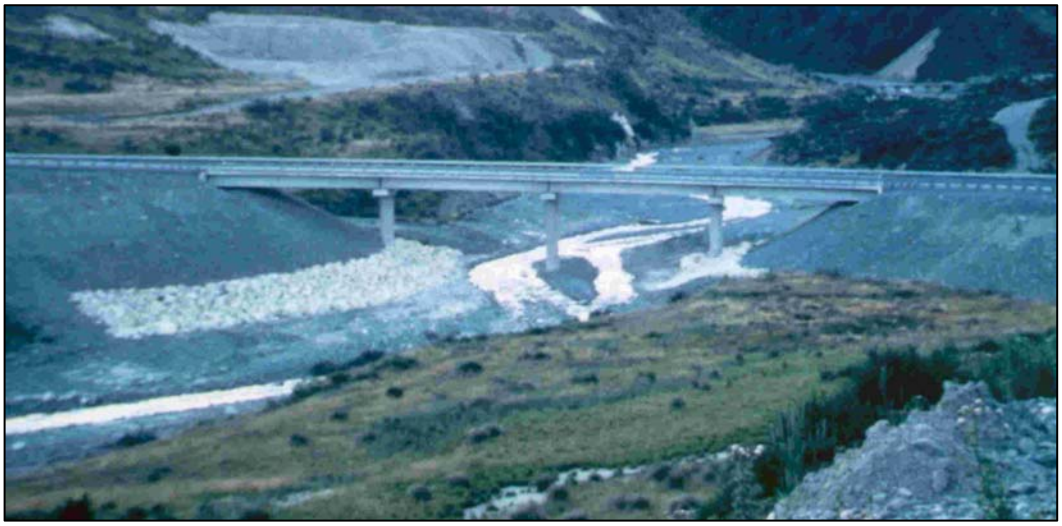


Figure B-5. Riprap bank protection around pier and abutment; Waimakariri River, New Zealand

Figure B-6. Abutment protection of the new bridge on Highway 151; Johns Creek in Dubuque County, Iowa

Figure B-7. Concrete-lined spill-through abutment protection for US Highway 137 bridge; Des Moines River in Wapello County, Iowa

Figure B-8. Riprap abutment protection for a new county bridge; Pike Run Creek in Muscatine County, Iowa

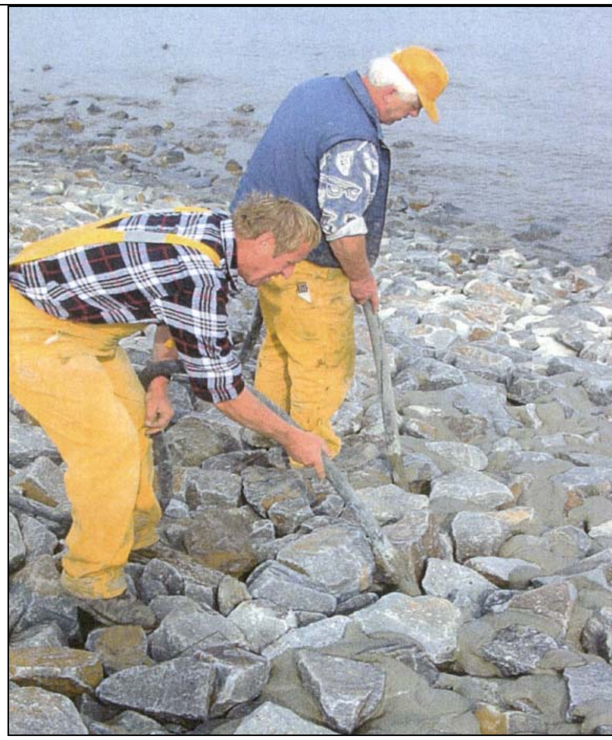


Figure B-9. Use of partially grouted riprap at an abutment; unknown river in Germany

Figure B-10. Pier-nose walls added to a bridge in order to fend debris from the bridge deck; Elk River, Kansas

Figure B-11. A "debris shark" designed to deflect debris from a bridge pier; Harpeth River, Tennessee

Figure B-12. Sloped nose of pier reduces ice loads on pier, and deflects ice from pier; Yellowstone River, Montana

Figure B-13. Removal of woody debris by a backhoe grab; Deep River, North Carolina

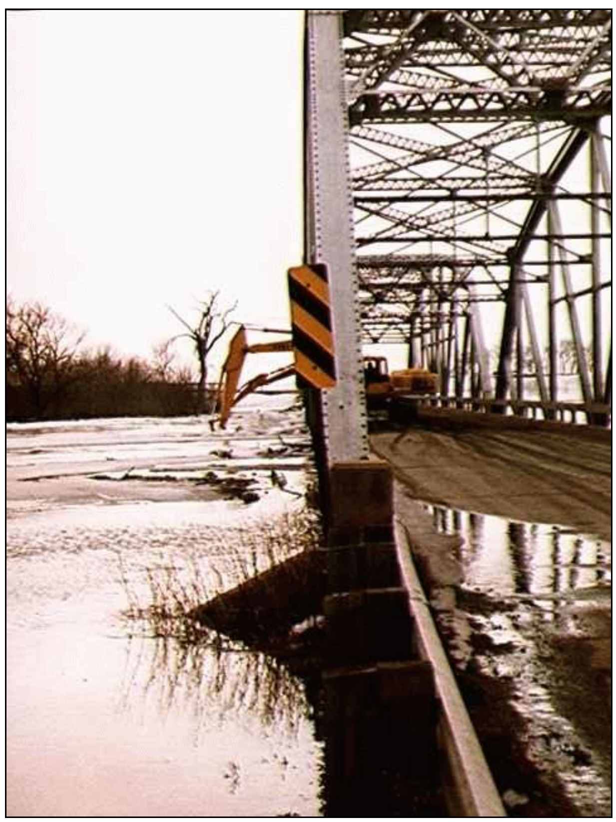


Figure B-14. Use of a backhoe for removing ice; Red River, North Dakota

3. Protection of lateral drainage

Figure B-15. Head-cutting protection of lateral drainage in Y26, Mud Creek in Muscatine County, Iowa

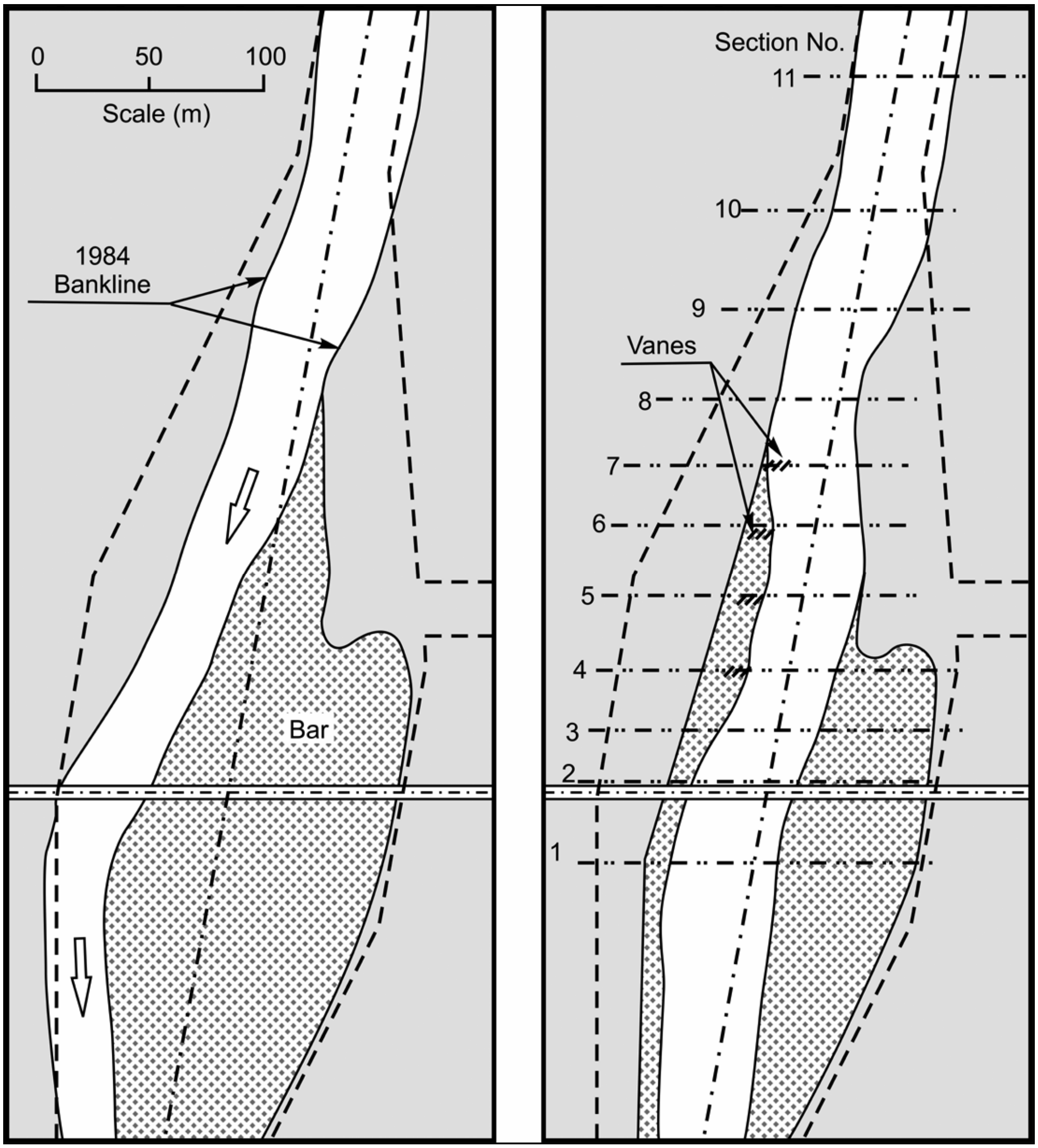
Figure B-16. A close-up view of head cutting protection of lateral drainage in Y26, Mud Creek in Muscatine County, Iowa

Figure B-17. Protection of lateral drainage using construction debris for Highway N16 bridge, East Nishnabotona River in Cass County, Iowa

Table B-2. Protection of upstream approach to the bridge

1. Upstream approach to the bridge
 *Figure B-18. Use of guidebanks fitted around abutments of a bridge over a braided channel; Lowe River, Alaska*
 *Figure B-19. An example of an upstream guidebank placed at a tight bend of a channel; Lowe River, Alaska*

2. Channel bank stability



(a) (b)

Figure B-20. Plan view of changes in channel alignment before ((a) in 1984) and after ((b) in 1989) installation of vanes; West Fork Cedar River, Butler County, Iowa

Figure B-21. Aerial photos showing changes in channel alignment before ((a) in 1984) and after ((b) in 1989) installation of vanes; West Fork Cedar River, Butler County, Iowa

Installation of Iowa Vanes in Wapsipinicon River bend during low flow in the Summer of 1988.

Wapsipinicon River bend at low flow, May 10, 1990, about two years after installation of Iowa Vanes.

Figure B-22. Vanes installed along the concave bank just upstream from the bridge crossing and their effectiveness in stabilizing eroded bank; Wapsipinicon River in Iowa

Figure B-23. A sample of timber hard point; Missouri River, Montana

Figure B-24. Hard points installed along the concave bank upstream from Highway 37 bridge; Boyer River near Dunlap in Crawford County, Iowa

Figure B-25. A single guide spur used to improve flow approach to a bridge awkwardly located in a tight bend of the Athabaska River, Alberta, Canada; flow is from bottom to top

Figure B-26. Timber hard points reinforced by riprap along the concave bank; Missouri River, Montana

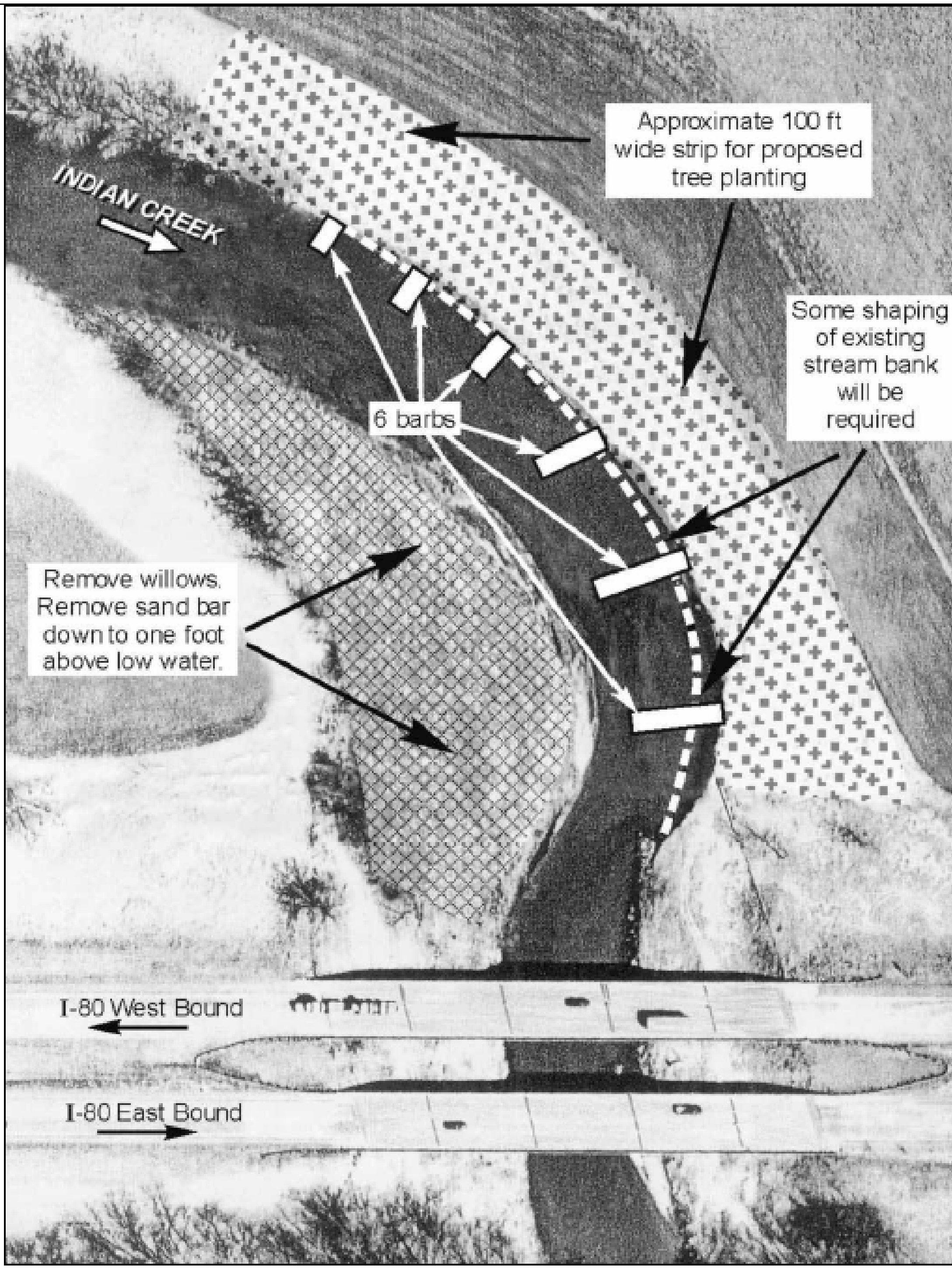


Figure B-27. Conceptual locations of barbs considered for installation along the outside bank upstream of the I-80 bridge; Indian Creek, Iowa

Figure B-28. Prototype installation of barbs along the concave bank (flow direction: top to bottom); unknown stream, Washington

Figure B-29. A spur dike extended from a concave bank, Missouri River, Montana

Figure B-30. Prototype installation of cable-tied blocks near an abutment –unknown river, New Zealand

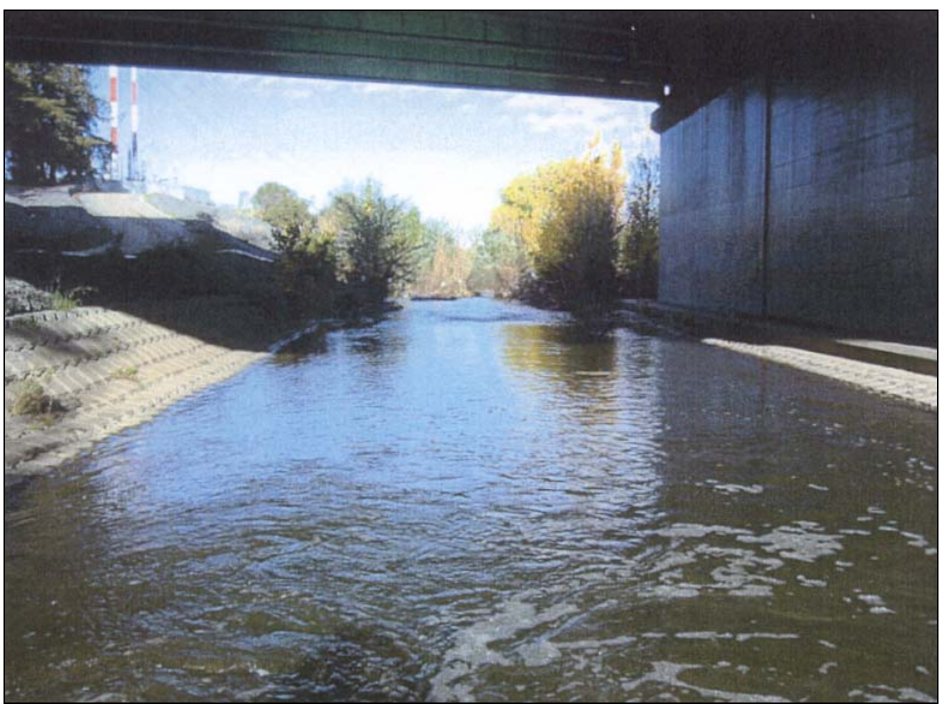


Figure B-31. Cable-tied blocks placed between abutment and first pier: Guadalupe River, California

Figure B-32. A further example of the use of cable-tied blocks for scour protection between abutment and first pier

Figure B-33. The repair of the abutment scour shown in Figure 5-23 entailed adding a span and moving the abutment back up the channel bank; Boyer River, Iowa

Table B-3. Protection of channel downstream of the bridge

1. General degradation of channel
 *Figure B-34. Downstream bank protection of Highway 151 bridge, Kitty Creek in western Iowa*
 *Figure B-35. Combination of sheet-pile weir and fish passage to prevent further stream-bed degradation due to head-cutting, and to enable fish to migrate upstream over the structure, East Tarkio Creek in western Iowa*

2. Prevention of knickpoint migration

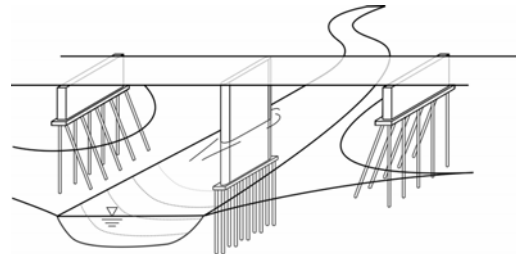
Figure B-36. A sheet-pile weir fortified with riprap downstream from County Road F52 bridge, Pigeon Creek in western Iowa

Figure B-37. A downstream view of knickpoint migration that was stopped by a spillway structure -- County Road L16 bridge over Willow Creek, 6 miles upstream of Woodbine, Iowa

Figure B-38. A concrete spillway constructed to stop knickpoint migration, Willow Creek in Harrison County, Iowa. The weir and bridge abutments form what in Iowa is known as a "Greenwood Bridge"

Figure B-39. A rock weir provided below County Road bridge on E16 to stop knickpoint migration, Porter Creek in Crawford County, Iowa -- notice that riprap is protected with grout so that rocks will not be dislodged during high flows

APPENDIX C:
A RISK ASSESSMENT METHODOLOGY



C.1 Introduction

Described here is a quantitative methodology for a bridge inspection and scour-risk assessment report. This suggested report methodology is **not** intended to replace existing inspection reports or guides. Rather, it is provided as an example that might be considered for adoption (in one form or another) by bridge-inspection authorities in Iowa.

The methodology comprises more than a check list, such as given in Chapter 6. It is arranged as a quantitative tool for scour-risk assessment, which, in the context of bridge monitoring, is a means for determining

1. The extent to which a hazard (i.e., scour) poses significant risk for a bridge;
2. The seriousness of the risk at one bridge relative to the risks faced at other bridges; and,
3. The set of precautions or repairs needed to mitigate the set of risks faced at several bridges.

Though the bridge inspector or monitor is not necessarily expected to follow a quantitative procedure when assessing the scour susceptibility of a bridge waterway, it is useful to introduce such a quantitative tool. The methodology is laid out in Table C-1, and Table C-2 gives a commentary list that explains the terms and statements in the inspection report given in methodology.

C.2 Benefits of a Risk Assessment Approach

Before proceeding, it is worth touching on the benefits of a risk assessment approach. Quantitative analysis of risk is increasingly used in the risk management of infrastructure components like bridges. For example, quantitative risk assessment helps in assigning priorities to infrastructure components in need of repair or replacement. Priorities are useful when resources (fiscal and time) are limited.

The risk-assessment methodology described here has a number of advantages:

1. A ranking system helps establish a priority order on the basis of bridge vulnerability;
2. A structure staged to eliminate quickly bridges that clearly are not vulnerable to scour, to identify bridges requiring only a modest level of maintenance, and scour-critical bridges; and,
3. Pictorial guides of conditions in conjunction with the data form so as to ensure consistency and completeness in reporting site information.

C.3 Assessment Steps

Assessment of a bridge waterway involves at least four steps, listed here as –

1. Background office review of the bridge;
2. Evaluating bridge waterway vulnerability;
3. Overall scour-risk assessment; and,
4. Recommendations on maintenance and repair actions.

Monitoring should be based on a suitably detailed plan of investigation, as well as forms for recording observations. A systematic methodology should be used each time the bridge is surveyed to provide a means of accurately identifying changes that have occurred at the bridge site, which may affect the safety of the bridge. The following is a list of necessary information required for a comprehensive, well-organized inspection:

- Scour Evaluation Studies - Examine any previous hydraulic engineering scour evaluation studies on the bridge. These studies provide theoretical ultimate scour depths for the bridge substructure elements.
- Previous Bridge Inspection Reports - Review previous report data taken from successive inspections to establish whether the waterway is stable, degrading or aggrading.

- Streambed Material/Foundation Design - Determine streambed material, if possible, and type of substructure foundation from as-built, design and construction drawings.
- Site Conditions - Become familiar with site conditions such as channel protection installations, waterway depth, alignment, and previously reported waterway conditions. Also establish floodplain elevation and flood-level frequencies.

It is customary to relate flow-depth and scour-depth distances to a benchmark elevation, such as the bridge deck elevation (Figure C-1). Other benchmark systems are used.

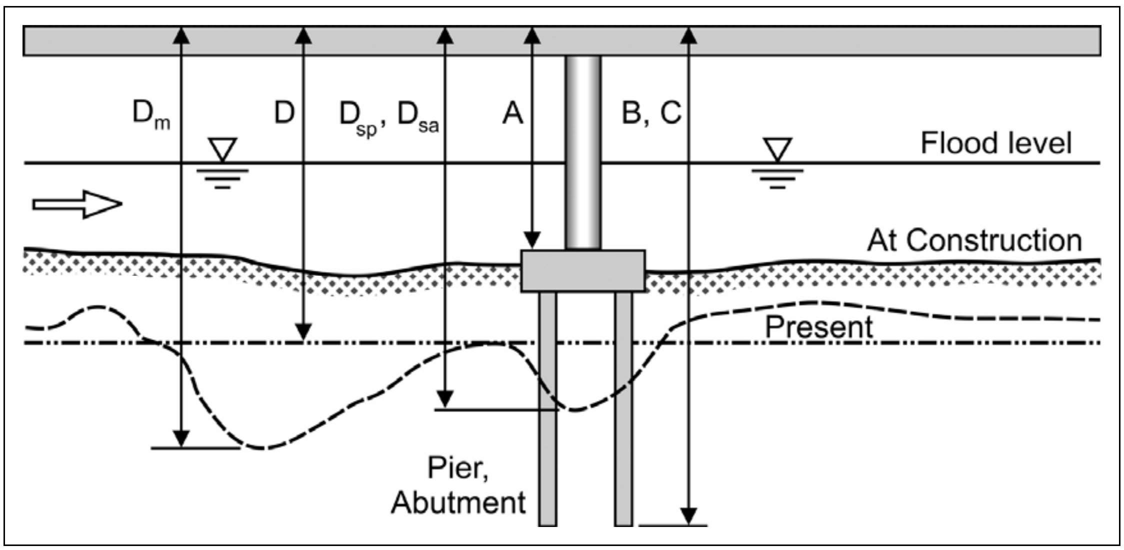


Figure C-1. Definition of distances from the bridge deck to the bed of the waterway channel and the foundation bearing levels. The distances are referred to in Tables C-1 and C-2.

C.3.1 Background Office Review

An early step in monitoring is office review of available information. It is a simple truism that effective monitoring requires clear and consistent documentation of the layout, main features, and dimensions of bridge and the waterway it spans. Such documentation also should note whether there is an existing concern regarding scour vulnerability.

C.3.2 Monitoring for Bridge Vulnerability

This subsequent step in monitoring entails noting the details about the waterway and the bridge. These individual details are summarized on the inspection report.

- From the field inspection, add information about individual aspects of the details bridge and waterway

- Rate individual aspects of the bridge and waterway as indicating high, unknown, medium, or low vulnerability to scour

- Combine individual ratings of aspects to give ratings of vulnerability for the following aspects of the bridge waterway:
  1. watershed developments/conditions influencing bridge site;
  2. Historical scour;
  3. Approach conditions;
  4. Channel aggradation;
  5. Waterway adequacy;
  6. Lateral movement of channel;
  7. Flow depths in bends, confluences, and bridge approaches; and,
  8. Local scour at abutments and piers.

- Estimate an overall rating of bridge vulnerability to scour, based on the eight ratings listed above.

Each assessment of vulnerability (individual aspects, groupings) is subjective, and relies upon engineering judgment and experience, for an appropriate rating. A high rating for combined grouping, or for the bridge overall, can be determined by a particular domineering aspect of the bridge or waterway (e.g., scour-induced movement of a foundation or collapse of an embankment), or by a weight of the contributing ratings (e.g., a notable degradation of the channel combined with increasing flow depths at the outside of a channel bend influencing the bridge foundations).

C.3.3 Overall Assessment of Scour Risk

Monitoring leads to an overall indication of scour vulnerability. In due course this indication is complied with risk assessments for other bridges, so that a priority ranking of bridge maintenance and repair actions can be prepared.

C.3.4 Repair Actions

Based on the level of concern expressed in a priority ranking, and on the physical nature of the damage (or possible impending damage) at a bridge, as well as a well defined list of repair options, the monitoring would lead to a recommendation as to appropriate maintenance and repair actions.

C.4 Example Form for Scour Risk Assessment

The following form given in Table C-1 is structured as an example of a quantitative methodology for scour-risk assessment. The form shows how the scour risk at a bridge may be assessed in a manner that enables risk management decisions to be made when monitoring entails inspecting numerous bridges, of which quite a few bridges may be prone, to varying degrees, to scour damage.

Table C-1. [Example] Bridge Waterway Assessment Report

1. OFFICE BACKGROUND REVIEW **[N=No, U=Unknown, Y=Yes]**

Bridge authority (DOT/County/City):	
Highway/Road:	Route Position:
Bridge name:	
Bridge closed	N U Y
Bridge scheduled for replacement or major repair	N U Y

If any of the above responses are 'Y', then go to the final scour-susceptibility assessment.

Bridge authority:	
River/stream/creek crossed:	
Year bridge constructed:	
Plan/drawing numbers:	
Foundations (identify: e.g., spread footings, piles, cylinders, other):	
Pier types (identify: e.g., none, walls or diaphragms, columns, inclined piers, piles with cap, spread footing, other):	
Abutment types (identify: e.g., vertical wall, wing wall, spill through (identify slope H:V), piled foundation, spread footing, other):	
Maximum distance (ft) from bridge deck to channel bed at foundations at construction ('U' if unknown):	A
Minimum distance (ft) from bridge deck to pier founding level ('U' if unknown):	B
Minimum distance (ft) from bridge deck to abutment founding level ('D' if unknown):	C
Bed materials (identify: e.g. erosion-resistant bedrock, semi-resistant bedrock, erodible bedrock, boulders, cobbles, gravels, sands, silts, clays, unknown):	
Grading of sediment deposits (identify: e.g. narrow, wide, unknown):	
Depth (ft) of sediment deposits ('U' if unknown):	
Historical scour at the bridge	N U Y
Historical scour of the channel	N U Y
Historical scour at surrounding bridges	N U Y
Previous screening classification:	
Previous screening recommendations:	

2. MONITORING OF BRIDGE VULNERABILITY (V)

[Vulnerability: H=high, U=unknown, M=medium, L=low; and, P = take photo or video evidence if waterway aspect is significant]

Office review of watershed developments/conditions influencing the bridge site		**Bridge rating (H, U, M ,L)**
Changes in watershed surface	H U M L	
Channel head-cutting, or nick-point migration	H U M L	
Sediment mining/ dredging or dumping	H U M L	
Channel straightening/ channelization	H U M L	
Channel diversion	H U M L	
Watershed-wide bank instability owing to channel migration/widening	H U M L	
Grade-control structure control of the hydraulic regime at the bridge site	H U M L	
Bridge on steep or active alluvial fan/ delta	H U M L	
Upstream or downstream check dam/ storage reservoir	H U M L	
Sediment bar control of the hydraulic regime at the bridge site	H U M L	
Waterfall control of the hydraulic regime at the bridge site	H U M L	
River/stream/ level-control of the hydraulic regime at the bridge site	H U M L	
Forestry operations	H U M L	

Historical scour		**Bridge rating (H, U, M,L)**
Scour experienced over bridge life (office review)	H U M L	
Implementation of previous screening recommendations	H U M L (P)	

Degradation and contraction		
Average present distance (ft) from bridge deck to channel bed ('U' if unknown)		D
Culvert of fixed invert	H U M L	**Bridge rating (H, U, M, L)**
Recent degradation exposing bridge foundations across the channel to distance below the bridge deck, D, approaching [A+(B-A)/2] or [A+(C-A)/2]	H U M L (P)	
Countermeasures present (identify: e.g. none, grade control structure, check dam, weir, channel lining, erosion-resistant bedrock):	H U M L (P)	
Countermeasures damaged/ineffective:	H U M L (P)	

Aggradation		**Bridge rating (H, U, M, L)**
Recent aggradation across the channel to a distance below the bridge deck, D, approaching [2A/3]:	H U M L (P)	
Countermeasures present (identify: e.g. none, upstream check dam/ debris basin, controlled channel clearing/ mining, other):	H U M L (P)	
Countermeasures damaged/ineffective:	H U M L (P)	

Waterway adequacy		Bridge rating (H, U, M, L)
Waterway significantly blocked (identify source: e.g. debris, bars, vegetation, foundations, guidebanks, scour countermeasures, other):	H U M L (P)	
High debris or flood marks:	H U M L (P)	
Debris/ sediment on superstructure:	H U M L (P)	
Countermeasures present (identify: e.g. none, relief/ overflow bridges/ channels, other):	H U M L (P)	

Lateral channel movement, channel widening, bridge approaches		
Waterway bank materials (identify: e.g. erosion-resistant bedrock, semi-resistant bedrock, erodible bedrock, boulders, cobbles, gravels, sands, silts, clays, unknown):		
Grading of waterway bank materials (identify: e.g. narrow, wide, unknown):		
Bridge approach materials (identify: e.g. erosion-resistant bedrock, semi-resistant bedrock, erodible bedrock, boulders, cobbles, gravels, sands, silts, clays, unknown):		
Grading of bridge approach materials (identify: e.g. narrow, wide, unknown):		
Bank erosion/ failure influencing the factors of safety for the bridge Foundations	H U M L (P)	**Bridge rating (H, U, M, L)**
Bank erosion! failure influencing the factors of safety for the bridge approaches	H U M L (P)	
Flow concentration at a bridge approach (identify source: ______________________________) (identify point of concentration: ______________________)	H U M L (P)	
Bridge approach toe erosion	H U M L (P)	
Bridge approach fill movement	H U M L (P)	
Countermeasures present (identify: e.g. none, riprap (note size), gabions, concrete blocks, tetrapods, used tires, planted vegetation, piles, jack or tetrahedron fields, groins, spurs, dikes, other):	H U M L (P)	
Countermeasures damaged! ineffective	H U M L (P)	

Flow depths in bends and confluences Bridge		Bridge rating (H, U, M, L)
Increased flow depths at the outside of a channel bend (up to 4 times the average depth in upstream cross-sections in straight reaches) influencing the factors of safety for the bridge foundations	H U M L (S)	
Increased flow depths in a channel confluence (up to 6 times the average depth in the upstream channel cross-sections) influencing the factors of safety for the bridge foundations	H U M L (S)	
Countermeasures present (identify: e.g. none, channel lining, erosion-resistant bedrock, other):	H U M L (P)	
Countermeasures damaged! Ineffective	H U M L (P)	

Local scour at piers and abutments	
Debris on the foundations or in the channel upstream H U M L (P)	
Angle of flood flow to pier centerline:	
Angle of flood flow to abutment centerline:	
Average approach flow depth (ft) for design floods ('U' if unknown):	Y
Maximum present distance (ft) from bridge deck to channel bed ('U' if unknown):	D_m
Projected width perpendicular to flood flow of debris-laden pier (ft) ('U' if unknown):	b_e
Approximate potential local pier scour (ft): $D_{sp} = (D+2.4b_e)$ ('U' if unknown):	D_{sp}
Projected length perpendicular to flood flow of debris-laden abutment (ft) ('U' if unknown):	L_e
Approximate potential local abutment scour (ft), D_{sa} = minimum of $(D+2L_e)$ and $(D+10y)$ ('U' if unknown):	D_{sa}

Local scour at piers and abutments		Bridge rating (H, U, M, L)
Foundation tilt/ Movement:	H U M L (P)	
Maximum possible present local scour, Dm, approaching [A+(B-A)/2] or [A+(C-A)/2]	H U M L	
Potential local pier scour, D_{sp}, approaching [A+3(B-A)/4]	H U M L	
Potential local abutment scour, D_{sa}, approaching [A+3(C-A)/4]	H U M L	
Spill-through abutment toe erosion	H U M L (P)	
Spill-through abutment fill movement	H U M L (P)	
Flow concentration at a bridge foundation (identify source: ____________________) (identify foundation: ____________________)	H U M L (P)	
Countermeasures present (identify: e.g. none, channel lining, erosion-resistant bedrock, riprap (note size), gabions, concrete blocks, tetrapods, used tires, sacrificial piles, deflector vanes, collars, underpinning, jack or tetrahedron fields, spurs, dikes, other):	H U M L (P)	
Countermeasures damaged/ineffective:	H U M L (P)	
Overall bridge vulnerability rating (YH, VU, VM, VL)[1]		

1. Based on an assessment of the eight ratings (H, U, M, L) above for the combined vulnerability groupings.

3. SCOUR-SUSCEPTIBILITY ASSESSMENT[1]

		Bridge Significance		
		SH	SM	SL
Bridge Vulnerability	VH	1	1	2
	VU	1	2	3
	VM	2	2	3
	VL	3	4	4
	N/A[2]	4		

Overall scour susceptibility[1] (1, 2, 3, 4)

1. scour-susceptibility ratings: 1 =highest susceptibility, 4 =lowest susceptibility.
2. N/A =not applicable, the rating category for a bridge not over a waterway, a closed bridge, or a bridge scheduled for replacement.

4. POSSIBLE ACTIONS – FOR OVERALL RATINGS OF 1, 2, OR 3

Monitoring (Suggested frequency:____________________)	☐
Detailed scour analyses	☐
Structural protection (possible options:____________________)	☐
Upstream channel modifications (possible options:____________________)	☐
Downstream channel modifications (possible options:____________________)	☐
Bridge replacement	☐
Bridge closure	☐
Other:	☐

Personnel

Office review by:	Date:
Field inspection by:	Date:
Scour-susceptibility assessment by:	Date:
Checked by:	Date:

Visual Records, Notes, and Comments

Standard photographs			
From bridge - looking upstream	☐	From bridge - looking downstream	☐
Looking downstream at bridge	☐	Looking upstream at bridge	☐

Notes and comments
(use channel plan/cross-section sketches as required)

1. Note factors indicating scour susceptibility.
2. Note individual foundations highlighted as scour susceptible.
3. Note locations of channel foundation erosion influencing the assessment.

The commentary given below (Table C-2) is written to aid assessment of bridge waterway details in regard to rating the relative scour-susceptibility of bridges. The comments take the form of brief explanations of the terms and the statements in the assessment methodology report (Table C-1), along with indicating the figures illustrating aspects of the report. The comments recognize the subjective nature of the interpretations to be made of the waterway conditions, and are written assuming some understanding of watershed, bridge, and scour terminology.

Table C-2. Commentary on Bridge Waterway Assessment Report

Assessment-report terms/ statements	Comments
Distances (ft) measured from the bridge deck to the channel bed and foundation levels	The bridge deck is chosen as a fixed point of reference elevation. It is assumed that any variation along the bridge deck is negligible. If this is not the case, then the bridge deck at a particular foundation (identify the chosen foundation on the screening form, e.g. true-right abutment) is chosen as the fixed point of reference elevation.
Maximum distance (ft) from bridge deck to channel bed at foundations is at construction	The distance A on **Figure C-1**. This distance is measured at foundations to reflect the initial embedment lengths. The maximum relevant value of A is adopted to reflect minimum embedment lengths. (**Figure C-1**)
Minimum distance (ft) from bridge deck to pier (abutment) founding level	The distance B (C) on **Figure C-1**. The minimum relevant value of B (C) is adopted to reflect minimum embedment lengths. (**Figure C-1**)
Bed materials	These reflect the relative erodibility of the channel bed.
Erosion-resistant bedrock	E.g., not highly broken or fractured: Granite, Basalt, Andesite, Gneiss, and Greywacke.
Semi-resistant bedrock	E.g., Dolomite, Limestone, Ignimbrite, Slate, Argillite, and Schist.
Erodible bedrock	E.g., Sandstone, Siltstone, Mudstone, Shale, and weathered bedrock.
Grading of sediment deposits (identify: e.g. narrow, wide, unknown)	Grading is range of sediment sizes. Sediments of a wide grading may armor to protect against erosion.
Depth (m) of sediment deposits	This reflects whether underlying bedrock may scour at the bridge site.

Historical scour at the bridge, Historical scour of the channel, Historical scour at surrounding bridges, Previous screening classification, Previous screening recommendations	Historical scour at the bridge foundations and approaches, scour away from the bridge foundations and approaches, scour at surrounding bridges. The existence of scour at surrounding bridges can indicate the watershed development that may influence bed levels at the investigated bridge site. Refer bridge reports, local experience, engineering experience, Bridge Descriptive Inventory "Condition" and "Action recommended" codings, etc.
Route traffic volume (vpd)	This reflects the vehicle route importance (vpd = vehicles per day)
Alternative routes; readily-available temporary bridges	These may reduce the significance rating for the bridge.
Alternative routes	Summarized in the Bridge Descriptive Inventory.
Utilities carried	Summarized in the bridge Descriptive inventory.
Bridge significance rating	This is assigned based on the traffic volume for the route, along with natures of the route and the bridge. For adequate alternative routes or readily-available replacement bridges, a lower bridge significance rating can be adopted as indicated.
Watershed developments/ conditions	Aerial photos are a particularly valuable aid in assessing watershed-wide factors influencing channel erosion at the bridge site.
Changes in watershed surface, forestry operations	Degradation, aggradation, and lateral instability can result from the surface being exposed and loosened, or covered and sealed. Surface changes can be caused by land clearings, landslides, surface erosion, fire, urbanization, changing vegetation cover, forestry operations, strip mining, agricultural activities, etc.
Sediment mining, dredging or dumping	Removal/ addition of sediment from/ to a channel can result in degradation/ aggradation and lateral instability.
Channel straightening/ channelization	Degradation and lateral instability can occur upstream of channel straightening, whereas aggradation and lateral instability are possible downstream of channel straightening. Channelization constraint of flows and sediment can result in degradation or aggradation, and lateral instability.

Channel diversion	Degradation and lateral instability can result from an increase in flow relative to sediment load in a channel. A decrease in flow relative to sediment load in a channel can cause aggradation and lateral instability.
Watershed-wide bank instability owing to channel migration/ widening	This reflects general lateral instability of the channel that may influence the bridge site.
Bridge on steep or active alluvial fan/ delta	Channels on steep or active alluvial fans are often characterized by significant degradation or aggradation, and episodes of significant lateral movement. This can be determined from site reconnaissance and an office review of maps and aerial photos.
Upstream or downstream check dam/ storage reservoir	An upstream dam can cause degradation and lateral instability at a bridge site by inhibiting sediment migration along the channel. A downstream dam can similarly cause aggradation and lateral instability at a bridge site. The opposite effects will occur for the removal of a dam.
Barrier beach control of the hydraulic regime at the bridge site, Sediment bar control of the hydraulic regime at the bridge site	Removal of hydraulic control (naturally during flooding) can result in degradation and lateral instability at the bridge site.
Waterfall control of the hydraulic regime at the bridge site	Upstream movement of the hydraulic control (naturally by erosion) can result in degradation and lateral instability at the bridge site.
Grade-control structure control of the hydraulic regime at the bridge site	Lowering of the hydraulic control can cause degradation and lateral instability at the bridge site. Aggradation and lateral instability can result from raising of the control.
Sea, lake or river level control of the hydraulic regime at the bridge site	Lowering of the level of the downstream receiving waters (sea, lake or converging river) can cause degradation and lateral instability at the bridge site. Aggradation and lateral instability can result from raising of the downstream controlling water level.
Scour experienced over bridge life, Implementation of previous screening recommendations	These are judged based upon an office review of bridge and waterway history (comments being recorded earlier in the screening form), and a field review of present conditions. Photograph previously-noted scour deficiencies that have not been remedied.
Field inspection/ review	It is expected that bridge inspectors look over both sides of the bridge from the bridge deck, particularly to identify debris build-up and local scour.

Average present distance (m) from bridge deck to channel bed	The distance D on **Figure C-1**. this reflects the average bed level across the site for present conditions. (**Figure C-1**)
Culvert of fixed invert: degradation and contract scour	Owing to the fixed-level nature of the invert of such a bridge opening, degradation and contraction scour may be more significant for these bridge openings (particularly downstream of the fixed invert).
Recent degradation exposing bridge foundations across the channel to a distance below the deck, D, approaching [A+(C-A)/2] or [A+(C-A)/2]	Degradation across the bridge opening that approaches half of the initial embedment length [(B-A) or (C-A)] for any foundation.
Scour countermeasures	Measures placed to prevent channel erosion. These measures vary according to the form of erosion occurring, appropriate measures being listed on the screening form for the different types of scour.
Counter measures present (identify: e.g. none, grade control structure, check dam, weir, channel lining, erosion-resistant bedrock, other), Countermeasures damaged/ ineffective	The presence of such countermeasures may reduce the vulnerability of the bridge to degradation and contraction scour. This protection may be reduced, however, if the countermeasures are damaged, or if they are assessed in the field inspection to be ineffective.
Recent aggradation across the channel to a distance below the bridge deck, D, approaching [2A/3]	Aggradation across the bridge opening that approaches one-third of the initial bridge opening depth (A) for any foundation.
Countermeasures present (identify: e.g. none, upstream check dam/ debris basin, controlled channel clearing/ mining, other), Countermeasures damaged/ ineffective	The presence of such countermeasures may reduce the vulnerability of the bridge to aggradation. This protection may be reduced, however, if the countermeasures are damaged, or if they are assessed in the field inspection to be ineffective.
Waterway adequacy	For flood flows, waterway inadequacy can exacerbate scouring with high flow velocities, large flow depths, and undesirable flow paths (e.g. overtopping the bridge or an approach, attacking channel banks, etc.).

Culvert of fixed invert: waterway adequacy	Waterway adequacy considerations are more important for a bridge than a culvert, i.e. a degree of waterway inadequacy is generally permissible and not a significant concern for culverts of fixed inverts.
Waterway significantly blocked	This typically reflects a reduction in waterway capacity and may be indicative of waterway inadequacy.
High debris or flood marks, Debris/ ice/ sediment on superstructure	These indicate the occurrence of large flow depths that may reflect waterway inadequacy.
Countermeasures present (identify: e.g. none, relief/ overflow bridges/ channels, other), Countermeasures damaged/ ineffective	The presence of such countermeasures may reduce the vulnerability of the bridge to waterway inadequacy exacerbating scour. This protection may be reduce, however, if the countermeasures are damaged, or if they are assessed in the field inspection to be ineffective.
Waterway bank materials	These reflect the relative erodibility of the channel banks.
Grading of waterway bank materials (identify: e.g. narrow, wide, unknown), Grading of bridge approach materials (identify: e.g. narrow, wide, unknown)	Grading is a range of sediment sizes.
Bridge approach	A bridge approach is an embankment supporting the road leading to the bridge, the embankment being founded in the waterway.
Bridge approach materials	These reflect the relative erodibility of the bridge approaches.
Thalweg	The thalweg is the line of lowest bed elevation along a channel.
Anabranches	Channel branches, similar to significant channel braids, which are relatively well-defined and stable.

Bank erosion/failure influencing the factors of safety for the bridge foundations, bank erosion/ failure influencing the factors of safety for the bridge approaches	Active bank failure/ erosion (especially along the toe or lower bank) can be evidenced by a number of symptoms: fresh vertical cut banks; (tension) cracks along the bank surface; irregular indentations in the bank surface; slump blocks; leaning or fallen vegetation along the bank line; vegetation, particularly live, in the flow; increased turbidity; newly formed bars immediately downstream; deflected flow patterns adjacent to the bank line; a deep scour pool adjacent to the toe of the bank; etc. Such symptoms (when significant, of notable rates, or influencing either foundations/ approaches directly or flows impacting the foundations/ approaches) can indicate increased vulnerability to scour for the bridge. Lateral movement is typically indicated by erosion/ failure co-existing along the outside banks of high curvature sections of the thalweg, bends, braids and anabranches. In contrast, channel widening is typically indicated by erosion/ failure co-existing along both banks, even in regions of high curvature in plan. Channel widening is commonly associated with ongoing vertical instability (aggradation or, more particularly, degradation).
Flow concentration at a bridge approach (identity source) (identity point of concentration)	A concentration of flow at a point on the approach can exacerbate scour at this point. Sources of flow concentration include flows in the thalweg; flows in a confluence; flows at the outside of a bend; deflected flows (e.g. by vegetation, debris, scour countermeasures, guidebanks, sediment bars, or adjacent bridge foundations); etc. use a sketch to identify actual or potential significant flow concentrations for the approaches.
Bridge approach toe erosion, Bridge approach fill movement	These reflect active scour of the bridge approach.

Countermeasures present (identify: e.g. none, riprap (note size), gabions, concrete blocks, tetrapods, used tires, planted vegetation, piles, jack or tetrahedron fields, groines, spurs, dikes, other, Countermeasures damaged ineffective	The presence of such countermeasures may reduce the vulnerability of the bridge to lateral channel movement, channel widening, or erosion of the bridge approaches. This protection may be reduced, however, if the countermeasures are damaged, or if they are assessed in the field inspection to be ineffective.
Increased flow depths at the outside of a channel bend (up to 4 times the average depth in upstream cross-sections in straight reaches) influencing the factors of safety for the bridge foundations	Secondary flows in channel bends can result in lowered bed levels, and increased flow depths, at the outsides of the bends. Such flow depths can be up to 4 times the average depth in upstream cross-sections in straight reaches. Any present or potential influence on bridge foundations during flooding of the presence of an upstream channel bend then needs to be assessed.
Increased flow depths in a channel confluence (up to 6 times the average depth in the upstream channel cross-sections) influencing the factors of safety for the bridge foundations	The mixing of flows in a channel confluence results in lowered bed levels, and increased flow depths, in the confluence. Such flow levels can be up to 6 times the average depth in the upstream channel cross-sections. Any present or potential influence on bridge foundations of the presence of a channel confluence then needs to be assessed.
Countermeasures present (identify: e.g. none, channel lining, erosion-resistant bedrock, other), Countermeasures damaged/ ineffective	The presence of such countermeasures may reduce the vulnerability of the bridge to scour in bends or confluences. This protection may be reduced, however, if they are assessed in the field inspection to be ineffective.
Debris on the channel foundations or in the channel upstream	The occurrence of moderate-to-heavy debris accumulations on the foundations or in the channel upstream indicates that projected foundation widths perpendicular to flood flows may need to be increased to allow for debris accumulations.
Angle of flood flow to pier centerlines	This is required in order to assess projected pier widths perpendicular to flood flows.

Angle of flood flow to abutment centerlines	This is required in order to assess projected abutment lengths perpendicular to flood flows
Average approach flow depth (ft) for design floods	This is required in order to assess potential scour depths at abutments.
Maximum present distance (ft) from bridge deck to channel bed	The distance D_m on **Figure C-1.** The maximum value of D_m across the channel (independent of the of the foundation positions) is adopted to reflect possible minimum embedment lengths for present conditions. (**Figure C-1**)
Projected width perpendicular to flood flow of debris-laden pier (ft)	Pier width inducing local scour allowing for debris accumulations and the angle of flood flow to pier centerlines.
Approximate potential local pier scour (ft) $D_{sp} = (D + 2.4b_e)$	The distance D_{sp} in **Figure C-1** (based on scour equation; e.g., HEC 18 or Melville and Coleman 2000). For piers socketed into erosion-resistant bed rock, potential local scour can be taken to be negligible, with $D_{sp} = D$. (**Figure C-1**)
Projected length perpendicular to flood flow of debris-laden abutment (m)	Abutment length inducing local scour allowing for debris accumulations and the angle of flood flow to abutment centerlines
Approximate potential local abutment scour (m) D_{sa} = minimum of $(D+2L_e)$ and $(D+10y)$	The distance D_{sa} on **Figure C-1** (based on Melville and Coleman 2000, for alternate conditions). For abutments socketed into erosion-resistant bed rock, potential local scour can be taken to be negligible, with $D_{sa} = D$. (**Figure C-1**)
Foundation tilt/ movement	Foundation tilt or movement, which can often be readily detected by sighting along bridge handrails, may reflect scour induced foundation undermining.
Maximum possible present local scour, D_m, approaching [A+(B-A)/2] or [A+(C-A)/2]	Present maximum local bed-level lowering at the bridge site approaching half of the initial embedment length [(B-A) or (C-A)] for any foundation. This assessment allows for some infilling of local scour holes as floods recede.
Potential local pier scour, D_{sp}, approaching [A=3(C-A)/4]	Potential local bed-level lowering approaching three-quarters of the initial embedment length (B-A) for any pier. (**Figure C-1**)
Potential local abutment scour, D_{sa}, approaching [A=3(C-A)/4]	Potential local bed-level lowering approaching three-quarters of the initial embedment length (C-A) for any abutment. (**Figure C-1**)
Spill-through abutment toe erosion, Spill-through abutment fill movement	These reflect active scour of the spill-through abutment.

Flow concentration at a bridge foundation (identify source) (identify foundation)	A concentration of flow at a bridge foundation can exacerbate scour at this foundation. Sources of flow concentration include flows in the thalweg; flows in a confluence; flows at the outside of a bend; deflected flows (e.g. by vegetation, debris, scour countermeasures, guidebanks, sediment bars, or adjacent bridge foundations); etc. Identify foundations of actual or potential significant flow concentration and use a sketch to identify the concentration of flow for each such foundation.
Countermeasures present (identify: e.g none, channel lining, erosion-resistant bedrock, riprap (note size), gabions, concrete blocks, tetrapods, used tires, sacrificial piles, deflector vanes, collars, underpinning, jack or tetrahedron fields, groines, spurs, dikes, other), Countermeasures damaged/ ineffective	The presence of such countermeasures may reduce the vulnerability of the bridge to local scour at piers and abutments. This protection may be reduced, however, if the countermeasures are damaged, or if they are assessed in the field inspection to be ineffective.
Overall scour susceptibility (1, 2, 3, 4)	Assessed based on the bridge significance and overall bridge vulnerability ratings. Ratings of '1' and '4' indicate the highest and lowest susceptibilities respectively.
Possible actions	Possible remedial actions are noted for overall scour-susceptibility ratings of 1, 2, or 3. possible actions include : monitoring of scour development at the bridge site (frequencies discussed below), detailed analyses of potential depths of scour components in accordance with the guidance of Melville and Coleman (2000), structural countermeasures and channel modifications (lists of countermeasures for different scour types are given above), bridge replacement, bridge closure, etc. Indicate applicable options and give details where possible.

Scour-monitoring frequencies	Commonly-adopted frequencies include: routine (associated with the biannual scour-screening program); seasonal (during or after seasons regularly of high flows), storm-based (during or after the passage of floods), and fixed (instrument based to give high frequency monitoring of scour levels).
Personnel	For quality assurance purposes, the personnel carrying out the reviews and assessments are identified, along with when the reviews and assessments were carried out.
Visual Records, Notes and Comments	These are recorded as required. Standard photographs of the bridge and waterway are required to be taken. On each photograph taken note the date, the bridge name, what is being viewed and where from. When viewing the bridge from upstream (or downstream), note the distance upstream (or downstream) from the bridge. When viewing the channel from the bridge, note the position on the bridge from which the photo was taken. Supplemental records are also useful for review of field conditions after the inspection. Note factors indicating susceptibility of the bridge to scour, individual foundations highlighted as scour susceptible, and locations of channel/ foundation erosion influencing the assessment.