Evaluation of Bridge Scour Research

DETAILS

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EVALUATION OF BRIDGE SCOUR RESEARCH

This digest summarizes key findings of NCHRP Project 24-27(01), "Evaluation of Bridge Scour Research: Pier Scour Processes and Predictions," conducted by University of Iowa under the direction of the principal investigator, Dr. Robert Ettema, now at the University of Wyoming; 24-27(02), "Evaluation of Bridge Scour Research: Abutment and Contraction Scour Processes and Predictions," conducted by Georgia Institute of Technology under the direction of the principal investigator, Dr. Terry Sturm; and 24-27(03), "Evaluation of Bridge Scour Research: Geomorphic Processes and Predictions," conducted by Ayres Associates, Inc., under the direction of the principal investigator, Dr. Lyle Zevenbergen. The digest is based on the three project final reports, which are available as *NCHRP Web-Only Documents 175, 181,* and *177*, respectively.

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INTRODUCTION

The United States Geological Survey (USGS) defines *scour* as the hole left behind when sediment (sand and rock) is washed away from the bottom of a river. Although scour may occur at any time, scour action is especially strong during floods. Swiftly flowing water has more energy than calm water to lift and carry sediment down river.

Scour affecting bridges may be classified as follows:

- *Local* scour is the removal of sediment from around bridge piers or abutments.
- *Contraction* scour is the removal of sediment from the bottom and sides of a river channel at the bridge opening. It is caused by the increase in the velocity of water as it moves through a bridge opening that is narrower than the river channel. The most common cause of this type of scour is contraction of the flow by bridge approach embankments encroaching onto the floodplain, into the main channel, or both.
- *Degradational* scour is the general removal of sediment from the river bottom by the flow of the river that, while a natural process, may cause removal of large amounts of sediment over time at the bridge site.

The obvious danger of scour at or near a bridge is that the scour will undermine the piers and abutments that support the bridge and cause its catastrophic failure. In 1987, the 35-year-old bridge carrying Interstate 90 over Schoharie Creek in New York State failed with loss of life during a spring flood. This flood was classified as a 50-year event; the bridge had experienced a 100-year event soon after its construction. The failure was initiated by extensive scour under one of the bridge piers; the absence of adequate countermeasures to scour at the pier as well as unnoted damage from the 100-year and later events contributed to the pier's failure.

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In the aftermath of this failure and the comprehensive investigations into its causes, FHWA instituted requirements for the states to identify overwater bridges vulnerable to scour and determine those where scour was severe. These inventories of bridge site examinations, often undertaken with the assistance of USGS, have allowed the states to plan and conduct maintenance and rehabilitation to remedy present scour and slow or prevent its future development.

Besides these practical measures, the states—individually and collectively through NCHRP, together with FHWA and USGS—embarked in the early 1990s on coordinated research programs to quantify and model the mechanisms of bridge scour and develop effective, efficient countermeasures to its occurrence.

Recently completed NCHRP Projects 24-27(01), 24-27(02), and 24-27(03) had the common objectives to (1) critically evaluate the body of bridge scour research completed worldwide since the early 1990s and (2) propose specific research results for adoption by AASHTO in its development of future editions of two key highway hydraulic engineering guidance documents: *Policy for Design of Highway Drainage Facilities* and *Recommended Procedures for Design of Highway Drainage Facilities.* Project 24-27(01) focused on pier scour, 24-27(02) on abutment and contraction scour, and 24-27(03) on geomorphology. In addition, each project was tasked with proposing future research in these three technical areas.

NCHRP RRD 378 summarizes the key deliverables of these projects. The following sections present the research results proposed for adoption by AASHTO in each of the three technical areas and proposed future research topics in each technical area.

RESEARCH RESULTS PROPOSED FOR ADOPTION BY AASHTO

Pier Scour Processes and Predictions

The results of NCHRP Project 24-27(01) are reported in *NCHRP Web-Only Document 175* (Ettema et al. 2011). This section summarizes the research results proposed for adoption by AASHTO. The main conclusions are linked to the following considerations:

1. The flow field and the potential maximum scour depth, at a pier scale, change in accordance with three variables: effective pier width, flow depth, and erodibility of the foundation material in which the pier is sited. Of these variables, effective pier width and flow depth are of prime importance because they determine the overall structure of the flow field. Effective pier width (a^*) embodies pier form and alignment relative to approach flow velocity. For non-cohesive foundation material (silts, sand, and gravel) erodibility is expressible in terms of a representative particle diameter.
2. To understand pier scour processes and develop reliable relationships for design estimation of scour depth, it is necessary to comprehend the main flow-field features driving scour and how the features may adjust in importance with varying pier sizes, shapes, and flow conditions. The flow field differs substantially for the narrow-pier and wide-pier categories of pier scour, with the transition-pier category being intermediate between them. These categories can be defined approximately as follows:
   - Narrow piers ($y/a^* > 1.4$), for which scour typically is deepest at the pier face.
   - Transition piers ($0.2 < y/a^* < 1.4$), for which scour depth is deepest at the pier face and is influenced by y/a^*.
   - Wide piers ($y/a^* < 0.2$), for which scour typically is deepest at the pier flank. It is relatively rare, for design scour estimation, that piers are in this category.

   The foregoing categories can be expressed in terms of y/a. Pier scour literature normally expresses data trends in terms of a dependent variable (notably, flow depth or bed particle diameter) relative to a pier's constructed width, a.
3. Because considerable uncertainty attends flow and boundary material at bridge waterways, design prudence requires estimation of a potential maximum scour depth, rather than a scour depth prediction. Potential maximum scour depth is the greatest scour depth attainable for a given pier flow field, and can be determined using the primary variables named in the paragraph above. Lesser scour depths result as additional variables are considered, but the uncertainties associated with the variables diminish the estimation reliability. Besides the uncertainties associated with foundation material erodibility, the tem-

poral development of scour entails significant uncertainty. Prediction (not design estimation) of scour depth for most pier sites usually involves a high level of uncertainty.

Several factors alter pier flow fields and complicate design estimation of pier scour. Factors affecting pier flow field include flow influences exerted by increased complexity of pier geometry, adjoining bridge components (abutment or submerged bridge deck), debris or ice accumulation, and channel morphology. Factors affecting boundary erosion include uncertain erosion characteristics of material (clay, rock), layering of boundary material, and protective vegetation.

The main conclusions of the evaluation of research results conducted in Project 24-27(01) are the following:

1. Since 1990, substantial advances have been made in understanding pier scour processes and predicting scour depth. In particular, the following aspects of pier scour have advanced:
   - The roles of variables and parameters defining pier scour processes.
   - Leading predictive methods for scour depth prediction that better reflect parameter influences.
   - Knowledge regarding pier scour in clay and weak rock.
   - Insight into pier-site complications caused by debris and ice, and by interaction with bridge components (abutment and bridge deck).
   - The capacity of numerical modeling to reveal the three-dimensional and unsteady flow field at piers in ways that laboratory work heretofore has been unable to provide.

   These advances address research problems identified in NCHRP Project 24-8 (Parola et al. 1996), such as scour at wide and skewed long piers, and the scour effects of debris accumulation. They also address aspects of pier scour not envisioned by NCHRP Project 24-8, such as the roles of turbulence structures within the pier flow field, three-dimensional numerical modeling, and scaling issues in the conduct of hydraulic models of pier scour. However, further significant research has yet to be done in each of these areas.
2. The following aspects of pier scour remain insufficiently understood:
   - The pier flow field, especially how it systematically changes with variations of the two primary length scales (effective pier width and flow depth). In other words, more work is needed to define the systematic changes in the flow fields associated with the narrow-, transition-, and wide-pier categories of pier scour.
   - Scour of boundary materials whose erosion characteristics are not adequately understood (some soils, rock). However, existing reliable data indicate that scour depths in cohesive soils and weak rock do not exceed those in cohesionless material.
   - Quantification of factors further complicating pier flow field (notably debris or ice accumulation, proximity of bridge components, channel morphology) and erodibility of foundation material (especially layered material where the surface layer protects lower layers).
   - Temporal development of pier scour depth.
3. The evaluation in *NCHRP Web-Only Document 175* describes the well-understood relationships between scour depth and significant parameters. Extensive use is made of Melville and Coleman (2000) in delineating the relationships, with more recent information cited from other sources. Notable examples of recent information are similitude in hydraulic modeling of turbulence structures; scour at large piers; erosion of clay (and, to a lesser extent, of rock); and the purported influences of suspended sediment.

   A group of primary parameters is identified in *NCHRP Web-Only Document 175* that define the structure and geometric scale of the pier flow field, and therefore determine the potential maximum scour depth. The secondary parameters characterize scour depth sensitivities within the geometric scale limit, and normally lead to scour depths less than the potential maximum scour depth. The values of the secondary parameters are subject to considerable uncertainty at pier sites.

   The primary parameters are as follows:
   - *y/a,* which indicates the geometric scale of the pier flow field in terms of approach

flow depth and pier width (in a vertical cross-sectional plane transverse to the pier and a plane streamwise to the pier).
- *a/D,* which relates the length scales of pier width and median diameter of bed particle.
- Ω, *a/b,* and θ, which define pier face shape, aspect ratio of pier cross-section (face width/pier length), and approach flow alignment to pier, respectively. These parameters may be merged with pier width, *a,* to form the compound variable a^* (effective pier width). It can be useful to express the two length-scale parameters as y/a^* and a^*/D.

The evaluation also explains the limiting extents to which parameter influences can be isolated from each other. Some variables exert multiple influences. Consequently, a limit is soon reached with the approach of formulating a predictive method based on a semi-empirical assembly of parameter influences.

4. An important conclusion drawn from the evaluation in *NCHRP Web-Only Document 175* is the need to transition from the present semi-empirical method for design estimation of scour depth used in HEC-18 and adopted in AASHTO policies and procedures (Richardson and Davis 2001a) to a new method better reflecting the relationships between the primary variables and the potential maximum scour depth at a pier. A new method is recommended here: the semi-empirical, Sheppard-Melville method as advanced during NCHRP Project 24-32 (Sheppard et al. 2011).

The Sheppard-Melville method better reflects flow-field changes, and thereby scour processes, as expressed in terms of the parameters of primary importance. Therefore, it is more readily extended to the transition- and wide-pier categories (i.e., it more expressly includes the length scales, y/a^* and a^*/D, and includes the flow-intensity parameter, V/V_c). Additionally, it is the method developed in an effort to account for flow-field adaptation to variations of y/a and a/D.

A useful aspect of the Sheppard-Melville method is that it can be simplified to reflect potential maximum scour depth associated with the three pier flow-field categories (narrow, transition, and wide). A weakness in the Richardson and Davis method is that it does not lend itself to this simplification.

Full use of the Sheppard-Melville method for predicting scour depth presently requires a modicum of further research regarding prediction of scour depth during live-bed scour at piers in the transition-pier category, and to a certain extent in the wide-pier category. This additional research is discussed in the section on proposed research.

The Richardson and Davis method has been in use for several decades and has been refined over time. It is well calibrated for estimating scour depth for piers in the narrow-pier and transition-pier categories. Its scour depth estimates for these applications concur reasonably well with those obtained in NCHRP Project 24-32 using the Sheppard-Melville method. Nonetheless, the method is shown not to reflect scour processes as well as does the Sheppard-Melville method.

5. Due to the limits inherent in semi-empirical formulations of pier scour depth, the evaluation recommends the use of a structured methodology for design estimation of pier scour depth. The methodology addresses four levels of pier site complexity. As pier site complexity increases, a graduated shift occurs from design reliance on a semi-empirical method (Sheppard-Melville) to hydraulic modeling, possibly aided by numerical modeling, as indicated in Table 1.

The methodology enables the designer to account for the scour processes yet also recognize the limits of existing semi-empirical methods for scour depth estimation. The leading semi-empirical methods for scour depth prediction (Sheppard-Melville and Richardson and Davis) were developed using data for simple pier forms and were adapted for common pier forms. The accuracy of the methods reduces as pier form complexity increases.

6. The following specific proposals have been made with respect to the updating of AASHTO's manuals:
   - Adopt the structured design methodology illustrated in Table 1.
   - Transition from the Richardson and Davis (2001a) method to the Sheppard-Melville

method (Sheppard et al. 2011), given in simplified form as Equation (1):

$$\frac{y_s}{a^*} = 2.5 \tanh\left[\left(\frac{y}{a^*}\right)^{0.4}\right] \quad (1)$$

- The former method (Richardson and Davis) inadequately reflects scour processes, though it is well adapted empirically to scour data. The latter method (Sheppard-Melville) better reflects scour processes. A modicum of further research is needed to complete the development of the Sheppard-Melville method. The present evaluation has occurred at a transitional period when it is recognized that the present design method for simple and common pier forms should be replaced, but a satisfactory replacement method has not yet been fully completed.
- The present version of HEC-18 should recommend the use of both the current method (Richardson and Davis, 2001a) and the Sheppard-Melville method. In due course, the latter method should completely replace the former one.

Abutment and Contraction Scour Processes and Predictions

The results of NCHRP Project 24-27(02) are reported in *NCHRP Web-Only Document 181* (Sturm et al. 2011). This section summarizes the research results proposed in that document for adoption by AASHTO.

NCHRP Project 24-27(02) established that none of the abutment scour or contraction scour formulas evaluated fully satisfied the following criteria:

- Adequacy in addressing parameters that reflect important physical processes governing abutment scour.
- Limitations of formulas in design applications with respect to ranges of controlling parameters on which they are based.
- Categorization and acceptability of laboratory experiments and research methods that led to the development of the formula (e.g., experimental duration, variety of particle sizes and types of sediment, realistic geometries and scales, characterization of flow field, degree of idealization, large database).
- Attempts to verify and compare formulas with other laboratory and field data, if any, with which a valid comparison can be made.
- Application and ease of use for design (notably as recommended in the *AASHTO Standard Specifications for Highway Bridges*).

Furthermore, none of the simple abutment scour formulas evaluated in the project would apply to all of the complexities found in the field. Finally, the idealized contraction scour formulas currently in use are problematic because of their basis in assumptions

Table 1 Summary of recommended structured design methodology.

Pier Design Complexity (Pier Form and/or Pier Site)	Design Method
Simple single-column pier forms (narrow- and transition-pier categories).	**Semi-empirical method:** Transition from current HEC-18 method (Richardson and Davis 2001a) to Equation (1) as simplified from Sheppard et al. (2011).
Common pier forms (piers with multiple components; e.g., column, pile cap, pile group).	**Semi-empirical method with effective pier shape and alignment factors:** Consider hydraulic model to validate scour depth estimate.
Common pier forms in complicating situations (debris or ice accumulation, abutment proximity, bridge-deck submergence).	**Empirical method combined with procedure to address scour contribution of site complication:** Consider hydraulic model to validate scour depth estimate.
Complex or unusual pier situations where a reliable method or information on parameter influences does not exist (e.g., scour for wide-pier category).	**Hydraulic modeling, possibly aided by numerical modeling:** An approximate scour depth estimate may be obtained using an empirical method suitably developed for the wide-pier category.

that are not satisfied for bridge contractions (which are inherently short contractions, and for which the flow is non-uniform). Given the state of current understanding of abutment/contraction scour, or lack thereof, it proved difficult to develop design-specific proposals. Some important strides forward have been made in the past decade, but much remains to be learned before the more settled and defined state of knowledge that currently exists with respect to pier scour is arrived at for abutment and contraction scour.

In spite of the caveats previously noted, some general and specific proposals can be made.

General Proposals

- The definition of abutment scour and the formulas by which it is estimated pertain to a combination of local scour due to large-scale turbulence generated by flow separation and constriction scour due to flow acceleration caused by the flow contraction itself. Under these circumstances, it would appear that contraction scour should not be computed separately from abutment scour estimates. Therefore, it is proposed that a combined abutment/contraction scour formula be developed.
- Given that many abutment failures due to scour are the result of collapse of an erodible embankment, it is proposed that geotechnical estimates of stability should accompany hydraulic scour estimates as suggested by NCHRP Project 24-20 (Ettema et al. 2010). The precise approach to formulating such estimates requires further work, however.
- It is proposed that abutment toe protection, guide banks, or both should be considered for all new installations of abutments. Furthermore, for setback abutments, the setback distance should be large enough to avoid failure of the main channel bank in the event of an embankment failure. This distance depends on the flow distribution in the bridge opening as well as the abutment characteristics.
- A small group of abutment scour formulas using the flow distribution in the bridge section or a similar independent variable are best for estimating abutment scour in compound channels. The idealized long contraction scour depth is a useful reference scour depth for these formulas.
- It is proposed that a clear distinction be made between abutment scour depth estimates by formulas developed for solid abutments and those for erodible embankments and abutments. These formulas should be applied only to the case for which they were developed. The solid abutment scour formulas will predict the maximum potential scour depth in comparison to erodible abutment/embankment scour formulas that consider the flow relief associated with embankment failure. Unifying these formulas with an adjustment factor for erosion strength of the embankment would be a useful goal.
- It is proposed that a renewed effort be undertaken to educate hydraulic engineers with respect to the complexities of abutment scour and the new numerical and physical modeling tools available to resolve difficult cases.

Specific Proposals

Contraction scour should be viewed as a reference scour depth calculation, as suggested in several recent investigations of abutment scour, and abutment scour should be taken as some multiple of contraction scour rather than additive to it. In this context, further refinement of contraction scour equations may not be the most productive approach; rather, the incorporation of contraction scour into abutment scour formulas may be a more realistic and useful goal.

A small subset of abutment scour formulas, each having its desirable attributes, should be unified into a single formula in order to develop more realistic and robust procedures for abutment scour prediction. Reducing these formulas to a common form and establishing upper and lower limits of expected abutment scour depending on the limitations of each formula would seem to be a practical path forward. The formulas judged to be most promising in this regard, and with respect to the established criteria, are the following:

- Ettema et al. (2010)—This formula is the only formula that considers an erodible embankment; it has the desirable attributes of reflecting the physics of the abutment scour process both in terms of flow constriction and turbulent structures of the flow separation process albeit in a rudimentary form; and it includes experiments with compound channel geometry although a wider array of experiments is needed. It could in theory be applied to scour Classes I, II, and III channels (where Class I refers to narrower bridge crossings of incised channels; Class II to wider bridge crossings, where the channel is typically compound; and Class III to bridges spanning wide braided river channels).

- Sturm (2006)—This formula includes a method of accounting for flow redistribution due to compound channel geometry with similar independent variables compared to the formula of Ettema et al., and it represents the other extreme of a solid-wall foundation as opposed to an erodible embankment. It is most applicable to Class II channels, Scour Condition B (defined as scour of the floodplain that occurs for abutments set well back from the main channel).
- Melville et al. (2006a)—This formula is most applicable to short, solid-wall abutments and depends on abutment length rather than the flow distribution in the contracted section, but it can be viewed as comparable to the first two formulas if some width of contracted flow, which is related to the width of the scour hole, is established in the contracted section through which all of the approach floodplain flow passes. It also is at the limit of a solid-wall foundation rather than an erodible one. It is most applicable to Class I and Class III channels.
- *ABSCOUR* (Maryland State Highway Administration 2010)—This formula has the desirable attribute of including the direct effect of flow redistribution on the floodplain through the Laursen contraction scour formula in terms of q_2/V_c, although the adjustment factors for spiral flow and velocity should be re-evaluated in the limit of severe contractions. In addition, the correction factor related to floodplain width seems to be an ad hoc adjustment for the specialized data of Benedict (2003) that applies only to South Carolina. These adjustment factors should all be reconsidered in the process of developing a unified formula that is more generally applicable.

Although the Briaud et al. (2009) formula does not satisfy the criterion for best parameter framework, it is one of the only databases for cohesive sediments, and the data could be useful in expanding the range of applicability of the final unified formula.

A unifying formula or family of formulas may be formed from the list above with a common set of independent variables, preferably of the form of the Ettema et al. formula. The Ettema et al. and Maryland formulas directly use idealized contraction scour as the reference variable for non-dimensionalizing the flow depth after scour at the bridge section while the others use the approach flow depth. Each of these approaches has desirable attributes, and each one should be tested in the effort to develop a unifying formula. Such a formula could provide an interim update to the HEC-18 formulas, which currently must be used with informed caution, until the proposed research needs discussed in this digest can be fully satisfied.

A flow chart should be developed as a guide to evaluate abutment scour in an informed manner and to assist the judgment of design engineers. Where a unified abutment scour formula predicts very large abutment scour depths or possible embankment failure, appropriate scour countermeasures should be indicated. Geotechnical evaluation of scour could become a routine part of the analysis. For more complex problems, hybrid numerical and laboratory hydraulic models should become a readily accessible option.

In the near term, until better methods are available for estimating the erodibility of the embankment itself, abutments should have a minimum setback distance from the bank of the main channel with riprap protection of the embankment and a riprap apron. The minimum setback distance would then be that recommended for the width of riprap aprons (see Lagasse et al. 2009: HEC-23). Other scour countermeasures, especially guide banks, should be seriously considered for protection of the embankment as well.

Further development of an educational curriculum for hydraulic engineers should be undertaken in order to emphasize the proper choice of parameters that go into any scour calculation and the use of two-dimensional and three-dimensional numerical models to better evaluate the hydraulic parameters. At least in the short term, two-dimensional numerical models should be used on all but the simplest bridge crossings as a matter of course. The prediction of critical velocity and the estimates of flow distribution in the contracted section are examples of parameters that are crucial to the success of any abutment scour formula. Furthermore, implementation of a computerized procedure as in ABSCOUR or HEC-RAS with controls on reasonable values of input parameters would be very helpful.

A long-term field program of obtaining high-quality, real-time field data should be undertaken. Simultaneous measurement of bed elevations and the flow field are possible with in-situ sensing devices that record the data and transmit them for real-time bridge monitoring on the internet. Sites without a large number of complicating factors could be identified, and full, reliable data sets of simultaneous hydraulic conditions and bed elevations could be obtained to better understand field scaling issues and the simultaneous interaction of various scour processes driven by the hydrodynamics of the flow. Although embarking on such a program will be expensive and require patience, the results will move the ultimate solution to the abutment scour problem forward more effectively than less expensive post-flood surveys.

Geomorphic Processes and Predictions

The results of NCHRP Project 24-27(03) are reported in *NCHRP Web-Only Document 177* (Zevenbergen et al. 2011). This section summarizes the research results proposed for adoption by AASHTO.

Table 2 presents a matrix of current practice for analyzing the potential for stream instability and scour at highway stream crossings derived from HDS-6 (Richardson et al. 2001b), HEC-18 (Arneson et al. 2012), and HEC-20 (Lagasse et al. 2001, Lagasse et al. 2012). Analytical tools are classified into three broad types (geomorphology; aggradation and degradation; and lateral migration and channel widening) and three levels of complexity (qualitative or conceptual assessment; quantitative analysis; and advanced, in-depth quantitative methods).

Geomorphology

Seventeen geomorphology research results were identified in NCHRP Project 24-27(03). The following eight results, further described in Table 3, are proposed for adoption:

- Downstream hydraulic geometry of alluvial channels.
- Channel avulsions on alluvial fans.
- Rosgen classification system and Natural Channel Design (see note to Table 3).
- Toolkit for fluvial system analysis.
- Regional risk analysis of channel stability.
- Fundamental concepts of fluvial geomorphology and river mechanics.
- Current state of practice for applying geomorphology to river engineering.
- Environmental performance standards for bridges.

Reconnaissance

Reconnaissance of a bridge site is an important tool for collecting appropriate data and information for use in assessing stream stability at the site and, therefore, is included as one of the seven primary research topics to be evaluated. Although not a specific type of analysis, bridge site reconnaissance provides information relative to the various factors identified for the three levels of analysis described in Table 2, as follows:

- Level 1 – geomorphic factors, channel type, rapid assessment, field evidence, headcuts, and nickpoints.
- Level 2 – channel evolution, armoring, geotechnical stability.
- Level 3 – stream reconnaissance, erodibility testing.

Eight site reconnaissance research results were identified in NCHRP Project 24-27(03). The following four results, further described in Table 4, are proposed for adoption:

- Assessment of channel stability at bridges in physiographic regions.
- Geomorphic analysis of large alluvial rivers based on widely accepted classification and analysis techniques.
- Digital mapping at bridge sites for detailed, advanced reconnaissance and monitoring.
- Diagnostic approach to assessing and monitoring stream channels.

Degradation and Aggradation

Degradation is the long-term lowering of bed elevation. Degradation can be a significant component of total scour, but it is not caused by the bridge or by highway constriction. Rather than occurring only in the vicinity of the bridge, degradation extends well upstream and downstream of the bridge. The two primary causes of degradation are sediment deficiency

(*text continues on page 13*)

Table 2 Current practice based on type and level of analysis.

Level of Analysis	Level 1 – Assessment (qualitative or conceptual)		Level 2 – Analysis (quantitative)		Level 3 – Advanced Methods (in-depth quantitative)	
FHWA Manual	HEC-20 (HEC-18)	HDS-6	HEC-20 (HEC-18)	HDS-6	HEC-20 (HEC-18)	HDS-6
Type of Analysis						
Geomorphology	Geomorphic Factors		Channel Response		Stream Reconnaissance	
	2.3	5.4.1	4.4	5.5	4.2, App. C	–
	Channel Type/Sediment Load		Lane Relationship		Complex Response	
	3.5.3	5.4.1	4.4.2	5.5.1	4.4.4	–
	Rapid Assessment		Lane S-Q thresholds			
	4.5, App. D	–	4.4.2	5.4.5		
	Channel Classification		Channel Evolution			
	4.3	5.4.1	2.2	–		
	Aerial Photo Review		Aerial Photo Evaluation			
	6.2.2	8.1.4	6.2.2	–		
Aggradation and Degradation	Bridge Inspection Records		Rating Curve Shifts		Sediment Transport Modeling	
	3.3.1, 6.3.1, (4.3.1, 11.2, 11.3.8)	–	3.6.7, (4.3.2)	–	6.3.3	4.9, 5.6.2
	Field Evidence		Sediment Continuity		Physical Modeling	
	6.3.1	–	2.4.2, 6.3.3	–	3.7	5.6.1
	Lane Relationship		Equilibrium Slope		Erodibility Testing	
	4.4.2	5.5.1	6.3.2	–	(App. L & M)	
	Base Level Change (+/–)		Incipient Motion			
	6.3.2	–	3.6.5, 6.3.2	3.5		
	Headcuts and Nickpoints		Armoring			
	6.3.2	5.2.4	3.6.6, 6.3.2	–		
Lateral Migration and Channel Widening	Bridge Inspection Records		Aerial Photo Evaluation		Sediment Transport Modeling Including Geotechnical Stability	
	3.3.1 (11.2, 11.3.8)	–	6.2.2	–	App. B	
	Field Evidence		Geotechnical Stability			–
	2.3.9, 3.5.4	5.8.1	2.3.9, App. B	–		
	Aerial Photo Review		Regime Equations			
	6.2.2	–	–	5.4.6		
			Channel Evolution			
			2.2	–		

Table 3 Strengths and weaknesses of proposed methods in geomorphology topic.

Result (Reference)	Level	Strengths	Weaknesses
Geomorphology			
Downstream Hydraulic Geometry of Alluvial Channels (Lee and Julien 2006)	2	Presents massive database (1,485 sites). Covers wide range of flow conditions for sand/gravel/cobble streams with meandering to braided planforms. Database used to calibrate and validate new and improved hydraulic geometry equations. 95% of the calculated hydraulic geometry parameters between 50% and 200% of field measurements. Equations can be used as a template to indicate whether or not a channel is in regime.	Equations only apply to stable alluvial channels. Range on calculated hydraulic geometry parameters (50% to 200% of observations) is large. Wohl (2004) indicates regime equations have mixed results for mountain streams. Relationships can be expected to be poorly suited to describe resistance to flow. Relationships are strictly only applicable to the data sets from which they were derived.
Channel Avulsions on Alluvial Fans (Field 2001)	2	Provides guidance on identifying and predicting sites of potential avulsion on active alluvial fans upstream of a highway crossing. Could be used to identify and implement countermeasures to prevent potential avulsions.	It is not known if methodology has been implemented specifically for the protection of transport infrastructure. Methodology predicts the location of a potential avulsion, but predicting the timing may be more subjective because it depends on occurrence of flow events.
Critical Evaluation of the Rosgen Classification and Associated "Natural Channel Design" (Simon et al. 2007—*see note below table*)	2	Explains why stream channel design and restoration should be based on physically based analyses and process-based approaches that are currently available and are founded on well-established scientific and engineering literature.	Authors have been known to be very critical of Rosgen. Consequently, those in the restoration business are likely to turn a deaf ear to these criticisms. Only further research and documenting of the success or failure of Rosgen's approach will determine whether or not it will stand the test of time.
Toolkit for Fluvial System Analysis (Bledsoe et al. 2007)	2	GeoTools has been designed to provide a wide range of useful information from a parsimonious set of inputs and to bypass the need for individual investigators to produce custom, "homegrown" data analysis tools.	Risk-based models based on metrics from GeoTools require regional calibration. Even though GeoTools has undergone beta testing on a range of different computer types and configurations, compatibility problems may still exist.
Regional Risk Analysis of Channel Stability (Bledsoe and Watson 2000)	2	The mobility index has explanatory power practically equaling that of models containing slope, discharge, and D50 as separate independent variables, especially for sand bed channels. The approach can be for predicting channel instability and scaling channel processes across diverse geological and climatic regions. Logistic regression models that use mobility index can predict unstable channel forms. Logistic models also provide a means of gauging channel sensitivity to modest changes in the controlling variables.	Predictions of widening in gravel-bed channels are less reliable due to uncertainties associated with defining the bank characteristics.

Table 3 (Continued).

Result (Reference)	Level	Strengths	Weaknesses
Geomorphology			
Fundamental Concepts of Fluvial Geomorphology and River Mechanics (Schumm and Harvey 2006)	1/2	Chapter provides a concise review of the current state of practice. Covers a number of concepts that are not included in HDS 6 and HEC-20 but which should be added. Covers systems approach to evaluating channel stability at a site; consideration of geomorphologic factors that influence landforms (engineering sites) and hazards associated with them, and, development of dimensionless stability numbers for evaluating incised channel evolution.	The chapter does not provide any original research. The concepts and approaches identified by the authors only provide general guidance on how one can identify existing hazards or problems and potentially identify future hazards or problems as they relate to a particular site.
Current State of Practice for Applying Geomorphology to River Engineering (Biedenharn et al. 2006)	1/2	Chapter provides a good overview of fluvial geomorphology and river mechanics concepts that will be of use to engineers. Many of these concepts are covered only generally in HEC-20 and HDS 6.	Chapter does not provide any original research and is primarily a reference tool.
Environmental Performance Standards for Bridges (Oregon DOT 2005)	1/2	Research reported addresses an issue that is very important to DOTs, which is avoiding difficulties in permitting. Research also addresses the philosophy of sound bridge design, which includes avoiding stream stability issues over the life of the bridge. Each of these goals is addressed by considering the function, continuity and connectivity of the stream and floodplain.	Fluvial design standard was targeted at conditions in Oregon so other standards would need to be developed for other regions. Another limitation, even potentially for Oregon, pertains to definition of the *functional floodplain.* There are no theoretical explanations given for defining the functional floodplain as 2.2 times the bankfull width. No justification is given for using the 10-year recurrence interval flood as the reference discharge for zero contraction scour.

NOTE: Simon et al. (2007) became part of the literature database based on the search criteria and specific journals that were included. It addresses limitations of Rosgen's methodologies as perceived by Simon et al. In order to not provide an exclusively one-sided discussion of Rosgen's approaches by this project, "Natural Channel Design" should be considered as a starting point for considering both limitations and benefits of these approaches. Lave (2009) provides a discussion which could serve as a source for discussing both sides of this issue. From the standpoint of this project, it is important to frame the discussion in the context of HEC-20, which is not a restoration manual. Only six pages of HEC-20 are devoted to channel restoration concepts. Rosgen's work related to Natural Channel Design (NCD) as a restoration method should be discussed in the HEC-20 restoration concepts section. NCD is not pertinent to predicting types and rates of channel instability because that is not the intent of NCD. As indicated by Lave (2009), the Rosgen NCD approach has as its stated goal the design of stable channels that do not adjust in dimension, horizontally or vertically. Although this goal may be shared by bridge engineers, in most cases it is better to recognize the potential for channel instability and allow for future channel adjustments in the design process.

Table 4 Strengths and weaknesses of proposed methods in site reconnaissance topic.

Result (Reference)	Level	Strengths	Weaknesses
Reconnaissance			
Assessment of Channel Stability (Johnson 2006)	2	This method avoids averaging out problematic conditions by rating vertical and lateral stability separately from overall stability. Several rating factors in the prior rapid assessment technique have been modified or replaced. Data sheets have been revised to make the method more systematic. Physiographic regions have influenced selection of stability factors to make the method broadly applicable. The method is targeted at identifying problems that could be of concern in a relatively short period of time (2-year inspection interval).	Because the method is simplified, there is risk of incorrect characterization. However, this limitation is countered by the recommendation that an indication of instability should lead to additional site investigation.
Geomorphic Analysis of Large Alluvial Rivers (Thorne 2002)	3	Research includes a systematic and flexible approach to dealing with catchment, reach and project scales. For each scale, a specific item or deliverable is identified, data requirements are identified, and a relative level of effort is identified.	Its use may be limited as it is a Level 3 analysis of geomorphological assessment, though for complex problems or large river crossings this would be a valuable resource.
Digital Mapping at Bridge Sites (Hauet et al. 2009)	3	Research provides an approach for detailed monitoring how river features near a bridge change through time using oblique (distorted) digital photography. Method may also be used to measure map flow velocities and pattern of water currents.	Specialized equipment, software, and training are required. Method proposed would only be applicable to limited conditions.
Diagnostic Approach for Assessing and Monitoring Stream Channels (Montgomery and MacDonald 2002)	2/3	Recognizes complexities of fluvial systems and range of responses that can occur. Identifies processes rather than forms. Requires investigation of the stream channel within the context of the watershed and geomorphic system. Does not try to oversimplify, but ties channel assessment with potential responses. Indicates which channel types are more susceptible to instability from specific changes in sediment and discharge. Method is flexible and adaptable.	Any diagnosis system is susceptible to bias or misinterpretation. System requires more comprehensive information than is typically collected or available. System requires experienced field staff with knowledge beyond that gained from training workshops and short courses. Authors acknowledge a bias toward mountainous western streams. These limitations make widespread adoption of the method unlikely.

and headcuts. Sediment deficiency results when an imbalance exists between the sediment supply and the sediment transport capacity in a river reach. Reasons for this imbalance include reservoirs, urbanization, and other land use changes. Headcuts (and nickpoints) progress from downstream and result from base-level lowering. Aggradation also results from a sediment imbalance when the sediment supply exceeds sediment transport capacity. Although not a scour component, aggradation impacts bridge hydraulic capacity and should be considered in design.

Six degradation/aggradation research results were identified in NCHRP Project 24-27(03). The following three results, further described in Table 5, are proposed for adoption:

- MDSHA cumulative degradation method, pool base-level method, and degraded stream profile method.
- Methods included in Melville and Coleman Bridge Scour manual.
- Stream gage regression method.

Table 5 Strengths and weaknesses of proposed methods in degradation/aggradation topic.

Result (Reference)	Level	Strengths	Weaknesses
Degradation/Aggradation			
MDSHA Cumulative Degradation Method (MDSHA 2007)	2	Cumulative degradation method and pool base-level method are reasonable and uncomplicated ways to estimate long-term channel degradation. Pool base-level method does not require a downstream control point. Estimation of degraded stream profile uses the riffle-crest line to calculate the degraded stream profile, which is a good first-order approximation. These methods are useful alternatives to using detailed sediment transport models.	These methods are primarily relevant to wadeable gravel-bed streams with a pool-riffle morphology. The range of channel slope covered extends only from 0.2% to 4%.
Methods in Bridge Scour Manual (Melville and Coleman 2000)	2	Regime formulations are easy to follow. Tractive force and competent velocity methods are physically based, so that they have the potential to produce reliable results. Methods described have simple equations that are not difficult to apply.	Graphical redistribution of the average scour depth to obtain the maximum scour depth is subjective. Regime formulations are not generally applicable: for example that of Lacey (1930) was designed for uncontracted sandy alluvial channel and that of Blench (1969) is valid only in well-maintained sand-bed irrigation canal systems. The limitations of the tractive force method are not discussed. The Competent velocity methods of Neill (1973), Alvarez and Alfaro (1973) and Holmes (1974) all have limitations.
Stream Gage Regression Method (James 1997)	2	Regression approach is simple to apply (spreadsheet) and can be used for any long-term gage. The paper illustrates the gage analysis approach and shows how bridge inspection records can be used for verification.	Only valid for locations with a nearby, long-term gage. Use of extrapolation for predicting future degradation is a significant limitation. However, residual plots indicate time trends of reduced degradation if these are present.

Channel Migration

Channel migration is the specific term for changes through time in the location of the channel of a watercourse that occur because of retreat of one bank at an erosion rate that is approximately matched by advance of the opposite bank through accretion. Channel migration results in lateral movement of the channel across the floodplain, either through incremental shifting at a rate related to channel width or more rapid relocation of the channel through an avulsion. Lateral migration in a bridge reach can pose a geomorphic hazard through altering the alignment of the channel relative to the bridge, generating scour adjacent to one of the abutments, and, in severe cases, threatening to flank the bridge entirely. It also generates additional sediment load and recruits large woody debris that may increase the risk of partial or complete blockage.

Of the nine channel migration research results considered, the eight results described in Table 6 are proposed for adoption:

- Channel lateral movement zone.
- Aerial photo comparison method.
- Methods presented by Melville and Coleman.
- Vegetation influence on migration.
- Multiple-bend cutoffs risks.
- Wood and logjam risks.
- Channel realignment to reduce hazard.
- Theory and modeling related to channel migration.

Channel Widening or Narrowing

Channel widening or narrowing is the specific term for changes in the top bank width of a channel that occur through time due to net retreat or advance of the banklines. Changes in width trigger further adjustments to the hydraulic geometry of the channel involving the wetted perimeter, mean depth, hydraulic radius, roughness, energy slope, and flow velocity. Extreme widening or narrowing are also associated with planform metamorphosis, which is the relatively rapid transformation of, for example,

Table 6 Strengths and weaknesses of proposed methods in channel migration topic.

Result (Reference)	Level	Strengths	Weaknesses
Channel Migration			
Channel Lateral Movement Zone (MDSHA 2007)	2	Delineation of the channel lateral movement zone and the frequency analysis of lateral channel movement are an improvement from aerial photo review in HEC-20. Approach presented is straightforward.	The procedure for delineating the channel lateral movement zone is still coarse. However, the manual states that a more detailed explanation of this procedure is under development.
Aerial Photo Comparison Method (Lagasse et al. 2004)	2	History of lateral migration at actual site in question provides a sound basis for prediction of future behavior. Attributes like soil strength and vegetation are implicitly accounted for in observed and predicted migration rates. Widely proven performance of R/W as a reasonable predictor of bend evolution. Extensive empirical database. Capability to adapt method to available data/expertise.	The main limitation is that because analysis is based on past history at the site, predictions may be unreliable if watershed or climate changes impact the hydrological or sediment regimes. Application of the more sophisticated versions of the model use GIS software that is now out of date.
Various Methods (Melville and Coleman 2000)	1/2	The research reported has been selected by the authors as being suitable for assessing the likelihood, rate and hazard associated with channel migration in both dynamically stable and unstable streams.	Main limitations stem from limited research, development and testing of methods presented. Some methods presented have been superseded by later versions developed since this book was published.

Table 6 (Continued).

Result (Reference)	Level	Strengths	Weaknesses
Channel Migration			
Vegetation Influence on Migration (Perucca et al. 2007)	2/3	Research establishes vegetation growth and decay interact with fluvial processes in meandering rivers, influencing rates, spatial, and temporal distributions of channel migration. It demonstrates reliable channel migration predictions are only possible when vegetation dynamics are taken into account. It shows vegetation cannot be treated as a passive attribute of riparian zone when assessing channel migration hazards at bridges.	The complexity of the models, heavy data requirements and the need for advanced modeling expertise currently preclude practical application of the method. The fluvial model uses a linear theory, which is known to be an inadequate representation of meander behavior. Models fail to account for changes in river width, variation of flow resistance with vegetation density, and influence of woody debris entering stream due to bank retreat.
Multiple-Bend Cutoffs Risks (Hooke 2004)	2	Research identifies that the probability of occurrence of a cluster of meander cutoffs (resulting in lateral channel migration and/or realignment that may pose a bridge hazard) might be predictable based on preexisting sinuosity relative to a critical value for planform instability. Research is based on a theory that is increasingly accepted in fluvial geomorphology, coupled with well documented evidence obtained from the River Bollin, UK. Long-term study of actual meandering stream.	The critical value for planform instability is poorly defined. A maximum value of 3.14 is suggested for unconstrained rivers, but this decreases with the degree of meander confinement due to limited width of the channel migration zone. To be generally applicable, the relationship between critical sinuosity and degree of confinement needs to be better defined based on further research at well documented sites on meandering rivers in a range of physiographic regions.
Wood and Logjam Risks (Brummer et al. 2006)	1/2/3	The research demonstrates that the addition or removal of large wood has marked impacts on avulsive channel migration. The paper presents Level 1 and Level 2 rules of thumb to estimate channel response. Numerical analyses presented in the paper could be used at Level 3 where risks justify this.	The geographical scope of the study is limited to the Pacific Northwest and the findings may not be simply transferable to other physiographic regions of the United States. The models used are quasi-steady and do not account for the geomorphic impacts of rapidly varying flow in flashy streams.
Channel Realignment to Reduce Hazard (Odgaard 2008)	2/3	This research provides a scientifically-based alternative to use of a “reference” reach when realigning a problematic channel to reduce hazards associated with channel migration.	The design method has not yet been tested or applied by practitioners. The approach is too new to have been proven to reduce risks associated with channel migration in bridge reaches.
Theory and Modeling Related to Channel Migration (Odgaard and Abad 2006)	3	This chapter presents a concise review of theory and modeling practice in the analysis of river meandering and channel migration.	Coverage focuses mainly on theories, analyses, and stabilization measures with which the authors are particularly associated.

a meandering planform into a braided channel (with extreme widening), or *vice versa* (with extreme narrowing). Widening in a bridge reach can pose a geomorphic hazard through increasing the degree of constriction scour at the bridge, generating scour adjacent to the abutments, and, in severe cases, threatening to flank the bridge entirely on one or both sides. It also generates additional sediment load and recruits large woody debris that may increase the risk of partial or complete blockage. Narrowing may increase velocities and general scour depths within the narrower channel.

Of the ten channel widening or narrowing research results considered, the six results described in Table 7 are proposed for adoption:

- Regional bankfull width relationships.
- Error estimation from aerial photos.
- Logistic analysis of channel pattern.
- Predicting channel pattern change.
- Bank erosion and vegetation effects.
- Methods presented in ASCE sedimentation engineering.

Sediment Dynamics

Sediment plays an essential role in fluvial processes. Most geomorphic processes and forms of a river system are related to changes in sediment conditions. Channels adjust their vertical and horizontal dimensions in response to the imbalance between upstream sediment supply and the reach's sediment transport capacity. For example, sediment trapping in reservoirs can result in severe riverbed lowering downstream, while excessive sediment resulting from landslides and bank erosion can lead to significant channel aggradation. When sediment supply from upstream reduces reaches, a braided river reach may alter itself to be a single-thread channel. Even when sediment supply and sediment transport capacity are matched, channels migrate by eroding banks and depositing sediment at point bars. Therefore, the identification of sediment source areas in the river system will benefit the understanding of ongoing geomorphic processes. In addition, sediment movement at the channel bottom has an influence on the reach's bed configuration, hydraulic resistance, and flood conveyance capacity.

Four sediment dynamics research results were identified in NCHRP Project 24-27(03). The following two results, further described in Table 8, are proposed for adoption:

- Channel forming discharge expanded discussion.
- Rosgen's WARSSS (Watershed Assessment of River Stability and Sediment Supply) concepts.

Numerical Modeling

Numerical modeling is a valuable tool for simulating a river system's geomorphic changes as most geomorphic processes are difficult to reproduce in terms of time scale. Numerous flow and sediment transport models have been developed or updated since 1990, partly because computing power has significantly increased. These models are quite different from each other in several ways. First, flow and sediment movement are described in a one-dimensional, two-dimensional, or three-dimensional domain. Second, flow is modeled to be steady, quasi-steady, or unsteady. Last, the complexity of models indicates how many hydraulic and geomorphic processes are included in them and how they couple processes with different temporal and spatial scales. Notice that no single model can fit modeling needs in all circumstances, as each model has its strengths and limitations. In addition, not all models are well calibrated or validated: some are still theoretical, some have been calibrated with laboratory data, and only a few have been calibrated with both laboratory and field data.

Numerical modeling, as a Level 3 procedure, requires a huge amount of effort for field data collection, parameterization, and calibration. Therefore, the evaluation in Project 24-27(03) concentrated on the few well-calibrated models and papers that provide reviews and instructions for flow and sediment transport modeling.

Six numerical modeling research results were identified in NCHRP Project 24-27(03). The following five results, further described in Table 9, are proposed for adoption:

- CONCEPTS model discussion.
- Sediment transport modeling review.
- CCHE2D model discussion.
- Discussion of one-dimensional sediment transport modeling.
- Discussion of two-dimensional and three-dimensional sediment transport modeling.

PROPOSED FUTURE RESEARCH STUDIES

Proposed future research studies needed to further advance or fill gaps in the research results examined in the three projects were identified.

Table 7 Strengths and weaknesses of proposed methods in the change in channel width topic.

Result (Reference)	Level	Strengths	Weaknesses
Change in Channel Width			
Regional Bankfull Width Relationships (Faustini et al. 2009)	2/3	This research uses advanced statistical analyses of a very large, national database. Relationships are easy to apply and allow estimates of the expected width to be made on the basis of only the drainage area and bed material type (gravel or sand) at the study site.	Utility is limited by weak regression relationships and high uncertainties in expected widths for some ecoregions. Relationships are inapplicable to large rivers (wider than 75 meters or with drainage areas > 10,000 km^2). Impacts of human activities in the watershed are poorly explained in several ecoregions.
Error Estimation from Aerial Photos (Mount et al. 2003)	2	Provides a simple method to assess errors involved in estimating widening rates from historical sequences of aerial photographs, which are often ignored by practitioners using historical aerial photographs.	Application of the error estimation method requires some practitioner training in photogrammetry which may limit widespread uptake and validation of the method in the USA.
Logistic Analysis of Channel Pattern (Bledsoe and Watson 2001)	2	Relatively high predictive capacities of the statistical models presented for stability versus instability in sand and gravel-bed rivers. The fact that application of these models requires only basic data on discharge, slope, and bed material size.	Statistical treatment has no causal basis. It cannot explain why a stream is stable or unstable. Influences of sediment supply and bank erosion resistance are not accounted for. Streams that plot as stable on the diagrams may still exhibit instability.
Predicting Channel Pattern Change (Lewin and Brewer 2001)	2	Shows that practitioners must not put too much faith in simple predictors of channel planform type, stability, and vulnerability to change. Points out that simple predictors may misclassify 10% to 15% of channels. States that predictors should not be used in isolation or where risks of misclassifying a channel are severe.	This research does not provide any improvement in the capability for simple prediction of planform pattern type, stability, or vulnerability to change. It merely points out problems with existing methods.
Bank Erosion and Vegetation Effects (Beeson and Doyle, 1995)	1	Presents case study of directly observed bank retreat that occurred during high flow events on four Canadian rivers in 1990. Erosion was five times more likely at unvegetated vs. vegetated bends. 34 of 35 bends that experienced severe bank retreat (greater than 45 meters) were unvegetated.	Research is based on just four, medium sized rivers in British Columbia. Findings may not be representative of other rivers of different sizes, with different types of vegetation or in different ecoregions of North America. Further research is needed to generalize the findings.
ASCE Sedimentation Engineering Methods (Pizzuto et al. 2006)	2	Older channel evolution models are updated. Bank and fluvial stability factors are used to identify channel evolution stages. Numerical width adjustment models are improved to make acceptable predictions of width adjustment. A procedure to handle width adjustment problems is proposed.	Numerical width adjustment models remain unproven because very few appropriate laboratory and field data sets are found to be suitable for testing them. No universal width adjustment model exists that is applicable to all the situations encountered by practitioners.

Table 8 Strengths and weaknesses of proposed methods in sediment dynamics topic.

Result (Reference)	Level	Strengths	Weaknesses
Sediment Dynamics			
Channel Forming Discharge (Doyle et al. 2007)	2	The article emphasizes that the use of a recurrence interval or bankfull discharge may only be applicable for generally stable channels.	Definition of effective discharge is subjective. Further justification is required for the use of "75% of sediment moved." Multiple discharges might be used for different purposes in stream restoration.
Watershed Assessment of River Stability and Sediment Supply (Rosgen 2006)	2	The procedure involves most factors that control watershed processes, and it is easy to follow.	Final stage of WARSSS might recommend a sediment transport model due to the complex channel response. Care must be taken when using a reference condition.

Table 9 Strengths and weaknesses of proposed methods in the numerical modeling topic.

Result (Reference)	Level	Strengths	Weaknesses
Numerical Modeling			
CONCEPTS Model (Langendoen et al. 2009)	3	The model presented (CONCEPTS) is able to simulate channel width adjustment based on the fundamental physical processes responsible for bank retreat.	CONCEPTS assumes one-dimensional, gradually-varying flow, does not simulate secondary flow. The model is truly valid only for straight channels or channels of very low sinuosity.
Sediment Transport Modeling (Papanicolaou et al. 2008)	2/3	The article provides review comments for most available sediment transport models, and some insights about model application, strengths, and limitations.	To engineering practitioners, the review may too be abstract and focused on the modeling and numerical computation aspects of sediment transport prediction.
CCHE2D Model (Jia and Wang 1999)	3	CCHE2D can predict channel migration including the effects of secondary flows, which are simulated in the model.	CCHE2D uses near bank shear stress to compute bank toe and surface erosion including secondary flow effects; however, it does not consider most bank failure mechanisms.
One-Dimensional Sediment Transport Modeling (Thomas & Chang 2006)	2/3	In this summary chapter the authors provide useful insights and lessons about one-dimensional computational sedimentation models for engineering practitioners based on long experience.	Coverage of how to apply one-dimensional computational sedimentation models is descriptive and wordy. It could be improved by including flowcharts and tables.
Two- and Three-Dimensional Sediment Transport Modeling (Spasojevic & Holly 2006)	3	Gives a clear introduction to the complicated procedure for numerical modeling of hydrodynamics and sedimentation that is useful background knowledge for practitioners. Provides three examples to which engineering practitioners can easily refer.	Approaches reviewed do not include bank mechanics, which is an important part of changes in channel morphology.

Table 10 Priority range for research needs (adapted from Parola et al. 1996).

Critical Priority
- Research that is necessary for improved solutions to widespread and costly problems.
- Research that is necessary to ensure public safety.
- Research that is essential to maintain an effective research agenda.
- Development of guidelines for the application of methodologies.

High Priority
- Research that is judged to have a high benefit-to-cost ratio.
- Research that is applicable to a large number of bridges.
- Research that will lead to substantial long-term improvement in scour prediction methodology.

Medium Priority
- Research on problems that relate to large numbers of bridges, but where benefits of a solution cannot be estimated.
- Research that will increase the accuracy of predictive procedures in the long term, but without immediate impact.

Low Priority
- Research on problems specific to a small number of bridges.
- Research on problems that infrequently cause bridge damage.

Similar to the classification used in NCHRP Project 24-8 (Parola et al. 1996), the proposed studies were assigned priorities of critical, high, medium, or low, as defined in Table 10.

Pier Scour Processes and Predictions

Tables 11 and 12 list prioritized research needs for design methodology and pier scour processes, respectively. For design methodology development, two research topics are of critical priority:

1. Estimation of potential maximum scour depth for piers in the changeover range from transition- to wide-pier categories, especially for live-bed conditions.
2. A reliable method for estimating potential maximum scour at piers in the wide-pier category.

Table 11 Research topics and priorities for single-column piers.

Topics	Priority
Design Issues	
Estimation of potential maximum scour depth for piers in the changeover range from transition- to wide-pier categories, especially for live-bed conditions.	Critical
Combination of pier scour and contraction scour, especially for cohesive soils.	High
Procedure for ascertaining probability that potential maximum scour will occur.	High
Physical Processes	
Flow field.	
• Systematic changes in flow field for piers in the transition- to wide-pier categories, determining potential maximum scour depth.	High
• Influence of bedforms on flow field during live-bed scour.	Medium
Erosion of foundation material.	
• Changes in erosion processes and scour form with changes from transition- to wide-pier categories. Especially important are alignment and shape factors for use in scour depth estimation.	High
• Erosion of non-cohesive material by turbulence structures.	Medium
• Erosion of cohesive material by turbulence structures.	Medium
• Temporal development of scour for the transition-pier category of scour, and for non-cohesive and cohesive foundation materials.	Medium

Table 12 Research topics and priorities for considerations complicating scour depth estimation.

Topics	Priority
Design Issues—Common Pier Forms	
Reliable shape and alignment factors for common pier forms. Adapt the Sheppard-Melville method, notably as expressed by Eq. (1), for use with common pier forms.	Critical
A body of scour data for common piers. The data can be used with the full Sheppard-Melville method.	Medium
A procedure for ascertaining probability that potential maximum scour will occur.	Medium
Design Issues—Complexities	
Accounting for bridge-deck submergence when estimating pier scour depth.	High
Pier scour in layered sediment (particularly when the top layer acts as an armoring layer) and in vegetated floodplains.	High
Scour depth estimation for selected common pier forms should account for debris accumulation.	Medium
Design Issues—Complex Pier Forms	
Scour depth estimation for piers of unusual or intricate geometry (development of hybrid approach).	Medium
Physical Processes	
Flow field.	
• Main features of flow field at common pier shapes with multiple components (notably – column, pile cap, piles)	High
• Pier flow-field interaction with bridge components, especially a bridge deck	High
• Influence of debris rafts or ice accumulations	Medium
• Flow-field interaction with channel features	Medium
Erosion of foundation material.	
The erosion processes associated with the flow-field complexities mentioned above.	Medium

For understanding pier scour processes, no research topics are identified as critical priority, though several are of high priority, all of which concern improved understanding of how site complications affect pier flow field. The high priority topics are:

- Debris accumulations.
- Flow field at common pier shapes with multiple components (notably, column, pile cap, piles).
- Flow field interaction with bridge components, such as a bridge deck or abutment.
- Flow field interaction with channel features.

In terms of longer-range research, a transition is underway in recent advances in experimental and numerical techniques used to investigate bridge scour processes that can capture the dynamics of the main turbulent coherent structures (e.g., horseshoe vortex system at the base of the pier, eddies shed in the separated shear layers, or large-scale rollers in the wake behind the pier) affecting pier scour. Recent advances include experimental studies based on the following techniques:

- Particle image velocimetry (PIV).
- Laser Doppler velocimetry (LDV).
- Large eddy simulation (LES).
- Detached eddy simulation (DES).

Numerical investigations have used fully three-dimensional non-hydrostatic methods. These experimental and computational approaches promise new insights into the fundamental physics of the flow and sediment transport processes at bridge piers and can lead to the development of more accurate relationships to predict local scour depth.

Abutment and Contraction Scour Processes and Predictions

Tables 13, 14, and 15 list prioritized research needs for improved understanding of abutment scour processes, improved design estimation of abutment scour depth, and improved methods for monitoring and maintenance.

In the category *improved understanding of abutment scour processes,* four of the six research needs are assigned critical priority, while in the category *improved design estimation of abutment scour depth,* six of the eight research needs are assigned critical priority.

Table 13 Prioritized list of research and education needs addressing improved understanding of abutment scour processes.

Aspect	Research Need		Priority
Laboratory Studies (L)	L1.	Additional laboratory hydraulic experiments on realistic abutment foundation structures and abutment shapes with and without countermeasures; methods of modeling embankment material; geotechnical stability aspects; modeling of intermediate length and short erodible embankments and wide abutments.	Critical
	L2.	Overtopping of erodible embankments and abutment scour under pressure scour conditions.	High
Field Studies (FS)	FS1.	Field studies with continuous hydraulic and scour monitoring that assess uncertainties in measurement and that can be compared with laboratory hydraulic models.	Critical
	FS2.	An overall survey to determine the statistical distribution of embankment failure (including types of failures) relative to other modes of bridge waterway failure.	Critical
Numerical Studies (NS)	NS1.	Investigation of sound use of two-dimensional (depth-averaged models) for determining flow distribution through bridge waterways for the short term combined with three-dimensional computational fluid dynamics (CFD) models and laboratory turbulence measurements to shed further light on hydraulic model scaling issue for the long term.	Critical
	NS2.	Education of engineers concerning limitations of one-dimensional abutment scour prediction formulas and the potential and applicability of two-dimensional and three-dimensional numerical modeling in combination with laboratory hydraulic modeling.	High

Table 14 List of design-related research tasks addressing improved design estimation of abutment scour depth coupled to research needs in Table 13.

Aspect	Research Need	Design-Related Research Task	Priority
Erodible Embankment Abutments	L1, FS1	1. Determine if and how the ABSCOUR method (MDSHA 2010) and that proposed by Ettema et al. (2010) can be merged and further developed. From diagnostic field studies, determine method veracity.	Critical
	L1, FS1	2. Further develop and check the validity of the geotechnical approach to estimating scour depth. From diagnostic field studies, determine method veracity.	Critical
	L1, FS1	3. Refine the methods in Task 1 for the limiting case of a short abutment as the channel becomes very wide. From diagnostic field studies, determine method veracity.	Critical
	L2, FS1	4. Ascertain how the methods in Task 1 apply, or should be adjusted, for embankments under pressure scour conditions and possibly overtopping. From diagnostic field studies, determine method veracity.	High
Solid Body Abutments	L1, FS1	5. Determine the extent to which the methods proposed by Sturm (2006) and Melville (1992, 1997) can be merged and further developed for solid-wall abutments and then combined with Task 1 in a comprehensive design procedure. From diagnostic field studies, determine method veracity.	Critical
	L2, FS1	6. Ascertain how the methods in Task 5 apply, or should be adjusted, for embankments under pressure scour conditions and possibly overtopping. From diagnostic field studies, determine method veracity.	High
Abutments Fitted with Scour Countermeasures	L1, FS1	7. Determine how the methods in Tasks 1 and 5 should be adjusted, for embankments fitted with scour countermeasures, notably an armored apron around the abutment toe or sheet-pile skirt. From diagnostic field studies, determine method veracity.	Critical
Two-Dimensional Flow Numerical Methods	N1	8. Utilize a two-dimensional flow model to determine peak values of flow velocity, unit discharge or shear stress in the vicinity of an abutment, especially if the abutment is located in a channel of irregular geometry, in order to estimate amplification of contraction scour at an abutment.	Critical

Table 15 Prioritized list of research and education needs addressing improved methods for monitoring and maintenance.

Aspect	Research Need*	Priority
Instrumentation for Routine Monitoring	I1. (a) New instrumentation and techniques for remote-sensing of abutment and bridge waterway state, and for accessible data and image storage; (b) Instrumentation for monitoring embankment soil conditions (leverage off U.S. Army Corps of Engineers [COE] levee studies); and (c) Low-cost instrumentation and techniques for small bridges or bridges in regions with limited resources to monitor bridges.	High
Instrumentation for Monitoring During Flood Flows	I2. (a) Instrumentation for obtaining waterway bathymetry data during flood flows; and (b) Instrumentation for monitoring embankment soil parameters during flood hydrograph passage.	High
Education	E1. Training of appropriate staff to conduct monitoring activities, and complete effective abutment maintenance.	High
Maintenance	M1. Innovative and efficient methods for repairing, stabilizing, or replacing weakened components of abutments (e.g., strengthening weakened spill-slope soil at abutment column).	Medium

*Needs I1, I2, and E1 can be combined.

Table 16 Prioritized list of research needs addressing geomorphic processes and predictions.

Research Need	Priority
Develop tools to assess the vulnerability of bridges to potential changes in flow regime and catchment sediment supply associated with catchment modification or climate change.	Critical
Develop practical predictive equations for headcut migration and scour at bridges that consider (1) plunge pool depth, (2) overall amount of long-term bed degradation, (3) triggering of channel widening, and (4) rate of upstream headcut migration.	Critical
Develop a manual that outlines the general character of an alluvial fan, discusses active alluvial fan processes in detail, and provides guidance on incorporating alluvial fan processes and impacts in bridge design.	High
Improve an existing two-dimensional flow and sediment transport model by adding a module that realistically simulates potential bank failure mechanisms.	High
Develop practically applicable tools to enhance existing risk assessment methods for channel scour, deposition, and lateral shifting at bridges so that they can explicitly account for the beneficial and adverse effects of the presence, removal, or reintroduction of vegetation.	High
Assess the environmental impacts of hydraulic bridge design with the goal of developing model agreements that can be tailored by state DOTs in coordination with state environmental agencies and the U.S. Fish and Wildlife Service.	Medium
Develop a concise design manual providing quantitative methods for evaluating bend and confluence scour at bridge crossings.	Medium
Test and advance the application of advanced mapping and monitoring technologies to bridge inspection, and prepare guidelines and standard procedures for the use.	Medium

Geomorphic Processes and Predictions

Table 16 lists prioritized research needs related to the overall topic of geomorphic processes and predictions. Two of the eight research needs are assigned critical priority.

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