

Stream Stability and Scour Countermeasures

Scour calculations at a pier or abutment assume the channel stays where it is. Real streams move sideways, cut down, build up and change form, and those changes can undo a scour evaluation in a few floods. This course covers how to recognize and analyze stream instability at a bridge, and how to select, size, detail and inspect countermeasures against instability and scour. It draws on HEC-20, Stream Stability at Highway Structures, 4th Edition (FHWA-HIF-12-004, 2012), Chapters 1, 2, 4, 5 and 6, and HEC-23, Bridge Scour and Stream Instability Countermeasures, 3rd Edition, Volume 1 (FHWA-NHI-09-111, 2009), Chapters 2 through 5. Section and equation numbers are given so you can check each point. Scenario numbers that do not come from these documents are labeled illustrative.

Learning objectives

- Recognize channel instability
- Classify countermeasures
- Design riprap concepts
- Inspect countermeasures

Why stream stability matters at bridges

HEC-20 Section 1.5 divides the factors that affect stream stability, and potentially bridge stability, into geomorphic factors and hydraulic factors. It warns that rapid and unexpected changes can occur in streams in response to human activities in the watershed or natural disturbances of the river system. The behavior of a stream at a crossing depends not only on how stable the stream looks at the bridge, but on the behavior of the whole stream system it belongs to. Changes upstream and downstream can affect future stability at the site, and natural disturbances such as floods, drought, earthquakes, landslides and forest fires can cause large changes in sediment load and in the channel itself. Those changes show up as three things a bridge engineer must watch for: **aggradation**, **degradation** and **lateral migration**.

The link to scour is direct. In the HEC-18 framework covered in *BR-H01, Scour Fundamentals and HEC-18*, total scour at a bridge is the sum of long-term aggradation or degradation, contraction scour and local scour. HEC-20 is the manual that deals with the first of those components and with the lateral movement that HEC-18's equations do not predict at all. A pier designed for local scour in a channel that later shifts 200 feet sideways may end up in the thalweg; an abutment set back on the floodplain may end up on an eroding outside bank. HEC-20 Section 1.3 notes that the NBI items most tied to stream stability are Item 60 (Substructure), Item 61 (Channel and Channel Protection), Item 71 (Waterway Adequacy) and Item 113 (Scour Critical Bridges). Under the 2022 SNBI these are replaced by new items, but the engineering questions they asked are unchanged.

HEC-23 then supplies the remedy side: a countermeasure matrix, four countermeasure groups, selection guidance by problem type, and design guidelines. This course follows that order, from recognizing instability to fixing and inspecting it. Plans of Action, which tie countermeasures and monitoring to a specific scour critical bridge, are covered in *BR-H02, Scour Critical Bridges and Plans of Action*.

Geomorphic and hydraulic factors

HEC-20 Section 1.5 lists the geomorphic characteristics of most interest to the highway engineer as the alignment, geometry and form of the channel. Factors that influence stability include stream size, flow habit (ephemeral or perennial) and the character of the bed and banks. The bed can be cohesive material, sand, gravel, cobbles, boulders or bedrock, and bank material may differ from bed material. The stream's relationship to its valley, the floodplain and planform, natural levees, incision and riparian vegetation are all indicators of stability or instability.

Human-induced changes are emphasized. HEC-20 names alteration of vegetative cover and changes in impervious area, which change hydrology, sediment yield and channel geometry. It also names channelization, straightening, levees and dikes, bridges and culverts, reservoirs, gravel mining and land-use changes as activities that can have major effects on streamflow, sediment transport and channel location. Section 2.4.3 goes further: human activities are the major cause of streambed elevation changes, and very few bed elevation changes are due to natural causes alone.

Hydraulic factors (HEC-20 Section 1.5) include bed forms and their effect on sediment transport and resistance, velocities and depths, the magnitude and frequency of floods, flood duration, time to peak and recession, flow classification, ice and floating debris, and flow constrictions. The bridge itself is a hydraulic factor: bridge length, location, orientation, span lengths, pier location and design, superstructure elevation, and the location and design of countermeasures all matter. In the bridge reach, the bridge's design and orientation induce contraction and local scour.

A practical way to think about it: geomorphic factors tell you which way the stream is likely to go over years and decades, and hydraulic factors tell you how hard it pushes during a given flood. A good stability assessment needs both.

Sediment continuity: why beds go up or down

HEC-20 Section 2.4.2 makes sediment continuity the primary principle for both qualitative and quantitative analysis of bed elevation change. The amount of material transported, eroded or deposited in an alluvial channel is a function of sediment supply and channel transport capacity. Supply comes from the watershed and from erosion in the upstream channel. Transport capacity depends on sediment size, discharge, and the geometric and hydraulic properties of the channel. When transport capacity equals supply, the reach is in equilibrium.

Stated simply, during a given period the sediment entering a reach minus the sediment leaving it equals the change in sediment stored in that reach. When supply is less than capacity, the reach erodes, or degrades, until the capacity at the outlet is satisfied, unless something limits erosion. When supply exceeds capacity, the reach deposits, or aggrades. HEC-20 identifies controls that limit erosion: human ones such as bank protection, grade control structures and stabilized bridge crossings, and natural ones such as rock outcrops or coarse sediment that forms a surface armor layer not moved by average flows.

This framework explains the classic patterns in HEC-20 Table 4.3, Interpretation of Observed Data. Upstream of a dam and reservoir, the channel tends to aggrade; downstream, where clear water leaves the dam with spare transport capacity, it tends to degrade. A clear-water diversion leaves the remaining channel prone to aggrade; a channel overloaded with sediment or straightened is prone to degrade. Head cuts indicate an unstable, degrading channel. Vegetated banks and a meandering form are associated with stability, while straight, braided and eroding-bank channels are marked unstable.

For the inspector, sediment continuity is a way to read the landscape. Gravel mining upstream, a new reservoir, a channelization project downstream that steepens the slope, or rapid urbanization in the watershed are all reasons to expect the bed at the bridge to change, even if it looked stable at the last inspection.

Channel form: straight, meandering, braided

HEC-20 Section 4.5.3 and its Figure 4.2 relate channel form to stability. Straight channels are relatively stable only where velocities and sediment load are low. As those increase, flow meanders within the channel, alternate bars form and a meandering pattern begins. Meandering channels become progressively less stable as velocity and bed load increase, and at high values the channel becomes braided. The presence and size of point bars and middle bars indicate relative lateral stability.

HEC-20 ties this to stream power: bed material transport is directly related to stream power, and relative stability decreases as stream power increases. Stream power is the product of bed shear stress and average velocity. Bed shear can be estimated with the average shear stress equation, the unit weight of water times hydraulic radius times slope (γRS).

HEC-23 Section 3.4 describes why braided streams are so troublesome at bridges. Braiding occurs where a stream is overloaded with sediment, causing deposition and aggradation; slope increases, velocities increase and multiple interconnected channels develop. It also occurs where banks are easily eroded and discharge varies widely. Braided channels change alignment rapidly and are very wide and shallow even at flood flow. That means high cost to span the whole system, unpredictable channel locations and flow directions, eroding banks, and openings blocked by bars and islands. Anabranching streams are different: flow is divided by islands rather than bars, the channels are more permanent and generally carry more flow.

HEC-23 also warns that a meandering stream may change to braided if its slope is increased by straightening or its dominant discharge increases. That is where the Lane relation, covered next, is useful.

The Lane relation for meandering versus braided sand-bed streams

HEC-20 Section 5.5.2 presents the Lane (1955) criteria, which relate channel slope and mean annual discharge to sand-bed channel form. In English units, with S the channel bed slope in ft/ft and Q the mean annual discharge in ft³/s:

- A sand-bed channel meanders where $S \cdot Q^{0.25} \leq 0.0017$ (Eq. 5.1; $K_u = 0.00070$ in SI).
- A sand-bed channel is braided where $S \cdot Q^{0.25} \geq 0.010$ (Eq. 5.2; $K_u = 0.0041$ in SI).

Between those lines is a transitional range in which a stream can readily change from one form to the other. HEC-20 notes that many U.S. rivers are intermediate sand-bed streams that plot in this zone. If a meandering stream's slope and discharge put it near the transitional zone, a relatively small increase in slope may cause it to change over time to a transitional or braided stream. HEC-20 also gives the Leopold and Wolman (1960) dividing line, $S \cdot Q^{0.44} = 0.06$ (English).

Illustrative example (numbers are not from HEC-20). A sand-bed stream has a mean annual discharge of 600 ft³/s and a slope of 0.0003 ft/ft. $Q^{0.25} = 600^{0.25} \approx 4.95$, so $S \cdot Q^{0.25} \approx 0.0015$, just below the meandering limit of 0.0017. A proposed channel straightening downstream would shorten the stream length by about a quarter, raising the slope to roughly 0.0004 ft/ft. Then $S \cdot Q^{0.25} \approx 0.0020$, which moves the stream into the transitional range. The Lane relation does not predict when or how fast the stream will change, but it tells the engineer that the project could push a stable meandering stream toward a less stable form, and that a closer Level 2 look is warranted.

HEC-23 Section 3.4 uses the same logic: if after a change in discharge or slope the stream still plots in the meandering zone, it will likely remain meandering; if it moves closer to or into the braided zone, it may become braided.

HEC-20's three levels of analysis

HEC-20 Section 1.7 says the evaluation and design of a highway stream crossing should begin with a qualitative assessment of stream stability, followed by quantitative analysis using basic hydrologic, hydraulic and sediment transport concepts. That analysis is adequate for many sites if the problems are resolved and the relationships among factors are explained. If not, more complex mathematical or physical modeling should be considered. Section 4.2 organizes this into three levels:

- **Level 1:** application of simple geomorphic concepts and other qualitative analyses.
- **Level 2:** application of basic hydrologic, hydraulic and sediment transport engineering concepts.
- **Level 3:** application of mathematical or physical modeling studies.

HEC-20 Section 4.5 states that a Level 1 qualitative analysis is a prerequisite for a Level 2 engineering analysis for bridge design, evaluation or rehabilitation. Level 1 ends in a decision: either the screening or evaluation can be completed on the qualitative findings, or Level 2 is needed.

Level 1: six steps

1. Define stream characteristics (Section 4.5.1), using the geomorphic factors in HEC-20 Chapter 2 and the reconnaissance and classification tools in Chapter 5.
2. Evaluate land use changes (4.5.2).
3. Assess overall stream stability (4.5.3), using Table 4.3 and Figure 4.2.
4. Evaluate lateral stability (4.5.4).
5. Evaluate vertical stability (4.5.5).
6. Evaluate channel response to change (4.5.6).

Level 2: eight steps

1. Evaluate flood history and rainfall-runoff relations (4.6.1).
2. Evaluate hydraulic conditions (4.6.2).
3. Bed and bank material analysis (4.6.3).
4. Evaluate watershed sediment yield (4.6.4).
5. Incipient motion analysis (4.6.5).
6. Evaluate armoring potential (4.6.6).
7. Evaluation of rating curve shifts (4.6.7).
8. Evaluate scour conditions (4.6.8).

The ordering is deliberate. Level 1 is cheap and fast and frames the problem; Level 2 uses engineering calculations to test what Level 1 suggested; Level 3 is reserved for complex, high-risk or unresolved cases. HEC-20 Section 4.3 notes that data needs depend on how unstable the stream is and how deep a study is needed, and that data from an extensive reach may be needed in complex, high-risk situations.

Field reconnaissance and rapid assessment

HEC-20 Section 1.6 says a necessary first step in any channel classification or stability analysis is a field site visit. Chapter 5 provides reconnaissance guidelines, geomorphic checklists and a rapid assessment method.

The rapid assessment method in HEC-20 Section 5.4 was developed by Johnson from existing methods and data collected at bridges in 13 physiographic regions. Its stated purpose is a quick assessment of channel stability as it affects bridge foundations, to document conditions and to judge whether more extensive geomorphic studies or full hydraulic and sediment transport analyses are needed. HEC-20 says such a method should be brief, simple, based on sound indicators and based on the needs of the bridge community.

The indicators move from the watershed down to the bridge. At the broad level they include watershed and floodplain activity, flow habit, channel pattern and type, and entrenchment. At the channel level they include bed material consolidation and armoring, bar development and obstructions. Bank indicators include bank material, bank angle, bank and riparian vegetation, fluvial cutting and mass wasting. Finally, the bridge's position relative to the channel is captured by the meander impact point and alignment. Each indicator gets a rating, ratings are summed, and the total is compared with stability definitions by stream type, using the Montgomery–Buffington classification. HEC-20 reports that weighting indicators gave the same results as equal weights, so the method uses equal weights.

HEC-20 gives practical field advice: view aerial photos of the crossing and surrounding area, and walk upstream and downstream rather than observing only from the bridge. Ideally, walk at least 10 channel widths upstream and downstream. The more of the stream observed, the better the observer understands it.

For inspection programs, the value is consistency. A numeric rapid assessment score repeated at each inspection gives a trend line, and a rising instability score is an objective reason to request a Level 2 analysis or to revisit the scour evaluation.

Lateral stability and meander migration

HEC-20 Section 6.3 notes that most streams are sinuous to some degree and most bank retreat and lateral migration happens along meander bends. It presents two related approaches: analysis of sequential historic aerial photographs, maps and surveys, and a simple overlay comparison technique.

Repetitive surveyed cross sections are the most accurate way to measure lateral change, HEC-20 says, but they are rarely available. The next most practical method is comparing sequential historic aerial photos, maps and surveys, following Brice's methodology. Accuracy depends on the length of record, the disturbances the system has experienced, and the number and quality of data sets. Multiple data sets spanning several tens of years to more than 100 years give much better predictions than two or three data sets over a short period. Predictions are much less reliable for channels that have been heavily modified or have undergone major adjustment due to land-use change.

HEC-20 addresses practical problems with photos. Their scale is often approximate, so contemporary maps are needed. Scale is corrected by measuring distances between several pairs of common reference points, such as building corners, road intersections, canals, rock outcrops or confluences, on both photo and map, and averaging. Distortion increases away from the photo center.

HEC-23 Section 3.3 states the design consequence plainly: the best countermeasure against meander migration is to locate the bridge on a relatively straight reach between bends. On some streams it may take years before a bend migrates to threaten the bridge; on others, migration rates are high enough that countermeasures should be built during initial construction. HEC-23 refers to NCHRP Report 533 for a method to estimate meander migration rates.

A field indicator worth knowing: the meander impact point. If the outside of a bend is aimed at an abutment, an approach embankment or a pier, every flood concentrates attack there. Tracking the impact point's position over successive inspections is one of the simplest ways to see lateral migration coming.

Vertical stability: degradation and aggradation

HEC-20 Section 2.4.1 defines aggradation and degradation as the raising and lowering of the streambed over relatively long distances and time frames. HEC-23 Section 3.5 describes their consequences at bridges. Degradation can cause the loss of piers in the channel and contribute to the loss of piers and abutments on caving banks. Aggradation reduces the waterway opening and, where channels widen because the bed is rising, overbank piers and abutments can be undermined. At worst, aggradation can cause a stream to abandon its channel and form a new flow path that isolates the bridge.

Evidence of degradation includes head cuts, perched tributaries or culvert outlets, exposed footings or piles that were once buried, steep and failing banks, and a progressive downward trend in streambed elevations at the piers between inspections. Evidence of aggradation includes reduced clearance under the superstructure, buried bearings or footings, sediment deposits in spans, and a rising bed trend. HEC-20 Level 2 Step 7, evaluation of rating curve shifts, uses stream gage records: a long-term shift in the stage-discharge relation at a gage can reveal bed lowering or raising over time.

The bridge record is a source of vertical stability data. Inspections that record channel bed elevations at each pier (HEC-23 Section 2.4.4 notes this is typical on a biennial schedule) create a time series. HEC-18's lesson from the Hatchie River failure, discussed in BR-H02, was that successive cross sections must actually be plotted together; otherwise a trend goes unrecognized.

Degradation is especially dangerous because it lowers the reference for every other scour component. Contraction and local scour start from the degraded bed, so a few feet of long-term degradation adds directly to the total scour depth at a foundation.

The HEC-23 countermeasure matrix and four groups

HEC-23 Section 2.3 introduces the countermeasure matrix (Table 2.1). It lists most countermeasures used by state DOTs and, for each, its functional applicability, suitability to river environments, general maintenance resources, which states have experience with it, and the design guideline reference. Section 2.5 lists the five characteristic categories as Functional Applications, Suitable River Environment, Maintenance, Installation/Experience by State, and Design Guidelines Reference.

The four main groups are:

- **Group 1, Hydraulic countermeasures:** designed to modify the flow or resist erosive forces.
 - 1.A River training structures, which modify flow and are classed by orientation: *transverse* (projecting into the flow at an angle or perpendicular, such as spurs and bendway weirs), *longitudinal* (parallel to flow or along a bank, such as guide banks and dikes) and *areal* (acting as a system, including channelization, flow relief and sediment detention).
 - 1.B Armoring countermeasures, which resist erosive forces without necessarily altering hydraulics: revetments and bed armor, either rigid or flexible/articulating, and local scour armoring at individual piers and abutments.
- **Group 2, Structural countermeasures:** modifications to the bridge foundation, either foundation strengthening or pier geometry modification.
- **Group 3, Biotechnical countermeasures:** vegetation, alone or combined with hard elements.
- **Group 4, Monitoring:** fixed instrumentation, portable instrumentation and visual monitoring.

HEC-23 Section 2.4.1 points out a key difference within armoring. Rigid revetments are typically impermeable and cannot conform to changes in the supporting surface, so they are subject to failure by undermining. Flexible or articulating revetments conform to settlement but can fail by removal and displacement of the armor. HEC-23 also notes that performance of hydraulic countermeasures depends on edge treatment and filter design.

Group 3 and Group 4: biotechnical and monitoring

HEC-23 Section 2.4.3 describes biotechnical countermeasures. Soft revetments made only of living plants or plant products are often called bioengineering; techniques combining vegetation with structural elements are biotechnical engineering, and where riprap is the hard component the term vegetated riprap is used. The matrix includes vegetated geosynthetic products, fascines and woody mats, vegetated riprap, root wads and live staking. These can be cost effective and improve aesthetics and habitat. HEC-23 is explicit about the limit, however: where failure of the countermeasure could lead to failure of a bridge or highway structure, the only acceptable solution in the immediate vicinity of the structure is a traditional hard engineering approach.

HEC-23 Section 2.4.4 describes monitoring. Monitoring does not fix a scour problem, but it allows action before public safety is threatened, and a well-designed program can be very cost effective. Fixed instruments are attached to the bridge at piers and abutments; sonar can provide a timeline of scour, while a magnetic sliding collar records only maximum depth. It may be impractical to instrument every pier, so the number and location should be defined. Portable instruments are more cost effective for covering an entire bridge but give no continuous watch, and the allowable level of risk sets how often they are used. Visual monitoring means regular inspection plus increased effort during high flows (flood watch). HEC-23 notes bed elevations are typically taken at each pier on a biennial schedule and compared with historical cross sections, and should also be taken during and after high flows. If measurements cannot be safely taken during a flood, the owner should decide whether the bridge is at risk and needs closure.

HEC-23 Section 3.6.3 adds a caution: monitoring during high flow may not reveal that a bridge is about to collapse, and closure may be impractical because of traffic, poor detours or emergency access. In those cases a countermeasure such as riprap combined with monitoring during and inspection after floods can protect the public without closing the bridge.

Selecting countermeasures by problem type

HEC-23 Chapter 3 organizes selection around the problem being solved.

Meander migration (Section 3.3)

Countermeasures protect an existing bank line, establish a new flow line or alignment, or control and constrict flow. The classes named are bank revetments, spurs, bendway weirs, longitudinal dikes, vane dikes, bulkheads and channel relocations, and a carefully planned cutoff can also work. HEC-23 warns that stabilizing the outside bank of a bend changes the cross section: scour deepens at the stabilized bank and the point bar on the inside steepens. Stabilizing a bend can also increase sinuosity upstream, so meander amplitude grows, radii shrink, deposition may occur and cutoffs can eventually happen, with hydraulic problems downstream as well. The thalweg location and flow direction at the bridge can change as upstream sinuosity increases.

Braiding and anabranching (Section 3.4)

Countermeasures usually aim to confine multiple channels to one, increasing transport capacity in the main channel and encouraging deposition in secondary channels. Typical measures are dikes from the margins of the braided zone to the bridged channel, guide banks at abutments with revetment on fill slopes, and spurs arranged to constrict flow to one channel. Anabranches are harder to confine because they are permanent and carry substantial flow; the choice may be between more than one bridge, a long bridge, or diverting anabranches.

Degradation (Section 3.5.1)

Check dams and similar structures (drop structures, cutoff walls, drop flumes) are the main tools. HEC-23 lists these recommendations: check dams or drop structures are the most successful technique for halting degradation on small to medium streams; channel lining alone may not succeed, and concrete and riprap linings have proved unsuccessful at stopping degradation; riprap on banks and spill slopes will fail if unanticipated degradation occurs; successful pier protection involves deeper foundations; jacketing piers with steel casings or sheet piles has worked where degradation extends only to the top of the original foundation; the most economical answer at new sites on small to medium streams is adequate foundation depth plus adequate abutment setback; rock-and-wire mattresses are recommended only on small channels (about 100 ft) with lateral instability and little vertical instability; and longitudinal stone toe dikes are effective against bank caving in degrading streams, with tiebacks to prevent outflanking.

Aggradation (Section 3.5.2)

Measures include channelization (dredging and clearing, debris basins, cutoffs, flow control structures, relief channels), bridge modification and continued maintenance. HEC-23 cautions that cutoffs need considerable study because they can cause erosion upstream and deposition downstream.

Countermeasures for contraction and local scour

HEC-23 Section 3.6.1 names revetment on channel banks and abutment fill slopes as the principal countermeasure against the effects of contraction. Spurs on the upstream side of a highway embankment can retard flow running along the fill, which otherwise joins the bridge flow at a sharp angle and adds contraction, vortices and turbulence. Guide banks improve flow alignment in the opening and reduce contraction scour, though their primary purpose is reducing local scour at abutments. HEC-23 warns about stabilizing only part of the perimeter: armoring the banks can exaggerate bed scour near them, armoring the bed can exaggerate lateral scour, and armoring the whole perimeter can push scour downstream or fail part of the system.

Abutments

HEC-23 Section 3.6.2 says properly designed guide banks eliminate eddies and cross-flow, protect the embankment, reduce local scour at the abutment and adjacent piers, and move scour to the upstream end of the guide bank. HEC-23 Figure 3.4 shows a typical guide bank layout after Bradley (1978) with a quarter-ellipse shape, length L_s and offset $0.4 L_s$. Short guide banks extending downstream to the tree line can move expansion scour away from abutments on cleared wooded floodplains. Design is in Design Guideline 15 of HEC-23 Volume 2.

Piers

HEC-23 gives three basic methods: (1) found the pier deep enough that maximum scour does not threaten it, which must be done on all new or replacement bridges; (2) for existing bridges, provide protection at or below the bed to inhibit a scour hole; and (3) prevent or weaken the erosive vortices. Streamlined, rounded noses reduce horseshoe vortex strength. Piers should be aligned with the main channel design flow and skew angles greater than 5 degrees should be avoided; where that is impossible, a single cylindrical pier or row of cylindrical columns gives less local scour. Rows of columns collect debris, which can greatly increase scour; webwalls can help, but a wall hit at a high angle of attack can greatly increase scour.

Riprap at existing piers is a retrofit or risk-reduction measure, not a substitute for adequate foundations on new or replacement bridges. Heaping stones around a pier is not recommended because it usually requires continual replacement; success has been better where the top of riprap is at or below the streambed. Sheet, H-pile or concrete piling placed around exposed

footings and tied to the cap can restore support, though the added mass increases scour depth. Construction cofferdams left in place higher than the contraction scour elevation can increase local scour and should be removed or cut off.

Design approach, service life and cost

HEC-23 Section 4.1.3 makes HEC-20 a prerequisite: the analysis procedures in HEC-20 are a necessary prerequisite to the detailed design of specific countermeasures, because installing a countermeasure causes the bed and banks to respond. The goal is a response that protects the crossing while minimizing adverse effects upstream and downstream. In general, a countermeasure should provide protection commensurate with the design event for the structure.

The matrix helps narrow choices; environmental impacts, maintenance, construction and legal considerations refine them; and the final, perhaps most important, criteria are initial and long-term cost. The countermeasure that gives the desired protection at the lowest total cost may be the best one. HEC-23 lists principles for design and construction, paraphrased:

- Initial and long-term cost should not exceed the benefits. Robust countermeasures belong on important bridges on main roads where failure would be intolerable; expendable works can be used where traffic is light, detours exist and failure risk is acceptable.
- Base designs on studies of channel trends and processes and on experience with comparable sites, and consider environmental effects up and downstream.
- Field reconnaissance by the designer, covering the watershed and river system up and downstream, is highly desirable.
- Time-sequenced aerial photography is a useful tool for long-term trends.
- Soil and geotechnical characteristics must be considered, possibly including slope stability under rapid drawdown, with input from a licensed geotechnical engineer.
- Consider physical model studies early.
- Inspect countermeasures periodically after floods, modify the design if needed, and document condition with photographs for comparison between inspections.
- In most cases the countermeasure does not cure the problem, so plan and fund continued maintenance.

Combined countermeasures must complement each other; one must not adversely affect another or the overall protection.

HEC-23 Section 4.1.2 addresses service life. Safety of the traveling public is the first priority. Service life should reflect the importance of the facility, the risk and consequences of losing it, and the difficulty and cost of future repair. The end of service life depends heavily on confidence that a degraded condition will be detected and corrected in time, for example in a post-flood inspection. For facilities rarely inspected, a conservative (shorter) service life is appropriate; a less conservative standard can be used for facilities inspected regularly. Maintenance that is not total reconstruction should not be treated as end of service life, and a life-cycle maintenance approach can extend service life and reduce total cost.

Riprap as a system: revetment and pier riprap sizing

HEC-23 Chapter 5 treats riprap as an integrated system whose performance depends on each component: the stone, its gradation and thickness, the filter, the subgrade, and the edge details.

Revetment

HEC-23 Section 5.2.2 reports that NCHRP Project 24-23 evaluated seven revetment equations against field and laboratory data and recommended the U.S. Army Corps of Engineers EM 1601 method for streambank revetment. Detailed design using

EM 1601, a standard gradation specification, a standardized size classification, and toe-down and transition guidance are in Volume 2, Design Guideline 4.

Piers

HEC-23 Section 5.2.3 gives the standard Isbash (1936) formula for riprap on a channel bed (Eq. 5.1):

$$D_{50} = 0.692 (K \cdot V)^2 / [2g (S_s - 1)]$$

where D_{50} is the median riprap size (ft), V is velocity (ft/s), S_s is the specific gravity of the stone (usually 2.65), g is gravitational acceleration and $K = 1.0$ for an unobstructed bed. To account for turbulence at piers, K is raised above 1.0. Hoffmans and Verheij recommend values up to 2.0 at circular piers using the local upstream velocity, which is equivalent to increasing shear stress by a factor of four. The HEC-23 design guideline uses $K = 1.5$ for circular piers and 1.7 for square piers; Parola's values ranged from 1.44 to 1.90 depending on geometry and angle of attack. NCHRP 24-23 concluded that the HEC-23 (Second Edition) and Parola equations best balance rarely undersizing pier riprap against excessive conservatism, and the HEC-23 equation was recommended. Full pier riprap guidance, including filters, extent and installation, is in Design Guideline 11.

Illustrative calculation (numbers are not from HEC-23). A round-nosed pier sees a local approach velocity of 8 ft/s. With $K = 1.5$, $K \cdot V = 12$ ft/s and $(K \cdot V)^2 = 144$. With $S_s = 2.65$ and $g = 32.2$ ft/s², the denominator is $2 \times 32.2 \times 1.65 \approx 106.3$. $D_{50} \approx 0.692 \times 144 / 106.3 \approx 0.94$ ft, or about 11 inches. For a square-nosed pier ($K = 1.7$), $(K \cdot V)^2 = 185$ and $D_{50} \approx 1.20$ ft. Note how sensitive the result is: because size varies with velocity squared, a 20 percent underestimate of velocity gives stone about 30 percent too small. This is a teaching example only; actual design must use the complete Design Guideline 11 procedure, including the velocity definition, gradation, layer thickness, extent and filter.

Abutments and countermeasures

HEC-23 Section 5.2.4 describes the FHWA abutment riprap approach of two equations, one for Froude numbers below 0.8 and one above, using a characteristic average velocity at the abutment toe estimated by the Set Back Ratio method; this is Design Guideline 14. Riprap at high-stress points on countermeasures such as the nose of a guide bank or spur is addressed in Design Guidelines 2 and 15, overtopping of embankments in Design Guideline 5, wave attack in Design Guideline 17, and bottomless culverts, where scour is greatest at the upstream corners, in Design Guideline 18.

Edges, filters and gradation

HEC-23 Section 5.2.7 says undermining of the edges of armoring countermeasures is one of the primary failure mechanisms. The head, toe and flanks must be designed so undermining cannot occur. For bed armor, key the edges into the subgrade to a depth below the combined expected contraction scour and long-term degradation. For side slopes, trench the revetment toe below the channel bed to the same depth. Where excavating that deep is impractical, a launching apron can supply enough rock to launch into the scour hole as it forms while keeping the exposed bank protected.

This ties the countermeasure directly back to the stability analysis. You cannot set a toe-down depth without an estimate of long-term degradation from HEC-20 and contraction scour from HEC-18. A revetment designed only for local conditions on a degrading stream is the case HEC-23 Section 3.5.1 warns about: riprap on banks and spill slopes will fail if unanticipated degradation occurs.

HEC-23 Section 5.3 covers filters. A granular or geotextile filter (or a composite of both) prevents the subgrade from washing out through the voids in the stone. Section 5.3.2 addresses placing geotextiles under water, and HEC-23 notes that geotextile sand containers offer a way to place a filter in a pier scour hole in flowing water.

HEC-23 Section 5.2.8 explains that because stone comes in a range of sizes and shapes, the required size is stated as a minimum representative size, such as a d_{50} or d_{30} (the size for which 50 or 30 percent by weight is smaller), or as an equivalent weight using an assumed density. Shape is described by the three axes of the stone, and specifications typically limit how elongated or flat stones may be. The NHI inspector guidance quoted in HEC-23 Section 5.5.1 gives a field rule: riprap should be well graded, with the maximum stone no more than about twice the d_{50} .

Partially grouted riprap, discussed in HEC-23 Section 5.6 and Design Guideline 12, allows smaller rock to be used for pier scour protection because the grout bonds stones into larger clusters while keeping some flexibility.

How riprap fails

HEC-23 Section 5.4.1, citing Blodgett and McConaughy (1986), stresses that riprap design methods mostly assume failure by particle erosion, but revetments fail in four ways:

1. **Particle erosion:** individual stones are dislodged by flow. Causes include stone too small, stones removed by impact or abrasion, bank slope so steep that the riprap's angle of repose is easily exceeded, and gradation too uniform.
2. **Translational slide:** a mass of stones moves downslope along a roughly horizontal fault line. Early signs are cracks in the upper riprap parallel to the channel. It is usually triggered when the bed scours and undermines the toe; other causes are a too-steep slope and excess pore pressure.
3. **Modified slump:** mass movement along a slip surface within the riprap blanket, with the base soil intact. Causes include riprap resting very near its angle of repose and loss of supporting stones lower on the slope.
4. **Slump:** rotational movement along a concave-upward surface caused by shear failure of the underlying soil, usually from excess pore pressure along an impermeable layer, too-steep slopes, or too much overburden at the top.

The summarized reasons for revetment failure are stone too small (because shear, velocity, curvature, discharge, abrasion or obstructions were underestimated), channel changes (impinging flow, flow directed at the ends of the protected reach, increased depth, scour), improper gradation, improper placement and too-steep slopes.

At piers, HEC-23 Section 5.4.2 describes riprap shear (stones moved by flow), winnowing (fine bed material pulled out through the voids), and edge failure (bed scour at the edge of the layer undermining the perimeter stones), along with bed form destabilization, where stones slide into the troughs of passing dunes and the layer thins. Under steady flow a thick riprap layer can be self-healing, but with increasing velocity and no filter these mechanisms combine into total disintegration (when stone is small relative to the bed sediment) or embedment failure (large stones sink into the bed). The pier list of causes adds increased angle of attack from channel change and a missing, inadequate or damaged filter.

Case study: Schoharie Creek, 1987

HEC-23 Section 5.4.3 summarizes the April 5, 1987 failure of the I-90 New York State Thruway bridge over Schoharie Creek, which killed 10 people and was investigated by the NTSB. The peak flow was 64,900 cfs, with a 70- to 100-year return period. The four piers stood on large spread footings 82 ft long, 18 ft wide and 5 ft deep, without piles, set 5 ft into very dense glacial drift that the designers considered nonerodible. Flume tests later showed some of that material eroded at 4 ft/s and

eroded rapidly at 8 ft/s. A 1:50 model indicated a velocity of 10.8 ft/s at the pier that failed, and models gave a maximum scour depth of about 15 ft; scour at the failed pier was 14 ft.

The plans called for riprap around the footings, but between 1953 and 1987 high flows removed much of it. The NTSB's probable cause was the Thruway Authority's failure to maintain adequate riprap around the piers, which led to severe erosion of soil beneath the spread footings, with lack of structural redundancy contributing to the severity. A 1979 consultant inspection had found most of the riprap at the piers missing, yet the last inspection, on April 1, 1986, did not detect any problem with the riprap.

HEC-23 draws two conclusions. Inspectors and supervisors must recognize that riprap does not necessarily make a bridge safe from scour, and inspectors must be trained to recognize when riprap is missing and what that means. For this course, Schoharie Creek also illustrates three earlier points: a countermeasure needs funded maintenance; an erodibility assumption about foundation material must be tested; and HEC-23's guidance that structural redundancy (such as continuous spans) helps protect against catastrophic failure when a substructure moves.

Inspecting countermeasures

HEC-23 Section 5.5.1 says inspection of riprap placement is typically visual inspection of installation and the finished surface, ensuring a dense, rough surface of well-keyed, graded rock of the specified quality and size, placed to minimize voids and at the specified thickness. Riprap that is part of channel stability works near a bridge is typically inspected in the biennial program, but the Plan of Action may require more frequent inspection or inspection after every flood above a stated magnitude. Underwater inspection of riprap should only be done by divers trained and certified for that work (see *BR-I09, Underwater Bridge Inspection for Engineers*).

HEC-23 quotes NHI course 135047, Stream Stability and Scour at Highway Bridges for Bridge Inspectors:

1. Riprap should be angular and interlocking; rounded stones and flat slabs of broken concrete paving do not make good riprap.
2. There should be a granular or geotextile filter between riprap and subgrade.
3. Riprap should be well graded, with maximum size no more than about twice the d_{50} .
4. At piers, riprap should generally extend up to bed elevation so the top is visible to inspectors during and after floods.
5. Strong indicators of problems: riprap displaced downstream; slumping of the blanket down slope; angular riprap replaced over time by smoother river-run material; physical deterioration, disintegration or abrasion; and holes where the filter is exposed or breached.

HEC-23 Section 5.5.2 refers to a recording system in its Appendix D with numerical ratings from 0 (worst) to 9 (best) and recommended actions tied to each rating. Section 5.5.3 adds performance evaluation: compare design parameters to field experience, longevity and maintenance history; compare actual flood loading to design loading; and compare present channel geometry and planform to conditions at installation, because lateral or vertical change can increase the angle of attack and the load on the riprap. Deficiencies should be corrected as soon as possible to prevent progressive failure over successive floods.

Beyond riprap

The same thinking applies to other countermeasures. For spurs, bendway weirs and guide banks, check whether the nose or upstream end is losing stone, whether flow is outflanking the structure at its bank tie-in, and whether the thalweg has moved relative to the design alignment. For check dams, look for undermining at the downstream face and flanking around the ends. For fixed scour monitors, confirm that instruments are working and that data are being reviewed, since a monitor no one

checks protects no one. HEC-23's design principles call for photographs at each inspection so changes can be compared over time.

Putting it together: an illustrative workflow

Illustrative scenario (site details are invented for teaching). A three-span bridge crosses a sand-bed stream. The latest inspection notes that the outside of an upstream bend now points at the left abutment, the left bank below the bridge is vertical and calving, and pier bed elevations are 2 ft lower than ten years ago. A Level 1 assessment follows HEC-20's six steps:

1. *Stream characteristics*: meandering, sand bed, low vegetated right bank, eroding left bank.
2. *Land use*: a large subdivision upstream and a sand and gravel operation two miles upstream.
3. *Overall stability*: Table 4.3 flags bank erosion as unstable; a Lane check places the stream near the transitional range.
4. *Lateral stability*: four sets of aerial photos over 40 years show the bend migrating about 6 ft per year toward the abutment (illustrative rate).
5. *Vertical stability*: the pier bed trend and mining upstream point to degradation.
6. *Response*: continued migration and degradation; the existing scour evaluation assumed a stable channel.

Level 1 concludes that Level 2 is needed. Level 2 would review flood history, run hydraulics, sample bed and bank material, check incipient motion and armoring potential, look at gage rating shifts, and recompute scour with a long-term degradation component. If the bridge becomes scour critical, it needs a Plan of Action (BR-H02).

Countermeasure selection then follows the HEC-23 matrix. For the migrating bend, options include bank revetment, spurs or bendway weirs, recognizing that stabilizing the bend will deepen scour at the protected bank and may increase sinuosity upstream. For degradation, a downstream grade control structure may be warranted. For the piers, riprap sized and detailed per Design Guideline 11 is a retrofit option, with toe-down below combined contraction scour and degradation, plus monitoring. The final choice weighs cost, maintenance and the importance of the route, and must come with a maintenance and inspection plan, because HEC-23 is clear that in most cases the countermeasure does not cure the problem.

This workflow is the practical message of the course: diagnose with HEC-20 before treating with HEC-23, size and detail the treatment for the changed channel, and keep inspecting it.

Key takeaways

- Stream instability (aggradation, degradation, lateral migration) can invalidate a scour evaluation; HEC-20 addresses what HEC-18's equations do not.
- Sediment continuity: supply less than transport capacity degrades the bed; supply greater than capacity aggrades it.
- Lane relation for sand beds: $S \cdot Q^{0.25} \leq 0.0017$ meandering, ≥ 0.010 braided (English units); in between is transitional.
- HEC-20 uses three levels: qualitative Level 1 (six steps) is a prerequisite for Level 2 engineering analysis (eight steps); Level 3 is modeling.
- Walk at least 10 channel widths up and downstream and use sequential aerial photos to judge lateral migration.
- HEC-23 groups countermeasures as hydraulic (river training, armoring), structural, biotechnical and monitoring; next to a structure, only hard countermeasures are acceptable where failure could fail the bridge.
- Edges fail first: key or toe riprap below combined contraction scour and long-term degradation, or provide a launching apron.
- Pier riprap is a retrofit, not a substitute for deep foundations on new bridges; inspect for displacement, slumping, rounded replacement stone and exposed filter.

References

1. FHWA, HEC-20 Stream Stability at Highway Structures, 4th Edition, FHWA-HIF-12-004, 2012
2. FHWA, HEC-23 Bridge Scour and Stream Instability Countermeasures, 3rd Edition, FHWA-NHI-09-111 and -112, 2009

Study text only; the final quiz is taken online. Verify all references against the edition your agency has adopted.