SUMMARY

Recognizing and anticipating channel instabilities is an important part of locating and designing highways in river environments. Channel instabilities include oscillations in channel bed elevation, variations in river orientation and location, and major river migrations or meanders. Factors affecting river stability have been classified as natural or accelerated. Natural instabilities result from changes in hydrometeorology whereas accelerated erosion is usually a result of man's activities within the watershed.

Identifying channel instabilities requires an understanding of the geomorphic processes occurring within the watershed in question and an awareness of all activities that affect stability. A thorough analysis of system stability should include consideration of past system changes and changes in progress, as well as a geomorphic analysis to predict future changes.

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Assessment of Channel Stability at Bridge Sites

JAMES C. BRICE

ABSTRACT

Assessment of channel stability from field study and the comparison of time-sequential aerial photographs provides information that is needed in site selection, bridge design, and countermeasure placement. Channel instability is indicated by bank erosion, progressive degradation (or aggradation) of the streambed, or natural scour and fill of the streambed. Bank erosion rates are related to stream type and are proportional to stream size. Predictions of future rates are based on past rates, as measured on time-sequential photographs or maps, and on the typical behavior of meander loops. Significant degradation of the streambed can usually be detected from indirect field evidence. The sites of greatest potential scour along a channel can be identified from channel configuration. Shift of the thalweg, which is a factor in the alignment of piers, is related to stream type and can be assessed from aerial photographs.

Hydraulic problems at bridges, although less prevalent than structural problems, are nevertheless significant. In the United States the annual damage to bridges and highways from floods has been estimated at $100 million during years of extreme floods (1). Stream-related damage and maintenance problems also occur when there are no floods, but the expense of such damage and problems is difficult to estimate. A study of hydraulic problems at bridges (2) has indicated that damage by streams can be reduced by considering channel stability in site selection, bridge design, and countermeasure placement.

The objective of this paper is to give a brief summary of geomorphic methods used to assess stream channel stability. These methods are presented in greater detail in a research report published by the Federal Highway Administration (3), and a checklist of geomorphic factors that should be considered in site selection and bridge design are given in an Appendix at the end of this paper.

Many engineers have evidently relied on engineering judgment, based on prior experience and hydraulic analysis of flow (4) to assess scour and other aspects of stream behavior. An assessment of channel stability, from field observations and interpretation of time-sequential aerial photographs, provides additional information to decision makers who select sites and design bridges.

Ideally a stable channel is one that does not change in size, form, or position over time. All alluvial channels change to some extent and therefore have some degree of instability. For engineering purposes, an unstable channel is one in which the rate or magnitude of change is so large that it becomes a significant factor in planning for or maintaining a bridge, highway, or other structure. Changes considered here are (a) lateral bank erosion, (b) degradation or aggradation of the streambed that continues progressively over a period of years, and (c) natural short-term fluctuations of streambed elevation that are usually associated with the passage of a flood (scour and fill).

Applying assessments of channel stability to planning bridges and countermeasures is well stated by Klingeman (5):

> Whereas designers often consider such changes (in bed configuration and channel flow alignment) as a function of stage, it may be more important to recognize the changes that might occur with time . . . best studied from a series of aerial photographs spanning several years. . . . From this assessment of channel stability the designer can expect to make sounder recommendations regarding the best location of the axis of the bridge, the locations of piers in the channel . . . and the likelihood for channel changes and potential maintenance problems during the life of the bridge.

PLANFORM PROPERTIES AND TYPES OF STREAMS

Stream planform properties indicative of channel stability (or instability) are most readily observed in aerial photographs. Unstable streams have wide unvegetated point bars (a and c in Figure 1), cut banks (b in Figure 1), and recent meander cutoffs (d in Figure 1). Stable streams (shown in Figure 2) have a fairly constant stream width, narrow point bars, and well vegetated banks. Major stream types (Figure 3) are characterized by these planform properties and by stability that lies within a fairly well-defined range.

Sinuous Canaliform Streams

The point bars of sinuous canaliform streams (Figures 2 and 3a) are typically covered with permanent vegetation, but narrow crescents of bare sediment may be visible at normal stage. Braiding and lateral bars are rare. If markings are visible on point bars, they tend to be concentric scrolls. Sinuosity tends to be moderate to high, but some reaches are nonsinuous. Banks tend to be well vegetated and cut banks are rare. Natural meander cutoffs are at the necks of meander loops, leaving crescentic oxbow lakes on the floodplain. This is the most laterally stable of all stream types, but meanders gradually migrate. If much vegetation is cleared along the channel, stability may quickly deteriorate; cut banks are an early indication of this. The rate of bedload transport is small in relation to suspended load.

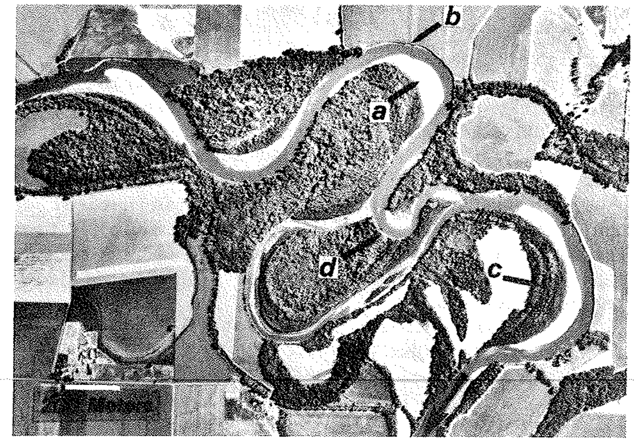

FIGURE 1 Aerial photograph showing typical features of a laterally unstable stream (West Fork White River near Newberry, Ind.).

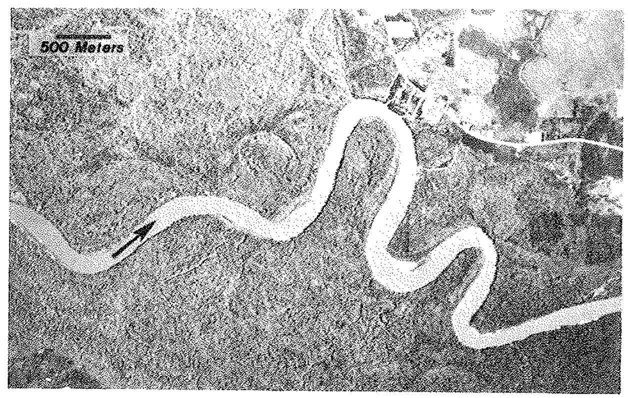

FIGURE 2 Aerial photograph showing typical features of a laterally stable stream (Apalachicola River near Bristol, Fla.).

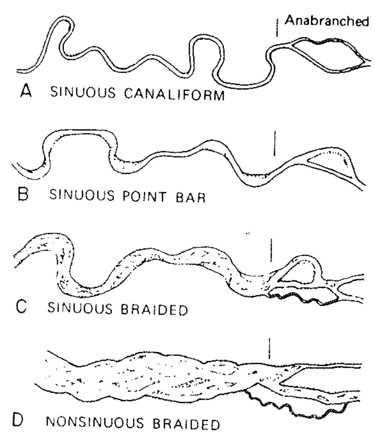

FIGURE 3 Major alluvial stream types.

Sinuous Point-Bar Streams

Bare point bars, clearly visible because of their light tone, tend to be conspicuous on aerial photographs of sinuous point-bar streams (Figures 1 and 3b). Markings on the point bars, if visible, tend to be concentric (location c in Figure 1). The channel may be locally braided and lateral bars may be present. Sinuosity tends to be moderate, but some reaches are nonsinuous. Cut banks are commonly present on the outside of bends. Both neck cutoffs and chute cutoffs occur, but neck cutoffs are more typical. The rate of bank erosion at bends is potentially high, but nonsinuous reaches may remain stable for decades. Sediment load tends to be moderate, and a significant part of the total load is transported as bed load, either sand or gravel. Most rivers in the United States are of the sinuous point-bar type.

Sinuous Braided Streams

Point bars, lateral bars, and midchannel bars are likely to be present in the channel of sinuous braided streams (Figure 3c). Markings on point bars are irregular or braided. Braiding may be local or general. In contrast with nonsinuous braided streams (Figure 3d), whose thalweg is discontinuous, the thalweg is continuous and likely to be meandering. On some braided point-bar streams, the position of the thalweg is fairly stable; on others, it shifts drastically during floods. The main channel, in contrast with the thalweg, tends to have a low sinuosity. Cut banks are common along the main channel, and natural cutoffs are generally of the chute type.

Sinuous braided streams have a potentially high rate of bank erosion. Rapid shift of the thalweg may cause alignment problems and bypassing of a bridge. Scour depth in the thalweg is potentially great, particularly if the bed material is silt or sand. Sediment load tends to be large and a significant part of total load is transported as bed load (sand, gravel, or cobbles).

Nonsinuous Braided Streams

A typical nonsinuous braided stream (Figure 3d) has a channel bordered by distinct banklines; within these banklines, the channel is divided by unvegetated bars or small vegetated islands. The banklines tend to be irregularly scalloped, with cut banks at indentations. Channel width may change drastically from place to place, but in most places the channel is wide and shallow, requiring a long bridge unless confined by suitable countermeasures. Although the channel is unstable in the sense that braids shift rapidly during floods, the bank erosion rates tend to be low or moderate. Bank erosion occurs where braids shift randomly against the bankline, and hence the point of erosion is unpredictable. Because the banks tend to be erodible, bank protection measures are required in the vicinity of abutments. Braids shift at each high flow, and unexpected depths of scour may occur where braids join to form a deep channel. Much of the load is transported as bed load, either sand, gravel, or cobbles.

Anabranching

Any of the four major stream types may be anabranched (Figure 3). Anabranching differs from braiding in that the flow is divided by islands, or sometimes bars, that are relatively permanent and are large in relation to channel width. The anabranches, or individual channels, are more widely and distinctly separated and more fixed in position than are the braids of a braided stream. A long bridge may be required unless the stream is crossed at a local point where it is not anabranched. If there are two or more anabranches at a crossing site, suitable countermeasures will permit a shorter bridge. If two bridges are used, percentage of total flood flow at each bridge may be difficult to predict. The stability of anabranches differs greatly on different streams, and the stability of each anabranch needs to be assessed as though it were a separate stream.

LATERAL STABILITY

Lateral instability at a bridge site may involve erosion of one or both banks, but commonly only one bank is eroded as the channel migrates laterally and changes its position relative to the bridge (Figure 4). Some degree of lateral migration is to be expected for bridge sites at bends in the channel, but bends may develop at sites where the channel was originally straight. One objective of stability assessment is to anticipate the migration of bends, or the development of new bends. The most common problems associated with lateral migration are the undermining of abutments and the exposure of pile bents that were originally placed on the flood plain.

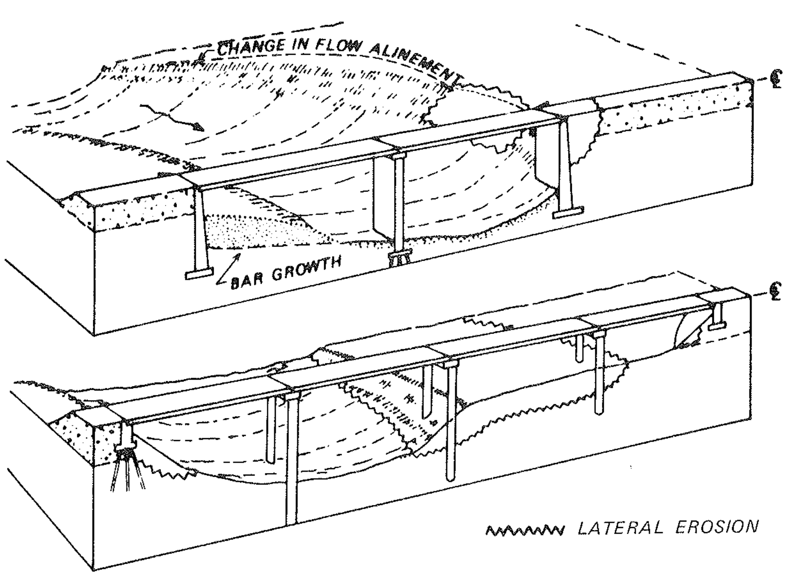

FIGURE 4 Lateral stream erosion and related hydraulic problems at bridges.

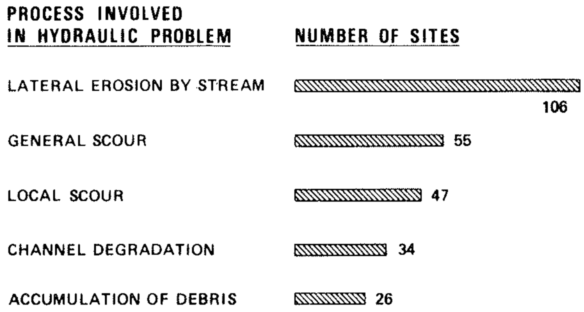

FIGURE 5 Relative importance of different processes in hydraulic problems at bridges.

Lateral erosion is probably more frequently involved in hydraulic problems at bridges than any other stream process. In a study of 224 bridge sites in the United States (2), hydraulic problems were attributed mainly to lateral stream erosion at 106 sites. Other stream processes (general scour, local scour, channel degradation, and accumulation of debris) were less common contributors to problems (Figure 5).

The lateral stability of a channel is measured from records of its position at two or more different times, and the available records are usually maps or aerial photographs. Surveyed cross sections, although useful, are rarely available. For most agricultural regions of the United States, aerial photographs are available for about the last 40 years. Information on the acquisition of time-sequential aerial photographs was given by Brice (3). Maps have the advantage of a longer time span, but time-sequential maps of suitable accuracy are unavailable for large areas of the United States.

Reference Points

Measurement of bank erosion on two time-sequential aerial photographs (or maps) requires the identification of reference points that are common to both. Discernible reference points are either cultural or natural features, which can be identified with much greater confidence by stereoviewing than by examination of a single photograph. If a stereopair is not available, a magnifying lens will assist in identification on a single photograph. In most regions, and particularly on floodplains, cultural features are more likely to maintain recognizable identity over a period of several decades than are natural features.

Cultural features useful as reference points include road and fence corners, buildings, irrigation canals, and bridges. In Figure 6, point 1 is a road corner, point 2 is a fence corner, point 3 is the end of a bridge, and point 4 is a farm building. Points close to the stream have been selected. Because of possible scale variation across the photograph, related to camera tilt, the usefulness of a reference point decreases with increasing distance from the channel. Among the natural features that maintain recognizable identity are rock outcrops and sharp bends in small incised channels. Isolated trees are sometimes useful, as are drainage features on floodplains and lakes of distinctive shape. On some wide, densely forested floodplains, no reliable reference points may be discernible in the vicinity of the channel, and bank erosion distances can only be estimated.

Comparison of Aerial Photographs or Maps

Assessment of lateral stability and the behavior of meanders is greatly facilitated by a drawing which shows the changes with time of banklines and other features of interest (Figure 7). To prepare such a drawing, the aerial photographs (or maps) are matched in scale and the pairs of fixed reference points are placed in register. This involves either (a) bringing the aerial photographs to the same scale by photographic enlargement, or (b) matching scales by projecting the image of one photograph onto another (or a tracing of the other). Projection can be done with a vertical reflecting projector, a graphical data transfer instrument, or an ordinary 35-mm slide projector (3).

FIGURE 6 Examples of reference points on time-sequential aerial photographs. (A) Points, indicated by numbers, on 1969 photograph of Cedar River, Iowa. (B) Corresponding points on 1937 photograph. (U.S. Dept. of Agriculture photographs).

Bank Erosion Rates

Bank erosion rates tend to increase with an increase in stream size, as expressed by channel width. In Figure 8, channel width refers to width as measured on aerial photographs, at straight reaches and the inflection points of bends. Median erosion rate was measured on time-sequential bankline diagrams for 36 streams in the United States (3). The dashed curve in Figure 8 is drawn arbitrarily to have a slope of 1 and a position (intercept) to separate most sinuous canaliform streams from most sinuous point-bar and sinuous braided streams. For a given channel width, sinuous canaliform streams tend to have the lowest erosion rates, and sinuous braided streams, the highest. Bank erosion could not be discerned for some sinuous canaliform streams, and an arbitrary rate of 0.01 meter per year was assigned to

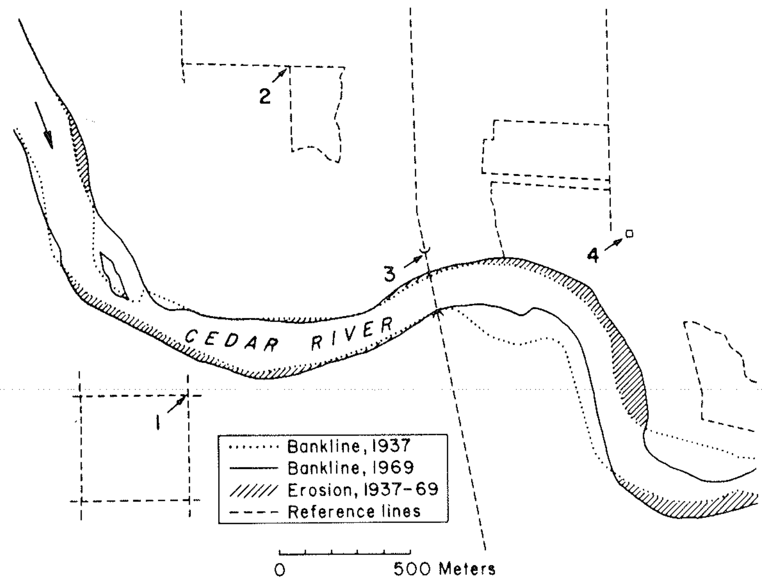

FIGURE 7 Time-sequential banklines for Cedar River, Iowa.

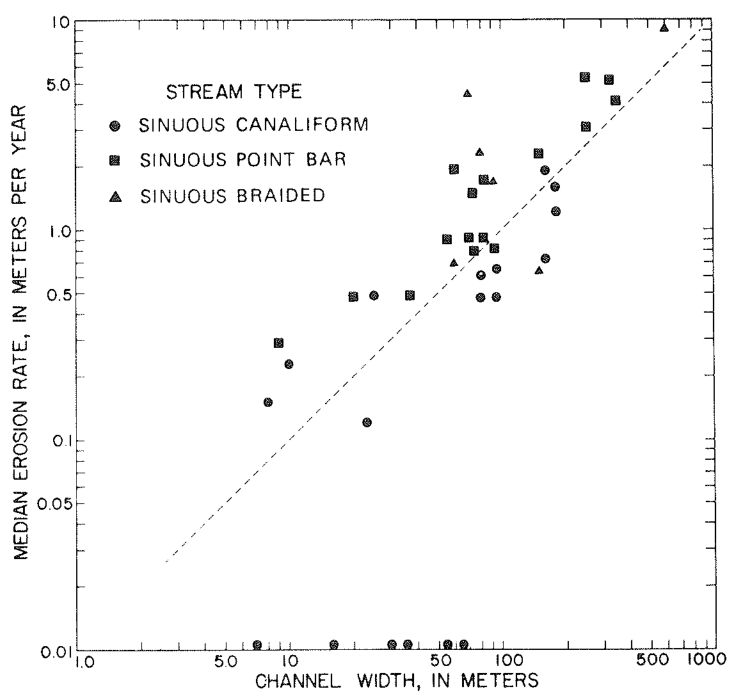

FIGURE 8 Bank erosion in relation to channel size and type.

these. Nonsinuous braided streams, not shown in Figure 8, plot well below the arbitrary curve because their channels are wide relative to their discharges. If nonsinuous braided streams and sinuous braided streams (both uncommon in most parts of the United States) are excluded, the dashed curve in Figure 8 provides a preliminary estimate of erosion rates that may be encountered at a particular site.

The lateral stability of different stream reaches can be compared by means of a dimensionless erosion index (3). The erosion index of a reach is the product of its median bank erosion rate expressed in channel widths per year, multiplied by the percent of reach length along which erosion occurred, multiplied by 1,000. Erosion indexes for 41 stream reaches in the United States are plotted against sinuosity in Figure 9. The length of most of these reaches is 25 to 100 channel widths. The highest erosion index values are for reaches whose sinuosity is 1.2 to 2 and whose type is either sinuous braided or sinuous point bar. An erosion index value of 5 (horizontal dotted line in Figure 9), which separates these types from most sinuous canaliform streams, is suggested as a boundary between stable and unstable reaches. Reaches having erosion index values less than 5 are unlikely to cause lateral erosion problems at bridges. As an example of the use of the erosion index for comparative purposes, the reach of the White River in Figure 2 has an erosion index of about 15, and the reach of the Apalachicola River in Figure 3 has an erosion index of about 4.

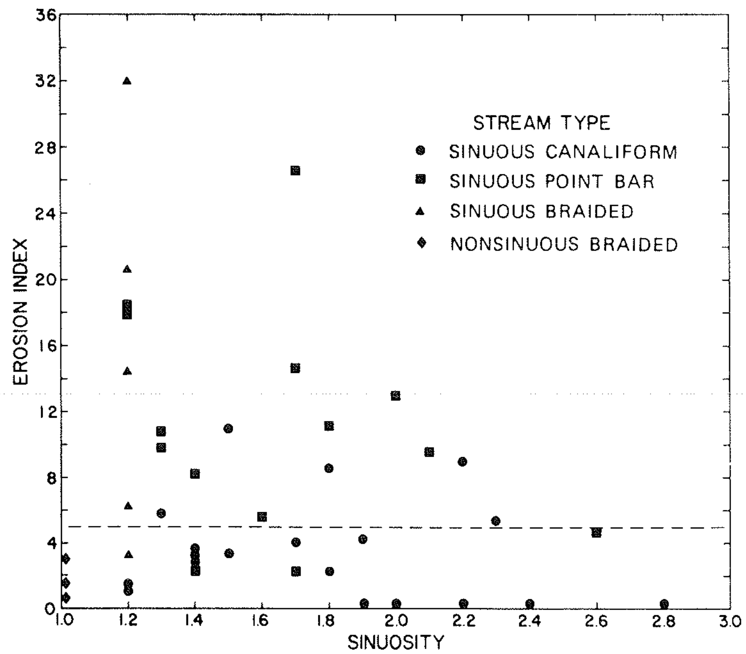

FIGURE 9 Erosion index in relation to sinuosity.

For all stream types, erosion rates are higher at bends than along straight reaches. On the other hand, stream types characterized by the highest sinuosities tend to be the most stable, because some degree of stability is necessary for high sinuosities to be maintained. An unstable stream will not remain highly sinuous for very long, because the sinuosity will be reduced by frequent meander cutoffs.

Prediction of Meander Loop Migration

Most lateral erosion problems at bridges are associated with the migration of meander loops or with the growth of new loops. Prediction of the rate and mode of loop migration may therefore be needed for planning purposes. Some progress is being made on numerical prediction of loop deformation and migration, applying to time intervals significant for engineering purposes (6). At present, however, the best available estimates are based on past rates of lateral migration at a particular reach and on the typical migration behavior of loops. As demonstrated by Nanson et al. (7), erosion rates at a particular loop may fluctuate substantially (and unpredictably) from one period of years to the next. Even so, a rational estimate of erosion at a meander loop, based on the probable distribution and rate of erosion, is better than none.

Erosion at loops involves extension (Figure 10a), translation (Figure 10b), or conversion to a compound loop (Figure 10c). Typically, a loop migrates mainly by translation, with some component of extension. Meanders tend to become compound because they have developed, by growth, a path length that is long in relation to the typical spacing of pools and riffles (or alternate bars) in the channel. Neck cutoffs (Figure 10d) are typical of canaliform and sinuous point-bar streams. As the degree of braiding increases, chute cutoffs (Figure 10e) are more probable. The cutoff of a meander loop, whether by natural or artificial means, tends to increase the bank erosion rate at adjoining loops. However, loop cutoffs are common in nature, and drastic consequences have rarely been observed.

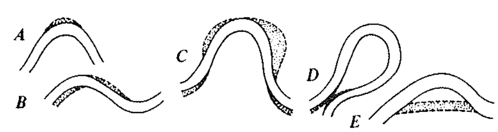

FIGURE 10 Modes of meander loop development and cutoff.

CHANNEL DEGRADATION

Progressive vertical changes in bed elevation (degradation or aggradation) are a common cause of hydraulic problems at bridges in some regions of the United States, and a potential cause in any region where channels are underlain by erodible materials. Degradation occurs more frequently then aggradation, and its consequences are more serious. Of the total number of gradation sites reported by Keefer et al. (8), sites having degradation problems were about three times more numerous than sites having aggradation problems.

Annual rates of degradation that are averaged over a period of time following some man-induced event, such as the closure of a dam or the straightening of a channel, are not a good basis for estimating future rates. According to Simons and Senturk (9), the rate of degradation downstream from a dam is rapid initially and decreases gradually as a new stable profile evolves. Similarly, available evidence suggests that the rate of degradation following channel straightening is likely to be rapid at first and to decrease gradually (10). From a comprehensive study of the effects of channel straightening on streams in western Tennessee, Robbins and Simon (11) were able to describe the channel degradation by an exponential decay function. They concluded that if there were no further disturbance the degradation or aggradation followed a predictable pattern and rate.

Field Assessment of Degradation

If a channel has been recently degrading at a rate that would significantly affect planning of engineering works, there is likely to be some observable evidence for this along the channel, as seen in the field or by stereoviewing of aerial photographs. Indicators of degradation are listed below in approximate order of reliability:

1. Channel scarps (headcuts, knickpoints). A migrating scarp in the long profile of a channel is unequivocal evidence of degradation, and the rate of degradation is related to the height and migration rate of the scarp. Channel scarps are easy to observe in ephemeral streams or small perennial streams, but are rarely observed in large perennial streams.
2. Gullying of minor side tributaries. As a stream degrades, its tributaries also degrade, and scarps may be present along their profiles.
3. High, steep, unvegetated banks. Some channels have higher banks than others of about the same width. Among the factors that determine bank height are degree of incision and erosional resistance of the banks. Where high banks are also raw and ungraded, recent degradation is suggested.

Other Methods of Assessment

Other methods of assessing channel degradation have been described by Keefer et al. (8). Changes in the elevation of the water surface are determined over a period of years, in relation to a fixed datum. Methods include (a) periodic measurements from bridge deck to streambed, where allowance can be made for local or general scour at the bridge; (b) plotting change in the stage-discharge relation at gauging stations; and (c) repetitive measurement of the longitudinal or cross profile of the stream channel.

NATURAL SCOUR AND FILL

Natural scour and fill has been neglected as a factor in bridge site location, probably because of its complexity and the lack of useful information on it. Bed elevation is difficult to measure during floods, and a reliable analysis of scour and fill requires measurement of several cross sections at about the same time. A continuous longitudinal bed profile along the thalweg is also highly desirable. In a particular cross section, the amount of scour and fill is unevenly distributed, and both the reference bed and the scoured bed are likely to be of irregular shape.

For most streams the magnitude of scour is substantially greater at some places along the channel than at others. According to Neill (12),

> The location of a bridge with respect to the river channel pattern in plan has an important bearing on its liability to bed scour. Bends and narrow sections may be liable to scour at high stages, regardless of the effects of bridge structures . . . . Straight or gently curved reaches with stable banks are to be preferred.

If, however, a crossing must be made on a meandering reach, identification of the segments of least potential scour may be a deciding factor in site location.

Scour below preflood bed elevation probably occurs at most cross sections of an alluvial stream at some time during the passage of a flood, although not at the same time nor to the same degree. At some sections, the scour is due to the migration of bed forms and the mean streambed elevation does not change significantly. In a detailed field study of scour and fill at 11 cross sections on the East Fork River in Wyoming, Andrews (13) measured scour that he considered significant (though less than 0.5 m) during flood crests at 6 of the 11 cross sections, and fill at 5 of the sections. At some time or other during the flood, net scour occurred at all except 2 of the sections.

Natural scour and fill refers to fluctuations of streambed elevation about an equilibrium position, which is commonly taken to be the position at low flow. These fluctuations are associated mainly with floods, and they occur without artificial constriction of the channel and without the presence of artificial obstructions such as bridge piers. The scour induced by a bridge is additive to natural scour. A bed elevation that has been raised or lowered is likely to return to its equilibrium position during the falling stages of the flood; however, the return may require weeks, months, or even years for some streams, particularly those having coarse bed material. Natural scour and fill occurs by three different mechanisms, which may operate jointly or independently: (a) bed form migration, (b) convergence and divergence of flow, and (c) lateral shift of thalweg or braids.

Bed Form Migration

The migration of dunes may result in an amount of scour that is sufficient to warrant consideration in the design of pier foundations. Allowance for scour due to the migration of sand waves is more problematical and would have to be determined from a continuous long profile of the stream at high stage. The maximum scour induced by the migration of a dune is about one-half dune height, and dune height is roughly estimated at one-third the mean flow depth. In sand-bed streams, dune migration can be expected if the quantity of bed load in transport is sufficient for dune formation. Stream type is a reasonably good indication of the bed-load characteristics of a stream. Canaliform streams that have very narrow point bars are likely to be transporting minor amounts of bed load. An increasing transport of bed load is indicated by an increase in degree of braiding.

Most migrating bed forms in gravel-bed streams can be regarded as bars, the height of which is related to flow depth. Migration of a bar through a bridge waterway is mainly of concern because of its deflection and concentration of flow. Bar migration tends to be a random process, and the tendency of bars in a stream to migrate is best determined from time-sequential aerial photographs.

Convergence of Flow

The flow conditions associated with changes in mean bed elevation are summarized by the convergent-divergent flow criterion of Leliavsky (14). Convergent currents in a natural stream are associated with erosion (scour), and divergent currents are associated with deposition (fill).

Persistent pools (Figure 11) in the long profile of an alluvial channel have the strongest convergence of flow and the greatest potential for scour. Such pools are best identified by a continuous bed profile along the thalweg, as sounded at high stage. On a gravel-bed "pool-and-riffle" stream, the water-surface profile at low stage is flattest over the pools and steepest over the intervening riffles. On a sand-bed stream, however, persistent pools may fill at low stage, their position may

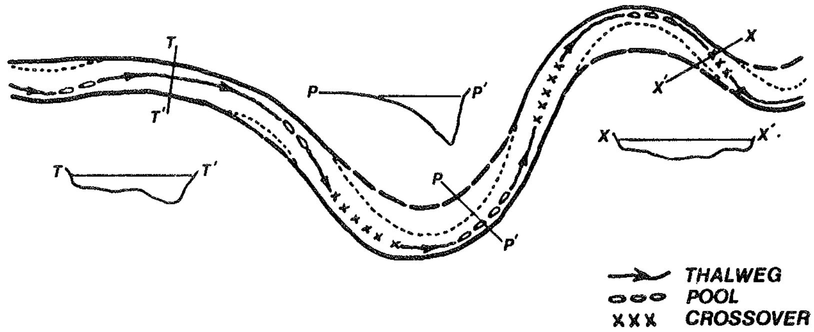

FIGURE 11 Pools, crossovers, and trace of thalweg.

shift to some degree, and they may be difficult to distinguish from random irregularities in the long profile. Pools, as well as riffles and crossovers, tend to be several channel widths in length, which is longer than most random irregularities. As the degree of braiding of a stream increases, the probability of persistent pools in the long profile decreases. Scour holes in braided streams are mostly at the confluence of braids.

For streams having wide point bars, crossovers (Figure 11) can usually be identified on aerial photographs taken at low flow. Pools cannot be observed directly, but they are typically located downstream from the apexes of bends and opposite the point bar. Pools may also occur in straight reaches, where their position is sometimes marked by an alternate bar. At low stage, water-surface width tends to be least at pools, greatest at riffles, and of intermediate value at transitional sites. At bankfull stage, the water-surface width tends to be greater at pools than at crossovers or transitional sections.

As suggested by Neill (15), field measurement of cross sectional area and flow velocity at an incised (straight) reach near bankfull stage provides a good basis for calculation of scour by extrapolation to the design flood. Furthermore, a comparative measurement of this same section at low stage gives the amount of scour from low stage to bankfull stage, which is valuable for confirming results obtained by computational methods. Klingeman (5) recommended that "The lowest undisturbed streambed elevation at or near the bridge crossing (other than a local scour hole) be used as a reference level in setting scour elevations of principal piers at or near the main channel."

Shift of Thalweg

Of the 224 bridge sites studied by Brice and Blodgett (2), hydraulic problems attributed to shift of the thalweg occurred at 6 sites. One of these (site 164, Fort George River, Florida) is at a sand-bed estuary, subject to strong tidal currents. Site 207, Leaf River, Mississippi, and site 170, Red River, Arkansas, are on sinuous point-bar streams having sand beds. At both sites, the thalweg shift was related to a slight curvature of the channel and took place over a period of years rather than during a single flood.

Site 16, Deer Creek, California, and site 186, White River, South Dakota, are at sinuous braided streams in which the thalweg tends to wander. Site 226, Boulder Creek, Washington, is on a steep non-sinuous braided stream having a cobble-boulder bed. The bridge clearance was greatly reduced by aggradation, and the thalweg shifted against an abutment. Although nonsinuous braided streams are commonly regarded as unstable because of the rapid and unpredictable shift of bars and braids, they are readily controlled with suitable countermeasures and are not a particular cause of hydraulic problems.

Instability of the streambed that results from shift to thalweg (or braids) is, like bank instability, related to stream type and can be assessed from study of aerial photographs. On sinuous canaliform streams, shift of the thalweg during flood is minimal. The channel tends to be relatively deep, narrow, and uniform from one place to another. In straight reaches, the alternate bars that indicate meandering of the thalweg are rarely present.

A greater shift of the thalweg, both at bends and in nearly straight reaches, can be expected on sinuous point-bar streams. Flood flow cuts across the ends of the point bars, which are wide and bare at low stage. In straight reaches, alternate bars, visible on aerial photographs taken at low stage, are commonly present. These alternate bars are significant in the planning of bridges and countermeasures, because they indicate the potential for shift of the thalweg and also for bank erosion where the current is deflected against the bankline.

CONCLUSIONS

1. Study of stream morphology on time-sequential aerial photographs provides information that is applicable to site selection and bridge design. By this means, information can be obtained on lateral stream stability, degradation, and natural scour and fill.

2. Lateral stability is related to stream type. Streams that have a uniform width and narrow point bars (canaliform streams) tend to be the most stable. Streams that have wide point bars and cut banks tend to be less stable and, for sinuous streams, stability tends to decrease with the degree of braiding. For a given stream type, median bank erosion rates tend to increase in direct proportion to stream size, as expressed by channel width.

3. Channel degradation is determined by measurement of progressive changes with time of streambed elevation in reference to a fixed datum. For man-induced degradation, the curve of cumulative degradation versus time is more likely to be asymptotic than linear. Equilibrium bed elevation is difficult to predict.

4. Scour by bed form migration is of consequence mainly in sand channels. Gravel bars tend to migrate on braided streams and to remain fixed at riffles on unbraided, pool-and-riffle streams. A migrating gravel bar may concentrate flow at a bridge and cause lateral bank erosion or local scour at piers.

5. Scour by convergence of flow is related to channel configuration and is greatest at persistent

deeps or pools in the channel-long profile, where the water velocity during floods is likely to be greatest. Many cross sections along a stream are transitional between pools and riffles. In general, the scour induced by a bridge will be greater at pools or pool-like cross sections than at riffles or riffle-like cross sections.

6. Shift of the thalweg with increase in stage is a significant factor in bridge design, not only for estimation of the point of maximum bed scour (and bank erosion) but also for alignment of piers with flood flow. Thalweg stability is related to channel stability and to stream type, and can be assessed from aerial photographs.

APPENDIX: CHECKLIST OF GEOMORPHIC FACTORS

Geomorphic factors relevant to site selection and bridge design are listed below in the form of questions. Exact answers to these questions can rarely be obtained, but even probable answers are worth considering.

Selection of Crossing Site

Site on a Nonsinuous Reach

1. Is site at a pool, riffle (crossover), or transition section?
2. Are alternate bars visible at low stream stage?
3. If midchannel bars are present, what would be the effect of their migration through the bridge waterway?
4. Is cutoff imminent at adjacent meanders?

Site at a Meander

1. What has been the rate and mode of migration of the meander?
2. What is its probable future behavior, as based on the past?
3. Is site at pool, riffle (crossover), or transition section?
4. Is cutoff of the meander, or of adjacent meanders, probable during the life span of the bridge?

Design of Bridge

Piers on Flood Plain or Adjacent to Channel

1. Is the channel migration rate sufficient to overtake piers during the life span of the bridge?

Piers in Channel

1. For pier orientation, what is probable position of thalweg at design flood?
2. For scour estimation, what is probable bed form height at design flood?
3. For scour estimation, what is natural mean bed scour at design flood?
4. For scour estimation, what is lowest undisturbed streambed elevation at or near the crossing site?
5. Does the stream have an unstable thalweg that has shifted with time?
6. Is there evidence of recent channel degradation?
7. Are any works of man in prospect that are likely to induce degradation or bank erosion?

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