Exhibit 12

Highways in the River Environment

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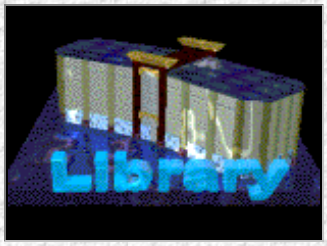
Welcome to HIRE - Highways in the River Environment



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it is well to consider a channel reach as part of a complete drainage system. Artificial controls that could benefit the reach may, in fact, cause problems in the system as a whole. For example, flood control structures can cause downstream flood damage to be greater at reduced flows if the average hydrologic regime is changed so that the channel dimensions are actually reduced. Also, where major tributaries exert a significant influence on the main channel by introducing large quantities of sediment, upstream control on the main channel may allow the tributary to intermittently dominate the system with deleterious results. If discharges in the main channel are reduced, sediments from the tributary that previously were eroded will no longer be carried away and serious aggradation with accompanying flood problems may arise.

An insight into the direction of change, the magnitude of change, and the time involved to reach a new equilibrium can be gained by studying the river in a natural condition; having knowledge of the sediment and water discharge; being able to predict the effects and magnitude of man's future activities; and applying to these a knowledge of geology, soils, hydrology, and hydraulics of alluvial rivers.

The current interest in ecology and the environment have made people aware of the many problems that mankind can cause. Previous to the present interest in environmental impact, very few people interested in rivers ever considered the long-term changes that were possible. It is imperative that anyone working with rivers, either with localized areas or entire systems, have an understanding of the many factors involved, and of the potential for change existing in the river system.

Two methods of predicting response are employed. They are the physical and the mathematical models. Engineers have long used small scale hydraulic models to assist them in anticipating the effect of altering conditions in a reach of a river. With proper awareness of the large scale effects that can exist, the results of hydraulic model testing can be extremely useful for this purpose. A more recent and alternative method of predicting short-term and long-term changes in rivers involves the use of mathematical models. To study a transient phenomenon in natural alluvial channels, the equations of motion and continuity for sediment laden water and the continuity equation for sediment can be used as discussed in Chapter 3 and Chapter 4.

1.3 Effects of Highway Construction on River Systems

Highway construction can have significant general and local effects on the geomorphology and hydraulics of river systems. Hence, it is necessary to consider induced short-term and long-term responses of the river and its tributaries, the impact on environmental factors, the aesthetics of the river environment and short-term and long-term effects of erosion and sedimentation on the surrounding landscape and the river. The biological response of the river

system should also be evaluated and considered.

1.3.1 Immediate Responses

Let us consider a few of the numerous and immediate responses of rivers to the construction of bridges, training and channel stabilization works and approaches.

In the preceding paragraphs we indicated that local changes made in the geometry or the hydraulic properties of the river may be of such a magnitude as to have an immediate impact upon the entire river system. More specifically, contractions due to the construction of encroachments usually cause contraction and local scour, and the sediments removed from this location are usually dropped in the immediate reach downstream. In the event that the contraction is extended further downstream, the river may be capable of carrying the increased sediment load an additional distance but only until a reduction in gradient and a reduction in transport capability is encountered. The increased velocities caused by encroachments may also affect the general lateral stability of the river downstream.

In addition, the development of crossings and the contraction of river sections may have a significant effect on the water level in the vicinity and upstream of the bridge. Such changes in water level upstream of the bridge are called backwater effects. The highway engineer must be in a position to accurately assess the effects of the construction of crossings upon the water surface profile.

To offset increased velocities and to reduce bank instabilities and related problems, one ends up, in many instances, with stabilizing or channelizing the river to some degree. When it is necessary to do this, every effort should be made to do the channelization in a manner which does not degrade the river environment, which includes the river's aesthetic value.

As a consequence of construction, many areas become highly susceptible to erosion. The transported sediment is carried from the construction site by surface flow into the minor rills, which combine within a short distance to form larger channels leading to the river. The water flowing from the construction site is usually a consequence of rain. The surface runoff and the accompanying erosion can significantly increase the sediment yield to the river channel unless careful control is exercised. The large sediment particles transported to the main channel may reside in the vicinity of the construction site for a long period of time or may be slowly moved away. On the other hand, the fine sediments are easily transported and generally pollute the whole cross section of the river. The fine sediments are transported downstream to the nearest reservoir or to the sea. As will be discussed later, the sudden injection of the larger sediments into the channel may cause local aggradation, thereby steepening the channel, increasing the flow velocities and possibly causing instability in the river at that site.

The suspended fine sediments can have very significant effects on the biomass of the stream. Certain species of fish can only tolerate large quantities of suspended

sediment for relatively short periods of time. This is particularly true of the eggs and fry. This type of biological response to development normally falls outside of the competence of the engineer. Yet his work may be responsible for the discharge of these sediments into the system. If he is unable to cope with the problem, the engineer should utilize adequate technical assistance from experts in fisheries, biology, and other related areas to overcome the consequences of sediment pollution in a river. Only with such knowledge can he develop the necessary arguments to sell his case that erosion control measures must be exercised to avoid significant deterioration of the stream environment not only in the immediate vicinity of the bridge but in many instances for great distances downstream.

Another possible immediate response of the river system to construction is the loss of the recreational use of the river. In many streams, there may be an immediate drop in the quality of the fishing due to the increase of sediment load, or other changed hydraulic characteristics within the channel. Some natural rivers consist of a series of pools and riffles. Both form an important part of the environment from the viewpoint of fisheries. The introduction of larger quantities of sediment into the channel and changes made in the geometry of the channel may result in the loss of these pools and riffles. Along the same lines, construction work within the river may cause a loss of food essential to fish life and often it is difficult to get the food chain reestablished in the system.

Construction and operation of highways in water-supply watersheds present very real problems and require special precautionary designs to protect the water supplies from highway residue. These residues may be largely sedimentary and may increase the turbidity of the water. There have been instances, however, where other unwelcome materials such as asphalt distillates and deicing salts which have been traced to highway operations.

The preceding discussion is related to only a few immediate responses to construction along a river. However, they are responses that illustrate their importance to design and the environment.

1.3.2 Delayed Response of Rivers to Development

In addition to the example of possible immediate responses discussed above, there are important delayed responses of rivers to highway development. As part of this introductory chapter, consideration is given to some of the more obvious effects that can be induced on a river system over a long time period by highway construction.

Sometimes it is necessary to employ training works in connection with highway encroachments to favorably align the flow with bridge or culvert openings. When such training works are used, they generally straighten the channel, shorten the flow line, and increase the local velocity within the channel. Any such changes made in the system that cause an increase in the gradient may cause an increase in local velocities. The increase in velocity increases local and contraction scour

with subsequent deposition downstream where the channel takes on its normal characteristics. If significant lengths of the river are trained and straightened, there can be a noticeable decrease in the elevation of the water surface profile for a given discharge in the main channel. Tributaries emptying into the main channel in such reaches are significantly affected. Having a lower water level in the main channel for a given discharge means that the tributary streams entering in that vicinity are subjected to a steeper gradient and higher velocities which cause degradation in the tributary streams. In extreme cases, degradation can be induced of such magnitude as to cause failure of structures such as bridges, culverts or other encroachments on the tributary systems. In general, any increase in transported materials from the tributaries to the main channel causes a reduction in the quality of the environment within the river. More specifically, as degradation occurs in the tributaries, bank instabilities are induced and the sediment loads are greatly increased. Increased sediment loads usually result in a deterioration of the environment.

1.4 The Effects of River Development on Highway Encroachments

Some of the possible immediate and delayed responses of rivers and river systems to the construction of bridges, approaches, culverts, channel stabilization, longitudinal encroachments, and the utilization of training works have been mentioned. It is necessary also to consider the effects of highway encroachments on river development works. These works may include, for example, water diversions to and from the river system, construction of reservoirs, flood control works, cutoffs, levees, navigation works, and the mining of sand and gravel. It is essential to consider the possible or probable long-term plans of all agencies and groups as they pertain to a river when designing crossings or when dealing with the river in any way. Let us consider a few typical responses of a crossing to different types of water resources development.

Cutoffs may develop naturally in the river system or cutoffs can be constructed by man. The general consequence of cutoffs is to shorten the flow path and steepen the gradient of the channel. The local steepening can significantly increase the velocities and sediment transport. Also, this action can induce significant instability such as bank erosion and degradation in the reach. The material scoured in the reach affected by the cutoff is probably carried only to an adjacent downstream reach where the gradient is flatter. In this region of slower velocities the sediment drops out rapidly. Deposition can have significant detrimental effect on the downstream reach of river, increasing the flood stage in the river itself and increasing the base level for the tributary stream, thereby causing aggradation in the tributaries.

Consider a classic example of a cutoff that was constructed on a large bend in one of the tributaries to the Mississippi. Along this bend, small towns had developed and small tributary streams entered the main channel within the bendway. It was decided to develop a cutoff across the gooseneck to shorten the flow line of the river, reduce the flood stage and generally

equations are now adequately developed for accurate prediction of alluvial riverbed profiles if an accurate sediment transport function and a bed roughness predictor were available. Improvement in model reliability requires further research in the areas described hereafter: (1) There is a strong need for a very reliable sediment transport relation because alluvial river-bed changes are the result of a streamwise gradient in the stream's sediment transport capacity; (2) The bed-armoring process during channel degradation is not well understood and has not been adequately formulated in a conceptual model. Armoring and coarsening of the bed-material size have a direct effect on the sediment-transport capacity and the bed-friction factor, and consequently affect the velocity, depth, and energy slope of the flow; (3) There is a need to develop a better friction-factor predictor that depends on flow depth and velocity and sediment discharge; (4) There is a need to incorporate into models the bank-erosion and channel-migration effects of channel widening; and (5) It is unlikely that an alluvial riverbed model that is applicable to all types of rivers will be forthcoming in the near future. Instead, each model will be most dependable for rivers of the type for which it was developed. Therefore, there is a need for an effort to classify natural rivers in terms of their hydraulic and geomorphologic characteristics, to guide engineers in the selection and application of a model that uses formulations of sediment discharge, channel roughness, channel widening, and so on that are most appropriate for their study cases.

If there is one important message to be drawn from this catalog of deficiencies, it is the following: Model developers and users must not let their preoccupations with improvements in numerical methods, user friendliness, program generalization, and other pleasant but peripheral concerns cause them to lose sight of the central and often unpleasant need to obtain a better understanding and conceptual formulation of the basic physical processes of alluvial riverbed evolution.

4.7 Highway Problems Related to Gradation Changes

Gradation problems at highway crossings include aggradation and degradation; lateral erosion problems often occur as a consequence of these changes. The highway problem most associated with aggradation is reduction of flow area, which increases backwater effects upstream of bridges and culverts. Problems associated with degradation are undermining of footings, pile bents, abutments, cutoff walls, and other flow-control or crossing structures. Degradation has also been found to undermine bank protection resulting in the instability of channel banks and increasing debris problems. A common problem associated with lateral erosion is bank slumping, which undermines abutments and piers located near the bank line. Another very common problem arises when beds of meandering streams encroach upon roadways.

Causes of gradation changes that have an impact on highway crossings can be classified into two basic categories: (1) the result of man's activities; and (2) natural causes or factors. An analysis of the case histories indicates that very few gradation changes were due to natural factors. Some gradation changes should perhaps be classified as being caused by a combination of both natural and man-induced factors. However, their number is so small that a separate category is not warranted. Because man's activities dominate the causes for gradation problems, they will be discussed first.

4.7.1 Changes Due to Man's Activities

The activities of man are literally changing the face of the Earth and generate accelerated erosion from watersheds. Some activities have had far-reaching consequences on streams and have caused, or contributed to aggradation and degradation problems at bridges. Construction of a bridge and approach embankments may also have consequences, but they are unlikely to

be far-reaching. Man's activities were found to be the major cause of streambed elevation changes. Because accelerated erosion is associated with man's activities, it is often possible to anticipate many impacts on bank stability and provide adequate bank protection in advance.

From an analysis of the case histories, man's activities resulting in gradation problems can be classified into the following categories: (1) channel alterations; (2) land use changes; (3) streambed mining/excavation; and (4) dams and reservoirs.

- **Channel Alterations**

  Straightening, dredging, clearing and snagging, artificial constrictions, and other alterations of natural channels are the major causes of streambed elevation changes. Channel straightening is the dominant activity. Examples of straightening and several others are presented in Keefer et al. (1980).

  Many of the straightened channels have degraded, and degradation is usually accompanied by widening of the channel, unstable banks and serious debris problems. The degradation is attributed to an increase in channel slope that results from shortening of channel length. The increase in channel slope increases the velocity and the shear stress on the bed. As a result, the channel bed degrades until the bed becomes armored or the channel widens and begins to meander to reduce the channel slope back to an equilibrium, or stable condition. There is some evidence that degradation, if it is to occur as a consequence of channel alteration, will be most rapid during a period shortly following the alteration and will thereafter occur at a decreasing rate.

- **Land Use Changes**

  Urbanization, agriculture, strip mining, and unregulated logging are other activities of man that cause gradation problems. Natural vegetation is extremely important in maintaining channel stability. The lateral stability of most streams in the United States, particularly in regions where agriculture or lumbering is practiced, has very probably been affected by the clearing of natural vegetation. Because this clearing has occurred more or less gradually over the past hundred years, the magnitude of the effect at a particular crossing site is sometimes difficult to assess.

  The result of deforestation and agricultural activities is generally toward increased peak flows and increased sediment yield. Channel widening and reduced sinuosity are common. Grazing along the streambanks may have significant effects on bank stability.

  Urbanization normally causes significant increase in the magnitude of runoff events while reducing their duration. Urban areas are also low sediment producers because of the large percentage of land covered by impervious surfaces. The combination of increased peak runoff rates and reduced sediment loads result in channel degradation, channel widening, and a reduction in channel sinuosity.

  Improper construction activities on the other hand are known to increase both discharge and sediment load. The removal of the vegetative cover accelerates the erosion process. The response of the system to the increased discharge is to increase channel width and reduce the radius of curvature. In response to increased sediment load, the stream will increase its tendency for bank erosion.

  Mining in an upland area may cause aggradation of channels, which are then subject to degradation after the mining ceases.

- **Streambed Mining/Excavation**

  If sand or gravel is removed from an alluvial channel in quantities that represent a substantial percentage of the annual bedload in transport, the channel will probably degrade. In addition,

removal of gravel from pits or trenches in or along the stream may result in a change in flow alignment at the bridge.

Downstream mining can also produce headcutting through a bridge waterway, undermining the structure. Mining operations upstream of the bridge waterway can also produce degradation at the bridge site and endanger the structure. Equation 4.5.3 provides a subjective tool for analysis of gradation changes. A case study illustrating problems at a bridge crossing due to gravel mining is presented in Chapter 7.

Highway engineers should, as a minimum, conduct bi-annual inspections of bridges upstream and downstream for gradation problems.

- **Dams and Reservoirs**

The effects of dams and reservoirs on a stream are complex and have not been thoroughly investigated. The consequences of dams and reservoirs include clear water releases; high, sustained, regulated flows; backwater; low, sustained, regulated flows; dam breach or removal; and high, controlled, irrigation canal releases.

Downstream from a reservoir, channel degradation is to be expected because of removal of sediment. This effect has been documented for many streams. The total amount of degradation is difficult to predict; if a sand-bed channel becomes armored with gravel, the amount may be small. On gravel-bed streams aggradation may occur downstream from the dam because the flow releases are insufficient to transport gravel brought in by tributary streams. Channel avulsions, which can present a serious threat to many engineering structures, are associated with most aggrading situations. Rapid lowering of river stage may result in severe bank slumping from pore-water pressures in the banks. However, the more general effect of reservoirs is probably to lessen hydraulic problems at highway crossings bridges, both by reduction of flood peaks and a reduction of lateral erosion rates.

Interbasin transfers of flow and diversions result in periods of channel instability and bank erosion until the new channel regime is established.

4.7.2 Natural Causes

Although problems resulting from natural causes are not as frequent as those resulting from man's activities, it is important to recognize natural causes in both design and maintenance of highway crossings.

Natural causes and complications from gradation problems include: alluvial fans, natural armoring, braiding, meandering/migration (natural cutoffs), recurrent flooding, high stream velocity, channel bed and bank material erodibility, fire, floating debris, mud and debris flows, earthquakes, tectonic activity, volcanic activity, and landslides.

- **Floating Debris**

Floating debris causes hydraulic problems at highway crossings nationwide. The problems are the greatest in the Pacific Northwest and the upper and lower Mississippi River Valley. Debris hazards are local and infrequent phenomena often associated with large floods. Most bridge destruction from debris is due to accumulation of debris against bridge components. Debris may partially or totally block waterways, create adverse hydraulic conditions that erode pier foundations and bridge abutments, may overtop roadways and cause structural damage. Many debris problems exist in forested areas with active logging operations. Highway crossings on streams where stream slopes are mild or moderate, in contrast to headwater streams, are more vulnerable to debris related hazards. Debris hazards occur more frequently in unstable streams

where bank erosion is active. Countermeasures presently used by highway agencies include: (1) sufficient freeboard, (2) proper pier spacing, (3) solid piers, (4) debris deflectors, (5) special superstructure designs, (6) flood relief structures, and (7) routine and emergency removal of debris at bridge crossings. Most debris transported in floods does not travel a great distance and often is observable locally along the streambanks upstream from the bridge prior to the flood. Rather than in congregations, debris usually moves as individual logs in a non-random path concentrating in the thalweg of the stream. Therefore, methods for evaluating its abundance and for mitigating its hazard are deemed feasible. Examples of debris control structures for culverts are given in Reihsen (1964).

- **Mud Flows and Debris Flows**

Fast melting snowpack and overabundance of soil moisture on steep slopes throughout the Western United States causes mudflows, debris flows and landslides, threatening bridges and highway structures. There is considerable evidence of damages to highway structures in the literature. For example Hungr et al., (1984) documented a bridge for which a concrete bridge beam has been demolished by point impact during a debris flow event.

In another example, the volcanic eruption from the magmatic blast of Mount St. Helens triggered a major slope failure on the north flank of the mountain. Mudflows and debris flows were generated and swept down the Toutle and Cowlitz Rivers destroying bridges, inundating buildings, and eventually blocking the navigation channel of the Columbia River. Bradley (1984) reported the Cowlitz has aggraded markedly as a result of the post eruption hyperconcentrated flows. The upper Cowlitz and the lower Toutle have shifted from meandering to braided streams, thereby causing some difficulties in preventing the failure of some remaining bridges.

Examination of typical watershed behavior and response provides information on the impact of changes on the fluvial system. Channel stability assessments and possible gradation changes are indicated in Table 4.7.1. Those findings reflect the observations of Keefer et al. (1980). An example relating to the use of this table is presented in Appendix 4, Problem 4.3.

4.7.3 Resulting Problems at Highway Crossings

Brown et al. (1980) reviewed current design practices to evaluate crossing design procedures and the effect of grade changes on these procedures. The parameters most influenced by grade changes are those used as input to the hydraulic design procedures currently in use. These input parameters include: design discharge; channel roughness; energy slope; bed slope; velocities; shear stresses; cross-sectional geometry; base level; flow depth; and flow alignment. Other components of crossing design affected by grade changes include foundation depth, bridge deck clearance, and flow opening size.

Problems encountered at bridge crossings include bridge capacity, backwater, pier and abutment alignment, footing depth at piers and abutments, and construction depth for flow-control and debris-control structures. With respect to bridge capacity and backwater, aggradation produces the most severe problems. However, debris problems associated with degradation can also have a significant impact on flow capacity and scour. Foundation depths for piers, abutments, and flow-control structures can be influenced in two ways by grade changes: the normal streambed base level will be altered; and the "normal" hydraulic conditions at a site used as input to local scour computations will be changed. The important components of bank protection design adversely affected by grade changes are key depths and the vertical extent of bank protection above and below the streambed.

Table 4.7.1 Channel Response to Changes in Watershed and River Condition (after Keefer et al., 1980)

Observed Condition	Channel Response			
	Stable	Unstable	Degrading	Aggrading
Alluvial Fan				
Upstream		X		X
Downstream		X	X	
Dam and Reservoir				
Upstream		X		X
Downstream		X	X	
River Form				
Meandering		X	Unknown	Unknown
Straight		X	Unknown	Unknown
Braided	X	X	Unknown	Unknown
Bank Erosion		X	Unknown	Unknown
Vegetated Banks	X		Unknown	Unknown
Headcuts		X	X	
Diversion				
Clear Water Diversion		X		X
Overloaded with Sediment				X
Channel Straightened		X	X	
Deforested Watershed		X		X
Drought Period	X			X
Wet Period		X	X	
Bed Material Size				
Increase		X		X
Decrease		X	Unknown	X

Problems encountered at culvert crossings can be the result of general grade changes produced by long-term changes in stream morphology or inadequate design and/or construction of culvert systems. The design components most often influenced are culvert capacity and structural stability. The greatest danger produced by aggradation is partial plugging of the culvert opening resulting in a damming effect and increasing the magnitude and frequency of flooding upstream of the structure. Degrading stream reaches affect culvert systems by reducing their structural stability. General streambed degradation has undermined the foundations of culverts resulting in their complete failure.

4.8 Stream Stability Problems at Highway Crossings

In the United States, the annual damages related to hydraulic problems at bridges and highways has been estimated at 100 million dollars during years of extreme floods. Damages by streams can be reduced by considering channel stability in site selection, bridge design, and countermeasure placement. Ideally, a stable channel is one that does not change in size, form, or position through time. However, all alluvial channels change to some degree and therefore have some degree of instability. For engineering purposes, an unstable channel is one whose rate or magnitude of change is great enough to be a significant factor in

the planning or maintenance of a highway crossing during the service life of the structure. The kinds of changes considered here are: (1) lateral bank erosion; (2) degradation or aggradation of the streambed that continues progressively over a period of years; and (3) natural short-term fluctuations of streambed elevation that are usually associated with the passage of a flood (scour and fill).

Stability is inferred mainly from the nature of point bars, the presence or absence of cut banks, and the variability of stream width.

4.8.1 Bank Stability

On a laterally unstable channel, or at actively migrating bends on an otherwise stable channel, the point bars are usually wide and unvegetated and the bank opposite to a point bar is cut and often scalloped by erosion. The crescentic scars of slumping may be visible from place to place along the bankline. The presence of a cut bank opposite to a point bar is evidence of instability, even if the point bar is vegetated. Sand or gravel on the bar appears as a light tone on airphotos. The unvegetated condition of the point bar is attributed to a rate of outbuilding that is too rapid for vegetation to become established. However, the establishment of vegetation on a point bar is dependent on other factors besides rate of growth, such as climate and the timing of floods. If the width of an unvegetated point bar is considered as part of the channel width, the channel tends to be wider at bends. Streams whose width at bends is about twice or more the width at straight reaches are here called wide-bend streams.

Oxbow lakes are formed by the cutoff of meander loops, which occurs either by gradual closure of the neck (neck cutoffs) or by a chute that cuts across the neck (chute cutoffs). Neck cutoffs are associated with relatively stable channels, and chute cutoffs with relatively unstable channels. Recently formed oxbow lakes along a channel are evidence of recent lateral migration. A recently formed lake is usually immediately adjacent to the channel and it transmits flow at high river stages. Commonly, a new meander loop soon forms at the point of cutoff and grows in the same direction as the previous meander. Cutoffs tend to induce rapid bank erosion at adjacent meander loops. The presence of abundant oxbow lakes on a flood plain does not necessarily indicate a rapid channel migration rate, because an oxbow lake may persist for hundreds of years.

Along an unstable channel, bank erosion tends to be localized at bends, and straight reaches tend to be relatively stable. However, meandering of the thalweg in a straight reach is likely to be a precursor of instability. Bars that occur alternately from one side to the other of a straight reach are somewhat analogous to point bars and are indicative of a meandering thalweg.

- **For Unstable Banks with Moderate to High Erosion Rate**

  The slope angle of unstable banks usually exceeds 30 percent, and a cover of woody vegetation is rarely present. At a bend, the point bar opposite to an unstable cut bank is likely to be bare at normal stage, but it may be covered with annual vegetation and low woody vegetation, especially willows. Where very rapid erosion is occurring, the bankline may have irregular indentations. Fissures, which represent the boundaries of actual or potential slump blocks along the bankline indicate the potential for very rapid bank erosion.

- **For Unstable Banks with Slow to Moderate Erosion Rate**

  If a bank is partly graded, the degree of instability is difficult to assess and reliance is placed mainly on vegetation. The grading of a bank typically begins with the accumulation of slumped material at the base such that a slope is formed, and progresses by smoothing of the slope and the establishment of vegetation.

- **For Stable Banks with Very Slow Erosion Rate**

Stable banks tend to be graded to a smooth slope and the slope angle is usually less than about 30 percent. In most regions of the United States, the upper parts of stable banks are vegetated, but the lower part may be bare at normal stage, depending on bank height and flow regime of the stream. Where banks are low, dense vegetation may extend to the water's edge at normal stage. Mature trees on a graded bank slope are particularly convincing evidence for bank stability. Where banks are high, occasional slumps may occur on even the most stable graded banks. Shallow mountain streams that transport coarse bed sediment tend to have stable banks.

Field information on lateral migration rates for channels of different sizes has been compiled by Brice (1982). Bank erosion rates tend to increase with increasing stream size. In Figure 4.8.1 channel width is taken as a measure of stream size. The dashed line is drawn arbitrarily to have a slope of 1 and a position (intercept) to separate most equiwidth streams from most wide-bend and braided point-bar streams. For a given channel width, equiwidth streams tend to have the lowest erosion rates, and braided point-bar streams the highest. Braided streams without point bars (diamond symbol, Figure 4.8.1) plot well below the arbitrary curve because their channels are very wide relative to their discharges. Channel width is an imperfect measure of stream size, as are drainage area and discharge, particularly for the comparison of streams in arid and semiarid regions with streams in humid regions. If braided streams and braided point-bar streams (which are uncommon in most parts of the United States) are excluded, the dashed curve in Figure 4.8.1 provides a preliminary estimate of erosion rates that may be encountered at a particular site. An example on how to use these results is presented in Appendix 4, Problem 4.4.

4.8.2 Stability Problems Associated with Channel Relocation

In some circumstances it could be advantageous to change the river channel alignment because of highway encroachments. When a river crossing site is so constrained by non-hydraulic factors that consideration to alternative sites is not possible, the engineer must attempt to improve the local situation to meet specific needs. Also, the engineer may be forced to make channel improvements in order to maintain and protect existing highway structures in or adjacent to the river.

Suppose a meandering river is to be crossed with a highway, as shown in Figure 4.8.2a. Assume that the alignment is fixed by constraints in the acquisition of the right-of-way.

To create better flow alignment with the bridge, consideration is given to channel improvement as shown in Figure 4.8.2b. Similarly, consideration for improvement to the channel would also be advisable for a hypothetical lateral encroachment of a highway as depicted in Figure 4.8.2c. In either case, the designer's questions are how to realign the channel, and what criteria to use to establish the cross-sectional dimensions.

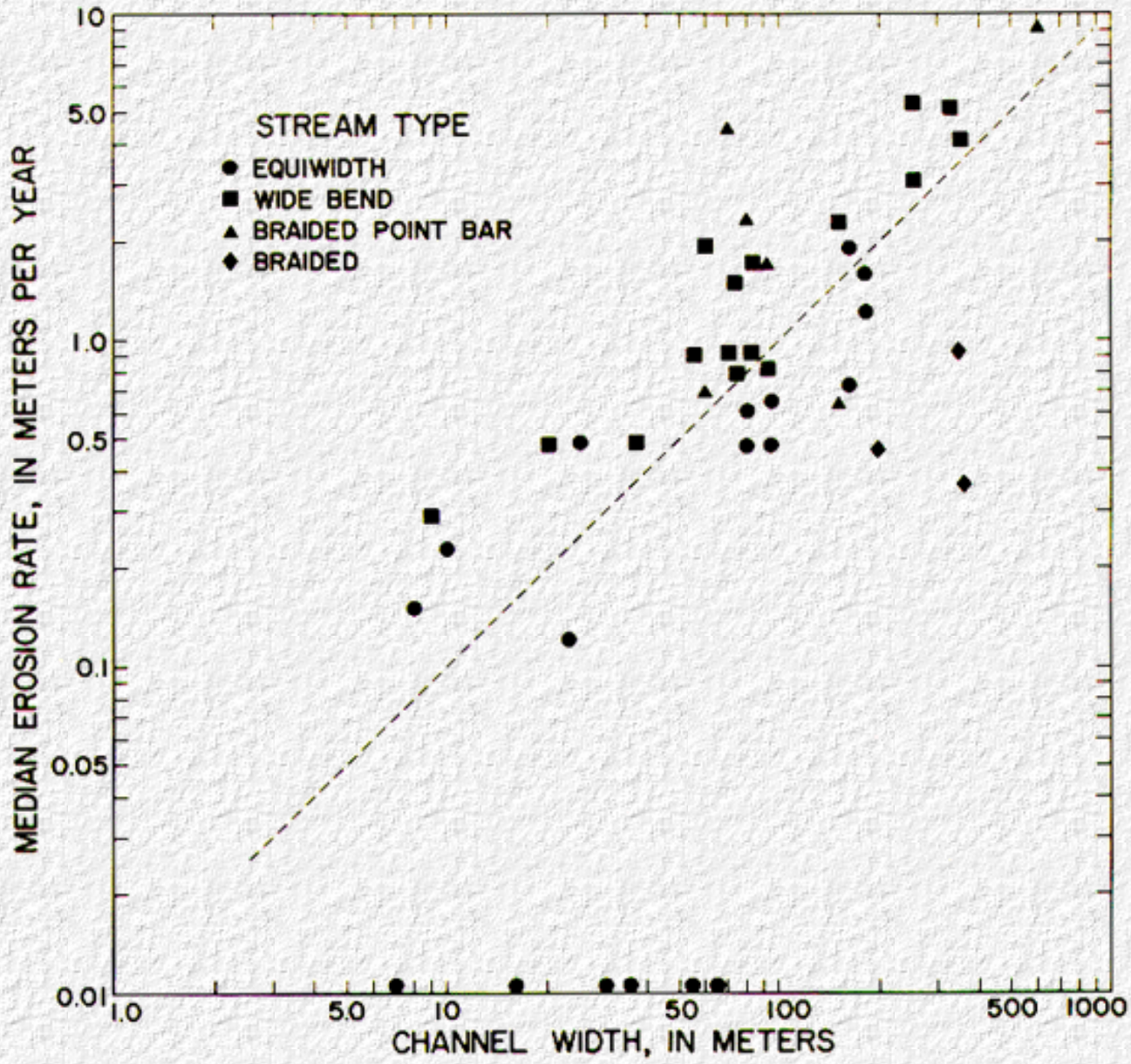

Figure 4.8.1. Median Bank Erosion Rate in Relation to Channel Width for Different Types of Streams (after Brice, 1982)

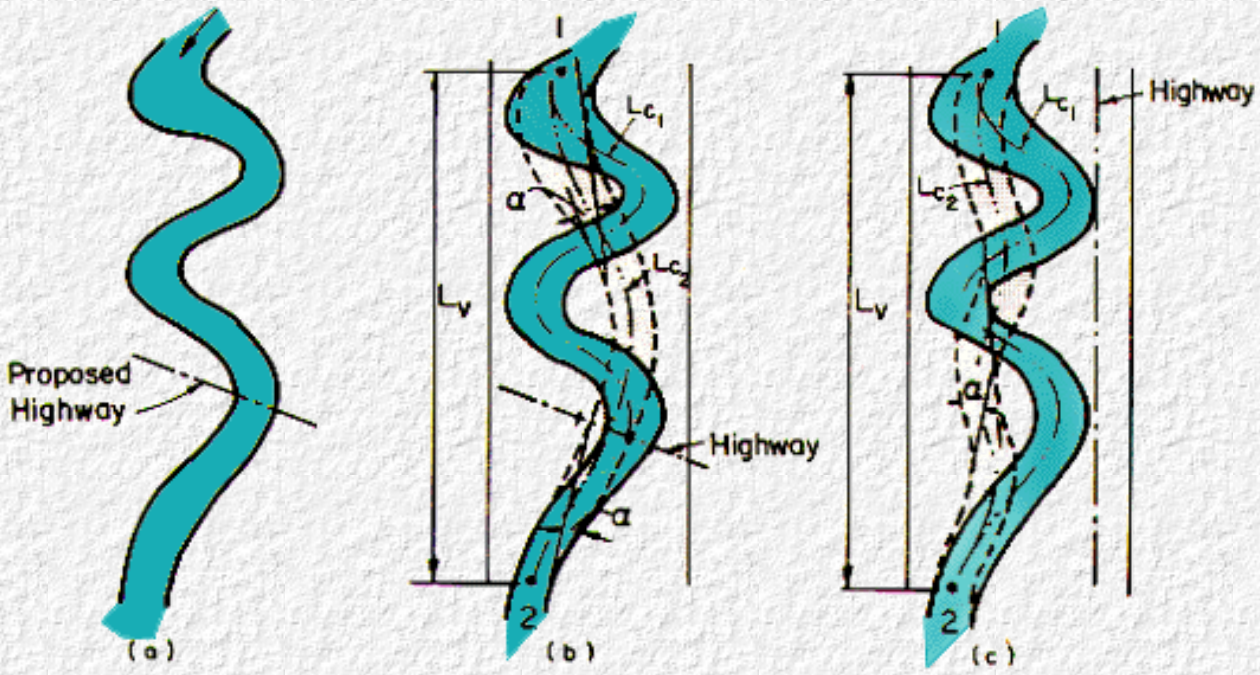

Figure 4.8.2. Encroachment on a Meandering River

Prior to realigning a river channel the stability of the existing channel must be examined using the methods outlined earlier. The stream classification, recent and past aerial photographs and field surveys are deemed necessary. The realigned channel may be made straight without curves, or may include one or more curves. If curves are included, the radii of curvature, the number of bends, the limits of rechannelization (hence the length or slope of the channel) and the cross-sectional area are decisions which have to be made by the designer. Different rivers have different characteristics and historical background with regard to channel migration, discharge, stage, geometry and sediment transport, and as indicated in the previous chapters, it is important for the designer to understand and appreciate river hydraulics and geomorphology when making decisions concerning channel relocation. It is difficult to state generalized criteria for channel relocation applicable to any river. Knowledge about river systems has not yet advanced to such a state as to make this possible. Nevertheless, it is important to provide some principles and guidelines for the design engineer.

As the general rule, the radii of bends should be made about equal to the mean radii of bends r_c, in extended reaches of the river. When the angle ϕ defined in Figure 4.3.5 exceeds about 40 degrees, this enables a sufficient crossing length for the thalweg to shift from one side of the channel to the other. Generally, it is necessary to stabilize the outside banks of the curves in order to hold the new alignment and depending upon crossing length, some amount of maintenance may be necessary to remove sandbars after large floods so that the channel does not develop new meander patterns in the crossings during normal flows.

The sinuosity and channel bed slope are related in the following way. The bed elevations at the ends of the reach being rechannelized, (designated 1 and 2, in Figure 4.8.2) are established by existing boundary conditions. Hence, the total drop in water surface bed elevation for the new channels (subscript 2) and the old channels (subscript 1) are the same.

$$\Delta z_1 = \Delta z_2 = \Delta z \qquad (4.8.1)$$

The length of channel measured along the thalweg is labeled L_c. Thus, the mean slope of the channel bed before relocation is

$$S_1 = \frac{\Delta z}{L_{c1}} \qquad (4.8.2)$$

and after relocation is

$$S_2 = \frac{\Delta z}{L_{c1}} \qquad (4.8.3)$$

Sinuosity is defined as the ratio of the length of channel, L_c to the length of the valley, or

$$S_n = \frac{L_c}{L_v} \geq 1 \qquad (4.8.4)$$

Clearly,

$$S_{n1} = \frac{L_{c1}}{L_{v1}} \qquad (4.8.5)$$

$$S_{n2} = \frac{L_{c2}}{L_{v2}} \qquad (4.8.6)$$

but

$$L_{v_1} = L_{v_2} = L_v \qquad (4.8.7)$$

and

$$\frac{\Delta z_1}{L_{v_1}} = \frac{\Delta z_2}{L_{v_2}} = \frac{\Delta z}{L_v} \qquad (4.8.8)$$

Thus,

$$S_{n1} S_1 = \frac{L_{c_1}}{L_v} \bullet \frac{\Delta z}{L_{c1}} = \frac{L_{c_2}}{L_v} \bullet \frac{\Delta z}{L_{c2}} = S_{n2} S_2 \qquad (4.8.9)$$

The new channel slope and channel sinuosity are inversely related. If $S_{n2} < S_{n1}$ then $S_2 > S_1$. The new channel alignment, hence S_{n2}, can be chosen by the designer with due consideration given to the radii of curvature, deflection angles and tangent lengths between reversing curves. As indicated before, consideration should also be given to prevailing average conditions in the extended reach. The new slope S_2 can be calculated from Equation 4.8.9, and the relationship for meandering should be satisfied.

$$S_2 Q^{1/4} \leq 0.0017 \qquad (4.4.18)$$

If S_1 is of such magnitude that Equation 4.4.18 cannot be satisfied with still larger S_2, the possibility of the river changing to a braided channel because of steeper slope should be carefully evaluated. With steeper slope, there could be an increase in sediment transport which could cause degradation and the effect would be extended both upstream and downstream of the relocated reach. The meander patterns could change. Considerable bank protection might be necessary to contain lateral migration which is characteristic of a braided channel, and if the slope is too steep, head cuts could develop which migrate upstream with attendant effects on the plain geometry of the channel. Even when changes in slope are not very large, a short-term adjustment of the average river slope occurs, consistent with the sediment transport rate, flow velocities and roughnesses, beyond the upstream and downstream limits of channel improvement. For small changes in slope, the proportionality (Equation 4.5.3), $QS \sim Q_s D_{50}$ tends toward equilibrium with slight increases in bed sediment size D_{50} and adjustment in the sediment transport rate Q_s.

A small increase in the new channel width could be considered which tends to maintain the same stream power, $\tau_o V$, in the old and new channels. That is,

$$(\tau_o V)_1 = (\tau_o V)_2 \qquad (4.8.10)$$

With substitution of $\tau_o = \gamma RS$, $V = Q/A$ and $R = A/P \cong A/W$, Equation 4.8.10 leads to

$$W_2 = S_2 W_1/S_1 \qquad (4.8.11)$$

Any designed increase in width should be limited to about 10 to 15 percent. Wider channels would be ineffective. Deposition would occur along one bank and the effort of extra excavation would be wasted. Furthermore, bar formation would be encouraged, with resultant tendencies for changes in the meander pattern leading to greater maintenance costs of bank stabilization and removal of the bars to hold the desired river alignment.

The depth of flow in the channel is dependent on discharge, effective channel width, sediment transport rate (because it affects bed form and channel roughness) and channel slope. Methods for determining flow depth were discussed earlier in this chapter.

The foregoing discussion pertains to alluvial channels with silt and sand sized bed materials. For streams with gravel and cobble beds, the usual concern is to provide adequate channel cross-sectional dimensions to convey flood flows. If the realigned channels are made too steep, there is an increased stream power with a consequent increase in transport rate of the bed material. The deposition of material in the downstream reaches tends to form gravel bars and encourages changes in the plan form of the channel. Short-term changes in channel slope can be expected until equilibrium is reestablished over extended reaches both upstream and downstream of the rechannelized reach. Bank stabilization may be necessary to prevent lateral migration and periodic removal of gravel bars may also be necessary.

4.8.3 Assessment of Stability for Relocated Streams

Brice (1980) reported case histories for channel stability of relocated streams in different regions of the United States. Based on his study, the recommendations and conclusions presented here apply to specific aspects of the planning and construction of channel relocation. They are

intended for assessment of the risk of instability and for reduction of the degree of instability connected with relocation. Serious instability resulting from relocation can be observed either when the prior natural channel is unstable or when floods of high recurrence interval occur during or soon after construction. Although there is an element of chance in channel stability, the experience represented by the study sites provides useful guidelines for improvement in the performance of channels relocated by highway agencies. Consideration of the following aspects of the channel relocation is required.

- **Channel Stability Prior to Relocation.** Assessment of the stability of a channel prior to relocation is needed to assess erosion-control measures and risk of instability. An unstable channel is likely to respond unfavorably to relocation. Bank stability is assessed by field study and the stereoscopic examination of aerial photographs. The most useful indicators of bank instability are cut or slumped banks, fallen trees along the bankline, and wide, unvegetated point bars exposed. Bank recession rates are measured by comparison of time-sequential aerial photographs. Vertical instability is equally important but more difficult to determine. It is indicated by changes in channel elevation at bridges and gaging stations. Serious degradation is usually accompanied by generally cut or slumped banks along a channel.
- **Erosional Resistance of Channel Boundary Materials.** The stability of a channel, whether natural or relocated, is partly determined by the erosional resistance of materials that form the wetted perimeter of the channel. Resistant bedrock outcrops, which extend out into the channel bottom, or that lie at shallow depths, will provide protection against degradation. Not all bedrock is resistant. Erosion of shale, or of other sedimentary rock types interbedded with shale, has been observed. Degradation was slight or undetected at most sites where bed sediment was of cobble and boulder size. However, serious degradation may result from relocation. Degradation may result from the relocation of any alluvial channel, whatever the size of bed material, but the incidence of serious degradation of channels relocated by highway agencies is slight.

  The cohesion and erosional resistance of banks tend to increase with clay content. Banks of weakly coherent sand or silt are clearly subject to rapid erosion, unless protected with vegetation. No consistent relation was found between channel stability and the cohesion of bank materials, probably because of the effects of vegetation.
- **Length of Relocation**. The length of relocation contributes significantly to channel instability at sites where its value exceeded 250 channel widths. When the value is below 100 channel widths, the effects of length of relocation is dominated by other factors. The probability of local bank erosion at some point along a channel increases with the length of the channel. The importance of vegetation, both in appearance and in erosion control, would seem to justify a serious and possibly sustained effort to establish it as soon as possible on the graded banks.
- **Bank Revetment**. Revetment makes a critical contribution to stability at many sites where it is placed at bends and along roadway embankments. Rock riprap is by far the most commonly used and effective revetment. Concrete slope paving is prone to failure. Articulated concrete block is effective when vegetation can establish in the interstices between blocks. Bank revetment is discussed in detail in the next chapter.
- **Check Dams (Drop Structures)**. In general, check dams are effective in preventing channel degradation. The potential for erosion at a check dam depends on its design and construction, its height and the use of revetment on adjoining banks. A series of low check dams, less than about 0.5 m in height, is probably preferable to a single higher structure, because the potential for erosion and failure is reduced. By simulating rapids, low check dams may add visual interest to the flow in a channel.

One critical problem arising with check dams relates to improper design for large flows. Higher flows have worked around the ends of many installations to produce failure.

- **Maintenance**. The following problems, subject to improvement by maintenance, were observed along relocated channels: (1) growth of annual vegetation in channel; (2) reduction of channel conveyance by overhanging trees; (3) local bank cutting; and (4) bank slumping. The expense of routine maintenance or inspection of relocated channels beyond the highway right-of-way is probably prohibitive.However, most of the serious problems could be detected by periodic inspection, perhaps by aerial photography, during the first 5 or 10 years after construction.
- **The Relationship between Sinuosity and Stability.** These are summarized as follows: (1) Meandering does not necessarily indicate instability; an unstable stream will not remain highly sinuous for very long, because the sinuosity will be reduced by frequent meander cutoffs; (2) Where instability is present along a reach, it occurs mainly at bends; straight segments may remain stable for decades; and (3) The highest instability is for reaches whose sinuosity is in the range of 1.2 to 2 and whose type is either wide bend or braided point bar.

4.8.4 Estimation of Future Channel Stability and Behavior

One objective of stability assessment is to anticipate the migration of bends and the development of new bends. Lateral erosion is probably more frequently involved in hydraulic problems at bridges than any other stream process. Problems caused by general scour, local scour, channel degradation and accumulation of debris are comparatively less common.

The lateral stability is measured from records of its position at two or more different times and the available records are usually maps or aerial photographs. Old surveyed cross-sections are extremely useful although unfortunately rarely available. It is recognized that some progress is being made on the numerical prediction of loop deformation and bend migration. At present, however, the best available estimates are based on past rates of lateral migration at a particular reach. However, erosion rates may fluctuate substantially from one period of years to the next.

Measurements of bank erosion on two time-sequential aerial photographs (or maps) require the identification of reference points which are common to both. Useful reference points include roads, buildings, irrigation canals, bridges and fence corners. This analysis of lateral stability is greatly facilitated by a drawing of time changes in bankline position. To prepare such a drawing, aerial photographs are matched in scale and the photographs are superimposed holding the reference points fixed.

Bank erosion rates increase with the stream size as shown in Figure 4.8.1. Sinuous canaliform streams can then be expected to have the lowest erosion rates and the sinuous braided streams, the highest.

The lateral stability of different stream reaches can be compared by means of a dimensionless erosion index. The erosion index is the product of its median bank erosion rate expressed in channel widths per year, multiplied by the percent of reach along which erosion occurred, multiplied by 1000. Erosion indexes for 41 streams in the United States are plotted against sinuosity in Figure 4.8.3. The length of most of these reaches is 25 to 100 times the channel width. The highest erosion index values are for reaches with sinuosity ranging between 1.2 and 2. Erosion indexes are large for sinuous braided and sinuous point bar streams as compared to sinuous canaliform streams. The erosion index value of 5, in Figure 4.8.3, is suggested as a

boundary between stable and unstable reaches. Brice (1984) considers that reaches having erosion indexes values less than 5 are unlikely to cause lateral erosion problems at bridges.

A general assessment of bank stability is made considering the following aspects.

- **Bank Erosion Rates.** Although it is theoretically possible to determine bank erosion rates from factors such as water velocity and resistance of the banks to erosion, practical and accurate means of making such a determination are still deficient. The results in Figure 4.8.1 provide a first approximation of migration rate of a bend regardless of the hydraulic conditions and sediment characteristics. Past rates of erosion at a particular site provide the best estimate of future rates. In projecting past rates into the future, consideration must be given to the following factors: (1) the past flow history of the site during the period of measurement, in comparison with the probable future flow history during the life span of the highway crossing. The duration of floods, or of flows near bankfull stages, is probably more important than the magnitude of floods; and (2) man-induced factors that are likely to affect bank erosion rates. Among the most important of these are urbanization and the clearing of flood plain forests.
- **Behavior of Meander Loops**. If the proposed bridge or roadway is located near a meander loop, it is useful to have some insight into the probable way in which the loop will migrate or develop, as well as its rate of growth. No two meanders will behave in exactly the same way, but the meanders on a particular stream reach tend to conform to one of the several modes of behavior illustrated in Figure 4.8.4.

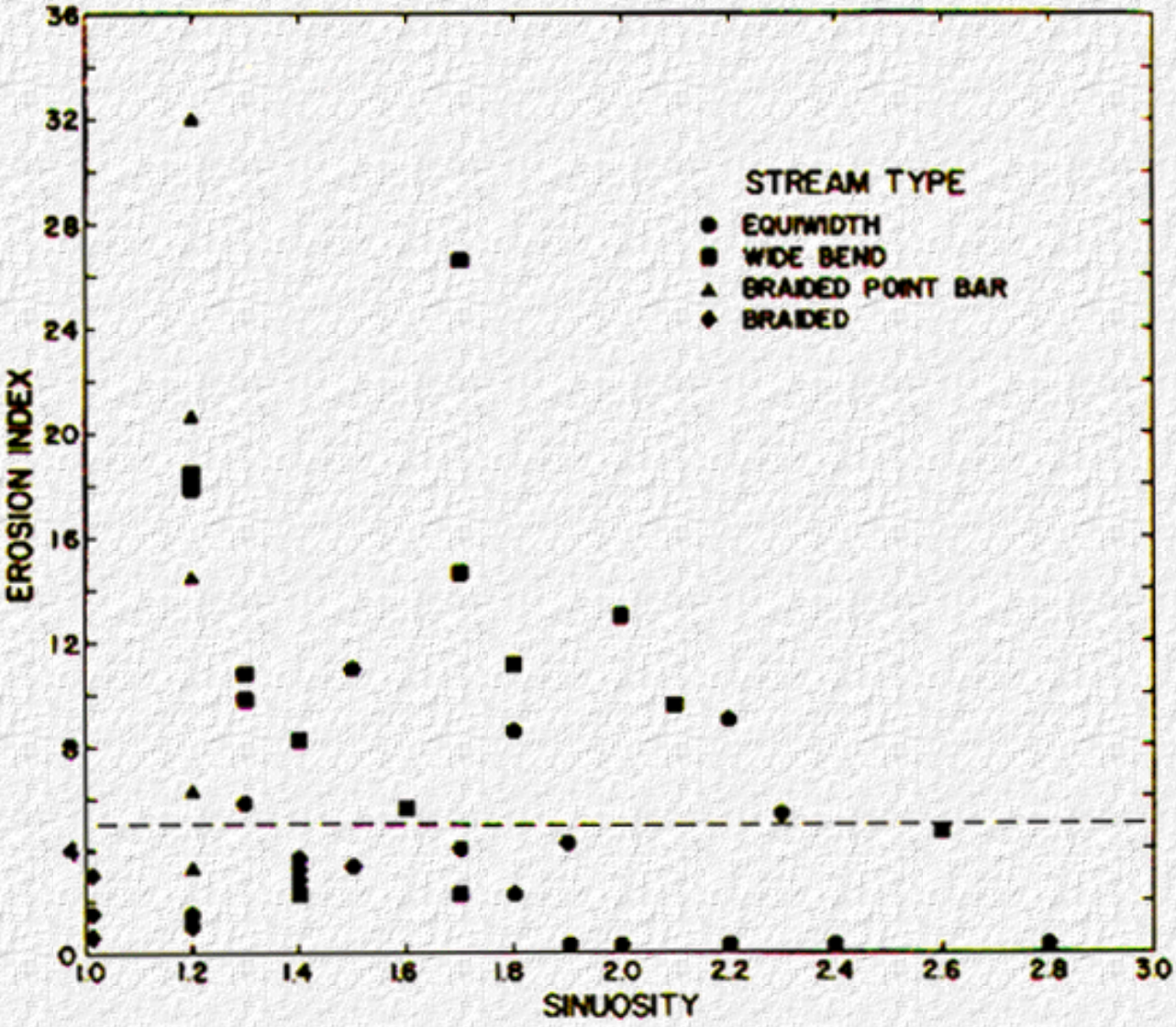

Figure 4.8.3. Erosion Index in Relation to Sinuosity (Ref. Brice, 1984)

Mode A (Figure 4.8.4) represents the typical development of a loop of low amplitude, which decreases in radius as it extends slightly in a downstream direction. Mode B rarely occurs unless meanders are confined by valley sides on a narrow flood plain, or are confined by artificial levees. Well developed meanders on streams that have moderately unstable banks are likely to follow Mode C. Mode D applies mainly to large loops on meandering or highly meandering streams. The meander has become too large in relation to stream size and flow, and secondary meanders develop along it, converting it to a compound loop. Mode E also applies to meandering or highly meandering streams, usually of the equiwidth point-bar type. The banks have been sufficiently stable for an elongated loop to form (without being cut off), but the neck of the loop is gradually being closed and cutoff will eventually occur at the neck. Modes F and G apply mainly to locally braided sinuous or meandering streams having unstable banks. Loops are cut off by chutes that break diagonally or directly across the neck.

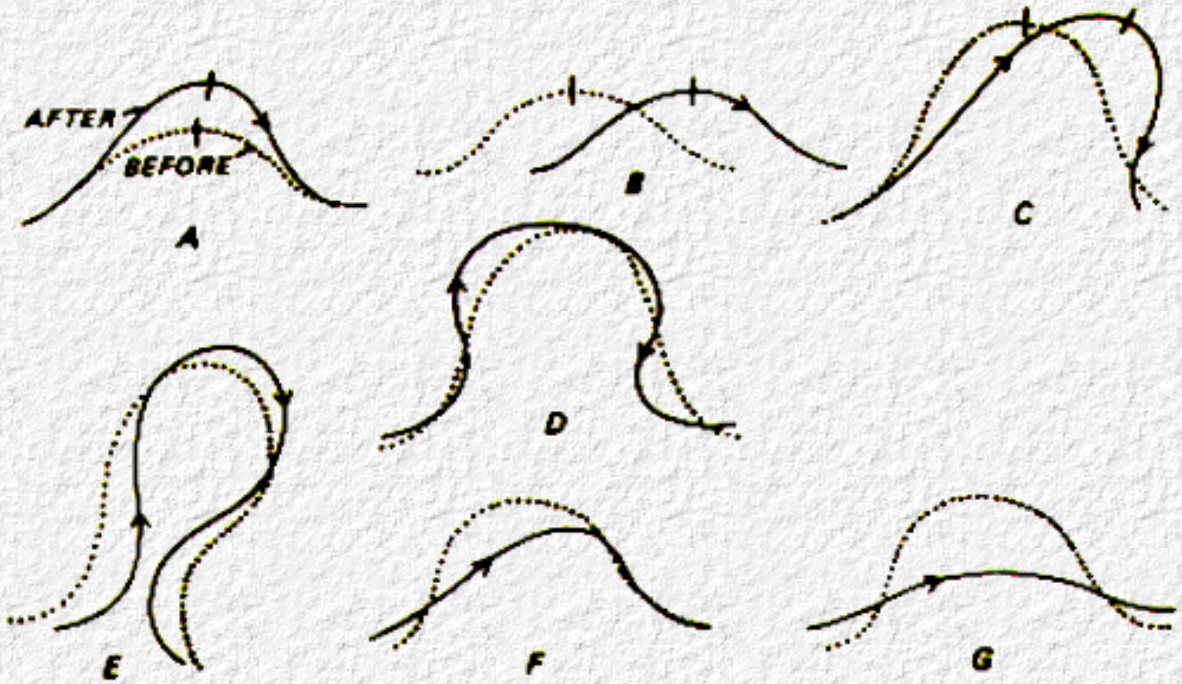

Figure 4.8.4. Modes of Meander Loop Development. A, Extension. B, Translation. C, Rotation. D, Conversion to a Compound Loop. E, Neck cutoff by Closure. F, Diagonal Cutoff by Chute. G, Neck Cutoff by Chute

- **Effects of Meander Cutoff** - If cutoffs seem imminent at any meanders in the vicinity of a proposed bridge crossing the probable effects of cutoff need to be considered. The local increase in channel slope due to cutoff usually results in an increase in the growth rate of adjoining meanders, and an increase in channel width at the point of cutoff. On a typical wide-bend point-bar stream the effects of cutoff do not extend very far upstream or downstream.
- **Assessment of Degradation** - Field sites having degradation problems are more numerous than sites having aggradation problems. Annual rates of degradation averaged from past records such as the closure of a dam give poor estimates of future rates of degradation. Typical situations exhibit an exponential decay function of the rate of channel degradation.

Recent evidence of degradation can be detected from field surveys or by stereo viewing of aerial photographs. Indicators of degradation are listed below in approximate order of reliability: (1) channel scarps, headcuts and nickpoints; (2) gullying of minor side tributaries; (3) high and steep unvegetated banks; (4) measurements of streambed elevation from a bridge deck; (5) changes in stream discharge relationships; and (6) measurements of longitudinal profiles.

- **Assessments of Scour and Fill** - Natural scour and fill refer to fluctuations of streambed elevation about an equilibrium condition. These fluctuations are associated mainly with floods and occur by three different mechanisms operating jointly or independently: (1) bed form migration; (2) convergence and divergence of flow; and (3) lateral shift of thalweg or braids.

  The maximum scour induced by the migration of a dune is almost one-half dune height, and dune heights are roughly estimated as one-third of the mean flow depth. In gravel bed streams, most migrating bed forms can be regarded as bars, the height of which is related to flow depth. The migration of a bar through a bridge waterway is mainly of concern because of the deflection and concentration of flow. Bar migration tends to be a random process and its motion can best be tracked from time-sequential aerial photographs.

  Gravel bars tend to migrate on braided streams and to remain fixed at riffles on unbraided pool and riffle streams.

  Flow convergence in natural streams is associated with scour whereas divergent currents are associated with deposition. Persistent pools 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. In braided streams, scour holes are found at the confluence of braids. Field measurement of cross-sectional area and flow velocity at an incised reach near bankfull stage provides a good basis for calculation of scour by extrapolation to the design flood.

  Instability of the streambed that results from shift of thalweg is related to stream type and can be assessed from study of aerial photographs. On sinuous canal form streams, shift of the thalweg during flood is minimal. A greater shift of the thalweg can be expected on sinuous point-bar streams. In straight reaches, alternate bars visible on aerial photographs taken at low stage are commonly present. These alternate bars indicate the potential for thalweg shifting and also for bank erosion when the current is deflected against the bankline. Shift of the thalweg with increase in stage indicates the location of the point of maximum bed scour and bank erosion and also the alignment of piers with flood flow.

- **Site Selection for Highway Crossings** - For most streams the magnitude of scour is substantially greater at some place along the channel than at others. Bends and narrow sections may scour at high stages regardless of the effect of bridge structures. Straight or gently curved reaches with stable banks are preferred.

  Considerations for the selection of a crossing site on a non-sinuous reach include: (1) is the site at a pool, riffle or transition section; (2) are alternate bars visible at low stage; and (3) what is the effect of migration of mid-channel bars, if any? With respect to meandering reaches, questions seeking solution include: (1) what has been the rate and mode of migration of the meander; (2) what is the probable future behavior, as based on the past; (3) is the site at a pool, riffle or transition section; and (4) is meander cutoff probable?