

Stepwise Procedure for Evaluating Stream Stability

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ABSTRACT

Systematic analytical procedures for evaluation of stream stability typically are not readily available to the highway engineer. To remedy this, the purpose of this paper is to outline a stepwise analytical procedure that may be utilized to evaluate stream stability. The procedure incorporates three levels of analysis of increasing complexity and is somewhat similar to a three-part approach that was used in the early 1980's when the authors were employed at Simons, Li and Associates. Through the efforts of many, that procedure evolved into a valuable tool for stream stability analysis. For the FHWA Hydraulic Engineering Circular No. 20, "Stream Stability at Highway Structures," the three level approach was further refined and organized to include development of flow charts to assist in evaluation of stream stability at bridge crossings.

The completion of each level of analysis results in an assessment of stream stability. Then, depending on the complexities of stream response or bridge design, the decision to proceed to the next level of analysis is made. The specific steps considered typical of Level 1 and Level 2 type analyses are outlined in this paper. The overall procedure provides a systematic approach to evaluation of stream stability at highway crossings, and will facilitate completion of such analyses by highway engineers.

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INTRODUCTION

A stable channel does not change in size, form, or position with time; however, all alluvial channels change to some extent and are somewhat unstable. For highway engineering purposes, a stream channel can be considered unstable if the rate or magnitude of change is great enough that the planning, location, design, or maintenance considerations for a highway encroachment are significantly affected.

Local instability caused by the construction of a highway crossing or encroachment on a stream is also of concern. This includes general scour caused by contraction of the flow, and local scour due to the disturbance of streamlines at an object in the flow, such as at a pier or an abutment.

Systematic, analytical procedures for evaluation of stream stability are not readily available to the highway engineer. The purpose of this paper is to outline a stepwise analytical procedure for evaluation of stream stability that will assist highway engineers responsible for completing such analyses.

GENERAL SOLUTION PROCEDURE

The inherent complexities of stream stability, further complicated by highway stream crossings, requires a multilevel solution procedure. The evaluation and design of a highway stream crossing or encroachment should begin with a qualitative assessment of stream stability. This involves application of geomorphic concepts to identify potential problems and alternative solutions. This analysis should be followed with quantitative analyses using basic

hydrologic, hydraulic, and sediment transport engineering concepts. Such analyses could include evaluation of flood history, channel hydraulic conditions (up to and including water surface profile analysis), and basic sediment transport analyses such as evaluation of watershed sediment yield, incipient motion analysis, and scour calculations. These analyses can be considered adequate for many locations if the problems are resolved and the relationships between different factors affecting stability are adequately explained. If not, a more complex quantitative analysis based on detailed mathematical modeling and/or physical hydraulic models should be considered.

In summary, the general solution procedure for analyzing stream stability could involve the following three levels of analysis:

- Level 1: Application of Simple Geomorphic Concepts and other Qualitative Analyses
- Level 2: Application of Basic Hydrologic, Hydraulic, and Sediment Transport Engineering Concepts
- Level 3: Application of Mathematical or Physical Modeling Studies

Level 1: Qualitative and Other Geomorphic Analyses

A flow chart of the typical steps in qualitative and other geomorphic analyses is provided in Figure 1. The six identified steps are generally applicable to most stream stability problems. These steps are discussed in more detail in the following paragraphs. As shown in Figure 1, the qualitative evaluation leads to a conclusion regarding the need for a more detailed Level 2 analysis or a decision to proceed directly to selection and design of countermeasures based only on qualitative and other geomorphic analyses.

Step 1. Define Stream Characteristics

The first step in stability analysis is to identify stream characteristics. Figure 2 illustrates a number of geomorphic factors that may assist in stream classification. Defining the various characteristics of

the stream according to this scheme provides insight into stream behavior and response, and information on impacting activities in the watershed. A good way to utilize Figure 2 is to simply circle the descriptions that best describe the stream characteristics. This can be completed with very little information, as in an office review of mapping or aerial photography, or after a complete field reconnaissance.

Step 2. Evaluate Land Use Changes

Water and sediment yield from a watershed is a function of land-use practices. Thus, knowledge of the land use and historical changes in land use is essential to understanding conditions of stream stability and potential stream response to natural and man-induced changes.

The presence or absence of vegetative growth can have a significant influence on the runoff and erosional response of a fluvial system. Large scale changes in vegetation resulting from fire, logging, land conversion and urbanization can either increase or decrease the total water and sediment yield from a watershed. For example, fire and logging tend to increase water and sediment yield, while urbanization promotes increased water yield and peak flows, but decreased sediment yield from the watershed. Urbanization may increase sediment yield from the channel.

Information on land use history and trends can be found in Federal, State and Local government documents and reports (i.e., census information, zoning maps, future development plans, etc.). Additionally, analysis of historical aerial photographs can provide significant insight on land use changes. Land use change due to urbanization can be classified based on estimated changes in pervious and impervious cover. Changes in vegetative cover can be classified simply as no change, vegetation increasing, vegetation damaged, and vegetation destroyed. The relationship or correlation between changes in channel stability and land use can contribute to a qualitative understanding of system response mechanisms.

LEVEL 1: QUALITATIVE ANALYSES

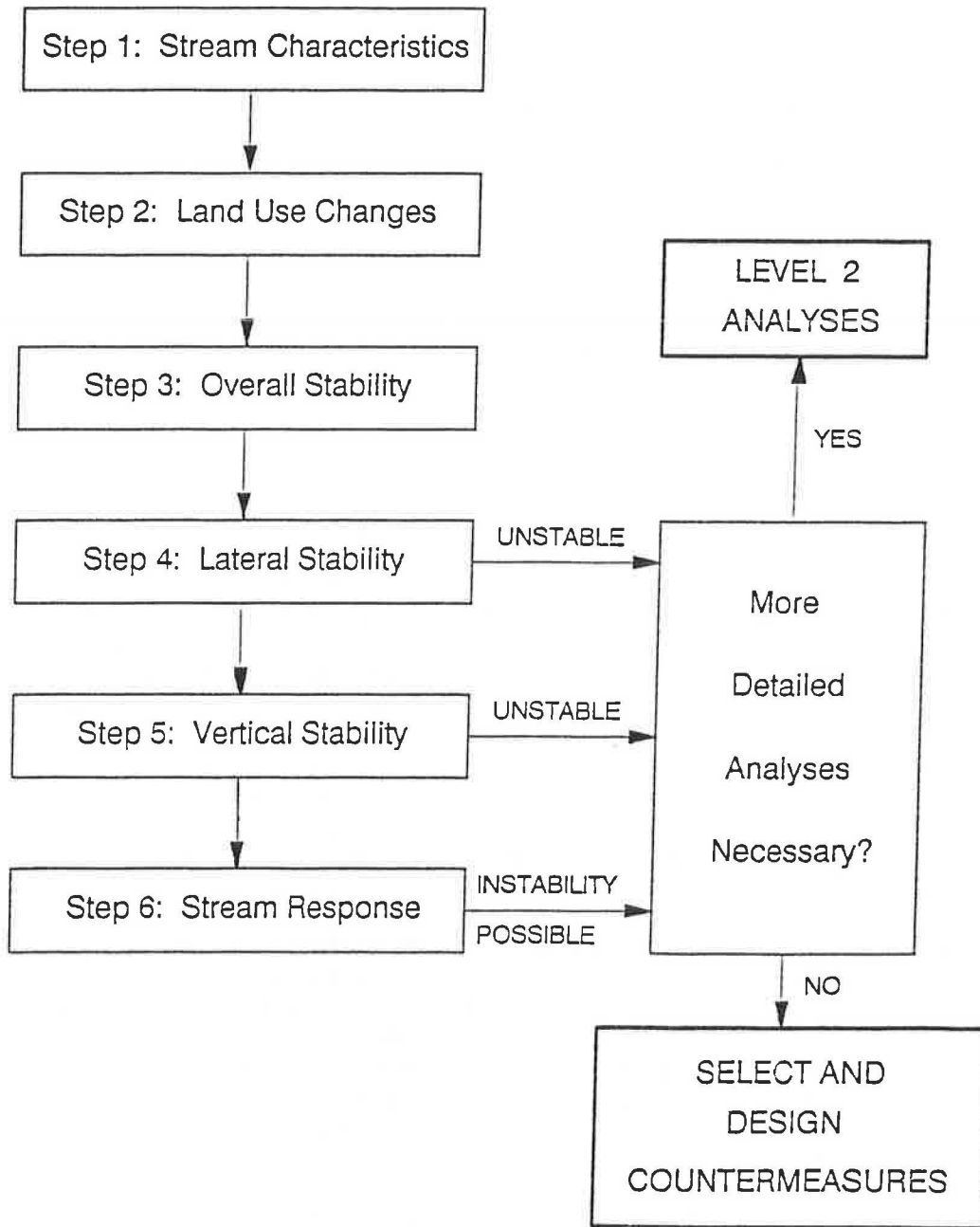


Figure 1. Flow chart for Level 1: Qualitative Analyses.


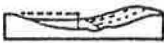



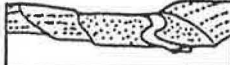
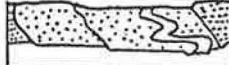




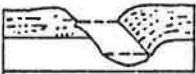
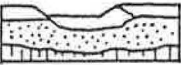




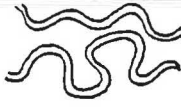








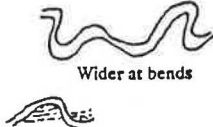
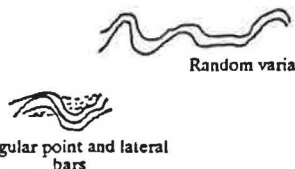

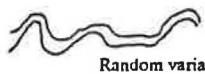
STREAM SIZE (SECT. 2.2.1)	Small (< 100 ft. or 30 m wide)	Medium (100-500 ft. or 30-150 m)	Wide (> 500 ft. or 150 m)		
FLOW HABIT (SECT. 2.2.2)	Ephemeral	(Intermittent)	Perennial but flashy Perennial		
BED MATERIAL (SECT. 2.2.3)	Silt-clay	Silt	Sand Gravel Cobble or boulder		
VALLEY SETTING (SECT. 2.2.4)	 No valley; alluvial fan	 Low relief valley (< 100 ft. or 30 m deep)	 Moderate relief (100-1000 ft. or 30-300 m)	 High relief (> 1000 ft. or 300 m)	
FLOOD PLAINS (SECT. 2.2.5)	 Little or none (< 2X channel width)	 Narrow (2-10 channel width)	 Wide (> 10X channel width)		
NATURAL LEVEES (SECT. 2.2.6)	 Little or None	 Mainly on Concave	 Well Developed on Both Banks		
APPARENT INCISION (SECT. 2.2.7)	 Not Incised	 Probably incised			
CHANNEL BOUNDARIES (SECT. 2.2.8)	 Alluvial	 Semi-alluvial	 Non-alluvial		
TREE COVER ON BANKS (SECT. 2.2.8)	< 50 percent of bankline	50-90 percent	> 90 percent		
SINUOSITY (SECT. 2.2.9)	 Straight Sinuosity 1-1.05	 Sinuous (1.06-1.25)	 Meandering (1.25-2.0)	 Highly meandering (> 2)	
BRAIDED STREAMS (SECT. 2.2.10)	 Not braided (< 5 percent)	 Locally braided (5-35 percent)	 Generally braided (> 35 percent)		
ANABRANCHED STREAMS (SECT. 2.2.11)	 Not anabranching (< 5 percent)	 Locally anabranching (5-35 percent)	 Generally anabranching (> 35 percent)		
VARIABILITY OF WIDTH AND DEVELOPMENT OF BARS (SECT. 2.2.12)	 Narrow point bars	 Wide point bars	 Irregular point and lateral bars	 Equiwidth	 Random variation

Figure 2. Geomorphic factors that affect stream stability

Step 3. Assess Overall Stream Stability

Table 1 summarizes possible channel stability interpretations according to the geomorphic factors identified in Figure 2, as well as additional factors that commonly influence stream stability. Figure 3 is also useful in making a qualitative assessment of stream stability based on stream characteristics. It shows that straight channels are relatively stable only where flow velocities and sediment load are low. As these variables increase, flow meanders in the channel, causing the formation of alternate bars and the initiation of a meandering channel pattern. Similarly, meandering channels are progressively less stable with increasing velocity and bed load. At high values of these variables, the channel becomes braided. The presence and size of point bars and middle bars are indications of the relative lateral stability of a stream channel.

Step 4. Evaluate Lateral Stability

The effects of the lateral instability of a stream at a bridge are dependent on the extent of the bank erosion and the design of the bridge. Bank erosion can undermine piers and abutments located outside the channel and erode abutment spill slopes or breach approach fills. Where bank failure is by a rotational slip, lateral pressures on piers located within the slip zone may cause cracks in piers or piling or may displace pier foundations. Migration of a bend through a bridge opening changes the direction of flow through the opening so that a pier designed and constructed with a round-nose acts as a blunt-nosed, enlarged obstruction in the flow, thus accentuating local and general scour. Also, the development of a point bar on the inside of the migrating bend can increase contraction at the bridge if the outside bank is constrained from eroding.

A field inspection is a critical component of a qualitative assessment of lateral stability. A comparison of observed field conditions with descriptions of stable and unstable channel banks helps qualify bank stability. Similarly, field observations of bank material, composition, and existing failure modes can provide insight

on bank stability.

Lateral stability assessment can also be completed from existing records of the position of a bend at two or more different times. Aerial photographs or maps are usually the only records available. Surveyed cross sections are extremely useful although rarely available. Some progress is being made on the numerical prediction of loop deformation and bend migration (Level 3 type analyses). At present however, the best available estimates are based on past rates of lateral migration at a particular reach. In using these estimates, it should be recognized that erosion rates may fluctuate substantially from one years-long period to the next.

Step 5. Evaluate Vertical Stability

The typical effects associated with gradation (bed elevation) changes at highway bridges are erosion at abutments and the exposure and undermining of foundations with degradation. Aggradation, a reduction in flow area under bridges resulting in more frequent flow over the highway, may also occur. Bank caving associated with degradation poses the same problems at bridges as lateral erosion from bend migration, but the problems may be more severe because of the lower elevation of the streambed. Aggrading stream channels also tend to become wider as aggradation progresses, eroding floodplain areas and highway embankments on the floodplain. The location of the bridge crossing upstream, downstream, or on tributaries may cause gradation problems.

Brown, et al. reported that serious problems at degradation sites are about three times more common than at aggradation sites.(5) This is a reflection of the fact that degradation occurs more frequently than aggradation, and also that aggradation does not endanger the bridge foundation. It does not, however, indicate that aggradation is not a serious problem in some areas of the United States.

Problems other than those most commonly associated with degrading channels include the undermining of cutoff walls, other flow-control structures, and bank protection. Bank sloughing resulting

Table 1. Interpretation of observed data.

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	X	Unknown	Unknown
Straight		X	Unknown	Unknown
Braided		X	Unknown	Unknown
Bank Erosion		X	Unknown	Unknown
Vegetated Banks	X		Unknown	Unknown
Head Cuts		X	X	
Diversion Clear water diversion		X		X
Overloaded w/sediment		X	X	
Channel Straightened		X	X	
Deforest Watershed		X		X
Drought Period	X			X
Wet Period		X	X	
Bed Material Size Increase		X		X
Decrease		X	Unknown	X

∇ The observed condition refers to location of the bridge on the alluvial fan, i.e., on the upstream or downstream portion of the fan.

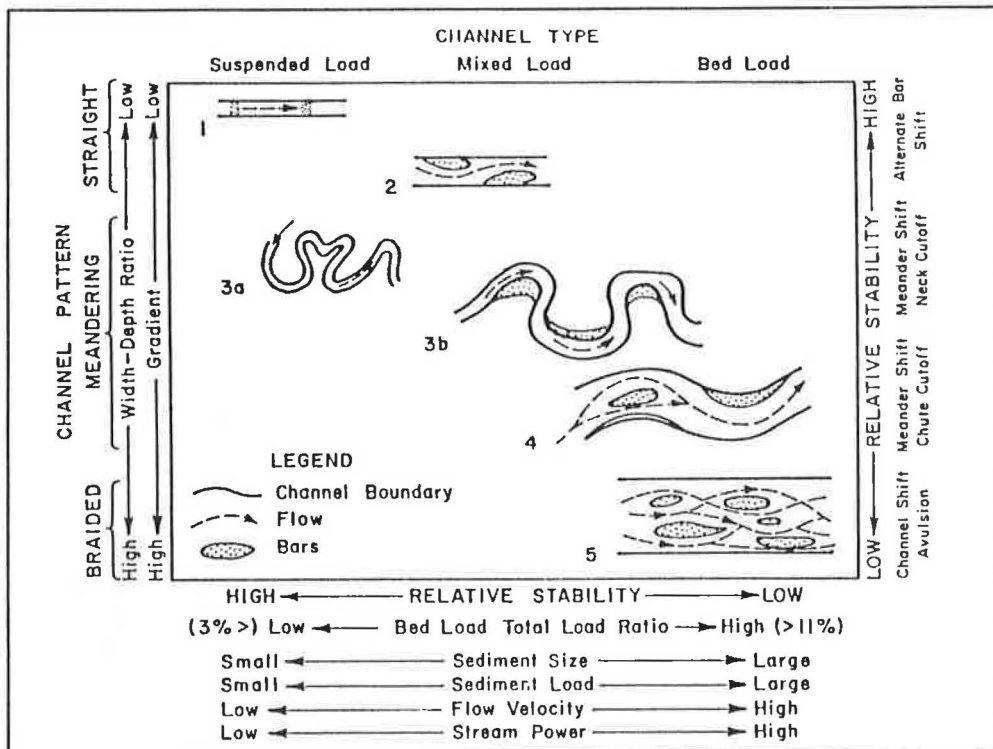


Figure 3. Channel classification and relative stability as hydraulic factors are varied

from degradation often greatly increases the amount of debris carried by the stream and increases the hazard of clogged waterway openings and increased scour at bridges. The hazard of local scour becomes greater in a degrading stream because of the lower streambed elevation.

Aggradation in a stream channel increases the frequency of backwater that can cause damage. Bridge decks and approach roadways become inundated more frequently, disrupting traffic, subjecting the superstructure of the bridge to hydraulic forces that can cause failure. In addition, approach roadways become subject to overflow that can erode and cause failure of the embankment. Where lateral erosion or increased flood stages accompanying aggradation increases the debris load in a stream, the hazards of clogged bridge waterways and hydraulic forces on bridge superstructures are increased.

Data records for at least several years are usually needed to detect gradation problems. This is due to the fact that the channel bottom often is not visible and changes in flow depth may indicate changes in the rate of flow rather than changes in gradation. Gradation changes normally develop over long periods of time even though rapid change can occur during an extreme flood event. The data needed to assess gradation changes include historic streambed profiles and long-term trends in stage-discharge relationships. Occasionally, information on bed elevation changes can be gained from a series of maps prepared at different times. Bed elevations at railroad, highway and pipeline crossings monitored over time may also be useful. On many large streams, the long-term trends have been analyzed and documented by agencies such as the U.S. Geological Survey and the U. S. Army Corps of Engineers.

Step 6. Evaluate Channel Response to Change

The knowledge and insight developed from evaluation of present and historical channel and watershed conditions, as developed above through Steps 1-5, provides an understanding of potential channel response to previous impacts

and/or proposed changes, such as construction of a bridge. Additionally, the application of simple, predictive geomorphic relationships, such as the Lane Relationship can assist in evaluating channel response mechanisms.(4)

Level 2: Basic Engineering Analyses

A flow chart of the typical steps in basic engineering analyses is provided in Figure 4. The flow chart illustrates the typical steps to be followed if a Level 1 qualitative analysis results in a decision that Level 2 analyses are required (Figure 1). The eight basic engineering steps are generally applicable to most stream stability problems and are discussed in more detail in the paragraphs which follow. The basic engineering analysis steps lead to a conclusion regarding the need for more detailed Level 3 analysis or a decision to proceed to selection and design of countermeasures without more complex studies.

Step 1. Evaluate Flood History and Rainfall-Runoff Relations

A detailed discussion of hydrologic analysis techniques, and the analysis of flood magnitude and frequency in particular, is presented in HEC-19 (6) and will not be repeated here. However, several hydrologic concepts of particular significance to evaluation of stream stability are summarized.

Consideration of flood history is an integral step in attempting to characterize watershed response and morphologic evolution. Analysis of flood history is of particular importance to understanding arid region stream characteristics. Many dryland streams flow only during the spring and immediately after major storms. For example, Leopold, et al. (7) found that arroyos near Santa Fe, New Mexico flow only about three times a year. As a consequence, dryland stream response can be considered to be more hydrologically dependent than the response of streams located in a humid environment. Whereas the passage of time may be sufficient to cause change in a stream located in a humid environment, time alone, at least in

LEVEL 2: BASIC ENGINEERING ANALYSES

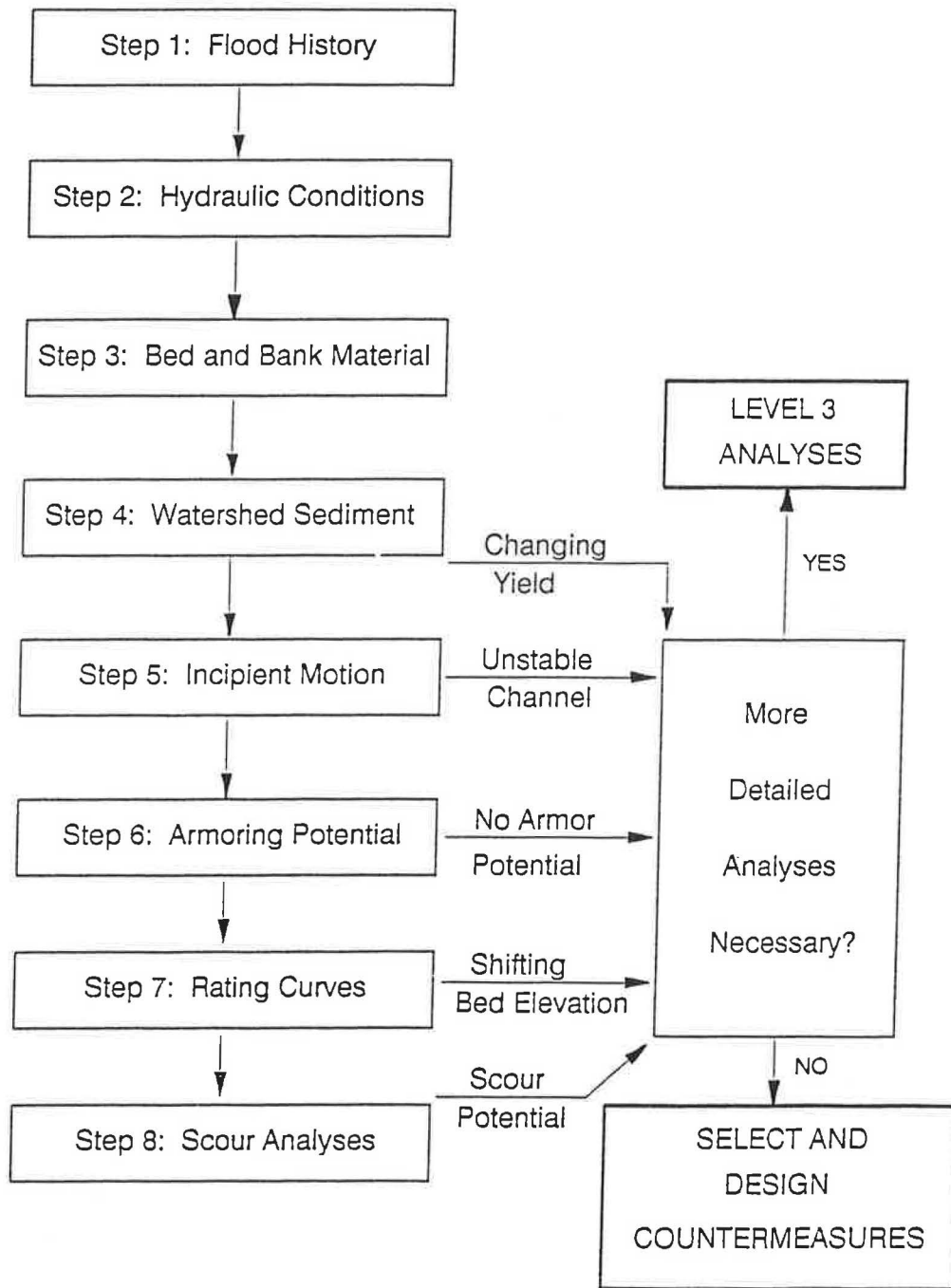


Figure 4. Flow chart for Level 2: Basic Engineering Analyses

the short term, may not necessarily cause change in a dryland system due to the infrequency of hydrologically significant events. Thus, the absence of significant morphological changes in a dryland stream or river, even over a period of years, should not necessarily be construed as being indicative of system stability.

Although the occurrence of single large storms can often be directly related to system change in any region of the country, this is not always the case. In particular, the succession of morphologic change may be linked to the concept of geomorphic thresholds as proposed by Schumm (8). Under this concept, although a single major storm may trigger an erosional event in a system, the occurrence of such an event may be the result of a cumulative process leading to an unstable geomorphic condition.

When flood records are available, the study of these records and corresponding system responses may help determine the relationship between morphological change and flood magnitude and frequency. Time-sequenced aerial photography or other physical information may provide such information. Evaluation of wet-dry cycles can also be beneficial to an understanding of historical system response. Observable historical change may be better correlated with the occurrence of events during a period of above-average rainfall and runoff than with a single large event. In addition, the study of historical wet-dry trends may explain certain aspects of system response. For example, a large storm preceded by a period of above-average precipitation may result in less erosion due to better vegetative cover than a comparable storm occurring under dry antecedent conditions; however, runoff volumes might be greater due to saturated soil conditions.

A good method for evaluating wet-dry cycles is the plotting of annual rainfall amounts, runoff volumes and maximum annual mean daily discharge for the period of record. A comparison of these graphs will provide insight into wet-dry cycles and flood occurrences. Additionally, a plot of the ratio of rainfall to runoff is a good indicator of watershed characteristics and historical changes in watershed condition.

Step 2. Evaluate Hydraulic Conditions

Knowledge of such basic hydraulic conditions as velocity, flow depth and top width for given flood events is essential for completion of a Level 2 stream stability analysis. Incipient motion analysis, scour analysis, and assessment of sediment transport capacity all require basic hydraulic information. Hydraulic information is sometimes required for both the main channel and overbank areas, as in the analysis of contraction scour.

For many river systems, particularly those near urban areas, hydraulic information may be readily available from previous studies such as flood insurance studies, channel improvement projects, and so on. In such cases, a complete re-analysis may not be necessary. In other areas however, hydraulic analysis based on appropriate analytical techniques will be required prior to completing other quantitative analyses in a Level 2 stream stability assessment. The most common computer models for analysis of water surface profiles and hydraulic conditions are the Corps of Engineers HEC-2 and the Federal Highway Administration WSPRO. For the analysis and design of bridge crossings, WSPRO is generally considered a better model. The computational procedure in WSPRO for evaluating bridge loss is superior to that utilized in other models, and the input structure of the model has been specifically developed to facilitate bridge design.

Step 3. Bed and Bank Material Analysis

Bed material is the sediment mixture of which the streambed is composed. Bed material ranges in size from huge boulders to fine clay particles. The erodibility or stability of a channel largely depends on the size of the particles in the bed. Additionally, knowledge of bed sediment is necessary for most sediment transport analyses, including evaluation of incipient motion, armoring potential, sediment transport capacity, and scour calculations. Many of these analyses require knowledge of particle size gradation, not just the median (D_{50}) sediment size.

Bank material usually consists of particles the same size as, or smaller

than, bed particles. Thus, banks are often more easily eroded than the bed, unless protected by vegetation, cohesion, or some type of man-made protection.

Of the various sediment properties, size is of the greatest significance to the hydraulic engineer, not only because size is the most readily measured property, but also because other properties, such as shape and fall velocity, tend to vary with particle size. A comprehensive discussion of sediment characteristics, including sediment size and its measurement, is provided in reference (9). The following information briefly discusses sediment sampling considerations.

Important factors to consider in determining where and how many bed and bank material samples to collect include:

1. Size and complexity of the study area
2. Number, lengths and drainage areas of tributaries
3. Evidence of or potential for armoring
4. Structural features that can impact or be significantly impacted by sediment transport
5. Bank failure areas
6. High bank areas
7. Areas exhibiting significant sediment movement or deposition (i.e., bars in channel)

Tributary sediment characteristics can be very important to channel stability, since a single major tributary or tributary source area could be the predominant supplier of sediment to a system.

The depth of bed material sampling depends on the homogeneity of surface and subsurface materials. Where possible, it is desirable to dig down some distance to establish bed-material characteristics. For example, in sand/gravel bed systems the potential existence of a thin surface layer of coarser sediments (armor layer) on top of relatively undisturbed subsurface material must be considered in any sediment sampling. Samples containing material from both layers would contain materials from two populations in unknown proportions, and thus it is typically more appropriate to sample each layer separately. If the purpose of the sampling is to evaluate hydraulic friction

or initiation of bed movement, then the surface sample will be of most interest. Conversely, if bed-material transport during a large flood (i.e., large enough to disturb the surface layer) is important, then the underlying layer may be more significant. Methods of analysis are given in reference (9).

Step 4. Evaluate Watershed Sediment Yield

Evaluation of watershed sediment yield, particularly of the relative increase in yield as a result of some disturbance, can be an important factor in stream stability assessment. Sediment eroded from the land surface can cause silting problems in stream channels resulting in increased flood stage and damage. Conversely, a reduction in sediment supply can also cause adverse impacts to river systems by reducing the supply of incoming sediment, thus promoting channel degradation and headcutting. A radical change in sediment yield as a result of some disturbance, such as a recent fire or long term land use changes, would suggest that stream instability conditions either already exist or might readily develop.

Assessment of watershed sediment yield first requires understanding the sediment sources in the watershed and the types of erosion that are most prevalent. The physical processes causing erosion can be classified as sheet erosion, rilling, gullying and stream channel erosion. Other types of erosional processes are classified under the category of mass movement, e.g., soil creep, mudflows, landslides, etc. Data from publications and maps produced by the Soil Conservation Service and the Geological Survey can be used along with field observations to evaluate the area of interest.

Actual quantification of sediment yield is at best an imprecise science. The most useful information is typically obtained not from analysis of absolute magnitude of sediment yield, but rather from the relative changes in yield as a result of a given disturbance. One useful approach to evaluating sediment yield from a watershed was developed by the Pacific Southwest Interagency Committee (10). This method, which was designed only to aid in broad planning, consists of a numerical rating of nine factors affecting sediment production in a watershed. This

then defines ranges of annual sediment yield in acre-feet per square mile. The nine factors are surficial geology, soil climate, runoff, topography, ground cover, land use, upland erosion, channel erosion and channel transport.

Other approaches to quantifying sediment yield are based on regression equations, as typified by the Universal Soil Loss Equation (USLE). The USLE is an empirical formula for predicting annual soil loss due to sheet and rill erosion, and is perhaps the most widely recognized method for predicting soil erosion. Wischmeier and Smith (11) provide detailed descriptions of this equation and its terms.

Step 5. Incipient Motion Analysis

An evaluation of relative channel stability can be made by evaluating incipient motion parameters. The definition of incipient motion is based on critical or threshold conditions where hydrodynamic forces acting on one grain of sediment have reached a value that, if increased even slightly, will move the grain. Under critical conditions, or at the point of incipient motion, the hydrodynamic forces acting on the grain are balanced by the resisting forces of the particle.

The Shields diagram may be used to evaluate the particle size at incipient motion for a given discharge (9). For most river flow conditions, the following equation, derived from the Shields diagram, is appropriate for evaluation of incipient motion:

$$D_c = \frac{\tau}{0.047(\gamma_s - \gamma)}$$

where D_c is the diameter of the sediment particle at incipient motion conditions, τ is the boundary shear stress (see (9) for equations defining the boundary shear stress), γ_s and γ are the specific weights of sediment and water, respectively, and 0.047 is a dimensionless coefficient often referred to as the Shields parameter.

As originally proposed, the Shields parameter was 0.06 for flow conditions in the turbulent range. The value of 0.047

was suggested by Meyer-Peter and Muller (12) and was further supported by Gessler (13). Recent research has indicated that this coefficient is not constant (values range from 0.02 to 0.10), and equations have been derived as a function of surface and subsurface particle size. As a first estimate, however, the use of 0.047 should provide reasonable results in most situations.

Evaluation of the incipient motion size for various discharge conditions provides insight on channel stability and how a flood might disrupt channel stability. The results of such an analysis are generally more useful for analysis of gravel or cobble-bed systems. When applied to a sand bed channel, incipient motion results usually indicate that all particles in the bed material are capable of being moved for even very small discharges, a physically realistic result.

Step 6. Evaluate Armoring Potential

The armoring process begins as the non-moving coarser particles segregate from the finer material in transport. The coarser particles are gradually worked down into the bed, where they accumulate in a sublayer. Fine bed material is leached up through this coarse sublayer to augment the material in transport. As sediment movement continues and degradation progresses, an increasing number of non-moving particles accumulate in the sublayer. Eventually, enough coarse particles can accumulate to shield, or "armor" the entire bed surface.

An armor layer sufficient to protect the bed against moderate discharges can be disrupted during high flow, but may be restored as flows diminish. Therefore, as in any hydraulic design, the analysis must be based on a certain design event. If the armor layer is stable for that design event, it is reasonable to conclude that no degradation will occur under design conditions. However, flows exceeding the design event may disrupt the armor layer, resulting in degradation.

The potential for development of an armor layer can be assessed using incipient motion analysis and a representative bed-material composition. In this case the representative bed-material composition is that which is

typical of the depth of anticipated degradation. For given hydraulic conditions the incipient motion particle size can be computed as discussed above in Step 5. If no sediment of the computed size or larger is present in significant quantities in the bed, armoring will not occur.

The D_{90} or D_{95} size of the representative bed material is frequently found to be the size "paving the channel" when degradation is arrested. Within practical limits of planning and design, the D_{95} size is considered to be about the maximum size for pavement formation (12). Therefore, armoring is probable when the computed incipient motion size is equal to or smaller than the D_{95} size in the bed material.

By observing the percentage of the bed material equal to or larger than the armor particle size (D_a), the depth of scour necessary to establish an armor layer can be calculated (15):

$$Y_s = y_a \left(\frac{1}{P_c} - 1 \right)$$

where y_a is the thickness of the armoring layer and P_c is the decimal fraction of material coarser than the armoring size. The thickness of the armoring layer (y_a) ranges from one to three times the armor particle size (D_a), depending on the value of D_a . Field observations suggest that a relatively stable armoring condition requires a minimum of two layers of armoring particles.

Step 7. Evaluation of Rating Curve Shifts

When stream gage data is available, such as that collected by the U.S. Geological Survey, an analysis of the stage-discharge rating curve over time can provide insight on stream stability. For example, a rating curve that was very stable for many years but shifted suddenly might indicate a change in watershed conditions causing increased channel erosion or sedimentation, or some other change

related to channel stability. Similarly, a rating curve that shifts continually would be a good indicator that channel instability exists. However, it is important to note that not all rating curve shifts are the result of channel instability. Other factors promoting a shift in a rating curve include changes in resistance to flow due to bed forms (or lack thereof), channel vegetation, ice conditions, beaver activity, etc.

The most common cause of rating curve shifts in natural channel control sections is generally scour and fill.(16) A positive shift in the rating curve results from scour, and the depth (and hence the discharge) are increased for a given stage. Conversely, a negative shift results from fill, and the depth and discharge will be less for a give stage.

Shifts may also be the result of changes in channel width. Channel width may increase due to bank-cutting, or decrease due to undercutting of steep streambanks. In meandering streams, changes in channel width can occur as point bars are created or destroyed.

Analysis of rating curve shifts is typically available from the agency responsible for the stream gage. If such information is not available, field inspection combined with the methods described by reference (16) can be utilized to analyze observed rating curve shifts. If the shifts can be traced to scour, fill, or channel width changes, such information will be a reliable indicator of potential channel instability.

Gaging stations where continuous sediment data are collected may also provide clues to the existence of gradation problems. Any changes in the long-term sediment load may indicate lateral movement of the channel, gradation changes, or a change in sediment supply from the watershed.

Step 8. Evaluate Scour Conditions

HEC-20 (4) provides an overview of scour at bridge crossings; HEC-18 (17) provides detailed computational procedures. These references should be consulted for bridge scour analysis procedures.

CONCLUSIONS

A systematic, analytical procedure for the evaluation of stream stability has been outlined in this paper. The procedure incorporates three increasingly complex levels of analysis. It was developed for the FHWA Hydraulic Engineering Circular No. 20, "Stream Stability at Highway Structures." (4) The completion of each level of analysis results in an assessment of stream stability, and then, depending on the complexities of stream response or bridge design, the decision to proceed to the next level of analysis is made.

The specific steps typical of Levels 1 and 2 analysis have been outlined. Level 3 analysis, involving detailed evaluation and assessment of stream stability, is accomplished with mathematical and/or physical model studies. However, the need for the detailed information and accuracy available from either of these model studies must be balanced by the time and money available. As accounting for more factors makes the analysis more complicated, the level of effort necessary becomes proportionally larger.

The decision to proceed with a Level 3 analysis has historically been made only for high risk locations, extraordinarily complex problems, and for forensic analysis where losses and liability costs are high; however, the importance of stream stability to the safety and integrity of all bridges suggests that Level 3 analyses should be completed routinely. The widespread use of personal computers and the continuing development of more sophisticated software have greatly facilitated completion of Level 3 investigations and have reduced the level of effort and cost required.

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