Prediction of Channel Bed Grade Changes at Highway Stream Crossings

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Changes in channel bed-level elevation associated with channel aggradation and degradation have been found to be a significant cause of hydraulic problems at bridges. Numerous techniques for evaluating the impact of these grade changes, from simple, qualitative geomorphic principles to complex, fully developed, computer models, are available in the literature. These techniques represent a wide range of levels of analysis data needs, difficulty of application, time requirements, and costs. The number of techniques available and the variety in their levels of accuracy emphasize the need to base grade-change predictions on more than one technique or model. An appropriate procedure starts with general observations and the evaluation of geomorphic principles and relations to establish the cause and direction of the change and is then built on by applying some of the simpler quantitative techniques. From this base, one or more of the levels of mathematical modeling can be applied. The level of sophistication used in the modeling process should be based on the physical processes causing the grade change, the economic importance of the particular crossing, and available time, manpower, and financial resources.

A recent study by Brice and others (1) of countermeasures for hydraulic problems at bridges revealed that a primary cause of hydraulic problems at highway crossing sites is a change in the base level of the river. Changes in channel bed level can be described by three interrelated phenomena: local scour, general scour, and aggradation-degradation (changes in channel grade). This paper deals with the prediction of changes in channel bed level due to aggradation and degradation.

The terms aggradation and degradation have been defined in a variety of ways. The differences in the definitions come from defining the limits of the perspective used to view the river in time and space. In this paper, aggradation and degradation are considered to be changes in stream-bed elevation resulting from a change in channel gradient over an extended reach of a river. Aggradation results in a general rising of the channel bed, and degradation results in a general lowering of the channel bed. The time period involved ranges from days and months to years. The change in channel gradient can be caused by natural factors and events or by human activities. Natural causes include channel cutoffs, alluvial fan development, tectonic activity, landslides, and climatic changes. Human activities include land use changes, construction activities, channelization, floodplain clearing, streambed mining, and damming and reservoir regulation. The length of reach affected by the change in gradient can range from several hundred feet to hundreds of miles and is defined by the location of channel bed-level controls both upstream and downstream of the activity causing the change.

TECHNIQUES FOR EVALUATING MAGNITUDE OF GRADE CHANGES

Grade changes in river systems can be predicted through the use of various levels of analysis, from simple to extremely complex. The simplest techniques involve the application of mathematical statements of geomorphic principles, and the most complex techniques require analysis of entire drainage systems by using detailed computer modeling of water and sediment transport processes. However, the majority of highway crossing design situations do not initially justify the application of extremely complex computer models. Therefore, a less-complex, intermediate range of prediction techniques is presented here, including geomorphic and basic engineering relations as well as some simpler modeling techniques.

Before the various techniques available are described, it is important to point out that the prediction of grade changes should never be based solely on one prediction technique or model. The art of predicting grade changes is not an exact science. The most reliable results can be obtained by applying several techniques and tempering the quantitative results with engineering judgment and experience.

Geomorphic and Engineering Relations

Useful geomorphic and engineering relations include Lane's relation (2), hydraulic geometry relations, incipient motion considerations, analysis of changes in bed material volume, and engineering relations developed for specific applications.

Lane's Relation

Analysis of actual grade changes is based on the concept of equilibrium. The most widely known geomorphic relation embodying the equilibrium concept is Lane's principle:

$$QS \sim Q_s D_{50} \tag{1}$$

where

Q = water discharges,
S = channel slope,
Q_s = sediment discharge, and
D_{50} = median sediment size.

Equation 1 can be used to qualitatively predict channel response to modifications within the water-sediment regime of a channel. Application of Equation 1 has been documented by Richardson and others (3).

Although Lane's relation produces only qualitative results, its use is an important initial step in analyzing channel response. The technique indicates the direction of a grade change and the potential severity of a given problem.

Hydraulic Geometry Relations

Relations describing the geometric shape of regime channels have been developed by numerous investigators (4-8). These relations denote proportionalities between bankfull or dominant discharge, sediment transport, and channel geometry.

Leopold and Maddock (4) have shown that in a drainage basin the types of hydraulic geometry relations that can be defined are those that relate channel width (W), depth (v), velocity (V), slope (S), and sediment load (Q_s) to the variation of discharge (Q) at a station and those that relate these parameters to the change in mean annual or bankfull flow in the downstream direction. The regime formulas describing these relations are given in the following equations:

$$W \sim Q^b \quad (2)$$

$$y_o \sim Q^f \quad (3)$$

$$V \sim Q^m \quad (4)$$

$$Q_s \sim Q^j \quad (5)$$

$$S \sim Q^z \quad (6)$$

Table 1 gives mean values for the exponents b, f, m, j, and z as reported by Leopold and others (9). Also included are theoretical values developed at Colorado State University (CSU). The variation among the values reported can be explained by differences in the physiographic characteristics of the regions in which the exponents were evaluated. Factors important to the morphologic development of stream networks include local geology, hydrology, type and density of vegetation, type and depth of valley alluvium, and controlling valley slope.

It is important that the appropriate exponent be used in applying the proportionalities in Equations 2-6. This can be done by using the exponents in Table 1 developed for the physiographic region that most closely resembles the region of interest. An alternative technique would be to develop new exponents based on information from watersheds in the same physiographic region as the stream system of interest. The second technique would provide the most reliable information.

An example of the application of hydraulic geometry relations can be found in Chapter 8 of the report by Richardson and others (3).

Incipient Motion Considerations

Before soils can be transported through a system, some critical condition must be reached above which sediment motion will occur. This incipient motion condition is reached when the hydrodynamic forces acting on the grain of sediment have attained a value that, if increased even slightly, will move the particle. Under these critical conditions, or at incipient motion, the hydrodynamic forces acting on the grain are just balanced by the resisting forces of the particle.

For noncohesive channel bed material, the beginning of motion is known to be a function of the Shields parameter, which can be represented as

$$\tau_c/(\gamma_s - \gamma)D_s \quad (7)$$

where

τ_c = critical boundary shear stress;
γ_s and γ = specific weights of sediment and water, respectively; and
D_s = characteristic diameter of the sediment particle.

The Shields parameter has been found to be approximately equal to 0.047 in situations where the flow boundary layer is fully turbulent. Theoretically, fully turbulent boundary flow occurs at shear Reynolds numbers larger than 400. This condition is satisfied by most river-flow situations.

Incipient motion considerations can be used effectively to calculate the limiting slope of a degrading channel bed. An example of such a calculation is provided in Chapter 8 of the report by Richardson and others (3).

Potential Change in Bed Material Volume

Another technique available for estimating the magnitude of potential grade changes is an analysis of the potential change in bed material volume in the vicinity of the crossing. This technique involves analysis of the transport capabilities of upstream reaches as well as those within the local reach of interest.

The analysis consists of applying sediment continuity to the reach of interest. To maintain continuity, the following equation must be satisfied:

$$\Delta V_o = [\Delta t/(1 - \lambda)] (Q_{so} - Q_{si}) \quad (8)$$

where

ΔV_o = sediment volume change within the reach,
Δt = time increment under consideration,
λ = bed material porosity,
Q_{so} = sediment transport rate out of the reach, and
Q_{si} = sediment transport rate into the reach.

The sediment continuity equation is applied with the aid of an appropriate sediment transport equation and an annual flow duration curve or other flow hydrograph. The choice of an appropriate sediment transport equation should be based on characteristics of the bed material in the reach of interest. The annual flow duration curve or other flow hydrograph can be constructed from stream-flow records.

The technique can be based on an annual flow hydrograph, a single storm hydrograph, or both. If average annual flows are anticipated to have the most significant impact on grade changes, an annual flow duration curve should be used for the analysis. If the major problem is anticipated to come from a single storm event or a series of storm events, the design storm flow hydrograph should be used for the analysis. In many cases, it is difficult to anticipate the type of flow event that will have the most impact on channel grade. In these cases, both flow events should be analyzed.

Applying the sediment continuity equation presented above requires the following steps:

1. Divide the flow hydrograph (annual or single event) into incremental time steps;

Table 1. Values of exponents in equations for hydraulic geometry of rivers.

	At Station					Downstream (bankfull or near annual flow)				
Location	b	f	m	j	z	b	f	m	j	z
Avg values for midwest United States	0.26	0.40	0.34	2.5		0.5	0.4	0.1	0.8	-0.49
Brandywine Creek, Pennsylvania	0.04	0.41	0.55	2.2	0.05	0.42	0.45	0.05		-1.07
Ephemeral streams in semiarid United States	0.29	0.36	0.34			0.5	0.3	0.2	1.3	-0.95
Appalachian streams						0.55	0.36	0.09		
Avg of 158 U.S. gauging stations	0.12	0.45	0.43							
Ten gauging stations on Rhine River	0.13	0.41	0.43							
Theoretical values (Colorado State University)	0.26	0.46	0.30		0.00	0.46	0.46	0.08		-0.46

2. With the channel geometry and bed material size gradation as input, compute the transported volume within each reach for each time interval (by using an appropriate sediment transport equation);
3. Apply the sediment continuity equation at each time step to compute the volume of material eroded during the time step;
4. Sum all ΔV_o's to find the total volume of material deposited or eroded during the time span of interest; and
5. Estimate a depth of deposition or erosion based on channel geometry and typical bed material porosity.

This technique provides an estimate of the magnitude of an aggradation or degradation problem at a local site on an annual or single-storm-event basis. It is not intended to provide a final estimate of the base level of the channel at the site. Such an estimate requires repeated application of the procedure over longer time spans and adjustments in channel slope and other hydraulic and geometric parameters at each step. This type of analysis is better suited for use with a digital computer and will be discussed later.

The technique described provides a relatively quick method of estimating the magnitude of an aggradation-degradation problem. It can be used to estimate changes in channel grade at a crossing and provide useful information for establishing the magnitude of a required maintenance program. It can also be used to evaluate quickly the relative importance of single storm events and average annual flow hydrographs to the grade change problem. An example application of this technique is presented by Brown, McQuivey, and Keefer (10, Appendix C).

Engineering Relations Developed for Specific Situations

In addition to the techniques already presented, there are a number of prediction techniques available that are based on assumptions that make them applicable only to specific cases. Time will not be taken here to explain these techniques in detail. They are described in the references cited below:

Problem	Reference
Degradation downstream of dams	Komura and Simons (11) Mostafa (12)
Aggradation upstream of dams	Bruk and Milorodov (13) Garde and Swamee (14)
Aggradation in streams from overloading	Soni (15) and others

Mathematical Modeling

Modeling techniques encompass sediment and flow routing computations over an extended reach of river. Sediment transport models range from methods that use hand calculation procedures aided by the use of small computers to fully developed dynamic models capable of handling unsteady, nonuniform flow routing and sediment routing by size fraction. Although this last model type could theoretically give excellent results, the data input requirements make it impractical to apply in many cases.

An analysis of typical highway-related aggradation-degradation problems and a review of available modeling techniques have revealed that most highway design situations do not require extremely complex models (10). In fact, a significant number of hydraulic problems at highway crossings occur on small- to medium-sized channels (less than 500 ft wide) (1), and a large number of these are in the 50- to 300-ft range. These channels can often be analyzed by using hand and/or computer-aided computation techniques or some of the simpler, fully computerized models.

An approach to modeling aggradation-degradation problems is presented below. Several levels of analyses found to be applicable to typical highway design situations are included in the discussion.

Background Data and Analysis

The development of an appropriate transport model requires a significant amount of background data and analysis before the actual profile analysis can be conducted. Background information includes locating channel controls, defining subreaches, collecting the hydraulic and geometric input, defining an appropriate flow event, establishing sediment boundary conditions, and selecting an appropriate time step for the analysis.

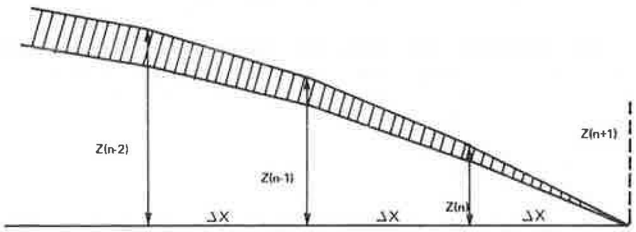
The first step in developing a system model is to locate the channel controls with respect to the particular aggradation or degradation problem. This defines the affected reach of the river and determines the extent of the river that should be included in the model. Channel controls can be either natural or man-made. Natural controls include outcrops of bedrock, heavily armored channel conditions, clay plugs, buried vegetation, fixed or controlled water surface levels, and, in some cases, tributary junctions. Most hydraulic structures built on rivers represent man-made controls. Typical examples include dams, weirs, spillways, free overfalls, underflow gates, sluice gates, culvert crossings, and some bridge crossings. Submerged pipelines can also act as controls.

With the controls established, the reach of interest is divided into subsections. The criterion for selecting the subsections is uniformity among hydraulic and geometric properties. These properties include channel slope, channel geometry, bed profiles, channel roughness, and bed material characteristics. The number of subsections or subreaches used depends on the degree of variance in the above parameters as well as the level of accuracy required in the results. Theoretically, the number used could range from one into the hundreds; however, increasing the number of subsections increases the number of computations required. Subreaches should be selected to provide the accuracy required by using the least number of sections. It is recommended that, if more than five subreaches are required, a digital computer be used for at least some of the computational steps.

The next step is to obtain the average hydraulic and geometric properties for the subreaches. These data include average channel geometry, reach lengths and slopes (defining the bed profile), estimates of channel roughness, bed material size distributions, and an approximate voids ratio for the bed material. The required precision of the input data will depend on the level of sophistication of the model being developed as well as the desired accuracy of the results. For example, channel geometry could be obtained in several ways. It could be estimated from site inspections, measured by using modern surveying techniques at one location per reach, or determined by surveying several locations within a reach and then averaging the resulting sections to get a section characteristic of the reach. Similarly, various levels of analysis could be used to obtain other required information.

The channel profile is then given in terms of (n + 1) bed elevations as shown in Figure 1. The ΔX's shown in the figure do not have to be equal, but for best results they should not vary by more than 35 percent.

Figure 1. Division of reach into finite elements.



Another input requirement for aggradation-degradation models is the selection of a flow event on which to base the grade-change prediction. The flow event chosen could be a single design storm, an annual flow duration curve, a series of synthetically generated annual flow hydrographs, or some other "average" discharge condition. The selection of an appropriate flow event is based on the hydraulic conditions that most influence the grade change. Often, several flow conditions must be evaluated to determine which will have the greatest impact.

Model boundary conditions must also be established. Sediment transport loads entering the model at the upstream control and other influent locations (at tributaries or other point load sources) must be estimated. Sediment loads entering the model at the upstream end can be computed by using an appropriate transport equation and assuming that the volume of material transported into the reach is equal to the capacity of the upstream reaches to transport sediment. If some other condition is known to exist, the sediment transport loads must be estimated by other methods.

The last step in setting up the model is to select an appropriate time interval (Δt) over which to compute incremental changes in the channel bed profile. The time interval selected does not have to remain the same for all steps; in fact, it is best to increase the Δt with each computational step because degradation and aggradation processes proceed most rapidly in the period immediately after the initiation of the grade change. If digital computer techniques are being used, however, the time steps should be equal in length. The value of Δt used depends on the type and cause of the grade-change problem as well as the hydraulic and geometric characteristics of the river system. The initial time interval is based on trial estimates of the initial grade-change rate. Subsequent changes in Δt at each step of the process are based on the actual rate of change documented in the preceding step. Consideration must also be given to the time steps in the discharge hydrograph to be used in the analysis.

Once the model is set up, the repetitive steps in computing the new profile can be started. This involves evaluating backwater conditions within the reach, computing sediment transport rates, and applying sediment continuity within each reach of each time step. As with other parts of the model setup, various levels of sophistication can be applied to each of the components involved.

Backwater Computation

Backwater profiles can be estimated by using normal depth consideration or calculated by using step backwater techniques. For the simplest applications, these computations could be made by hand. However, they can be easily programmed for repetitive use.

Normal depth can be calculated by using the Manning equation (given here in metric units):

$$Q = (1.0/n)\,AR^{2/3}S^{1/2} \tag{9}$$

where

n = Manning resistance parameter,
A = flow area, and
R = hydraulic radius.

The equation for trapezoidal channels can be expressed as

$$Q = (1.0/n)\left([(zy^2 + by)^{5/3}S^{1/2}] / \left\{ [b + 27(1 + z)^{1/2}]^{2/3} \right\} \right) \tag{10}$$

where z equals side slope (horizontal to vertical) and b equals bottom width. Either of these equations can be solved for y in terms of the other known parameters by a trial-and-error method.

Step backwater techniques have been covered in many texts (3,16,17). The calculations can be performed by hand or programmed for computer solution.

For complex situations that involve many bridges, culverts, and long reaches of river, it is often necessary to use a developed computer program such as the U.S. Army Corps of Engineers HEC-2 or others (18) to compute a water surface profile. The use of such a model is the only way to analyze large systems efficiently.

Each of the backwater techniques discussed is based on rigid boundary hydraulics, and care must be used in applying them to analyze alluvial systems. To account for the change in geometry produced in alluvial systems, the channel boundary must be adjusted during each time step to account for the computed aggradation and/or degradation. A technique developed by Chang and Hill (19) can be used to adjust the channel geometry, or aggradation and degradation volumes can be distributed uniformly across the channel.

Sediment Transport

The second step involved in computing the new profile is to evaluate the sediment transport along the channel within each subreach. Many transport equations are available, ranging in complexity from those that require simple graphical procedures (20) to those that require many calculations (21). Numerous texts cover the development of sediment transport relations; included among these are reports by Simons and Senturk (22) and the American Society of Civil Engineers (ASCE) Task Committee (23). In most cases, the development of sediment transport relations is based on specific bed material types (sand, gravel, cobble, or cohesive clays) and transport mechanisms (wash load, bed load, suspended load, or total bed material load). Therefore, it is important that bed material type and transport mechanism be considered in choosing an appropriate transport equation.

Brown, McQuivey, and Keefer (10), Simons and Senturk (22), and the ASCE Task Committee (24) provide comparisons of available transport relations. Table 2 illustrates the applicability of some of these relations to various conditions. The relations presented do not constitute a complete list of available equations.

Sediment Continuity

Once the sediment transport rates are established for each subreach, the following sediment continuity equation can be applied over segments of the channel

Table 2. Applicability of sediment transport relations.

			Bed Material Load		
Material	Method	Wash Load	Suspended	Bed Load	Total Load
Sand	Einstein		X	X	
	Modified Einstein	X	X	X	X
	Colby	Measured or estimated	X	X	X
	Schoklitsch			X	
Gravel and cobble	Schoklitsch			X	
	Meyer-Peter, Muller			X	
Cohesive	Ariathurai, Krone/ Parthenaides	Measured or estimated	X		

for the given time interval to determine the amount of aggradation or degradation:

$$[1/(1-\lambda)](\partial q_s/\partial x) = (\partial Z/\partial t) \quad (11)$$

where

q_s = sediment transport rate per unit width,
x = channel distance, and
Z = elevation.

Equation 11 is applied for each section, starting with the section between cross section (n + 1) and n in Figure 1. In the figure, the hatched area represents the volume to be eroded, which is (1/2) • $\Delta Z(n)$ • Δx. According to Equation 11, this equals the difference in sediment load at (n + 1) and n times the time interval Δt and times a coefficient converting weight into corresponding volume. The resulting equation is solved for Z(n), which produces

$$\Delta Z(n) = -2 \cdot \left\{ [g_s(n+1) - g_s(n)]/\Delta x \right\} \cdot \Delta t \quad (12)$$

The result is negative in the case of degradation and positive in the case of aggradation.

A similar procedure is then applied to the next section, which yields

$$\Delta Z(n-1) = \Delta Z(n) - 2 \left\{ [q_s(n) - q_s(n-1)]/\Delta x \right\} \quad (13)$$

and so on until the ΔZ's of all cross sections are determined. The geometry of all cross sections is then adjusted to reflect the degradation or aggradation. A new profile is determined by adding ΔZ to the previous Z.

The procedure described is repeated until the limits of the final equilibrium profile are approached. Because of the asymptotic nature of grade changes, it becomes evident that the final profile is being reached when successive ΔZ's become small. This final equilibrium profile can be evaluated separately by using the incipient motion criteria discussed earlier.

Several parts of the above procedures can easily be programmed on calculators or small computers. They include the sediment transport equation, the hydraulic properties of cross sections, normal depth or backwater computations, and the sediment continuity equation. Small programs for each of these procedures would greatly reduce the number of individual computations required and would therefore reduce the time required to apply the technique.

Fully Computerized Models

A number of fully computerized mathematical models dealing with sediment transport have been published in recent years. These models are based on the modeling concepts discussed above. Three models are representative of the types currently available.

Thomas and Prashuhn (25) present a sediment model coupled with a step backwater calculation. This results in a fairly inexpensive computational procedure and can be used over long periods by assuming a series of steady-state discharges (say, mean monthly). Chang and Hill (19,26) use a similar steady-state analysis. However, their model incorporates procedures to evaluate sediment transport through channel bends and to distribute scour and deposition across the cross section based on relative tractive force. The Chen-Simons model was developed at CSU and is one of a variety of models available there. The Chen-Simons model consists of a linear, implicit, finite-difference flow model coupled with a sediment transport model. This is a sophisticated technique but one that provides a high degree of accuracy.

LEVEL OF ANALYSIS

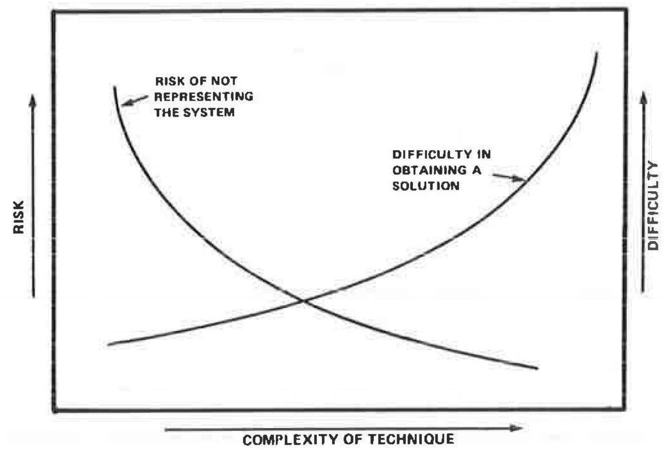
The cost of any engineering analysis is a function of the level of effort, which in turn depends on the accuracy required, the time available, and the analysis techniques used in reaching the solution. Techniques for estimating the magnitude of grade changes, ranging in complexity from simple geomorphic principles to complex computer models, have been discussed. Generally, the more complicated the analysis technique, the more accurate the solution becomes; however, the time, application difficulty, and associated costs also increase.

Because time, manpower, and money are always limited, decisions must be made regarding the degree of complexity needed to evaluate a given situation. According to Overton and Meadows (28), if a highly complex mathematical representation of the system under study is made, the risk of not representing the system will be minimized but the difficulty of obtaining a meaningful solution will be maximized. Many data will be required, and programming effort and computer time will be significant. Furthermore, the resource constraints of time, money, and manpower may be exceeded.

On the other hand, if a greatly simplified solution technique is used, the risk of not representing the physical system will be maximized but the difficulty in obtaining a solution will be minimized. Figure 2 shows the general concept of "trade-offs" involved in considering the complexity of the solution technique.

The application of all analytic procedures requires trained personnel to evaluate and interpret the results. Geomorphic concepts do not require extensive mathematical or computer analysis; however, they do require a very well-founded knowledge of the significant physical processes. Engineering relations and mathematical models can be used as "black box" calculations by support personnel. How-

Figure 2. Model complexity trade-offs.



ever, the design engineer must provide the proper input and be capable of interpreting the output.

The choice of an appropriate level of analysis must be based on available time, manpower, and financial resources. These are influenced heavily by the economic importance of a particular highway crossing as determined through risk analysis (29-31). It is also important to consider the governing physical processes and the sensitivity of system response at each site in determining an appropriate level of analysis.

CONCLUSIONS

Changes in channel bed-level elevation caused by aggradation and degradation processes have been found to be a significant cause of hydraulic problems at highway stream crossings. The number, variety, and level of analysis of the techniques available for predicting grade changes emphasize the uncertainty involved in calculations of sediment transport. It is important that grade-change predictions be based on more than one prediction technique or model and that the quantitative results be tempered by engineering judgment and experience. An appropriate solution procedure starts with the evaluation of geomorphic principles and relations (such as Lane's relation) to establish the cause and direction of the grade change. This can be built on by applying quantitative geomorphic and engineering relations (incipient motion considerations, change in bed material volume, etc.) as well as relations developed for specific grade-change problems. At this point a decision must be made to determine the level of analysis desired for additional work based on available time, manpower, and financial resources as well as risk considerations. Based on this decision, one or more levels of mathematical modeling can be applied.

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Abridgment

Stream Channel Grade Changes and Their Effects on Highway Crossings

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Stream channel degradation and aggradation are significant hydraulic problems at river crossings. Degradation is lowering of the streambed, independent of scour caused by obstructions or constrictions. Rapid or long-term degradation is usually due to a significant change in normal sediment-transport relations. Aggradation is stream infilling and occurs when more sediment is supplied to a stream than the stream is capable of transporting. Problems caused by stream degradation are far more common than those caused by aggradation. If actions are to be taken to protect a highway crossing against grade changes, early recognition of these hazards is imperative. Techniques for determining whether a crossing is experiencing degradation or aggradation are observation of stream characteristics (geomorphology), anticipation of gradation changes based on watershed activities, and measurement of pertinent stream dimensions. Streams in areas of high sediment yield are most prone to grade changes. Severe grade changes are often due to human intervention in natural stream processes. The problems associated with degradation and aggradation warrant special attention because protective measures effective against local hydraulic hazards are ineffective for protection against grade changes.

Degradation is lowering of a stream channel caused by a significant change in normal sediment-transport relations. It is independent of scour created by isolated obstructions or constrictions. Aggradation occurs when more sediment is supplied to a stream than the stream is capable of transporting. To deal with grade changes, it is necessary to understand what causes them and how to recognize their features.

The processes of streambed grade changes have been defined differently by various authors (1-3). The differences in definition stem from differences in the limitations on temporal and spatial perspective; as a result, grade changes are sometimes confused with scour and fill.

The pervasive nature of grade changes is often described in terms of a long time and great distance. This is an accurate description of many case studies but fosters the misconception that all grade changes progress similarly. When basic stream-forming factors are altered, the stream response is to change channel geometry. The direction of change, whether vertical or lateral; the rate, whether in seconds or in decades; and the distance affected, whether in meters or kilometers, is dictated by the physics of the situation involved. Degradation or aggradation that is significant enough to be of engineering concern is caused by major changes in the river environment.

HIGHWAY PROBLEMS DUE TO GRADE CHANGES

The extent of stream degradation and aggradation in the United States is demonstrated by a 1978 Federal Highway Administration (FHWA) research study (4). Data from 224 sites that were experiencing various hydraulic problems were assembled and carefully analyzed. Thirty-nine of these sites (17.4 percent) had undergone changes in streambed elevation.

Degradation is the lowering of a stream channel; therefore, a problem at crossings is the exposure of footings, pilings, and foundations (see Figure 1). Undermining of channel banks or highway fill results in failure of bridge approaches, revetment, and other countermeasures. Undermining of channel banks causes general stream instability and exacerbates debris problems (5). Channel instability is often a clue to future degradation problems; on the other hand, some instability problems (channel cutoffs) result in degradation. Degradation alters crossing conditions so that hydraulic hazards that under design conditions pose no significant threat to the integrity of crossings become critical. For example, local scour considered acceptable under design conditions could cause bridge failure when superimposed on a degraded channel.

Aggradation--general infilling of a stream channel--causes a reduction in the flow area available at crossings (see Figure 2). In extreme cases, the flow area is less than that necessary for design discharges, which results in overtopping of the roadway or bridge deck. During flooding enough horizontal or turning movement can occur to cause bridge damage. Aggradation increases stream instability because excessive sediment carried by an ag-