Prepared for the Nebraska Department of Roads

Open-bottom Culverts in Nebraska
A Literature Review

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Chapter 1 Introduction

The U.S. Army Corps of Engineers (USACE) reissued nationwide stream crossing permits in 2012, stopping short of requiring that culverts placed in streams must maintain natural low flow conditions for those streams. However, the general nationwide trend is certainly moving in the direction of reducing impacts of stream crossings on stream geomorphology and habitat. Common practice in Nebraska and other states utilizes box culverts and other rigid-boundary culverts with fixed beds at stream crossings. Such culverts act as grade control structures, preventing head cuts from traveling upstream. Benefits of the fixed bed culverts include that prevention of head cut migration can protect the stream crossing infrastructure and potentially protect natural stream morphology upstream of the culvert. However, perched culverts do also acts as barriers for upstream migration of fish and other aquatic species. This reduction in stream connectivity may prevent native species from migrating, but it may also prevent invasive aquatic species from becoming more widely established.

In some cases, it may be advisable to use bottomless culverts or bridges to facilitate aquatic organism passage and to accommodate their habitat. A bottomless culvert is a three-sided culvert that uses the natural streambed for its bed; consequently, if adequately designed, it is an environmentally better alternative to traditional culverts and short span bridges. However, such culverts may be less economical or less reliable if not carefully sited and designed. Thus, it is a useful activity to determine relevant stream characteristics at stream crossings for better assessment of concerns at potential bottomless culvert sites. Such characteristics may include local stream morphology, streambed material characteristics, hydrology, and hydraulics. The Nebraska Department of Roads (NDOR) and the University of Nebraska-Lincoln are conducting research that will provide an evaluation tool allowing the NDOR to evaluate conditions to determine the feasibility of bottomless culverts at proposed stream crossing sites.

One goal of this literature review is to summarize past work that is relevant to the analysis of bottomless culverts. This literature review focuses on the following; (a) stream classification and channel stability, (b) Scour problems and countermeasures, (c) culvert design and stability and (d) aquatic organism passage (with a focus on fish migration).

Chapter 2 Channel Stability

2.1 Introduction

Annually, a large number of bridges and culverts are installed to traverse streams, most of which are alluvial streams. The functionality and stability of bridge and culvert structures depends on the stability of the associated stream system. A stable stream channel is one whose bed slope and cross-section allows it to transport water and sediment from the upstream watershed without aggradation, degradation, or bank and bed erosion. However, several factors can affect the stability of a stream and consequently the stability of a stream crossing. These factors can be classified as geomorphic or hydraulic.

According to Lagasse et al. (1995)rapid and unexpected changes in channel form can occur in a stream in response to both natural (floods, drought, earthquake, forest fire etc.) and human disturbances (channelization, land cover land use change) of the fluvial system and it surroundings. Local conditions introduced by installation of stream crossings also can affect channel form. The implications of such changes in channel form make it important to understand channel geomorphology, location, and behavior. Furthermore, numerous channel characteristics such as bed forms, flow resistance, flow velocity, and depth can greatly influence the stability of stream channels at highway crossings. River classification can provide insight into potential instability problems (Lagasse et al. 2012) . River classification, the effects of geomorphic and hydraulic factors on stream stability, and recommended countermeasures are discussed in this chapter.

2.2 Stream Classification

Many researchers working with rivers are keen to understand the processes that influence the behavior and patterns of river systems. The vast differences (including geomorphology and hydrology) that exist in various river systems under a wide variety of conditions make this process complex to research (Rosgen,1994). In regards to river systems, Rosgen says,"what initially appears complex is even more so upon further investigation". Despite this complexity, many stream-order classification systems have been developed, but none has been universally accepted (Ward et al, 2008).Ward et al. (2008)mentioned that one of the most commonly used methods is the system developed by Strahler in 1952.Strahler described the smallest headwater tributaries as first order streams. Where two first order streams met he described as a second order stream and where two second order streams met he described as a third order stream ,and so on. This is illustrated in figure 2.1below.

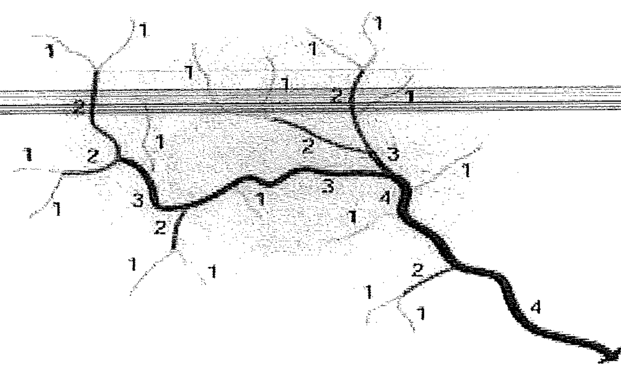

Figure 2.1 Stream Order Classification

The Stream Order Classification relates drainage area to stream size. Streams are placed into classes starting from first order (smallest) up to 12^{th} order(largest) streams. First and second order streams are formed mostly on steep slopes, with high stream velocities. First, second, and third order streams are also referred to as headwater streams and are located in the upper reaches of a watershed. Fourth order to sixth order streams are classified as medium streams. All streams larger than sixth order are classified as rivers. A vast majority of the streams in the Midwestern region of the United States are headwater streams (first to third order) that have been modified for agricultural purposes. Figure 2.2 shows an example of a typical Midwestern stream.

Figure 2.2 A typical modified headwater stream in Midwestern United States (Ward et al. 2008).

Another stream classification system that has gained wide recognition in the United States is the Rosgen Classification, which was proposed in 1994 by D.L Rosgen. The Rosgen Classification Method set up a river inventory hierarchy that allows assessment of the river system at various levels. The system is shown in Figure 2.3 and described in Table 2.1.

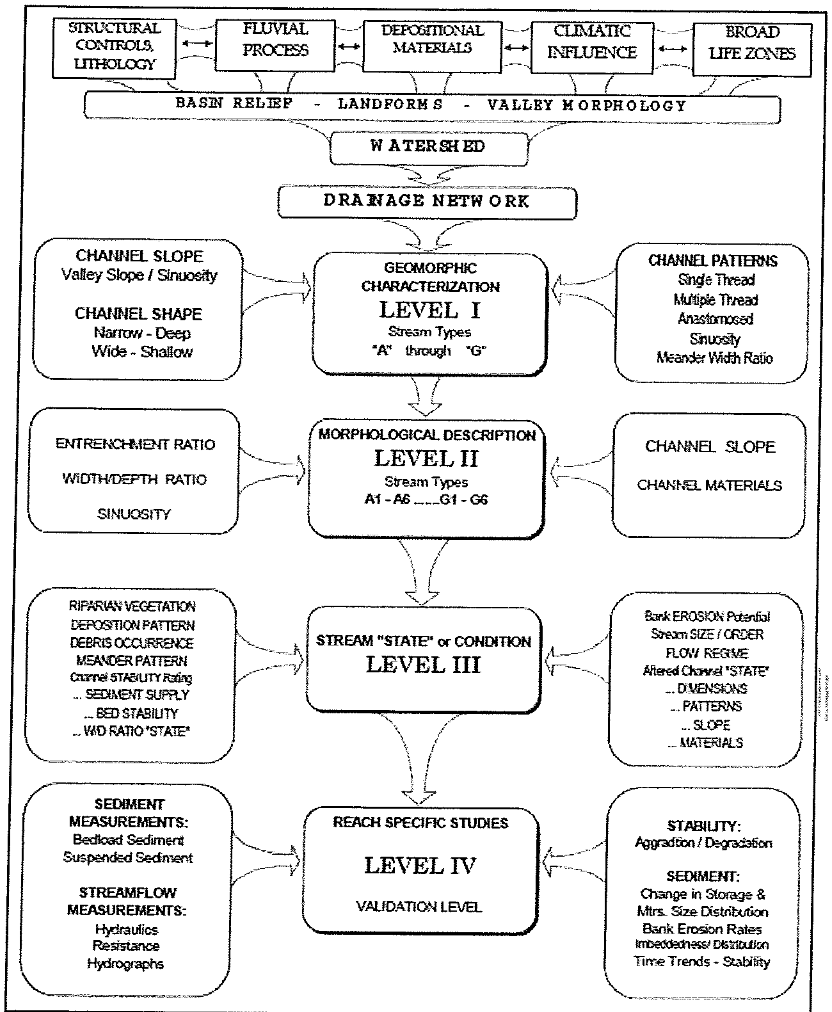

Figure 2.3 The Hierarchical River Inventory Stratifying stability prediction and detailed river measurements by valley types and stream types for various levels of inquiry(Rosgen 2001)

Table 2.1 Hierarchy of river inventory

Level of detail	Inventory description	Information required	Objectives
I	Broad morphological characterization	Landform, lithology, soils, climate, depositional history, basin relief, valley morphology, river profile morphology, general river pattern	To describe generalized fluvial features using remote sensing and existing inventories of geology, landform evolution, valley morphology, depositional history and associated river slopes, relief and patterns utilized for generalized categories of major stream types and associated interpretations.
II	Morphological description (stream types)	Channel patterns, entrenchment ratio, width/depth ratio, sinuosity, channel material, slope	This level delineates homogeneous stream types that describe specific slopes, channel materials, dimensions and patterns from "reference reach" measurements. Provides a more detailed level of interpretation and extrapolation than Level I.
III	Stream "state" or condition	Riparian vegetation, depositional patterns, meander patterns, confinement features, fish habitat indices, flow regime, river size category, debris occurrence, channel stability index, bank erodibility	The "state" of streams further describes existing conditions that influence the response of channels to imposed change and provide specific information for prediction methodologies (such as stream bank erosion calculations, etc.). Provides for very detailed descriptions and associated prediction/interpretation.
IV	Verification	Involves direct measurements/observations of sediment transport, bank erosion rates, aggradation/degradation processes, hydraulic geometry, biological data such as fish biomass, aquatic insects, riparian vegetation evaluations, etc.	Provides reach-specific information on channel processes. Used to evaluate prediction methodologies; to provide sediment, hydraulic and biological information related to specific stream types; and to evaluate effectiveness of mitigation and impact assessments for activities by stream type.

According to (Rosgen 2001) initial assessment is done at all four levels until a quantitative relationship is established by prediction. Level I and II assessments are done to establish stratification of the reach by valley and stream type. Whereas Level III (stream state or condition level), is used to predict the stream stability. Level IV on the other hand is validation of inventory. It is the level at which measurements are made to validate the relationship(s) between the processes. This requires detailed measurements over a long period.

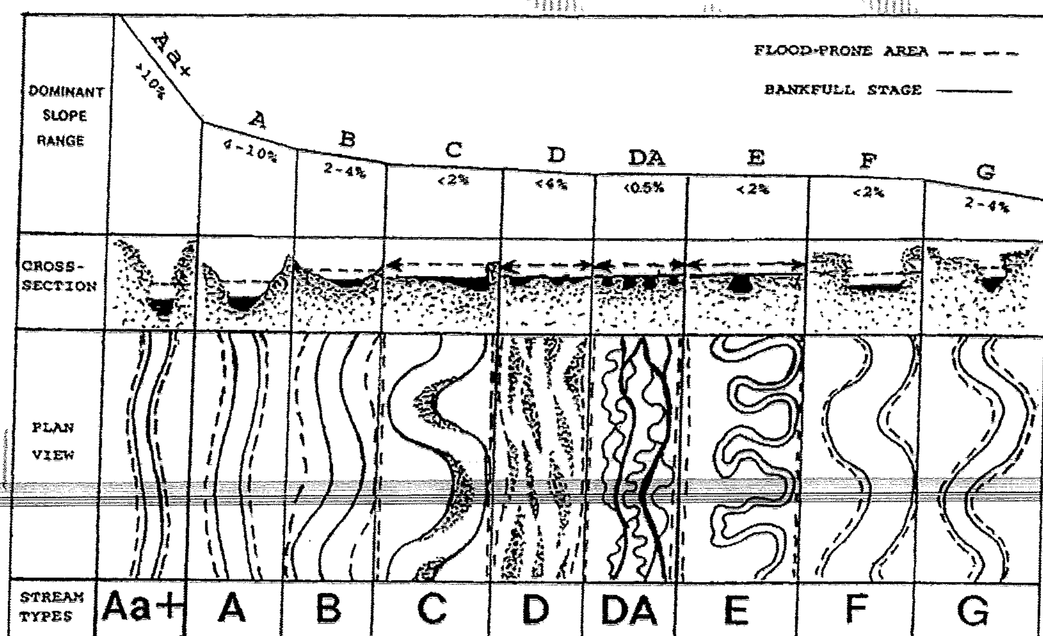

Figure 2.4 Longitudinal, cross-sectional and plan views of major stream types

Rosgen used longitudinal profiles inferred from topographic maps to differentiate streams into slope categories that replicate stream morphology. These stream classes range from Type Aa+ (very steep) to Type G (gullies) as shown in Figure 2.4 (also see Figures 2.5-2.11) and as described in Table 2.2.

Figure 2.5 Rosgen Type A

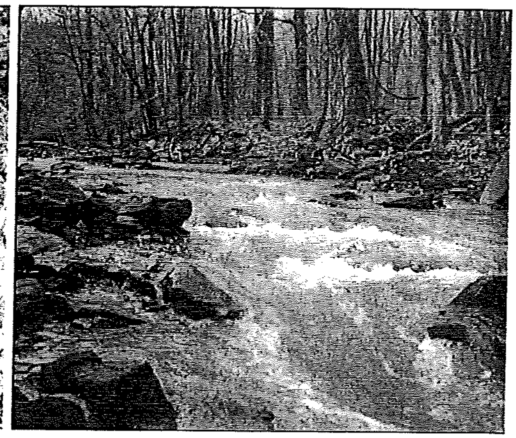

Figure 2.6 Rosgen Type B

Figure 2.7 Rosgen Type C

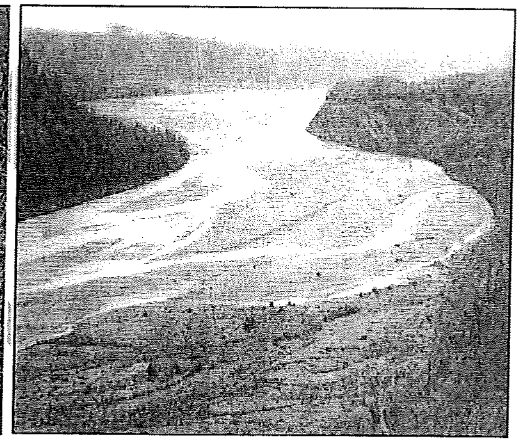

Figure 2.8 Rosgen Type D

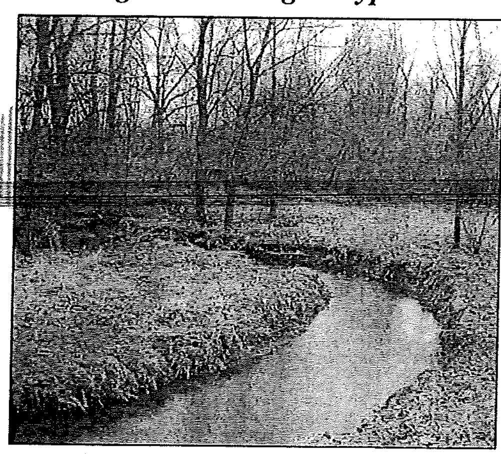

Figure 2.9 Rosgen Type E

Figure 2.10 Rosgen Type F

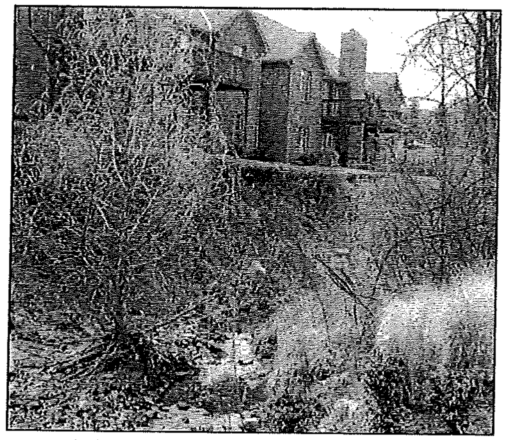

Figure 2.11 Rosgen Type G

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Table 2.2 Summary of delineative criteria for broad-level classification

Stream type	General description	Entrenchment ratio	*W/D* ratio	Sinuosity	Slope	Landform/soils/features
Aa +	Very steep, deeply entrenched, debris transport streams.	< 1.4	< 12	1.0 to 1.1	> 0.10	Very high relief. Erosional, bedrock or depositional features; debris flow potential. Deeply entrenched streams. Vertical steps with/deep scour pools; waterfalls.
A	Steep, entrenched, cascading, step/pool streams. High energy/debris transport associated with depositional soils. Very stable if bedrock or boulder dominated channel.	< 1.4	< 12	1.0 to 1.2	0.04 to 0.10	High relief. Erosional or depositional and bedrock forms. Entrenched and confined streams with cascading reaches. Frequently spaced, deep pools in associated step-pool bed morphology.
B	Moderately entrenched, moderate gradient, riffle dominated channel, with infrequently spaced pools. Very stable plan and profile. Stable banks.	1.4 to 2.2	> 12	> 1.2	0.02 to 0.039	Moderate relief, colluvial deposition and/or residual soils. Moderate entrenchment and *W/D* ratio. Narrow, gently sloping valleys. Rapids predominate with occasional pools.
C	Low gradient, meandering, point-bar, riffle/pool, alluvial channels with broad, well defined floodplains	> 2.2	> 12	> 1.4	< 0.02	Broad valleys with terraces, in association with floodplains, alluvial soils. Slightly entrenched with well-defined meandering channel. Riffle-pool bed morphology.
D	Braided channel with longitudinal and transverse bars. Very wide channel with eroding banks.	n/a	> 40	n/a	< 0.04	Broad valleys with alluvial and colluvial fans. Glacial debris and depositional features. Active lateral adjustment, with abundance of sediment supply.
DA	Anastomosing (multiple channels) narrow and deep with expansive well vegetated floodplain and associated wetlands. Very gentle relief with highly variable sinuosities. Stable streambanks.	> 4.0	< 40	variable	< 0.005	Broad, low-gradient valleys with fine alluvium and/or lacustrine soils. Anastomosed (multiple channel) geologic control creating fine deposition with well-vegetated bars that are laterally stable with broad wetland floodplains.
E	Low gradient, meandering riffle/pool stream with low width/depth ratio and little deposition. Very efficient and stable. High meander width ratio.	> 2.2	< 12	> 1.5	< 0.02	Broad valley/meadows. Alluvial materials with floodplain. Highly sinuous with stable, well vegetated banks. Riffle-pool morphology with very low width/depth ratio.
F	Entrenched meandering riffle/pool channel on low gradients with high width/depth ratio.	< 1.4	> 12	> 1.4	< 0.02	Entrenched in highly weathered material. Gentle gradients, with a high *W/D* ratio. Meandering, laterally unstable with high bank-erosion rates. Riffle-pool morphology.
G	Entrenched "gulley" step/pool and low width/depth ratio on moderate gradients.	< 1.4	< 12	> 1.2	0.02 to 0.039	Gulley, step-pool morphology with moderate slopes and low *W/D* ratio. Narrow valleys, or deeply incised in alluvial or colluvial materials; i.e., fans or deltas. Unstable, with grade control problems and high bank erosion rates.

The stream properties presented in Table 2.2 are the expected mean values for each stream class. It is common for some streams not to meet the expected specified value, especially in the mid-western regions. Ward et al. (2008) mentioned that this is because few streams in the mid-west were used to develop the Rosgen method. He further mentioned that the majority of streams in the mid-western region fall between Types C and E. Type C streams are found in areas of flat plains that have a wide range of bed slopes, with silt and clay banks and beds. Type E streams are similar to Type C streams, except that they do have a lower width-to-depth ratio. Type F streams are common in urbanized areas and are prone to human changes such as removal of floodplain vegetation, channelization and/or control structures (e.g. stream crossings) (Ward et al. 2008).According to (Ward et al. 2008),Type G streams are mostly constructed agricultural ditches, typically found in agricultural regions of the mid-west. It is worth to noting that Types C, E and F streams are usually classified as fourth order streams or greater. Stream classification may prove to be a useful tool for providing insight into potential instability or problems associated with a given stream type prior to construction.

2.3 Geomorphic factors affecting stream stability

The majority of the streams crossed or altered by stream crossings are alluvial streams that are prone to bank erosion, sediment deposition, island formation, and side channel modification over time (Lagasse et al. 2012).These gradual or rapid changes are a result of hydraulic forces exerted on the banks and bed. As a result, these channels recurrently change shape and position. The geomorphic factors affecting the stability of streams are given in Figure 2.5.

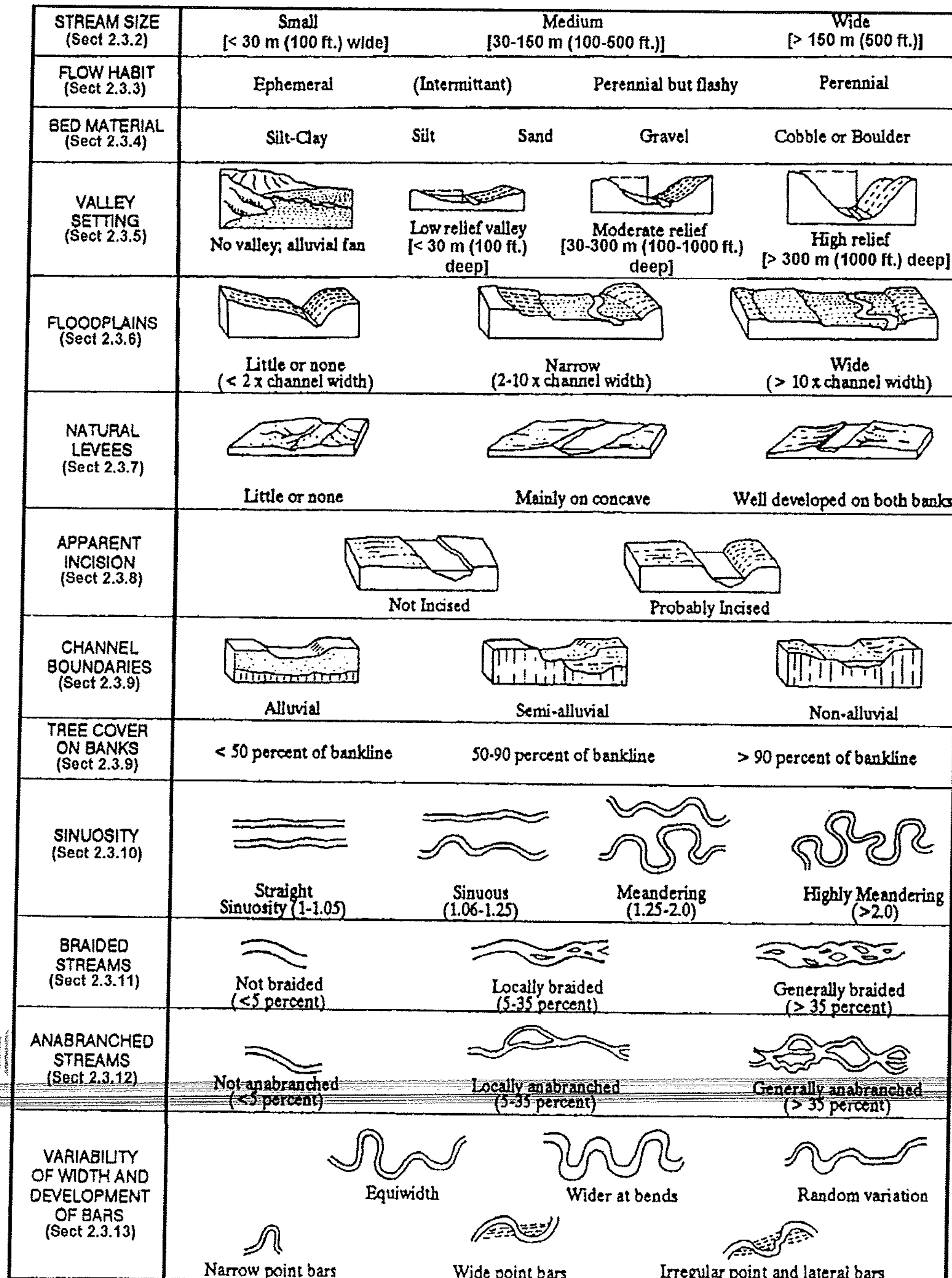

Figure 2.5 Geomorphic factors affecting stream stability (adapted from FHWA 1978, (Lagasse et al. 2012))

The potential for scour and lateral erosion is strongly influenced by stream depth and size. Scour increases with stream depth; whereas lateral erosion increases with stream size. Stream depth also has a tendency to increase with size. Therefore scour depth tends to increase with stream size. The width of a stream channel is commonly measured from bank-to-bank. For equilibrium streams, in a situation where one bank is indefinite, the line of permanent vegetation on the inside of the bank isused as the best indicator of the bank line.

The stability of both perennial and ephemeral streams depends on the channel boundaries and bed material. Streambeds are classified as silty-clay, sand, gravel, cobble, or boulder depending on the dominant size of the bed material. Streambeds having high sand or sand-silt contents are more susceptible to scour. On the other hand, streams found in hilly or mountainous regions are generally steep with coarse bed material and are non-alluvial and stable. Furthermore, streams found in areas of lower relief have higher potential to erode laterally and are often unstable. During flood events, water overflows the channel banks and has the tendency to deposit its sediments on the flood plain, forming natural levees. At the overbanks, the flow velocity is lower than in the main channel, therefore the coarse material will be quickly deposited. Lagasse et al. (2012) mention that streams with well-developed natural levees usually have constant width and a lower rate of lateral erosion.

A stream has the tendency to cut into the bed of a valley through degradation. This process is referred to as incision. Apparent incision of a stream is defined by the height of its banks at normal flow relative to its width. This is known as the Bank Height Ratio (see Figure 2.6).

Stability Rating	Bank Height Ratio
Stable (low risk of degradation)	1.0 - 1.05
Moderately unstable	1.06 - 1.3
Unstable (high risk of degradation)	1.3 - 1.5
Highly unstable	> 1.5

Figure 2.6 Bank stability rating (Rosgen 2001)

Analysis of the bed and boundary material characteristics, the ability of the stream flow to mobilize and transport sediment, and the bank and channel vegetation distribution provides important insight about channel stability. The level of instability is also controlled by the frequency and magnitude of flood events and the resulting discharge from these flood events. Approximately 90 percent of changes in stream channels are recorded when the flow equals or exceeds the dominant discharge (Lagasse et al. 2012).Understanding the particle sizes of the banks and bed material provide insight to the stability of these channels (the visible appearance of the channel material can be a good indicator of channel stability).Lagasse et al. (2012)provided the following identifying characteristics that can be associated with erosion rate:

Bank slope

- Banks slopes exceeding 30 percent with rare presence of woody vegetation cover are unstable. Irregular indentations are a good indicator of rapid erosion.
- Presence of debris (e.g., falling trees) is a good indicator of eroding banks. Eroding banks indicate unstable banks with potential to block culverts and bridges openings.
- Stable banks, banks with slopes of less than 30 percent, on the other hand, have slow erosion rates.

Figure 2.7 Active bank erosion showing vertical bank cuts and falling vegetation (Lagasse et al. 2012)

Bank materials

- Non-cohesive materials are more susceptible to removal of particle grains from the bank, and for this reason are prone to erosion. The rate of erosion is dependent on particle size, bank slope, magnitude and direction of velocity adjacent to the bank, turbulence, shear stress exerted on the banks and seepage forces.
- Cohesive materials are more resistant to surface erosion. The cohesive nature of the sediment reduces the effects of seepage and subsurface flow. However, such banks can fail due to the mass wasting process, especially in saturated and/or undercut conditions.
- Composite or stratified banks are composed of materials of various sizes, have variable permeability, or display variations in cohesion. In composite banks, an adjacent layer of cohesive materials may protect the non-cohesive banks. However, this type of bank is prone to erosion and sliding.

The failure type of each of the above conditions are portrayed in Figure 2.8

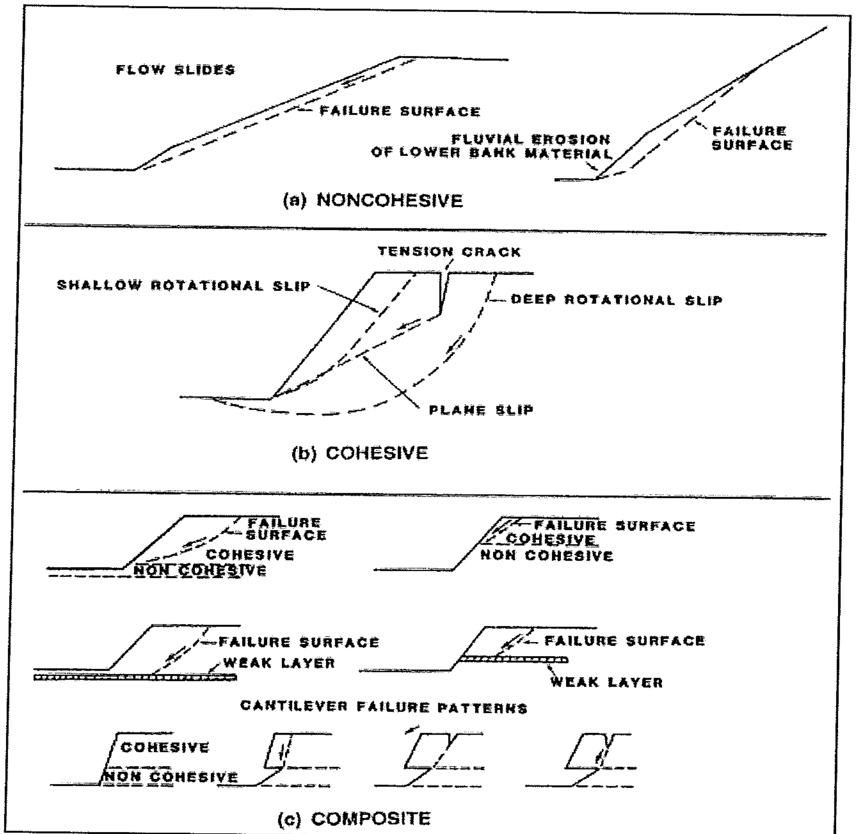

Figure 2.8 Typical bank failures (after FHWA 1985) (Lagasse et al. 2012)

The geomorphic factors discussed above will result in aggradation or degradation of the streambed. Aggradation is the increase in channel bed or flood plain elevation due to the deposition of sediment that occurs when the amount of available sediment is greater than what the stream can carry. Degradation is the lowering of the streambed surface, or floodplain, through erosion.

2.4 Hydraulic factors affecting stream stability

The geometry of a stream crossing is an important factor for consideration in the design of a stream crossing structure and in the assessment of potential stream instability. Consequently, assessments of the factors that differentiate stream flow and channel geometry are important considerations in the design of culvert structures against scour and stream instability.

As an introduction, hydraulic principles are based on the basic laws of conservation of mass, energy, and momentum. The equations of continuity, energy, and momentum are derived from these three laws, respectively. In addition, these three equations and Manning's equation are the fundamental equations for analysis of closed and open channel hydraulics. These equations are given as follows;

1. The continuity equation

$$Q_1 = Q_2 = A_1 V_1 = A_2 V_2 \qquad 2.1$$

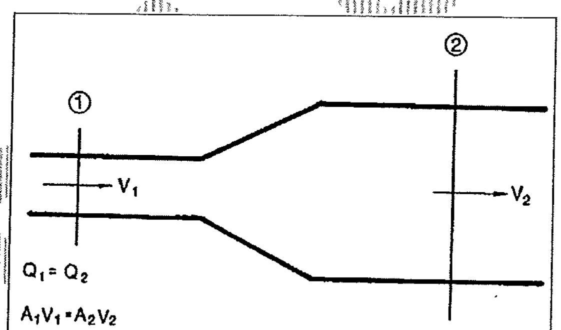

Figure 2.9 Definition sketch of continuity

2. The energy equation

$$Z_1 + y_1 + \frac{V_1^2}{2g} = Z_1 + y_2 + \frac{V_2^2}{2g} + h_l \qquad 2.2$$

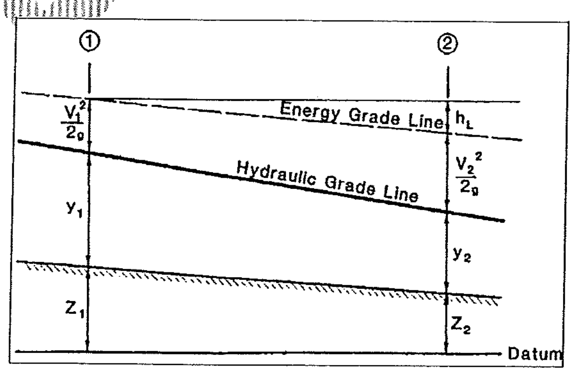

Figure 2.10 Definition sketch forenergy in open channel flow

3. The momentum equation

$$\sum F = \sum_{out} \rho QV - \sum_{in} \rho QV \qquad 2.3$$

4. The Manning equation

$$V = \frac{K_u}{n} R^{2/3} S^{1/2} \qquad 2.4$$

where V in mean cross-sectional velocity, A is the area perpendicular to velocity, Q is the volume flow rate, Z is the elevation above datum, y is depth of flow at a cross-section, h_L is the energy head loss, F is force, and ρ is the fluid density. In addition, R is the hydraulic radius (area/wetted perimeter), S is the channel slope, and n is Manning's coefficient of channel roughness, K_u is a unit conversion factor equal to 1.0 for SI units and 1.486 for English units. The above equations are the fundamental equations for estimating flow and depth in a stream channel.

Error! Reference source not found. (adapted from Lagasse et al. 2012) shows more specific channel hydraulics factors of a stream that affect channel stability.

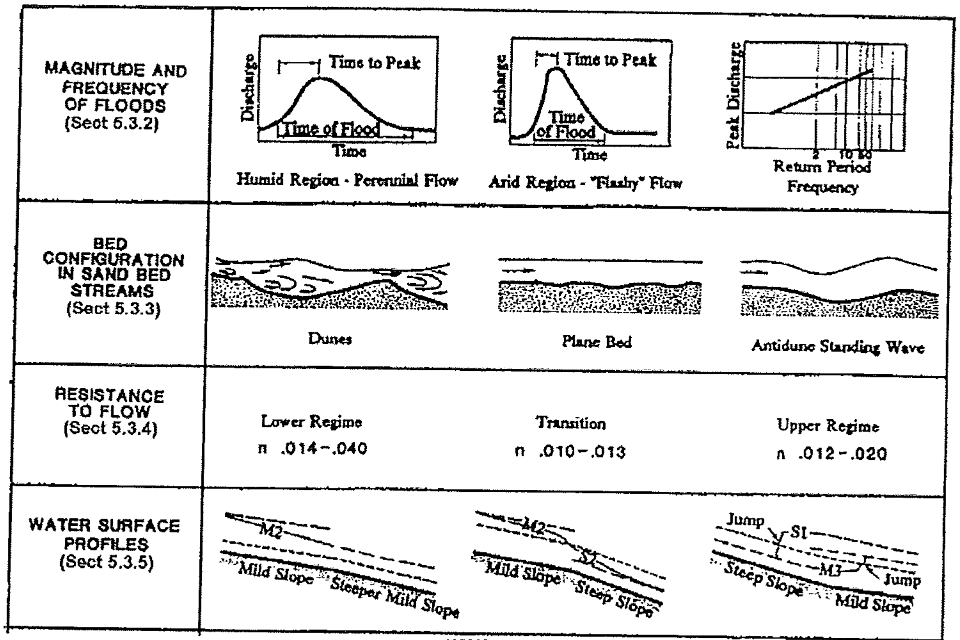

Figure 2.11 Hydraulic factors affecting stream stability (Lagasse et al. 2012)

The magnitude and frequency of floods are usually analyzed on a regional basis by the USGS or other agencies. The resultant peak discharges and flow depths from statistical storm events are determined using gaging stations and the results are extended to represent the total population of streams in the watershed. Statistical techniques such as the Pearson Type III distribution are used to establish the frequency of these storm events (Lagasse et al. 2012). If a design flood is considered for analyzing stream stability it should be the resulting storm magnitude and depth that will cause overtopping of the banks.

Bed configurations have a significant effect on resistance to the flow, velocity, depth, and sediment transport. Understanding the bed forms present in a stream channel is important for estimating the Manning's roughness coefficient. The types of bed roughness in a sand channel and the effect of bed forms on water surface elevation are shown in Figure 2.12and Figure 2..

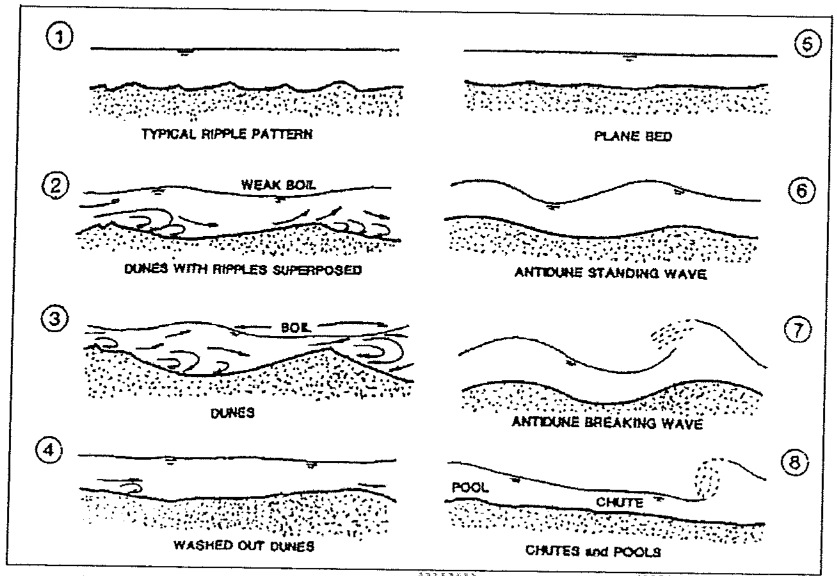

Figure 2.12 Forms of bed roughness in sand channels

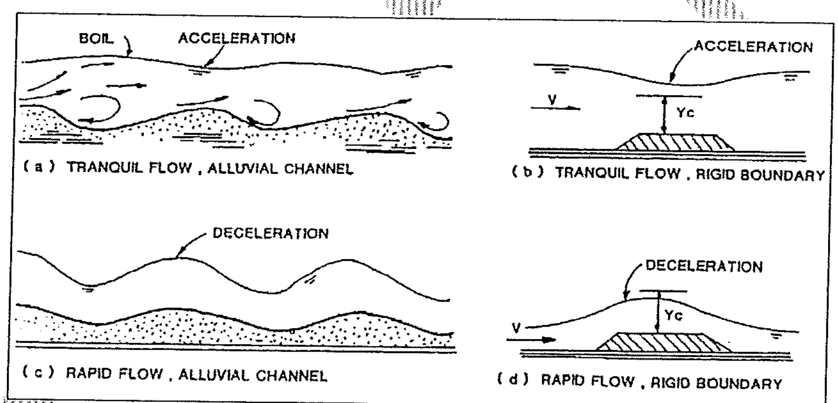

Figure 2.20 Association between water surface and bed forms

Lagasse et al. (2012) explained that high flows could shift bed form characteristics from a dune bed to a transition or plane bed, consequently decreasing the flow resistance by one-half to one-third. Decreasing flow resistance will result in increasing velocity and reduced depth and a corresponding increase in scour around abutments and channel banks, creating instability.

2.5 Assessment of stream channel stability

Some factors that affect stream channel stability that are of importance to engineers involved with designing road-stream crossing structures such as culverts and bridges were discussed earlier. However, the primary task of the engineer is to use quantitative assessment methodologies that can differentiate between the various stability states. Rosgen (2001) mentioned that the stability prediction and validation method is based on a hierarchical framework developed using field measured variables to assess:(1) stream state or channel condition variables,(2) vertical stability (degradation/aggradation),(3) lateral stability, (4) channel patterns,(5) stream profile and bed features,(6) channel dimension factor, (7) channel scour/deposition,(8) stability ratings, (9)dimensionless ratio sediment rating curves, and (10) stream type evolution scenarios. Rosgen used these ten steps to develop a sequential methodology for field assessment of stream stability. A brief discussion of these steps is discussed in the following sections.

2.5.1 Stream Channel Condition or "State" Categories

Channel characteristics are determined from field inspection and measurements. This can be achieved by evaluating the following seven categories and associated variables: (1) riparian vegetation, (composition, density), (2) sediment deposit patterns, (3) debris occurrence (large woody debris), (4) meander patterns, (5) stream size or stream order, (6) flow regime (perennial, ephemeral, etc.) and (7) altered state (channelization, levees, straightening etc.).Rosgen (2001) mentioned that these seven conditions provide insights about the characteristic of the stream being assessed.

2.5.2 Vertical Stability (Aggradation/Degradation)

The vertical stability of the stream banks is determined from the bank height and entrenchment ratio measured from the field see Figure 2.6. Bank height ratios greater than 1.2 are an indication of significant stream bank erosion. In such cases, the bank height is mostly below the depth of riparian vegetation roots. It is important to determine if the stream no longer inundates the adjacent floodplain because of stream incision (degradation) by calculating the entrenchment ratio. According to Rosgen (2001), the entrenchment ratio is calculated by determining the flood-prone width of the channel when the depth is twice the bankfull depth. The entrenchment ratio is then the ratio of the flood-prone width to the bankfull width. If the entrenchment area is less than 1.4 the stream is entrenched. The deposition of coarse material on the flood plain and a very high width/depth ratio is an indication of aggradation.

The longitudinal profile of the channel reach, the bank-full height and the lowest bank height provide evidence of channel degradation; either moving downstream or in the form of a knickpoint advancing from the downstream direction. Knickpoints occur as a result of differential erosion rates upstream and downstream of the knickpoint (resulting in a change in the channel slope). The creation and migration of knickpoints have a critical influence on the stability of a stream channel. Knickpoints are known to cause channel-widening, lead to bank failures and steepen side banks. From Table 2.3 increases in channel width to depth ratio will result in channel instability. Figure 2.13 and Figure 2.14 are photos from a knickpoint study site in Mud Creek Mills County, Iowa. Figure 2.21 shows bank failures that result from the passage of a knickpoint through loess soils.

Figure 2.13 Knickpoint effect on stream stability (A) Steepening of side slopes,(B) Bank failure, (C) Channel Widening (Courtesy of Clark K Kephart)

Figure 2.22 shows one of a series of knickpoints that has passed through the site. The presence of a knickpoint in the channel is a confirmation of channel degradation and potential instability. As knickpoints migrate upstream, the existence or appearance of a knickpoint downstream of an existing road-stream crossing (or a potential site for a stream crossing) is a good reason for concern. In the case of fixed-boundary culverts, the arrival of a knickpoint at a stream-crossing will leave the culvert perched. In the case of moveable beds, the arrival of a knickpoint at a stream crossing can potentially undercut abutments and piers.

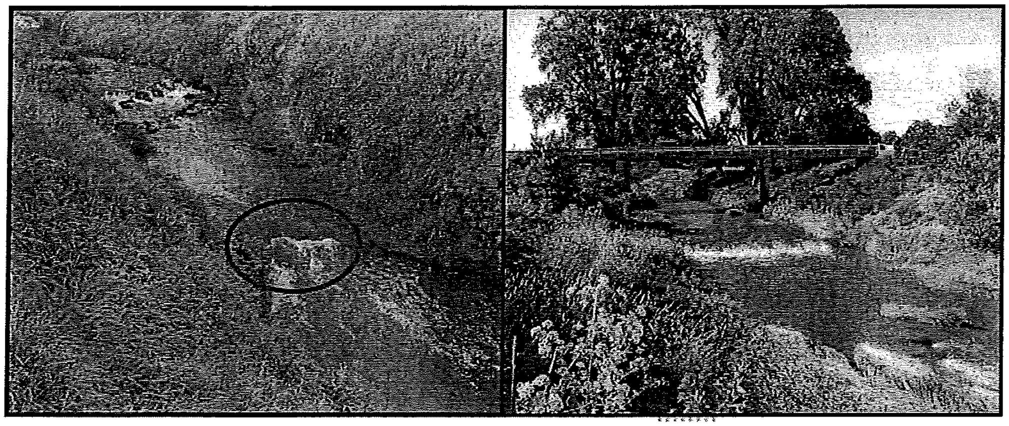

Figure 2.14 (A) Knickpoint , (B) Knickpoint moving upstream towards Elderberry bridge, Iowa

2.5.3 Lateral Stability

Along with bed degradation and aggradation, lateral containment and potential lateral enlargement of the stream channel is also an important consideration. Rosgen (2001) mentioned that parameters used for assessing lateral stability include; (1) the meander to width ratio (degree of confinement), (2) the stream bank erosion hazard index (BEHI) and (3) the near- bank stress (NBS).The meander to width ratio is the ratio of the meander length to the bankfull width. The amount of sediment generated by a stream is the annual lateral stream bank erosion rate multiplied by the bank height and stream length for specific BEHI and NBS ratings. Important Level IV data may include installation of toe pins in cross-sections in order to accurately measure stream bank erosion rates and lateral accretion, but an accurate assessment of the erosion rate can require a long observation period.

2.5.4 Channel Patterns

Channel pattern analysis may include the calculation of dimensionless ratios like the ratio of the curvature to bankfull width, sinuosity, arc length, arc angle, and the meander to width ratio. It is important to use dimensionless ratios since reference reach geometric data differ if the stream is of a different size, even if the valley and stream type of the reference reach is the same. Level IV analysis may also utilize aerial photo trends and cross-sections showing channel meander migration.

2.5.5 River Profile and Bed Features

The longitudinal profile of the channel can be determined and used to identify changes in the channel slope as compared to the valley slope (the results are sensitive to sediment transport and the energy balance). Some parameters that may be of importance and can be computed from longitudinal profile data include: (1) the pool-to-pool spacing, (2) the ratio of maximum pool depth to mean channel depth, and (3) the maximum depth of riffles to mean bankfull depth. Decreases in the maximum pool depth to mean channel depth ratio, widening of the stream, decreases in sinuosity, and increases in slope are all indicators of stream instability. The spacing of steps and pools in steeper stream types are inversely proportional to slope and directly proportional to channel width (Rosgen, 2001). Rosgen explained that the complete removal of large woody debris mostly will result in increased step to pool spacing and consequently increase the potential for channel degradation because of an increase in excess stream energy. Level IV validation of predicted estimates may be obtained by initiating a temporal profile observation with a benchmark tied to a series of permanent cross sections or station points.

2.5.6 Channel Dimension Relations

A change in the bankfull width to mean bankfull depth ratio is a very good indicator of a departure from reference reach characteristics and also of instability.

Table 2.3 Width to depth ratio and channel instability

Stability Rating	Ratio of W/D Increase
Very stable	1.0
Stable	1.0 - 1.2
Moderately unstable	1.21 - 1.4
Unstable	> 1.4

Large width to depth ratios are associated with accelerated streambank erosion, excessive sediment deposition, changes in streamflow, shifts from one stream type to another (because of channel widening), etc. On the other hand, a decrease in the width to depth ratio is an indication of channel incision. The Level IV analysis establishes benchmark cross-sections that can be used to determine degree and rate of change in both width to depth and bank height ratios.

2.5.7 Stream Channel Scour

In some cases, the critical dimensionless shear stress can be calculated in order to determine the size of sediment that can be transported by the channel and the Shields relation can be applied to compare the existing slope to that required to transport the largest sediment present in the reach. The following equations can be used:

$$\tau_{ci} = 0.0834\left({d_{50}}/{ds_{50}}\right)^{-0.872} \qquad 2.5$$

$$d = \frac{\tau_{ci}\gamma_s D_i}{S} \qquad 2.6$$

where: τ_{ci} is the critical dimensionless shear stress, d_{50} is the median diameter of bed material, ds_{50} is median diameter of a bar sample, d is mean bankfull depth, S is the water surface slope at the bankfull stage, D_i is the largest diameter of particle on the bar and γ_s is the submerged specific weight of sediment. The effects of stream channel scour on hydraulic structures such as culverts will be discussed in detail in the next chapter.

2.5.8 Stream Channel Stability Rating (modified Pfankuch procedure)

A stability rating can be calculated to evaluate the stability of the upper and lower banks and the streambed for evidence of aggradation or degradation. Pfankuch proposed this system in 1975. The system ranks a channel based on the risk of instability with a higher number meaning greater risk of instability. The Pfankuch method of rating was modified to take stream type into consideration (Rosgen 2001) as shown in Figure 2.15.

Stream Type	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6
Good (Stable)	38-43	38-43	54-90	60-95	60-95	50-80	38-45	38-45	40-60	40-64	48-68	40-60
Fair (Mod. Unstable)	44-47	44-47	91-129	96-132	96-142	81-110	46-58	46-58	61-78	65-84	69-88	61-78
Poor (Unstable)	48+	48+	130+	133+	143+	111+	59+	59+	79+	85+	89+	79+
Stream Type	C1	C2	C3	C4	C5	C6	D3	D4	D5	D6		
Good (Stable)	38-50	38-50	60-85	70-90	70-90	60-85	85-107	85-107	85-107	67-98		
Fair (Mod. Unstable)	51-61	51-61	86-105	91-110	91-110	86-105	108-132	108-132	108-132	99-125		
Poor (Unstable)	62+	62+	106+	111+	111+	106+	133+	133+	133+	126+		
Stream Type	DA3	DA4	DA5	DA6	E3	E4	E5	E6				
Good (Stable)	40-63	40-63	40-63	40-63	40-63	50-75	50-75	40-63				
Fair (Mod. Unstable)	64-86	64-86	64-86	64-86	64-86	76-96	76-96	64-86				
Poor (Unstable)	87+	87+	87+	87+	87+	97+	97+	87+				
Stream Type	F1	F2	F3	F4	F5	F6	G1	G2	G3	G4	G5	G6
Good (Stable)	60-85	60-85	85-110	85-110	90-115	80-95	40-60	40-60	85-107	85-107	90-112	85-107
Fair (Mod. Unstable)	86-105	86-105	111-125	111-125	116-130	96-110	61-78	61-78	108-120	108-120	113-125	108-120
Poor (Unstable)	106+	106+	126+	126+	131+	111+	79+	79+	121+	121+	126+	121+

Figure 2.15 Modified stability rating for reach condition by stream type

2.5.9 Stream type evolutionary scenarios

Progressive changes in stream shape and form over a period (stream evolution) can be used to estimate channel instability. A typical example is shown in Figure 2.16 adapted from (Rosgen 2001).He explained that a C4 stream (a gravel-bed, meandering channel with a floodplain)can undergo conversion to a G4 stream (an incised gully channel type), which can further progress to an F4 stream (an entrenched, meandering channel), which can undergo further widening to eventually return to a C4 stream type. Understanding the evolution sequence of a stream is an important factor in analyzing stream stability.

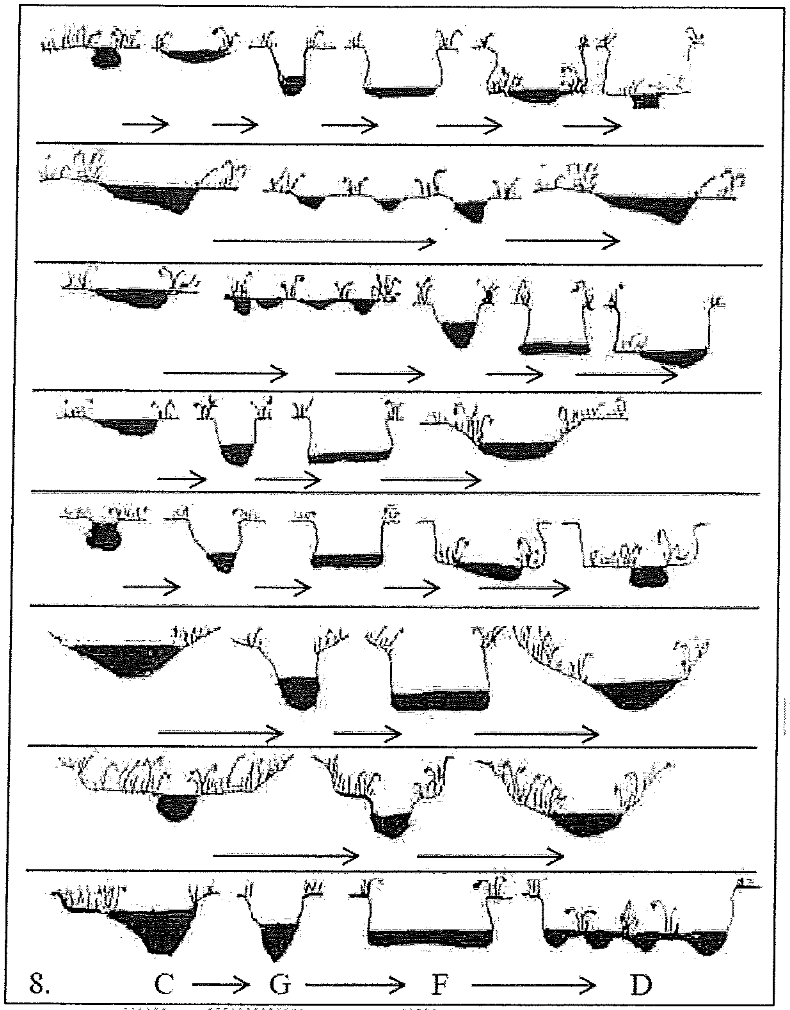

Figure 2.16 Stream evolution scenarios

2.5.10 Morphology

A good understanding of the effect of stream crossings on channel morphology will assist in designing stream crossing structures to accommodate geomorphic changes, reduce the potential of failure of stream crossing structures and minimize effects of the stream crossing on the riparian environment (SHA 2007). A table of general observations that are useful for understanding an existing or potential site is provided by SHA (2007) in Table 2.4.

Table 2.4 Culvert observation criteria (SHA 2007)

Features	General Observations	Indications and Considerations
Aggradation upstream of culvert	Upstream sediment deposition	Upstream backwater may have caused a reduction in sediment transport capacity upstream of culvert. May indicate that the culvert size is inadequate.
Suppressed culvert inlet	Culvert inlet invert below upstream channel invert.	Culvert should be examined to determine whether the channel has aggraded within the culvert or whether the culvert was intentionally constructed with its inlet invert below the upstream invert of the channel.
Debris on culvert inlet	Debris and upstream sediment deposits	Culvert is incapable of transporting the supplied debris load. If the debris blockage is chronic, then the upstream channel may have responded by aggrading and migrating laterally because of persistent backwater effects. Debris blockage may also affect roadway overtopping frequency, which may cause embankment damage.
Skew of channel to culvert inlet	Bank erosion, scour holes at the inlet, and misalignment of the channel and culvert	Culvert inlets misaligned with the flow may cause bank erosion, scour hole formation around wing walls, and reduced flow conveyance. Reduced conveyance may lead to sediment deposition upstream, upstream flooding, and increased frequency of roadway overtopping.
Downstream bank erosion	Erosion of bends downstream of culvert outlet	High velocity flow exiting the culvert can cause severe bank erosion in downstream bends.
Outlet scour pool	Scour hole with riffle downstream composed of ejected sediment	High velocity flow exiting the culvert can form a large scour hole downstream that may undermine the culvert outlet.
Perched outlet	Step in the low-flow water surface profile at the culvert outlet	The culvert outlet is considered "perched" if the outlet invert is elevated with respect to the low-flow channel water surface immediately downstream. Perched outlet conditions are a result of (1) downstream channel degradation that has migrated upstream to the culvert outlet and/or (2) high outlet-velocity flow that has caused outlet scour of a steeply sloping downstream channel. Often, channel degradation and high outlet-velocity flow combine to cause large scour holes and perched outlets. Degradation initiated by channel disturbances downstream of the culvert will be indicated by degradation of the channel well beyond the limits of the culvert outlet scour pool. On the other hand, scour caused solely by high outlet-velocity flow discharging from the culvert outlet tends to be limited to the extent of the scour hole and the deposited material eroded from it. On steep streams, long scour holes at outlets can effectively reduce the slope of the downstream channel, resulting in a perched outlet.
		Fish passage may be impeded by a perched culvert outlet.
Suppressed culvert outlet	Culvert outlet invert below downstream channel invert.	Culvert may have been constructed with its outlet below the downstream invert of the channel. Culvert should be examined to determine whether the channel has aggraded within the culvert or whether the culvert invert was intentionally placed below the upstream streambed elevation. *(continued)*

Table 2.4 (continued) Culvert observation criteria (SHA 2007)

Features	General Observations	Indications and Considerations
Sediment deposit downstream of outlet pool	Aggradation downstream and deep pool within culvert	Channel aggradation in the channel downstream of the culvert may cause backwater into the culvert that can reduce its capacity to convey flood flow.
Wide and/or multiple-barrel/ cell culvert	Sediment deposition in one or all culvert barrels or cells	Channel may have been widened locally to transition into a wide box or multiple-cell/barrel culvert. Expanding the channel width may have resulted in deposition in several barrels/cells, reducing the design capacity of the culvert.
Modification to culvert to facilitate fish passage	Fish ladders, baffles, lowered inverts, low flow weirs, and other culvert modifications; constructed riffles, grade control structures, and other channel modifications	Various structures have been used to facilitate fish passage in culverts. Structures and channel modifications may have been constructed to reduce or eliminate the perched condition at the culvert outlet and to increase the low-flow channel depth in the culvert.

Chapter 3 Scour

3.1 Introduction

Scour is defined as the erosion or removal of stream bed or bank material from bridge foundations and culvert inlet and outlets due to flowing water. It is the most common cause of highway bridge and bottomless culverts failures in the United States. This is because of the increase in velocity at the approach and exit of these structures. Scour, if allowed to progress, can undermine culvert and bridge stability. Cohesive and composite soils are more scour-resistant, whereas non-cohesive soils are more susceptible to scour. Nevertheless, the ultimate scour depth in cohesive or composite soils can be as deep as scour in non-cohesive soils (Arneson et al. 2012). The total scour at stream crossings consists of three components:

- Long term degradation of the stream bed
- General scour at the bridge
- Local scour at the piers or abutments

These three components are summed to obtain the total scour. Scour in riverine environments is generally manifested in one direction (i.e. downstream). Bottomless culverts are typical constructed on a spread footing foundation and as a result, the issue of scour is very important to the design of these structures. According to Kerenyi et al. (2007) and Arneson et al.(2012) many state highway agencies prefer bottomless culverts to be founded on solid rock formations. The consequences of failure require that a rigorous method for estimating depth of scour be developed for all types of soil formations. Scour problems associated with bottomless culverts are comparable to abutment and contraction scour at bridges and as such can be analyzed in a similar fashion. Note that stream stability is closely related to scour, and understanding both processes is paramount to the proper design and construction of bottomless culverts. The basic concept and the effect of scour on road-stream crossing structures and the countermeasures required to remedy issues associated with scour are discussed in this section.

3.2 Types of scour

3.2.1 Long term degradation

Long-term degradation (lowering or scouring) of streambed elevation can be caused by natural or man-induced conditions, affecting the road-stream crossing reach. Degradation happens because of a deficit in upstream sediment supply relative to current stream hydraulic conditions. This deficit may occur because of a change in channel slope, a change in peak discharge, a change in the amount of available sediment, or a change in sediment mobility. Long term degradation does not pertain to scour associated with individual storm runoff events, rather, long term bed elevation changes occur as a result of things like installation of dams and reservoirs, changes in watershed land use and land cover (e.g., deforestation, urbanization, etc.),channelization and changes in the channel base level, and removal of material from the stream bed.

According to Kerenyi et al. (2007),long-term assessment can be conducted using qualitative and quantitative relations and by using computer models such as HEC-RAS. In addition, the USGS maintains gaging stations at some crossing sites, with historic records of stream discharge with respect to depth. According to Kerenyi et al. (2007), a plot of stream depth over time for a particular discharge value can provide insight into the changes in channel elevation over time. Figure 3.1 is an example plot of change in stream bed elevation due to long term degradation using USGS gaging station data from 1900-1990.

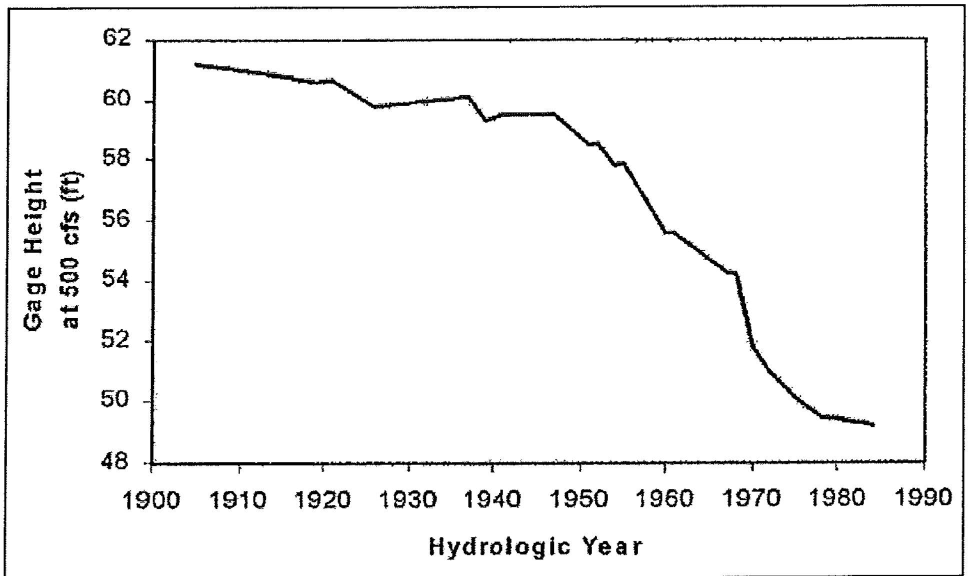

Figure 3.1 Specific gage data for Cache Creek, California showing change in gage height over time for the same discharge (500cfs)

3.2.1.1 Incipient motion analysis

The study of geologic and geomorphologic conditions provides insight into the potential for long-term streambed elevation change. One widespread quantitative technique for analyzing streambed aggradation and degradation is incipient motion analysis. Incipient motion is the condition established when the hydrodynamic forces acting on a hypothetical sediment particle on the bed of a channel is just enough to move the particle. The sediment particle will begin to move when the flow induced shear stress reaches or exceeds a specific critical value. The incipient motion of a particle is often defined using a standard or modified form of the Shields parameter (Buffington and Montgomery 1997). The Shields parameter is a dimensionless critical shear stress defined by the equation:

$$\tau_{c_i}{}^* = {}^{\tau_{c_i}}/_{(\rho_s - \rho) g D_i} \qquad 3.1$$

where τ_{c_i} is the critical shear stress of incipient motion for grain size D_i,ρ_s is the density of the sediment, ρ is the fluid density, and g is the gravitational acceleration. According to Buffington and Montgomery (1997)) the critical shear stress value of the median grain size particle ($\tau_{c_{50}}{}^*$) is most relevant for high boundary Reynolds number (gravel- bedded) type flow.Buffington and Montgomery (1997) went on to cite the work done by many other researchers in this field as follows; Shields (1936) demonstrated that for near-uniform grains $\tau_{c_{50}}{}^*$ varies with critical boundary Reynolds number (express as $Re_c{}^*$).Shields (1936) and Nikuradse (1933) obtained a similar constant value for critical shear of approximately 0.06 for values of critical Reynolds number that are greater than 489.

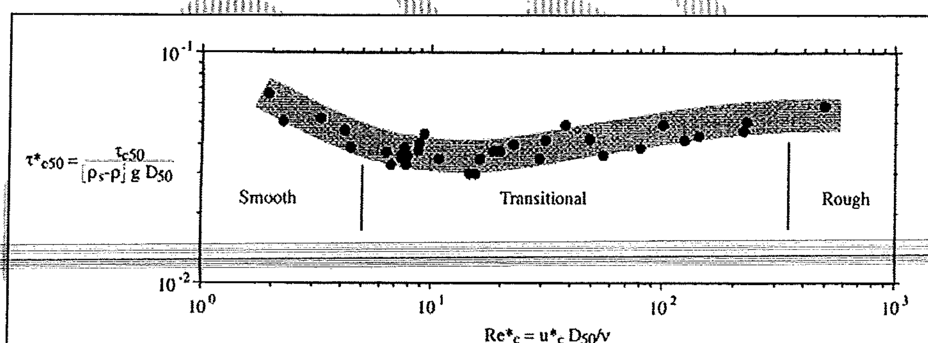

Figure 3.2 Shields (1936) curve (Buffington and Montgomery 1997)

The critical boundary Reynolds number is defined by the equation;

$$Re_c{}^* = u_c^* k_s / \nu \qquad 3.2$$

$$u_c^* = \left({}^{\tau_c}/_{\rho}\right)^{1/2} \qquad 3.3$$

where u_c^* is the critical shear velocity, k_s is the boundary roughness length scale (height of roughness element,$k_s \sim D_{50}$) and ν is the kinematic viscosity.

In addition Buffington and Montgomery (1997), mention that numerous researchers have acknowledged that incipient motion of a particular grain size is dependent on a probability function of the turbulent shear stress at the bed and inter-granular geometry of bed material. It is also affected by grain shape, sorting and packing of the bed material. Consequently, the resulting modified Shields parameter was reported as approximately 0.046 for a 50% chance of a particle moving in a turbulent regime flow. Recent research conducted by numerous researchers has reported a similar value; Miller et al. (1977) and Yalin and Karahan both reported a critical Shields parameter of 0.045 (without considering it as a probability function). Buffington and Montgomery (1997) studied over 600 data over a span of eight decades. They concluded that the value of 0.045 is biased towards experimental settings. They argued that the bias resulted because specific particle grain sizes were used. They report a range of critical Shields parameters of 0.030 to 0.086 and mentioned that less emphasis should be placed on choosing a universal value for $\tau_{c_{50}}{}^*$, but instead more emphasis should be placed on choosing values based on the purpose of the use of the parameter, taking into consideration boundary conditions similar to the intended use. The high Reynolds number critical Shields parameters determined by several researchers are shown in Figure 3.3(Crookston 2008).

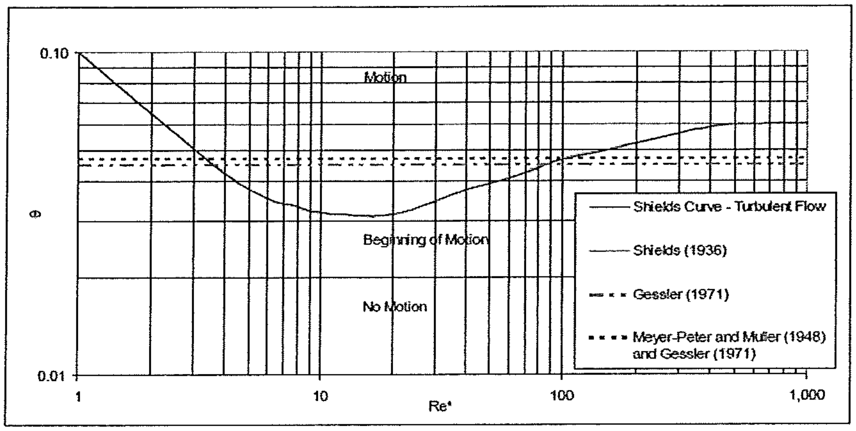

Figure 3.3 Shields parameter for beginning of motion

Velocity fluctuations due to turbulence and the frequency of the fluctuations can impact incipient motion(Crookston 2008). Numerous other factors also influence movement of bed material including: particle size, particle shape, fluid and sediment density, sediment packing, and gradation. Figure 3.4 is a graph for predicting the velocity required to initiate motion of a particular stone with a specific diameter and weight. Crookston (2008),mentioned that several researchers have investigate the relationship between critical velocity and stone size, including Li(1959), Zeng and Wang (1963),and Keown (1983).They found that depth is important for predicting particle motion for a selected flow velocity. Crookston however suggested that comparing observed velocities (incipient motion velocity) with the relationship presented in Figure 3.4 could provide insight for predicting incipient motion of various bottomless culvert substrates.

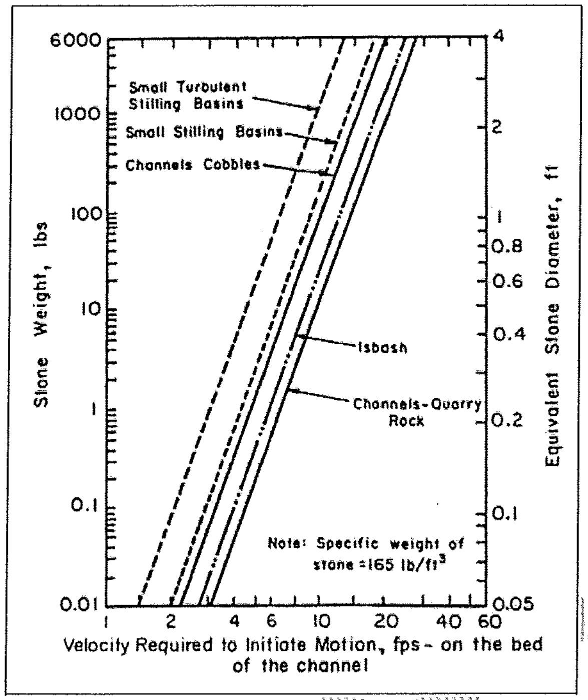

Figure 3.4 Critical Velocity to initiate motion on the bed of channel

3.2.2 Contraction scour

Contraction scour (also called general scour) is the lowering of the streambed elevation at abridge location and is related to a transient storm event. Contraction scour does not include long-term changes that result from channel degradation or localized scour occurring at abutments, piers, and foundations (Scholl and Thornton. 2008). Conversely, contraction scour occur as a result of increased flow velocity and shear stress resulting from a decrease in flow area by natural contraction of the flow channel or by the presence of a bridge or culvert. In addition, it will occur where overbank flow is forced back into the main channel by a road embankment in close proximity to the bridge (Kerenyi et al. 2007).

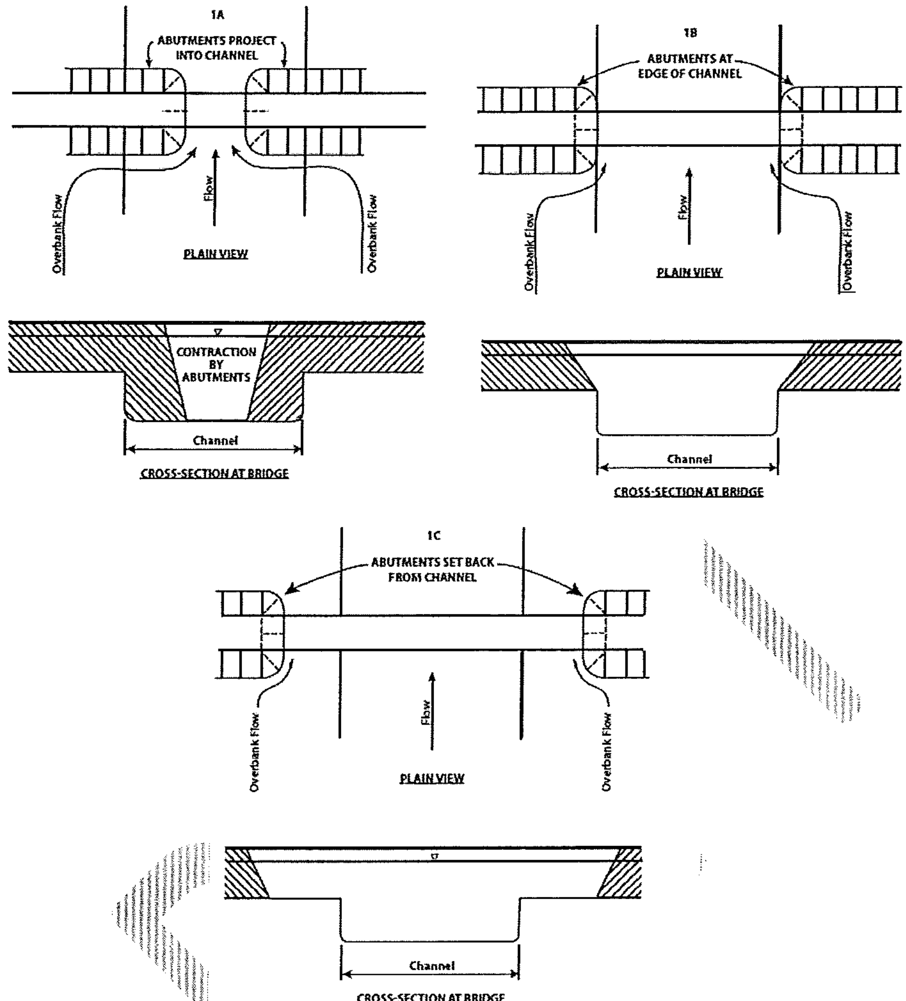

Figure 3.5 Flow forced into the main channel by (A) narrow abutments and (B) embankments blocking the floodplain. (C) Contraction scour can be reduced by setting the abutments back farther. (Scholl and Thornton, 2008)

3.2.2.1 Live-bed contraction scour

Live-bed scour occurs when there is transport of streambed material from the upstream reach into the contracted section. When live-bed scour occurs, the sediment transported into the contracted cross section will be less than that transported out of the cross-section. The area of the cross-section will increase until the sediment transported into and out of the section are balanced (Scholl and Thornton, 2008). Arneson et al. (2012)mentioned that the width of the contraction is normally constrained, and as a result, the depth will increase until the sediment flow into and out of the section are balanced. Arneson et al. (2012)reported the following equation (after Laursen, 1990) for estimating live-bed scour based on the transport of sediment upstream and downstream of a long contraction (under uniform flow conditions):

$$\frac{y_2}{y_1} = \left({}^{Q_2}/_{Q_1}\right)^{6/7} \left({}^{W_1}/_{W_2}\right)^{k_1} \left({}^{n_2}/_{n_1}\right)^{k_2} \tag{3.4}$$

$$y_s = y_2 - y_0 = (averagescourdepth) \tag{3.5}$$

where, y_1 and y_2 are the average depth in the main stream channel and contracted section respectively, y_0 is the existing depth in the contracted section before scour. Q_1 and Q_2 are the flow in the upstream channel and in the contracted channel, respectively. W_1 and W_2 are the bottom width of the main channel upstream of and at the contracted section, respectively. n_1 and n_2 are the Manning n values upstream of and at the contracted section, respectively. And k_1 and k_2 are exponents giving in Table 3.1.

Table 3.1 Values of depending on mode of bed material transport

V_*/ω	k_1	k_2	Mode of Bed Material Transport
<0.50	0.59	0.066	Mostly contact bed material discharge
0.50 to 2.0	0.64	0.21	Some suspended bed material discharge
>2.0	0.69	0.37	Mostly suspended bed material discharge

Where $V_* = \sqrt{gyS_1}$ is the shear velocity in the upstream section, ω is the median fall velocity of the bed material based on D_{50} (given in Figure 3.6), and S_1 is the slope of the energy grade line of the main channel. Units are metric system units.

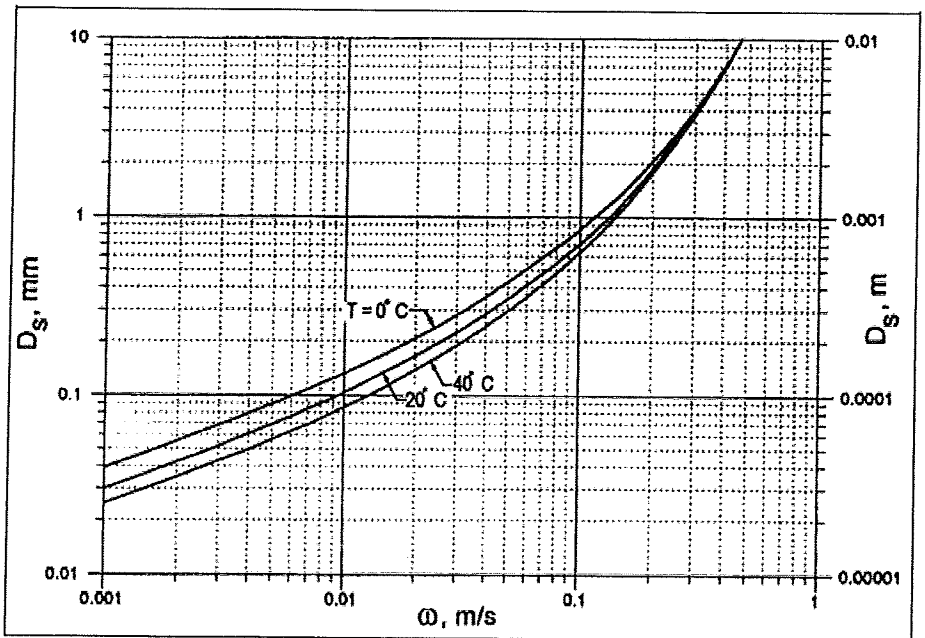

Figure 3.6 Fall Velocity of sand-sized particles with specific gravity of 2.65 in metric units(HEC-18)

3.2.2.2 Clear-water contraction scour

Clear water contraction scour occurs if there is no sediment transported into the contraction from an upstream reach and if the sediment transported into the contraction is less than the sediment carrying capacity of the flow. In the case of clear water contraction scour, the area of the contracted section increases until the critical shear stress τ_c of the bed material is surpassed or the velocity of flow (V) is equal to the critical velocity (V_c) of the bed material. Similar to live-bed scour, the widths of stream crossings are usually constrained. Thus, for clear-water scour the depth will increase until a limiting condition is met (Arneson et al. 2012). The equation for estimating clear-water contraction scour is reported in HEC-18 (after Laursen, 1963) with metric units. In the case of clear-water scour, at equilibrium the average bed shear stress at the contracted section (τ_o) is equal to the critical bed shear stress for incipient motion (τ_c) i.e;

$$\tau_o = \tau_c \tag{3.4}$$

Assuming that the flow depth at the contraction is uniform and using the Manning equation, it can be shown that the average bed shear is given by:

$$\tau_o = \gamma y S_f = \frac{\rho g n^2 V^2}{y^{1/3}} \tag{3.5}$$

And for fully-developed clear-water contraction scour, the Shields relation yields:

$$\tau_c = K_s(\rho_s - \rho) g D \tag{3.6}$$

Finally, 3.7 and 3.8 can be used to solve for y:

$$y = \left(\frac{n^2 Q^2}{K_s(S_s - 1) D W^2}\right)^{3/7} \tag{3.7}$$

Where y is the average equilibrium depth in the contracted section after scour, S_f is the slope of the energy grade line, D is the diameter of the smallest non-transportable particle in the bed material(Note that D_m can be substituted into equation 3.9 for D, where D_m=1.25D_{50}). W is the bottom width of the contracted section, n is the Manning Coefficient (n=0.034$D_{50}{}^{1/6}$ = 0.040D_m). D_m is the effective mean bed material size, K_s, is the Shields coefficient(~0.039), S_s is the specific gravity of the sediment (2.65 for quartz), γ is the unit weight of water, V is the average velocity in the contracted section and ρ_s and ρ are the density of sediment and water, respectively. Note that equations 3.6 through 3.9 are based on several assumptions that limit the applicability of the equations. For example, the use of a constant Shields coefficient requires that the sediment be relatively large.

According to Arneson et al. (2012)experiments conducted in the lab and field with bed materials of sand, gravel, cobbles and boulders suggested that the K_s

required to initiate motion ranges from 0.01 to 0.25 (and is a function of particle size Froude number and size distribution).Substituting the suggested values of the parameter into Equation 11 gives:

$$y = \left(\frac{V^2}{40D^{2/3}}\right)^3 \qquad 3.8$$

$$y = \left(\frac{Q^2}{40{D_m}^{2/3}W^2}\right)^{3/7} \qquad 3.9$$

$$y_s = y - y_o = \text{(average scour depth)} \qquad 3.10$$

The above equations were derived assuming homogenous bed particle diameters and using the layer with the finest size distribution to calculate the D_{50}. Stratified materials will result in a conservative estimate of contraction scour. Using the equations to sequentially represent multiple layers of a stratified bed would likely produce poor results(Arneson et al. 2012).

If a permissible velocity method is used to assess initiation of motion, the critical velocity (V_c) for the initiation of motion of the bed materials is given by the equation:

$$V_c = \left[\frac{K_s^{1/2}(S_s-1)^{1/2}D^{1/2}y^{1/6}}{n}\right] \qquad 3.11$$

Substituting in K_s= 0.039,S_s =2.65 and n= $0.041D^{1/6}$ yields:

$$V_c = 6.19y^{1/6}D^{1/3} \qquad 3.12$$

3.2.3 Local Scour

Local Scour occurs because of obstruction and abrupt changes in the direction of flow; it is caused mainly by acceleration of the flow and by vortices induced by bridge piers, abutments, embankments, and other structures that obstruct the flow. Furthermore, either live-bed or clear-water scour can occur downstream of culverts, grade-control structures, drop structures, etc. The following factors affect the magnitude of local scour depth: (1) the velocity of the approach flow, (2) the depth of flow, (3) the width of the obstruction, (4) the size and gradation of bed material, (5) the projected length of the obstruction into the flow,(6) the angle of approach of the flow,(7) the shape of the obstruction, (8) the bed configuration, (9) the shape of the obstruction, and (10) the presence of debris or ice. According to Scholl and Thornton (2008),field and laboratory studies have shown that the maximum local abutment scour in culverts occurs at the upstream entrance. In addition the scour depth is dependent on both the entrance conditions and whether the scour is live-bed or clear-water. Froehlich's live-bed equation is commonly used for estimating live-bed abutment scour near the upstream culvert face and is given as:

$$y_s = 2.27 y_a K_1 K_2 \left(\frac{L'}{y_a}\right)^{0.43} Fr^{0.61} + 1 \text{(units in ft-lb-s)} \qquad 3.13$$

Where y_s is local scour depth (in *ft*) and y_a is the average depth of flow in the over bank area.K_1 and K_2 ($K_2 = (\theta/90)^{0.13}$) are the coefficients for abutment shape and embankment skew angle, respectively (see Table 3.2 for values of K_1). L' is the length of active flow obstruction by the embankment.Fr is the Froude number of the approaching stream. Equation 3.15 is applicable for clear-water local scour.

Table 3.2 Values of K_1 for different abutment shapes

Table 7.1. Abutment Shape Coefficients.	
Description	K_1
Vertical-wall abutment	1.00
Vertical-wall abutment with wing walls	0.82
Spill-through abutment	0.55

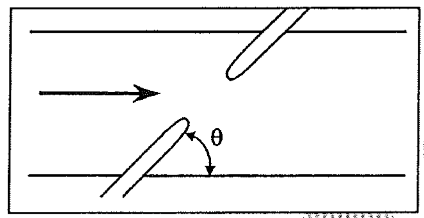

Figure 3.7 Orientation of Embankment angle, θ, to the flow

The local scour at the culvert outlet is given by the equation:

$$\frac{y_s}{R} = \frac{\alpha}{\sigma^{1/3}} C_h C_s \left[Q/\left(g^{1/2}R^{5/2}\right)\right]^{\beta} (t/316)^{\theta} \qquad 3.16$$

Where y_s is depth of scour (*ft*), R is the hydraulic radius, α = 2.27 (for non-cohesive materials), σ is the bed material size standard deviation, C_h and C_s are coefficients for outlets above the bed and for culvert scour, respectively (see Table 3.3), θ = 0.06 for non-cohesive materials, and t is time of scour (usually t=30minutes except when known to be otherwise).

Table 3.3 Coefficient for culvert scour equation

Table 5-1. Coefficients for Culver Outlet Scour - Cohesionless Materials

	α	β	θ
Depth, h_s	2.27	0.39	0.06
Width, W_s	6.94	0.53	0.08
Length, L_s	17.10	0.47	0.10
Volume, V_s	127.08	1.24	0.18

Table 5-3. Coefficients (C_h) for Outlets above the Bed**

*H_d	Depth	Width	Length	Volume
0	1.00	1.00	1.00	1.00
1	1.22	1.51	0.73	1.28
2	1.26	1.54	0.73	1.47
4	1.34	1.66	0.73	1.55

*Height above bed in pipe diameters **Coefficient derived for sand bed materials

Table 5-4. Coefficients (C_s) for Culvert Slope

Slope%	Depth	Width	Length	Volume
0	1.00	1.00	1.00	1.00
2	1.03	1.28	1.17	1.30
5	1.08	1.28	1.17	1.30
≥7	1.12	1.28	1.17	1.30

3.2.4 Scour at Bottomless Culverts

The major concern about use of bottomless culverts at stream crossings is that they have mobile beds and if improperly designed are much more susceptible to failure by scour than traditional culverts. Scour is greatest at the upstream entrance corners of the culvert. The primary contributors to total scour at bottomless culverts are general and local scour. However, if multiple bottomless culverts are used in parallel, the locations where the walls of each culvert meet will behave like bridge piers and must be designed for total scour, including degradation. Two phases of laboratory studies sponsored by FHWA ((Kerenyi et al. 2007; Kerenyi et al. 2003; Kerenyi et al. 2003)concluded that scour in bottomless culverts is a combination of contraction scour (due to the primary flow) and abutment scour caused by strong turbulence and local vortices (due to secondary flow; the vortices occur in the separation zone) as depicted in Figure 3.8.

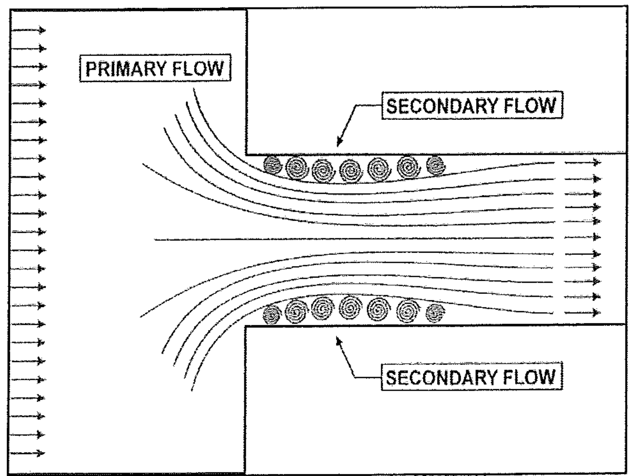

Figure 3.8 Flow concentration diagram

Figures 3.9 through 3.11 demonstrate the development of local scour at the edges of a bottomless culvert. Figure 3.9 is a definition sketch of the bed prior to the initiation of a test. Figures 3.10 and 3.11 show the development of scour holes near the edges of the culvert for unsubmerged flow and submerged flow, respectively.

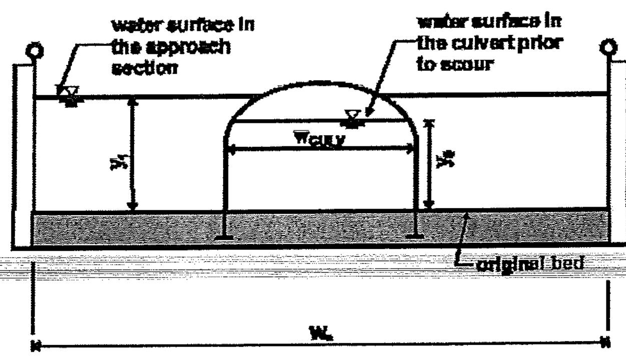

Figure 3.9 Definition sketch of culvert and bed prior to scour (unsubmerged flow)

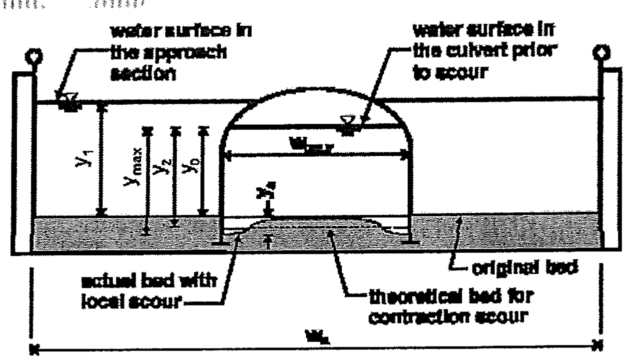

Figure 3.10 Definition sketch after scour (unsubmerged flow)

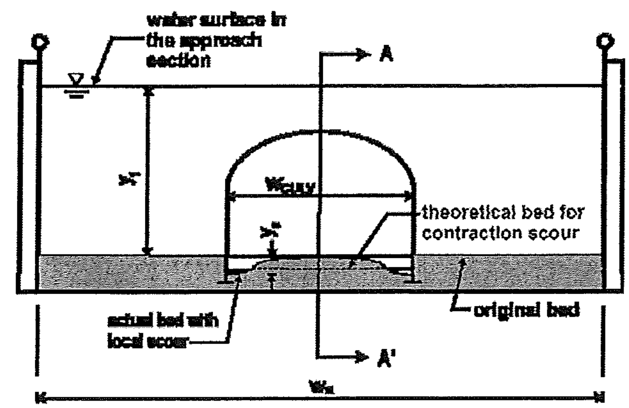

Figure 3.9 Definition sketch after scour (submerged flow)

Figure 3.12 shows a side view of the development of a scour hole at the outlet of the bottomless culvert due to flow acceleration.

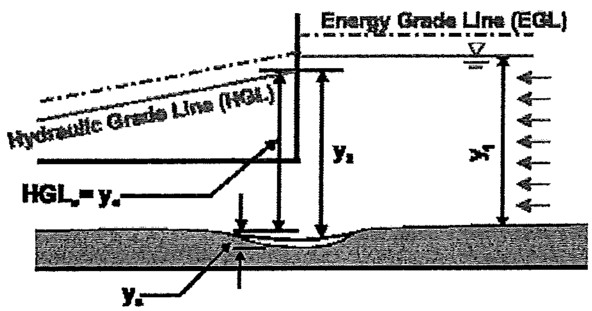

Figure 3.10 Section A-A' (after scour submerged condition)

Kerenyi et al. (2003) developed scour equations for clear-water conditions for bottomless culverts for two cases: (a) with wing walls (b) and without wing walls.

When wing walls were used at the entrance of the culverts, the maximum scour depth was given by:

$$y_{max} = K_u Q_{BI}^{0.28} \left(\frac{Q}{W_c D_{50}^{1/3}}\right)^{0.26} \tag{3.16}$$

$$y_s = y_{max} - y_o \tag{3.17}$$

Where y_{max} is the flow depth at culvert entrance corner including contraction and local scour, Q is the discharge, Q_{BI} is the discharge blocked by the road embankment on one side of culvert, W_c is culvert width, y_s is scour at the culvert entrance, y_o is the flow depth before scour, and K_u = 0.84 (*English*) or K_u = 1.16 (*metric*).

When wing wells were not used at the entrance of the culvert, the maximum scour depth was given by:

$$y_{max} = K_u Q_{BI}^{0.12} \left(\frac{Q}{W_c D_{50}^{1/3}} \right)^{0.60} \quad 3.18$$

$$y_s = y_{max} - y_o \quad 3.19$$

Where K_u =0.57 (*English*) or K_u = 0.88 (*metric*). For total scour in bottomless culverts, the long-term degradation must be estimated and added to the local and contraction scour. Wingwalls were found to significantly reduce local scour at the inlet corners of the culvert.

3.2.5 Scour Countermeasures

There are several available scour countermeasures. However, determining which mechanisms are responsible for scour in any given case is necessary to assess which techniques can best alleviate a particular problem. According to Lagasse et al. (2001),a typical example is that contraction scour results from a sediment imbalance across most or all of the channel, while local scour at a pier or abutment results from the action of vortices at the obstruction, whereas long-term degradation is considered a channel instability problem. Despite the fact that it possible to predict occurrence of scour at a given location, it is highly possible to be in error when estimating the magnitude and exact location. As a result, Lagasse et al. (2001)suggest that it is often advisable to "wait and see" until the magnitude and location is obvious before implementing a counter measure, this being the best economic approach. Scholl and Thornton (2008) reported that Lagasse together with other researchers (2007) further suggested using a factor of safety that was higher than the minimum of 1.5 (used at design stage) around the abutments and piers to provide for the complex hydraulic conditions associated with scour.

Wingwalls and riprap are traditional countermeasures that are widely used in many culverts (including bottomless culverts) as countermeasures. However, other options include: articulated concrete block (ACB), concrete armor units, gabions, grout-filled bags, cross vanes and pile dissipators at the outlet.

The Phase I and II laboratory study sponsored by FHWA tested several countermeasures, including riprap, cross vanes and pile dissipators in clear-water laboratory conditions. They found that the equation presented earlier for estimating scour is valid for bottomless culverts. They tested the impact of using different wingwall configurations on scour-hole depth and found that by changing the angle of the wingwall, the negative impacts of turbulence shear on scour-hole development could be minimized, and as a result scour depths could be minimized. An eight-degree wingwall, which is the most practicable field-type wingwall configuration, was tested and found to reduce turbulence and scour depth by an amount that was comparable to the reduction associated with the installation of an elongated streamlined bevel wingwall. However, the elongated streamlined beveled wingwall was found to be optimal, except that it is more difficult to implement in the field.

Riprap is the most practical countermeasure technique and is widely used. The FHWA study found that the equation given below is the most appropriate equation for estimating appropriate riprap size.

$$\frac{D_{50}}{y_o} = \frac{0.38F_O^{0.66}}{SG-1} = \frac{0.38}{SG-1}\left(\frac{V_{AC}^2}{gy_o}\right)^{0.33} \qquad 3.14$$

Where y_o is the water depth at the culvert entrance before scour occurs, SG is the specific gravity of the riprap, D_{50} is the median sediment size, V_{AC} is the average velocity in the contracted zone prior to scour in the vicinity of the upstream corner of a culvert, F_o is the Froude number in the contraction zone. Validation of Equation 3.20 is shown in Figure 3.11.

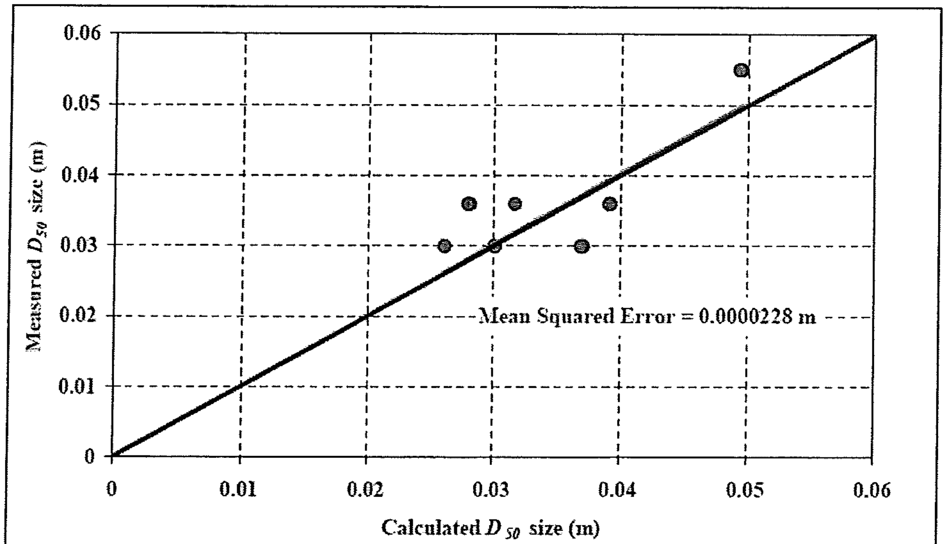

Figure 3.11 Graph validation of D50 for riprap sizing

HEC-20 ((Lagasse et al. 2001) and the Phase I and II laboratory reports by FHWA (Kerenyi et al. 2007)) provide additional detail on design and implementation of scour countermeasures.

Chapter 4 Culvert Design

4.1 Introduction

Culverts are designed to convey stream flow through road-stream crossings without causing destructive backwater, extreme flow constriction, or excessive outlet velocities.

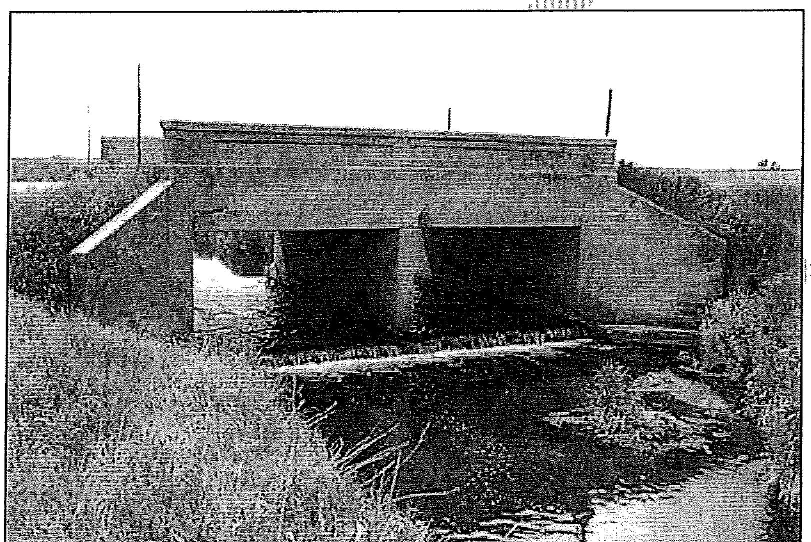

Figure 4.1 Culvert structure

Culverts are available in many different shapes and geometries. They can be made with rigid or flexible material and entirely enclosed, or they may be constructed to be supported on a spread footing foundation with the streambed as the bottom (bottomless culvert). Typical cross-sectional shapes for closed conduits and bottomless culverts are shown in **Error! Reference source not found.**. The selection of a particular shape is cost dependent. Limitations are based on the roadway profile, channel characteristics, allowable headwater elevation, flood event, and flood frequency.

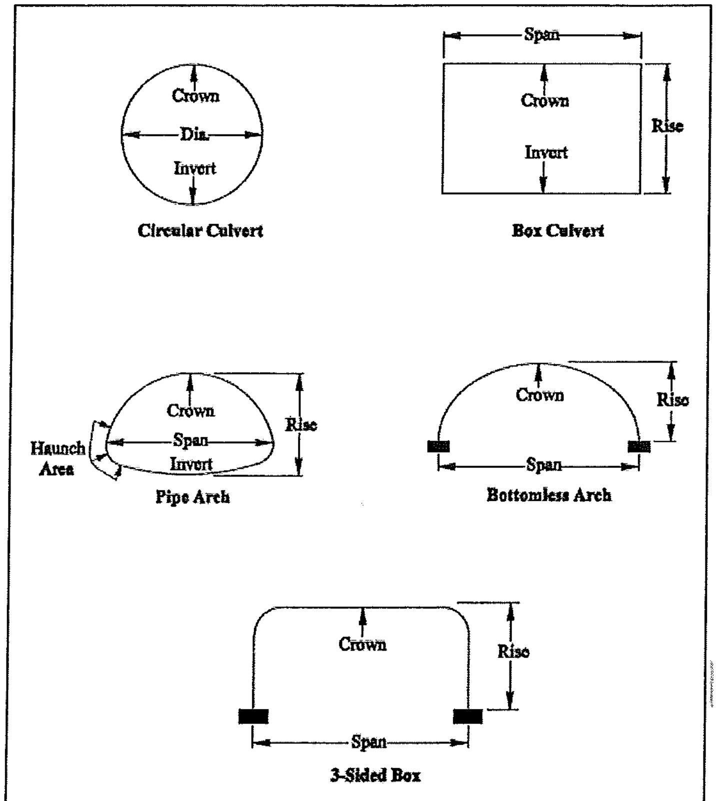

Figure 4.2 Commonly used culvert shapes (WSDOT 2010)

In conditions where adequate hydraulic capacity at locations with low embankments or wide waterways is required, multiple barrel culverts are used. However, multiple barrels are prone to clogging as the area between the barrels can trap debris and sediments. Furthermore, they are subject to excessive sedimentation when used in a stream that is artificial widened (Rossow 2007).

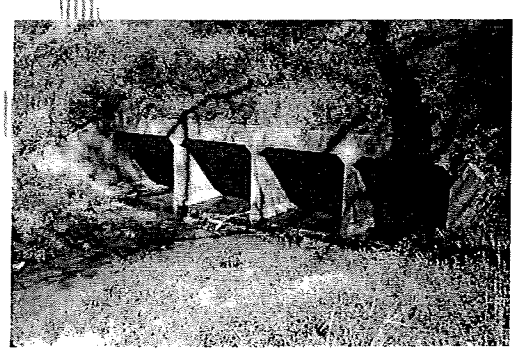

Figure 4.3 Multiple barrel culverts

The most commonly used culvert type in the state of Nebraska is the closed conduit type. Both circular culverts and box culverts are widely implemented. There is some concern about closed conduit culverts because they create a barrier to aquatic organisms in some cases. The most widely used alternative in Nebraska is the use of bridges; for small streams this alternative is generally not economical or appropriate and is typically not hydraulically required (Schall et al. 2012). A second alternative is the use of bottomless culverts or embedded culverts. The former necessarily has a much larger opening than the closed conduit and can conduct flow at lower velocities, and the natural invert solves the problem of passage of aquatic organisms (see **Error! Reference source not found.** through 4.6). The latter also has a natural invert, but also has an embedded fixed invert that may act as a failsafe in the case of excessive stream degradation. Embedded culverts are typically buried into the ground to about 20-40 percent of the culvert height (Schall et al. 2012).

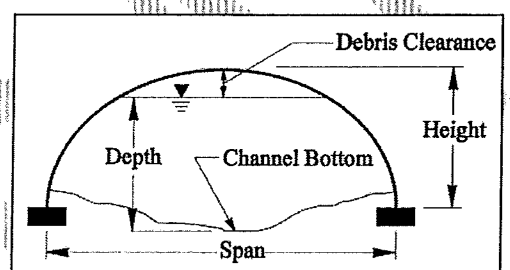

Figure 4.4 Typical Bottomless Culvert (WSDOT 2010)

There are numerous concerns associated with the use of bottomless culverts- especially in the state of Nebraska where bed soils are not well-armored. The primary concern arises from the fact that bottomless culverts most often have a vertical wall supported on a spread footing foundation. Scour around these foundations is a major cause of failure of this type of culvert structure. The embedded culvert on the other hand can provide some protection against excessive scour (WSDOT 2010).

It is important to note that in order to validate the use of bottomless culverts; one must understand the design of culverts, the effects of channel characteristics and stability, and effects of scour and possible countermeasures.

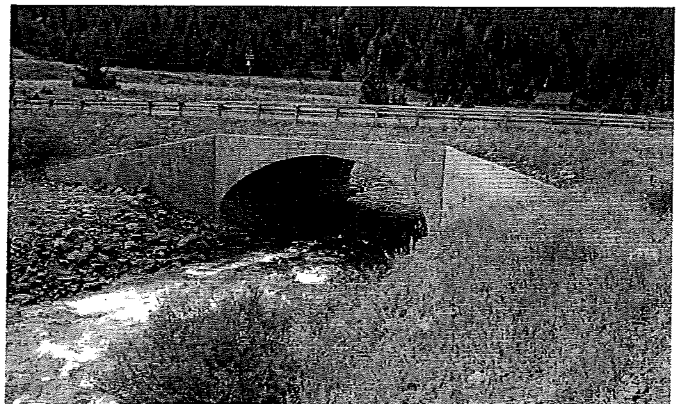

Figure 4.5 Bottomless culvert

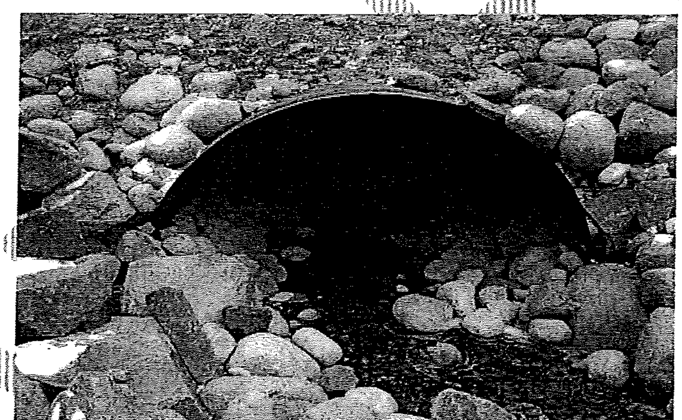

Figure 4.6 Embedded Culvert

4.2 Culvert Flow Control

Culvert flow analysis is a complex process, as it is common for non-uniform flow to occur, and the depth of flow can change either gradually or rapidly throughout a reach (Schall et al. 2012). According to Schall et al. (2012), accurate analysis would include backwater and drawdown calculations, an energy and momentum balance, and analysis of results derived from modeling. They also mention that FHWA analyzed culvert designs based on flow control and location of the point of control. A control is a location where there is a unique relationship between stage and discharge – it is generally a location where the flow passes through critical depth. There are two types of controls - inlet and outlet controls. A common method of culvert design is based on the use of design charts and nomographs. The following design criteria are important considerations for culvert design: (a) velocity limitations –both minimum and maximum, (b) length and slope – which should be similar to site conditions, (c) buoyancy protection – the culvert can be anchored using the headwall, tail wall and other means, (d) flood frequency – most often the 100-year flood is used, (e) debris control – a debris control manual is often consulted, (f) headwater limitations, (g) tail water depth, and (h) flow control, inlet and outlet.

4.2.1 Type of Flow Control

If the flow condition is such that the flow inside the culvert barrel is supercritical, the critical (control) section will be at the culvert inlet, such flow condition is called inlet control. Whereas, if the flow inside the culvert barrel is subcritical the flow control (critical section) is at the outlet of the culvert, this is called outlet control.

4.2.1.1 Inlet Control

Inlet control is typical on steep slopes, and the culvert barrel is able to convey more flow than the inlet can pass. Inlet control in a culvert can be unsubmerged (Figure 4.7A and C) and submerged (Figure 4.7B and D). The flow passes through critical just downstream of the inlet and is supercritical in the culvert barrel. In case B and D where the outlet is submerged the flow in the barrel will undergo a hydraulic jump to subcritical. This ensures that inlet control is maintained. Schall et al. (2012) further explained that submergence of the inlet and outlet will result in development of sub-atmospheric pressures that might create an unstable condition that will cause the barrel to alternate between full flow and partially full flow. In addition, they mentioned that submergence of the inlet would cause the inlet to behave as an orifice. The inlet control design can be done using nomographs or using appropriate equations and design figures.

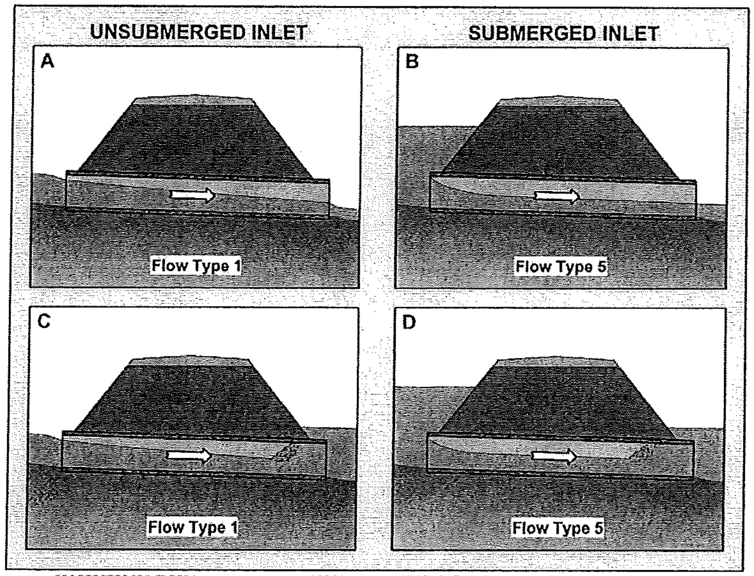

Figure 4.7 Inlet control

The following conditions will influence inlet control: (a) headwater depth, (b) inlet cross-sectional area, and (c) inlet configuration. Inlet configurations include thin edge projecting entrances, mitered entrances, square edge head wall entrances, groove edge projecting entrances, and beveled entrances (see Figure 4.8 and Figure 4.9). Culvert capacity is not affected by the hydraulic condition downstream of the inlet control – more specifically, culvert roughness, slope and length of the barrel, and outlet conditions do not affect capacity because inlet conditions limit the flow (Grand Junction Municipal Code 2012).

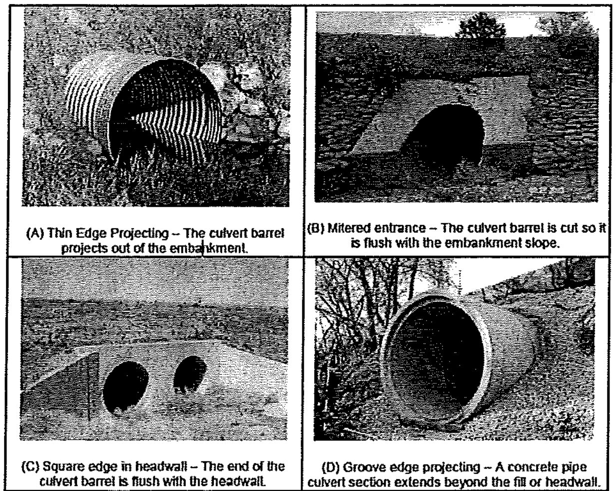

Figure 4.8 Typical inlet configuration (Schall et al. 2012)

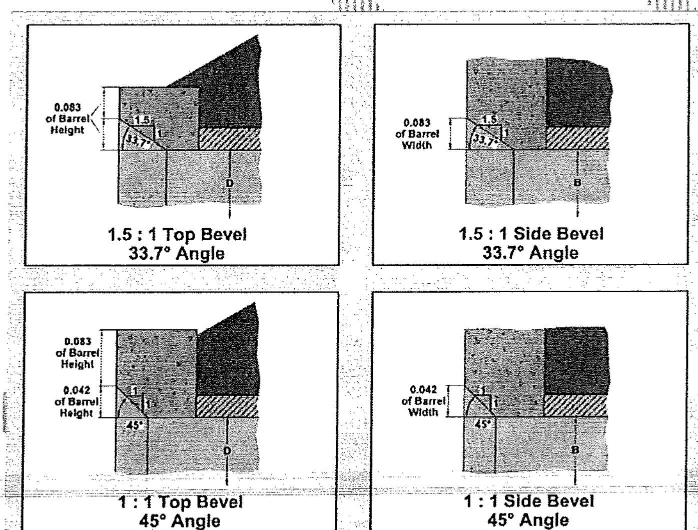

Figure 4.9 Beveled edges (Schall et al. 2012)

4.2.1.2 Inlets with Headwalls, Wingwalls and Aprons

The hydraulic efficiency of a culvert is a significant factor in design of culverts and it is dependent on the inlet conditions. Improving the inlet conditions can greatly increase the hydraulic efficiency of a culvert. Consequently, good headwall design can greatly improve the efficiency of the inlet, provide embankment stability, protect embankments against erosion, and protect the culvert from buoyancy failures. In addition, a good head wall can be used to shorten the length of the required structure.

Wingwalls are commonly used where the adjacent channel side slopes at the inlet are unstable, or when the culvert is placed at an angle to the stream alignment (City of Lincoln 2004). Aprons on the other hand are used at the toe of the headwall to protect the bed. When the headwater and the approach velocity are high, the apron will prevent scour at the inlet. Rounding the edges at the entrance will further increase culvert efficiency by reducing flow contraction as shown in Figure 4.10.

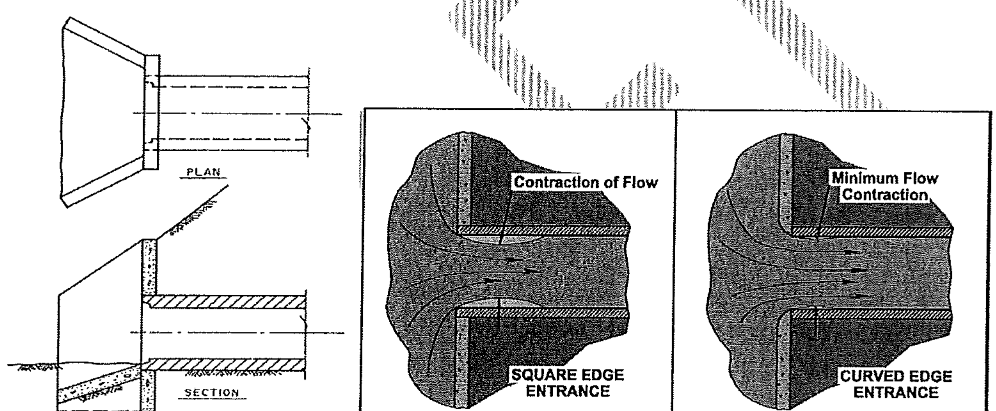

Figure 4.10 Headwall, wingwalls and inlet geometry effects.

4.2.1.3 Outlet Control

In contrast with inlet control, outlet control is typical of relatively flat slopes and when the culvert barrel is not capable of conveying the amount of flow that the inlet will accept. The flow in the barrel is either subcritical or pressurized flow and the critical section is just downstream of the outlet. In the case of outlet control, the capacity of the culvert barrel is influenced by the same factors that influence inlet control but roughness, slope and culvert length, culvert size and shape, and depth at the outlet also have an influence. Additionally, the culvert can be partially full or full, and the inlet can be unsubmerged or submerged as shown in Figure 4.11. Barrel roughness is a measure of the hydraulic resistance provided by the culvert barrel and is a function of culvert material type. It is represented by the Manning roughness (n). When a bottomless culvert is used the composite Manning roughness (n_c) given by the following equation can be used in place of n;

$$n_c = \left[\sum_{i=1}^{G} \left(\frac{p_i n_i^{1.5}}{p}\right)\right]^{0.67} \qquad 4.1$$

Where G is the number of different materials in the wetted perimeter (p_i) of the bottomless culvert system. The wetted perimeter is influenced by each material that makes up the flow boundary. The total wetted perimeter is p and n_i is the Manning roughness of each independent material that contributes to the flow boundary. In the case of the bottomless culvert, the barrel slope should be the slope of the channel. The depth downstream of the culvert is most often the normal depth.

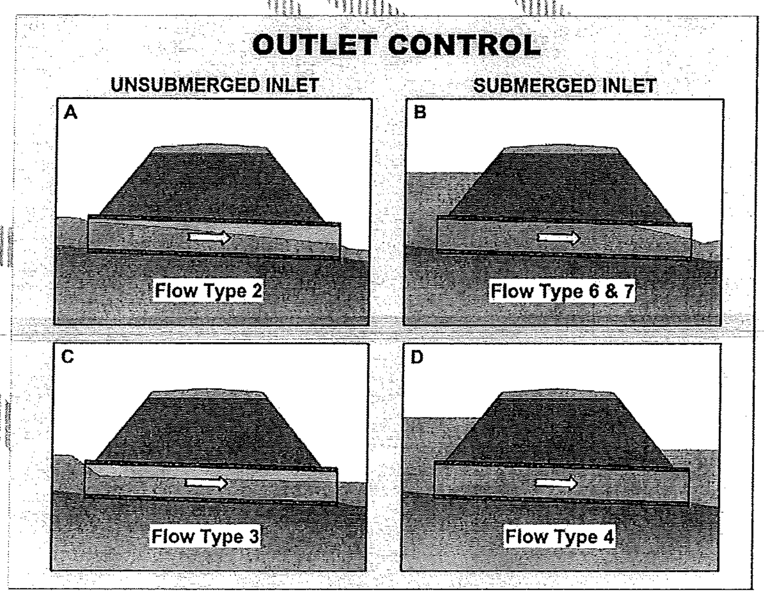

Figure 4.11 Outlet Control

For outlet control, the full barrel flow condition is analyzed using the energy balance equation as depicted by Figure 4.12 and given below as:

$$HW_o = TW + H_L - LS \qquad 4.2$$

Where

$$H_L = H_e + H_f + H_o + H_g \quad 4.15$$

HW_o is the headwater depth above the entrance invert, TW is the depth above the outlet invert, LS is the drop in elevation of the bed through the culvert, $H_L$is the total energy required to pass flow through the culvert barrel, H_e is the entrance loss, H_f is the friction losses through the barrel , and H_o is the exit loss. H_g consists of losses due to the presence of a gate and must be included only when appropriate. The various terms are defined as follows:

$$H_e = k_e\left(\frac{V^2}{2g}\right) \quad 4.16$$

$$H_f = \left[\frac{K_u n^2 L}{R^{1.33}}\right]\left(\frac{V^2}{2g}\right) \quad 4.17$$

$$H_o = \frac{(V - V_d)^2}{2g} \quad 4.18$$

Where V is velocity in the barrel, V_d is the downstream velocity, K_u is a factor equal to 29 in English units and 19.63 in SI units, R is the hydraulic radius, L is the culvert length and k_e is the inlet efficiency. The above equations are applicable only to the flows shown by Figure 4.11B and D.

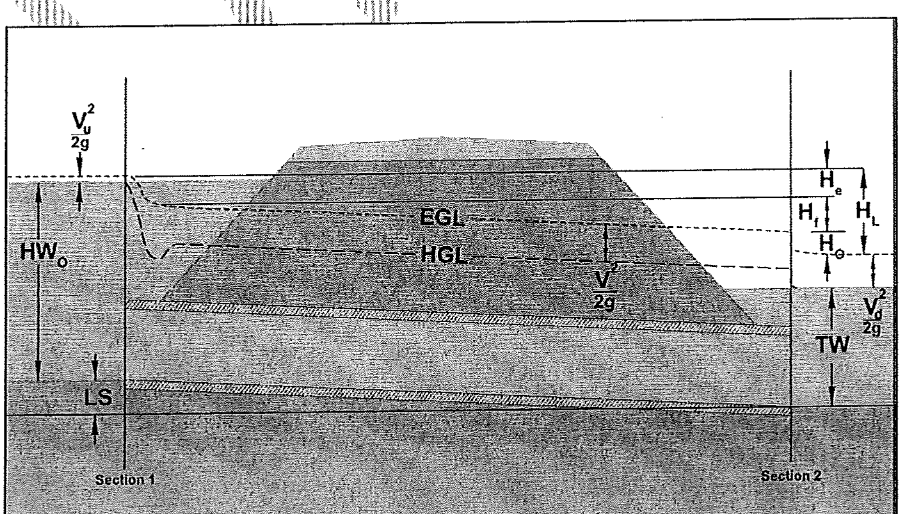

Figure 4.12 Full flow energy and hydraulic grade lines (Schall et al. 2012)

When the culvert is flowing partly full (Figure 4.11A and C) a backwater calculation is required. Schall et al. (2012)explain that the backwater calculation can be avoided using some conditions founded by FHWA. Upon performing a series of backwater calculations they found that it is possible to start the hydraulic grade line at a depth of $(d_c + D)/2$ or at the depth of tail water (whichever is greater) above the outlet invert and then extend a straight HGL line upstream to the culvert inlet using the friction slope ($S_f = H_f/L$) as shown in Figure 4.13D.

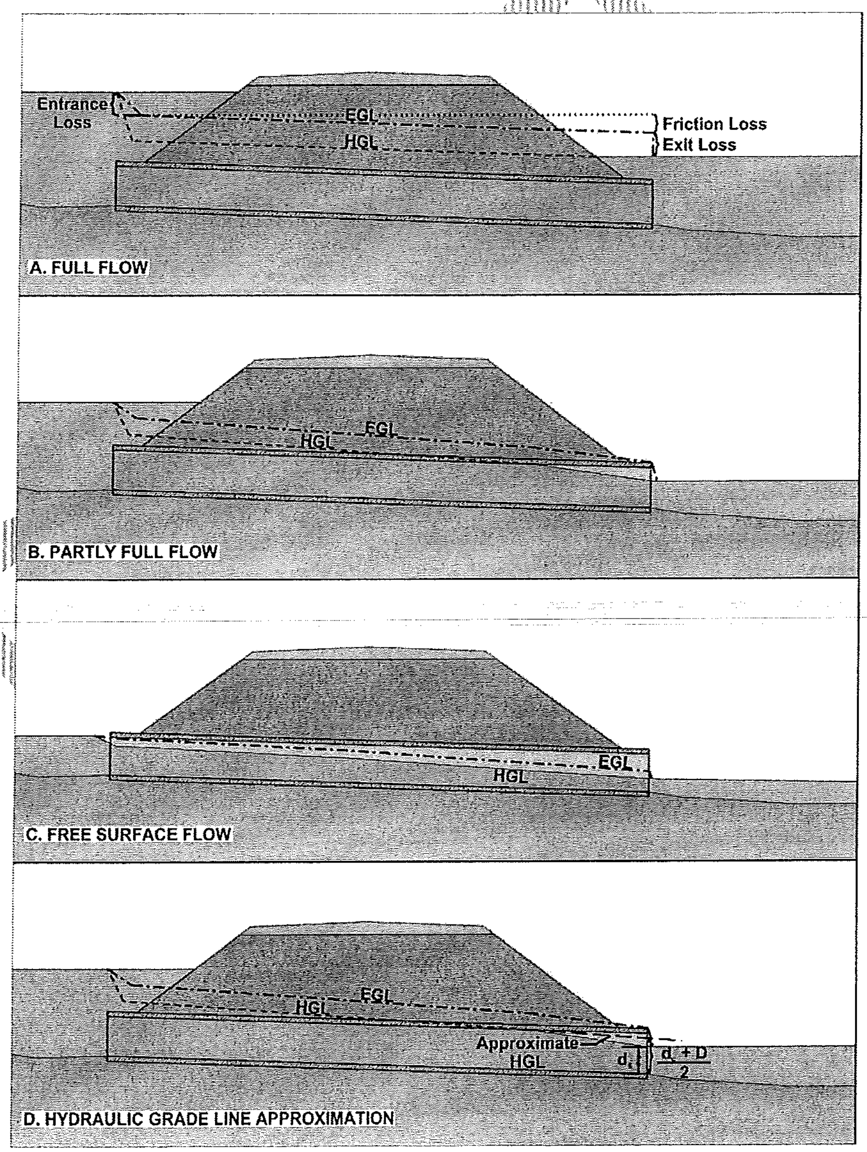

Figure 4.13 Outlet control energy and hydraulic grade line

Chapter 5 Aquatic Organism Passage (AOP)

5.1 Introduction

The survival of aquatic organisms (and other wildlife) and the preservation of their populations is sometimes dependent on ease of movement of the species along river and stream corridors. Long, linear ecosystems and undisturbed river and streams are the optimum environment for sustenance of these aquatic organisms. The construction of culverts at road-stream crossings can have a negative effect on the natural ecology, hydrology, and geomorphology of these waterways (Levine et al. 2007) in many cases. The consequences of culvert installations include changes in stream velocities and geomorphology, which in turn can lead to channel degradation or aggradation, disrupting the continuity of rivers and streams, and their natural ecosystem, and resulting in stream or river fragmentation.

According to Jackson (2003), the USGS (2001) mentioned that over half of the culverts assessed by the U.S. Forest Service and the Bureau of Land Management (BLM) in Oregon and Washington were identified as barriers to juvenile salmonid fish passage. The movement of these organisms within rivers and stream corridors is very important to the survival of individual organisms and the perseverance of their populations. Kilgore et al. (2010) used the simple diagrammatic presentation shown in Figure 5.1, to explain the effect of stream and river fragmentation on aquatic organism passage and survival. The figure presents the negative effects of culvert installation sequentially: (a) undisturbed habitat is shown first, with filled in area representing available salmonid habitat, (b) habitat with ineffective culvert causing habitat fragmentation is shown by different fill colors, (c) the fragmented system after a few years is shown with no fill areas representing areas that are inaccessible to the salmonids, and (d) finally the fragmented system is shown after a long period of time, with only a small fraction of the original watershed still available to the salmonids.

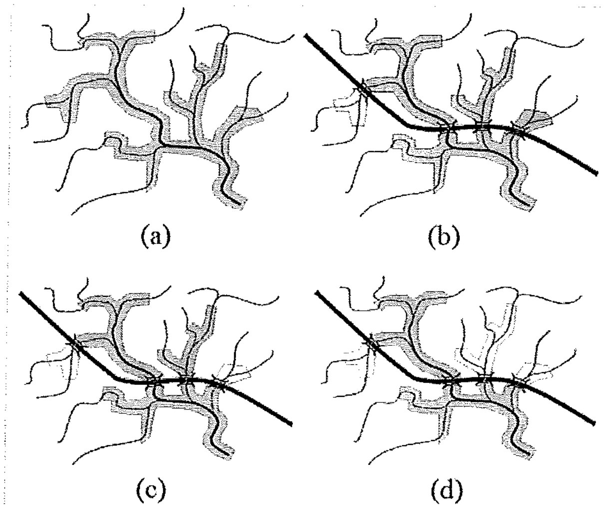

Figure 5.1 Changes in fish habitats over time after roadway fragmentation

This section of the review focuses on the barrier to aquatic organism passage created by the presence of a culvert in a stream. These barriers typically pose hydraulic conditions that are beyond the physical navigational capabilities of the aquatic organisms in the stream. Limiting physical conditions include excessive water velocity, excessive turbulence due to inlet contraction, inadequate depth for fish to swim through (extremely low flows), drops at culvert inlets or outlets, excessive culvert length, and presence of physical barriers such as baffles, debris and large sediment trapped in the culvert barrel. The severity of the effects of culvert conditions on fish and other aquatic organism passage has mandated the need for more careful culvert design in some states. In order to modify existing culvert designs to accommodate aquatic organism passage, this chapter identifies flow parameters that are of importance and the physical capabilities of organisms to overcome barriers of particular sizes.

5.2 Fish Physiology

Extensive knowledge of the capabilities of aquatic organisms has not been historically required for culvert design. Nevertheless understanding fish physiology and their ability to swim is useful in the design of culverts for imitation of natural systems. Kilgore et al. (2010) mentioned after Webb (1975) that fish utilize two muscle systems for movement : a red muscle system (aerobic) for low-intensity actions and a white muscle system (anaerobic) for shorter but high-intensity actions. Unfavorable swimming environments can result in the extensive use of the white muscle system causing extreme fatigue and the need for extended periods of rest (Kilgore et al. 2010).

The survival of fish species (and other aquatic organisms) is reliant on their access to suitable habitat conditions necessary for feeding, breeding, and shelter from adverse conditions. This habitat can vary from short reaches of rocky stream beds to many interconnected miles of stream corridor (Jackson 2003). The need for fish to move through a river and stream system may include the need to reach food sources, find places to mate or establish nesting areas, and respond to changes in stream conditions such as temperature, flow velocity or depth. These movements can be daily or seasonal, and are both upstream and downstream. Furthermore, aquatic movement has been found to be important for maintaining a balanced stream ecosystem. According to Jackson (2003) there is a tendency of organisms and nutrients to be carried downstream with the flow and consequently the movement of organisms upstream can restore balance to upstream reaches.

The survival of many aquatic species is dependent on a balanced ecosystem, and survival concerns are not limited only to fish species. For example, mussel larvae known as glochida can attach to the gills or fins of fish. Fish carry the larvae throughout watersheds, a process necessary for proper development and spreading of the species. The inability of fish to reach some parts of a watershed will greatly affect the viability of these types of organisms (Jackson 2003).

The Nebraska Department of Environmental Quality (1997-2001) conducted a study including measuring the status of biological integrity of the state's streams and in their studies they found that there are fifty species of fish consisting of twelve families in Nebraska. The majority of species were found in the Elkhorn River Basin and the most commonly found species were the Sand shiner and the Bigmouth shiner (Bazata 2005). Information about these species may later be useful for determining which watersheds have the greatest need for connectivity.

5.2.1 Movement Capability

Fish movement capabilities are separated into three categories: sustained, prolonged and burst speeds. The description of each movement type, the muscle system used and the potential duration of movement are given in Table 5.1(Kilgore et al. 2010).

Table 5.1 Muscle type and relation to muscle system utilization (adapted from Bell, 1986 and Powers and Orsborn, 1985)

Movement Type	Description	Muscle System	Period
Sustained	Used for long periods of travel at low speeds. Normal functions without fatigue.	Red (purely aerobic)	Hours or days
Prolonged	Short periods of travel at high speeds resulting in fatigue	Red and White	0.25 to 200 minutes
Burst	Maximum swimming speed or jumping, inducing fatigue.	White (purely anaerobic)	0 to 15 seconds

To reach burst speed the fish utilizes the white muscle tissue, which will require a significant rest period. Persistent use of white muscle will cause extreme fatigue in fish. Regions of high velocity may exceed the burst swimming capability of a particular fish species, preventing passage. On the other hand, long continuous culverts flowing with moderate velocities may require long swimming durations that could also be beyond the capabilities of a particular species (Kilgore et al. 2010).

High velocity zones, long culverts and changes in channel level with respect to culvert geometry may all act as barriers to fish movement. According to Kilgore et al. (2010), numerous researchers have conducted studies to establish the swimming capabilities of different fish species, and relative swimming abilities of various adult and young fishes are given in Figure 5.2 and Figure 5.3.

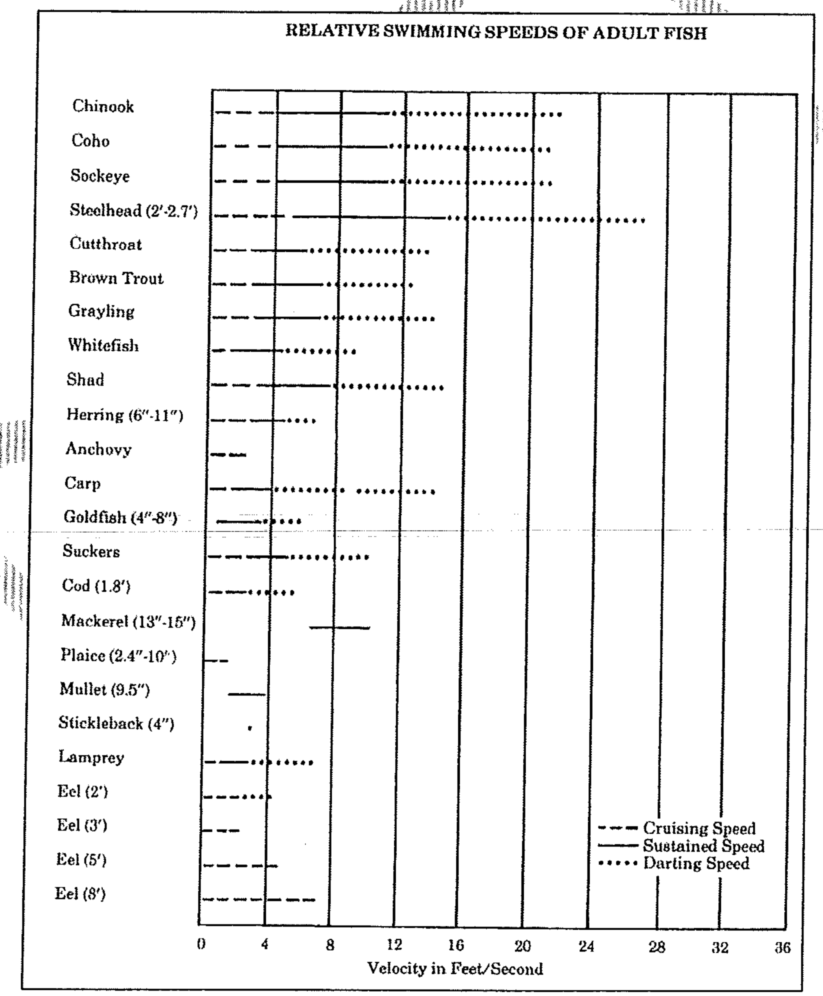

Figure 5.2 Relative swimming abilities of adult fish

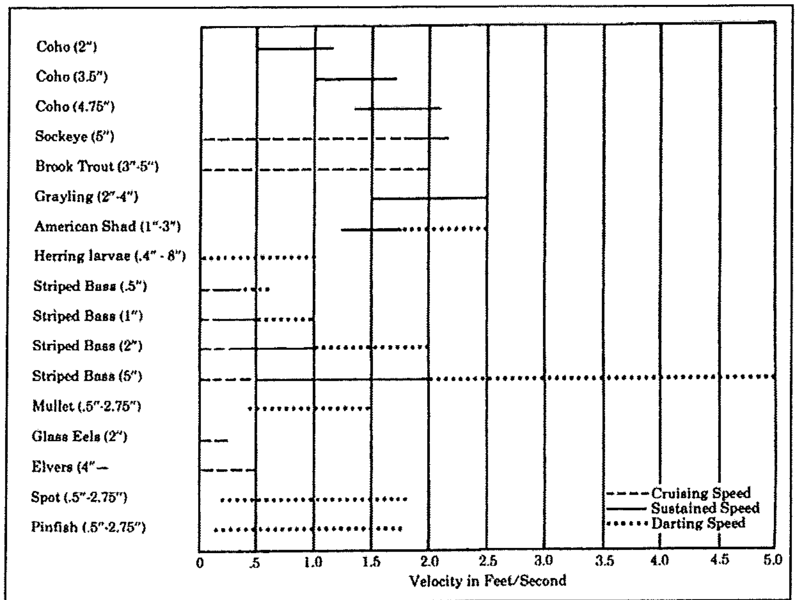

Figure 5.3 Relative swimming abilities of young fish

5.2.2 Depth of flow

A minimum flow depth is required in a stream channel for fish passage and survival. In order to eliminate the risk of fish starving for oxygen and to allow fish to reach full swimming potential, some research has suggested that the depth of water in a channel must meet certain requirements. These requirements can vary from species to species according to Kilgore et al. (2010). Typical examples of the requirements mentioned by Kilgore et al. include: (a) Alaska suggested that flow depth be greater than 2.5 times the height of the caudal fin of the fish as shown in Figure (adapted from Alaska Department of Fish and Game and Alaska Department of Transportation, 2001), (b) the Washington Department of Fish and Wildlife specified a minimum depth of 0.8 ft for Adult Trout, Pink and Chum Salmon, and 1.0 ft for Adult Chinook, Coho, Sockeye or Steelhead, and (c) the Maine Department of Transportation (2004) suggested a depth of 1.5 times the fish body height.

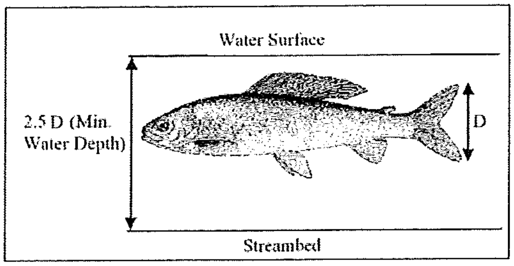

Figure 5.4 Proposed minimum water depths for fish passage in Alaska

Table 5.2 adapted from the Washington fish passage manual (Bates et al, 2003) demonstrates the relation between allowable culvert length, flow velocity and water depth for different fish species using exhaustion and swimming criteria (Kilgore et al. 2010). The culvert velocity threshold was developed using the exhaustion criteria. The exhaustion criteria rely on the rate and duration of energy consumption. Kilgore mentioned that Washington State utilizes the criteria for adult trout as the design threshold.

Table 5.2 Fish passage design criteria for culvert installations (Washington fish passage manual)

		Adult Trout > 6 in (150 mm)	Adult Pink or Chum Salmon	Adult Chinook, Coho, Sockeye or Steelhead
Culvert Length (ft)	Culvert Length (m)	Maximum velocity, ft/s (m/s)		
10 – 60	3-18	4.0 (1.2)	5.0 (1.5)	6.0 (1.8)
60 – 100	18-30	4.0 (1.2)	4.0 (1.2)	5.0 (1.5)
100 – 200	30-61	3.0 (0.9)	3.0 (0.9)	4.0 (1.2)
> 200	> 61	2.0 (0.6)	2.0 (0.6)	3.0 (0.9)
		Minimum water depth, ft (m)		
		0.8 (0.24)	0.8 (0.24)	1.0 (0.30)
		Maximum hydraulic drop in fishway, ft (m)		
		0.8 (0.24)	0.8 (0.24)	1.0 (0.30)

5.3 Passage Barrier

Fish passage barriers are conditions in a stream that exceed the capabilities of the fish to navigate the stream. The barriers that are of greatest concern in the present research include: high in-stream velocities, excessive turbulence, perched culverts, debris clogging the culvert barrel, and low flow depths. Any of these barriers may limit or prevent fish passage or may result in extreme exhaustion in fish before they successfully pass the barriers (Kilgore et al. 2010). Table 5.3 provides a template for categorizing barriers and their potential impacts, while Table 5.4 contains extreme culvert and stream conditions and the possible barriers that they pose.

Table 5.3 Fish barrier categories and their potential impacts (Kilgore et al. 2010)

Barrier Category	Definition	Potential Impacts
Temporal	Impassable to all fish at certain flow conditions (based on run timing and flow conditions)	Delay in movement beyond the barrier for some period of time
Partial	Impassable to some fish species, during part or all life stages at all flows.	Exclusion of certain species during their life stages from portions of a watershed
Total	Impassable to all fish at all flows	Exclusion of all species from portions of a watershed.

Table 5.4 Culvert or stream characteristics and associated barriers that they pose

Culvert Characteristic	Possible Barrier
Outlet drop and outlet perch	Jump barrier
Culvert slope	Velocity barrier
Culvert slope times length	Exhaustion barrier
Presence of natural stream substrate	Depth barrier
Relationship of tailwater control elevation to culvert inlet elevation	Depth and velocity barrier

5.3.1 Excessive Velocity

Excessive velocity can occur within the barrel of the culvert or at the inlet or outlet because of lack of channel roughness, culvert placement (at an inappropriate slope), and/or contraction at the inlet (Connecticut Department of Environmental Protection 2008). Channel placement at an improper slope can also result in a hydraulic jump, which can be difficult for some species to navigate (see Figure 5.5 Example of a potential velocity barrier).

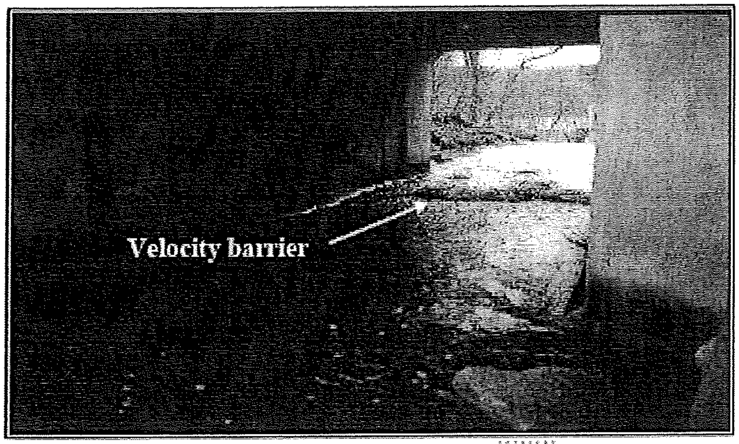

Figure 5.5 Example of a potential velocity barrier

Velocities that affect fish passage may include: (a) boundary layer velocities – the velocities within the boundary layer are reduced below the average channel velocity as a result of the influence of culvert roughness. The thickness of the boundary layer is important since this layer is utilized by the fish for swimming and resting, (b) the average cross-sectional velocity is higher than near-boundary velocities and provides a conservative velocity that can be used for design, (c) the maximum point velocity may be the result of the presence of a disturbance within the barrel and may require fish burst speed for passage, and (d) the inlet transition velocity may be the result of higher local channel slope at the inlet of the culvert, and may act to limit aquatic species passage. However high inlet transition velocities can potentially be mitigated by using improved inlet designs (e.g., wingwalls, aprons, etc.).

5.3.2 Excessive Turbulence

Turbulence in culverts is often generated by measures provided to reduce culvert velocity. Such measures include increasing roughness. Kilgore et al. (2010) discuss how Washington and Maine Departments of Transportation use an Energy Dissipation Factor (EDF) to estimate turbulence for allowing fish passage as follows;

$$EDF = \gamma QS/A \quad 5.1$$

where Q is the flow rate, S is the slope of culvert, A is the flow cross-sectional area and γ is the unit weight of water. They further explain that Washington State suggested that maintaining EDF to a value less than 7.5 ft-lb/ft^3 for a rough channel is deemed appropriate for fish passage.

5.3.3 Perched Culverts

A drop at a stream crossing outlet or a step at the inlet may require aquatic species to have jumping capabilities. This requirement is problematic for small and weak fish species. Perched culverts are drops in the streambed level downstream of the culvert outlet, and may be the result of long-term excessive scour and erosion, freezing and thawing of the streambed at the outlet, improper installation of the culvert, or downstream degradation of the channel. An example of a perched culvert is shown in Figure . The ability of a fish to navigate perched culverts depends on the jumping ability of the fish species, long-term hydraulic characteristics of the stream, and flow conditions in the culvert when the outlet depth is critical. See Table 5.2 for some examples of fish jumping capabilities.

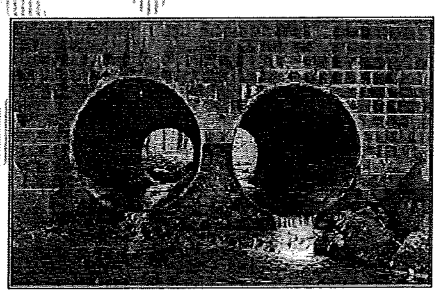

Figure 5.6 Example of a perched culvert

5.3.4 Debris and sediment accumulation

Debris accumulation is most common at undersized culverts, in the presence of large roughness elements, or at the connection between multiple barrel culverts (see Figure 5.4). Roughness elements and/or the presence of trapped debris within a culvert barrel can facilitate deposition of sediment within the barrel, thereby increasing clogging of the culvert.

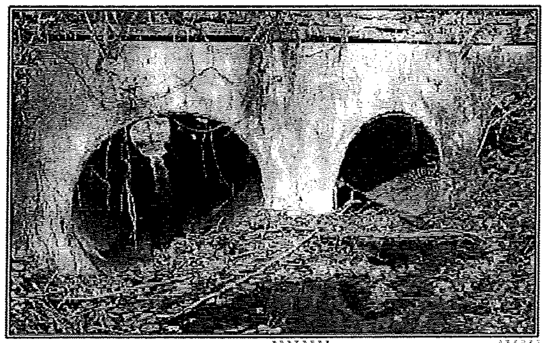

Figure 5.4 Debris blocking the entrance to a multiple barrel culvert (Connecticut Department of Environmental Protection 2008)

5.3.5 Shallow depth

Shallow depths are common in culvert stream crossings during low flow periods and can result in the inability of aquatic species to navigate the culvert. Low depths can also reduce oxygen levels in the water. Shallow water can hinder the ability of a fish to thrust forward, consequently reducing the ability of the fish to swim upstream.

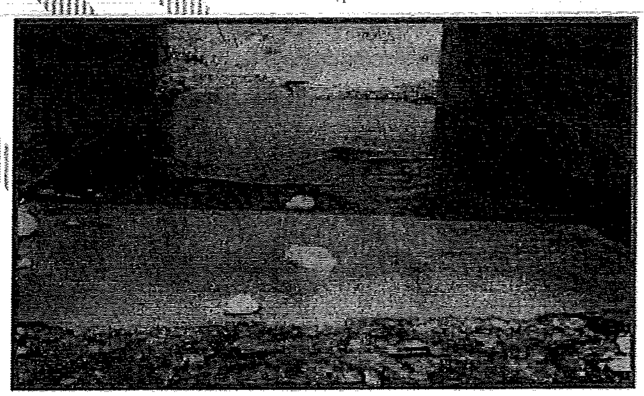

Figure 5.5 Inadequate depth conditions in a culvert (Connecticut Department of Environmental Protection 2008)

5.3.6 Bottomless culverts

The use of wide span bridges or bottomless culverts (Figure 5.9) has the potential to minimize the conflict between aquatic species passage and stream-crossings, primarily because the constraints necessary to guarantee safe culvert design are the same constraints that are necessary to guarantee good aquatic species passage. These constraints include, lower velocities (and consequently larger depths), a stable bed without head cuts, the elimination of locations with excessive shear, and in general, characteristics that mimic the local stream system. However, the implementation of bottomless culverts will also almost certainly increase installation costs because such structures will require larger flow cross sections and safety accommodations to mitigate the hazards associated with potential scour or degradation of the stream bed.

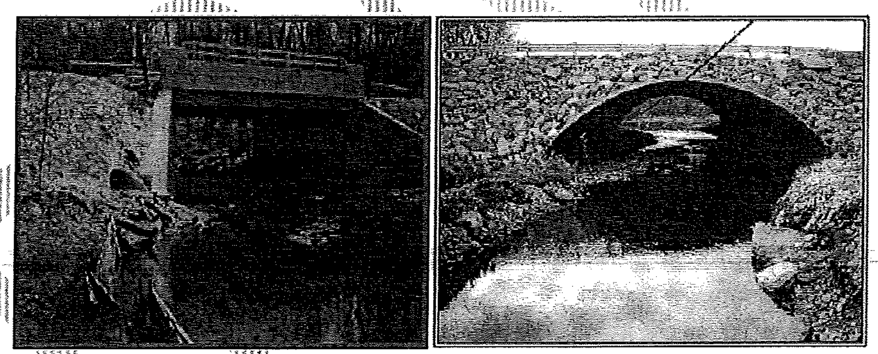

Figure 5.6 Clear span bridges and bottomless culverts as alternatives to traditional culverts

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