

A reexamination of the Design Document HEC-26  
The Process and its Implications

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A project submitted to the faculty of  
Brigham Young University  
in partial fulfillment of the requirements for the degree of  
Master of Science

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April 2016

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## ABSTRACT

### A reexamination of the Design Document HEC-26 The Process and its Implications

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Increased awareness of aquatic organisms has shifted designers' focus from designing exclusively hydraulically competent culverts to the inclusion of culverts passable by aquatic organisms. Among the several guides that have been presented in order to minimize impact on Aquatic Organism Passage (AOP) is HEC-26. HEC-26 provides a quantitative stream simulation design for AOP that incorporates geomorphic based design. Its premise is that hydraulic and shear stress continuity constitute a surrogate parameter for AOP. As such, a literature review of sediment transport, incipient motion, and basic transport equations are given.

A detailed account of the process required to determine bedload mobility is documented. This section includes the channel and culvert mobility conditions that require redesign of the culvert. Assumptions are stated and justified and a detailed walkthrough is provided. The successive results show mobility at each upstream surveyed cross-section for twelve possible flows, ranging from the peak hydraulic discharge to low fish passage flow.

Implications of bedload mobility combined with these results lend themselves to three conditions that define culvert bed replenishment. When these three conditions are met, a culvert can conservatively be considered to replenish. When the culvert can be proven to replenish, oversizing culvert bed material to provide a stable bed at peak flow is unnecessary. The computational method provided in this report delivers the conditions for which not oversizing the culvert bed material to guarantee bed stability for design flows.

Keywords: sediment transport, incipient motion, HEC-26, replenishment, HEC-RAS, HY-8, fish passage culvert design



## ACKNOWLEDGEMENTS

There are many individuals who helped me in the culmination of this project. To begin, I would like to thank Kyle Rowley for helping me understand the crazy things you do for the sake of research. Thanks to Matt George for providing the kind of get-it done attitude with his own project and being a wordsmith for tricky sentences. I'm grateful to Fernando and Victoria Rivera for the willingness to help me with technical concerns and the report figures.

I thank my advisor, Dr. Rollin Hotchkiss, for his countless hours listening to my unprocessed ideas and pointing me in the right direction. I am especially grateful for his mentorship and life advice. I would like to thank my committee for being my favorite professors at the university and for being willing to help me whenever I needed. I acknowledge Roger Kilgore and thank him for sending me the RAS files and answering some technical questions about the design process.

I'm so grateful to my parents and in-laws for their encouragement and support. I acknowledge the sacrifice and sustaining influence of my wife Nicolea. Without her continued reassurance and buoying influence this report would not have been possible.



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# **1 INTRODUCTION AND BACKGROUND**

## **1.1 Purpose**

The purpose of this report is to show that oversizing culvert bed material to provide a stable bed at peak flow is not always necessary when designing a culvert for aquatic organism passage (AOP). The motivation for designing a stable bed at peak discharge comes from the recognition that “the benefits of natural streambeds and embedded culverts are widely recognized in AOP applications, (Venner Consulting and Parsons Brinkerhoff, 2004; Bates et al., 2003; Taylor and Love, 2003; and Clarkin et al., 2003). Bed material provides barrel roughness, which provides areas of low velocity that may be conducive to passage, mimics natural hydraulics, and is self-sustaining when designed properly (White, 1997)” (Kilgore et al., 2010).

There are two reasons that it is not always necessary to oversize bed material in a culvert. First, such oversizing may not mimic the natural streambed (as in case of sand-bed channels) and second, simulations show that sediment may actually replenish the culvert from upstream. This report demonstrates a simulation method that determines if replenishment does occur for a given site and hence provides justification to not oversize sediment within.

## 1.2 Sediment Transport in Rivers

When a river carries sediment, it is called an alluvial river. Non-alluvial rivers will not be covered in this report as they have no sediment transport component. There are three terms that are important to review. *Competence* refers to the largest diameter of sediment that a river can move; it is a hydraulic limitation to move sediment. *Capacity* is the maximum amount of bedload of a given size that a river can transport, a concept similar to that of saturation. Lastly, *sediment supply* is the amount and size of sediment available for transport. These terms and concepts are important for engineers or designers who wish to fully understand and address problems in a particular stream. As a general rule, the transport of finer materials is supply limited while the transport of larger material is capacity limited. This report assumes that there are no restrictions on supply. We assume that upstream of the reach of interest, there is a limitless amount of the same material that we see in the given reach. This allows us to focus solely on the competence of the stream under historically-based and organism-based flows such as peak discharge and high passage flow.

## 1.3 Culverts and Aquatic Organism Passage

As the human population has grown and expanded over time, and as technology and engineering have advanced, roads have spread across the globe. Whenever a road crosses a stream and its span over the stream is less than 20 feet, a culvert will be installed. Culverts are commonly made of corrugated metal pipe (CMP), but can be fabricated from concrete, steel, or PVC. Culverts, however, can prevent upstream aquatic organism passage due to a change in channel velocity because of a flow constriction. It may also limit passage due to an exorbitant length. Another barrier might be that the shear stress acting on an aquatic organism may cause it

to be unable to pass the culvert. Drops at inlets or outlets or insufficient depth also constitute possible barriers (Hotchkiss and Frei 2007).

These barriers can represent a major threat to the ecological connectivity of a stream. Habitat fragmentation decreases both population density and species richness, and significantly impacts community composition, species interactions and ecosystem functioning (Didham 2010). Sheer and Steel et. al. 2006 noted that the primary fish passage barrier of the 1,491 anthropogenic barriers in the Willamette River Basin are culverts under roads. As shown in Figure 1, fish habitat can go from a) genetic and spatial homogeneity to b) installation of roads, creating several impassable culverts causing habitats to disconnect creating weaker, smaller populations to c) population extirpation occurring after a few years to d) a long-term fragmented ecosystem. Environmentally-aware engineers and designers must know and design to prevent this avoidable conclusion.

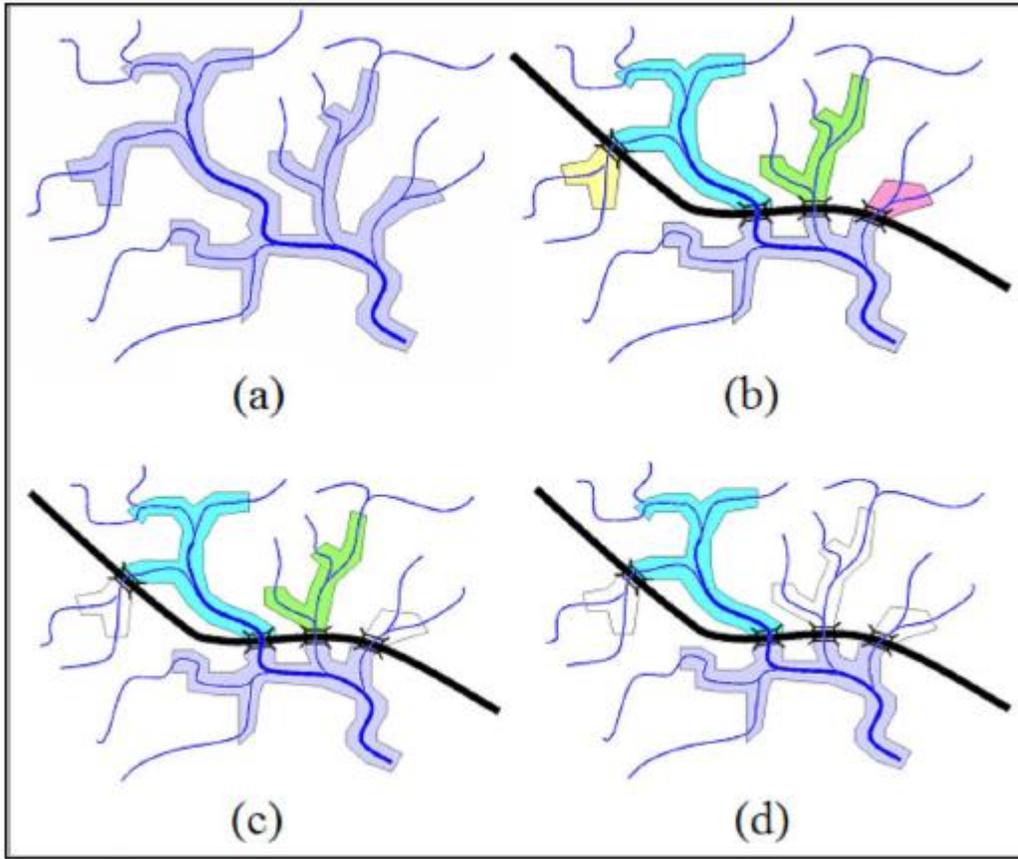


Figure 1: Changes in Fish Habitat Use over Time after Roadway Fragmentation (Hotchkiss and Frei, 2007)

#### 1.4 HEC-26

A variety of culvert designs that consider hydrological, geological, and economic factors including FishXing and state DOT design guides have been presented in order to minimize impact on fish and other aquatic organisms (Barnard et al. 2013 and USFS 2008). In 2010, another culvert design document, HEC-26, was published by the Federal Highway Administration (FHWA) to help engineers solve the aquatic barrier problem in the absence of locally mandated design guidelines (Kilgore et al. 2010). Its purpose is to assist in the design of culverts that simulate the natural stream in order to facilitate aquatic organism passage. It

corroborates the findings of many geomorphic-based design approaches and furthers their work by providing quantitative methods to restore aquatic habitat.

The purpose of HEC-26 is to provide a quantitative stream simulation design procedure that incorporates geomorphic-based principles. There are many benefits of designing a culvert using the guidance found in HEC-26. When a culvert is designed according to its guidelines, it will satisfy peak hydraulic criteria which will protect the public road. The design procedure is objective and does not rely on estimated parameters. HEC-26 also provides an excellent basis for justifying larger expenditures for larger diameter pipes. Additionally, the design procedure does not target specific organisms but produces designs for more diverse species.

The premise on which HEC-26 operates is that streambed sediment constitutes viable fish habitat. This is proposed because fish and other aquatic organisms experience the same forces and stresses as the streambed material. Thus the underlying hypothesis is that if sediment material in a culvert barrel simulates the natural material upstream and downstream, and if flow hydraulics within the barrel are close to conditions in the stream, that aquatic organisms will be able to freely move upstream through the culvert. The design goal is to provide a stream crossing that has “an equivalent effect, over a range of stream flows, on the streambed material within the culvert compared with the streambed material upstream and downstream of the culvert. When this is achieved and the velocities and depths are comparable to those occurring in the stream, the conditions through the crossing should present no more of an obstacle to aquatic organisms than conditions in the adjacent natural channel.” (HEC26, page 1-1).



## 2 SEDIMENT TRANSPORT AND INCIPIENT MOTION

### 2.1 Various Definitions

Over the course of the last two centuries, great advances have been made in quantifying the process of sediment transport. There are several factors which tend to move sediment. These include shear stress, impact force, and lift forces such as buoyancy, pressure gradient forces, and turbulence forces. The semi-empirical work done by Shields (1936) covered the shear stress and buoyant forces. He plotted dimensionless shear stress against the dimensionless particle Reynolds number to yield a line that represented incipient motion, or where critical shear equaled applied shear. Any combination of particle size and flow characteristics that is plotted above the curve is mobile whereas any that fall below the line are immobile. The line itself represents the boundary of incipient motion (Figure 2). More recently, researchers have been studying the effect of turbulent forces on incipient motion. Lajeunesse et. al. 2010 showed that particles under turbulent forces exhibit intermittent motion and found coefficients satisfying the erosion-deposition model for turbulent flows put forth by Charru. Amoudry (2014) presented a numerical model that incorporates turbulence to predict sediment scour and sediment transport for non-uniform open channel flow and even estuarine situations.

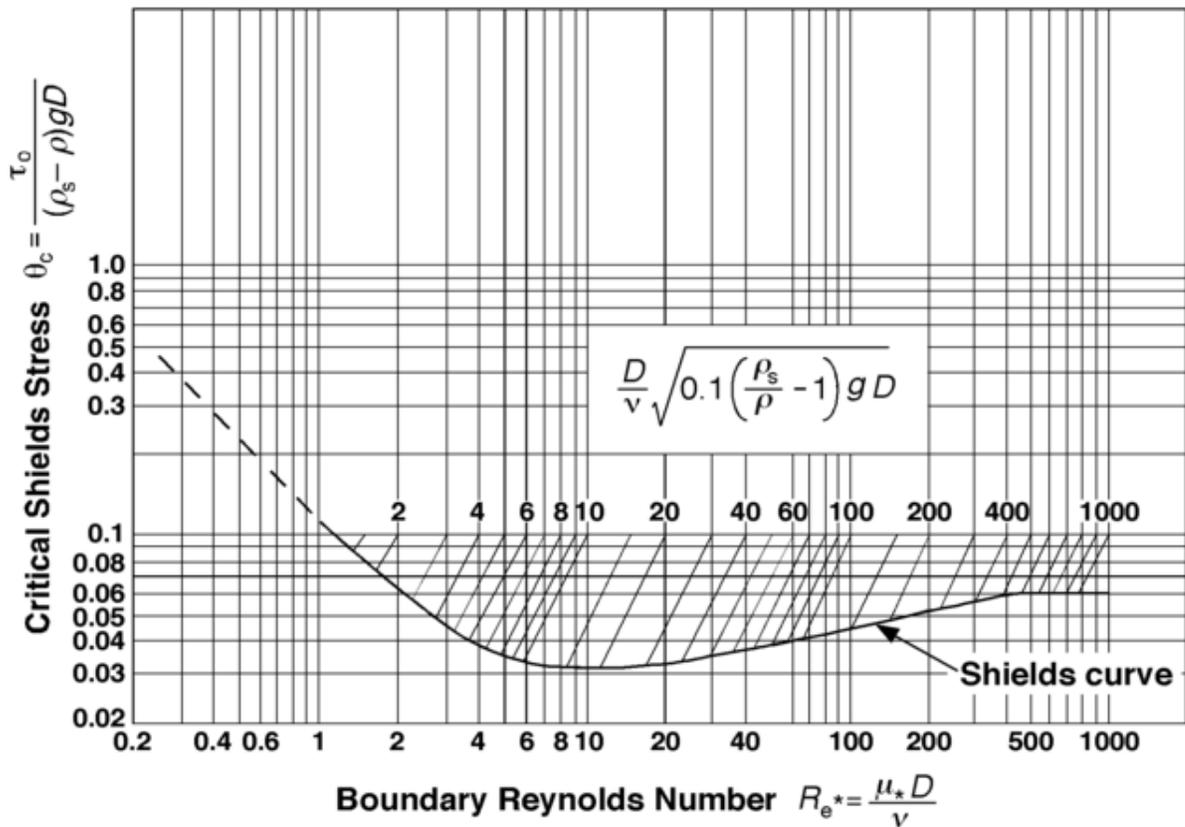


Figure 2: The Shields Diagram.

The work of this project does not account for these more recent developments in sediment transport theory. Rather, it focuses on the simplified approach by using the depth slope product to compare it against the semi-empirical permissible shear stress resulting from the pioneering work done by Shields. This is because the programs that are widely used by designers have not yet incorporated the more recent developments including turbulent forces.

Additionally, there are three general types of bedload formulae: excess shear stress (DuBoys 1879), excess discharge (Schoklitsch 1934), and excess stream power (Bagnold 1980). Of these three, the most commonly used appears to be the DuBoys method. This is also the most

largely used in the design examples in HEC-26. The three equations are written below for clarification.

$$\text{Excess shear stress:} \quad (\tau_a - \tau_{cr}) \quad q_{sb} = X' \tau_0 (\tau_0 - \tau_{cr})$$

$$\text{Excess discharge:} \quad (q - q_{cr}) \quad q_{sb} = X'' S_E^k (q - q_{cr})$$

$$\text{Excess stream power:} \quad (\omega - \omega_{cr}) \quad q_{sb} = (\omega_0 - \omega_{cr})^{3/2} d^{2/3} D_{50}^{-1/2}$$

Where:

$\tau_a$  = applied shear stress (FL<sup>-2</sup>)

$\tau_{cr}$  = critical shear stress (FL<sup>-2</sup>)

$q$  = unit width discharge (L<sup>2</sup>T<sup>-1</sup>) (see Equation 7)

$q_{cr}$  = critical unit width discharge (L<sup>2</sup>T<sup>-1</sup>) (see Equation 6)

$\omega$  = stream power (FL<sup>-1</sup>T<sup>-1</sup>)

$\omega_{cr}$  = critical stream power (FL<sup>-1</sup>T<sup>-1</sup>)

$q_{sb}$  = sediment transport rate per unit channel width (FT<sup>-1</sup> or L<sup>3</sup>T<sup>-1</sup>)

$S_E$  = energy slope (dimensionless)

$X'$ ,  $X''$ , and  $k$  = empirically determined coefficients

$d$  = the flow depth (L)

$D_{50}$  = the median diameter of sediment (L)

Further description of excess stream power will not be covered in this document as only the excess shear stress and excess discharge methods are used in the analysis performed in HEC-26. Further explanation of these equations will be given in sections 2.1.1 and 2.1.2.

### 2.1.1 Excess Shear Stress

Excess shear stress states that incipient motion occurs when the applied shear exceeds the permissible shear on a given particle. To determine the excess shear stress, two different shear stresses are needed. As mentioned above, to compute the applied shear stress, we adhere to the concept of incipient motion as stated in HEC-26. This concept is known as the depth-slope product. It assumes flow is steady and uniform and uses a reach or cross-sectionally averaged depth and slope. Though this is only an approximation of reality, it is generally adequate for design purposes. The equation for applied shear stress is found below in Equation 1.

$$\tau_a = \gamma R S_E \quad (\text{Eq. 1})$$

Where:

$\gamma$  = the specific weight of water ( $\text{FL}^{-3}$ )

$R$  = the hydraulic radius (L)

Equation 1 yields the amount of shear acting on a certain particle. Applied shear is the power to move an object and as such it has nothing to do with the size, shape or weight of the particle. In the HEC-26 analysis, the hydraulic radius  $R$  is replaced with the maximum depth  $Y_{\max}$ . This modification is conservative as it allows for greater moving power. The modified equation is shown below in Equation 2.

$$\tau_a = \gamma Y_{\max} S_E \quad (\text{Eq. 2})$$

Where:

$Y_{\max}$  = the maximum channel depth (L)

The hydraulic radius is defined as the area of flow over the wetted perimeter of the stream. As a channel gets very wide, this becomes the depth of the channel. For all cross-sections except the one immediately upstream and downstream of the culvert, it suffices that hydraulic radius be set to the maximum depth of the given cross-section. For these two specific locations, the way to find the required term of maximum depth will be determined by the water surface Elevation minus the respective Culvert Invert minus the embedment (Equation 3). These parameters can be found in the detailed culvert output table in HEC-RAS.

$$Y_{max} = WSE - Culv.Invert - embedment \quad (\text{Eq. 3})$$

Energy slope is defined as the slope of the energy gradeline. It is not equivalent to the bed slope unless under uniform flow conditions. The energy slope is computed in HEC-RAS and this will be used for all cross sections except the most important two, the ones immediately upstream and downstream of the existing culvert. These two will be calculated using the Manning's equation found below in Equation 4.

$$S_E = \left( \frac{Vn}{1.49R^{2/3}} \right)^2 \quad (\text{Eq. 4})$$

Where:

$V$  = average velocity of flow in main channel ( $LT^{-1}$ )

$n$  = composite Manning's roughness ( $TL^{-1/3}$ )

The composite Manning's roughness follows from HEC-26 in Equation 5.

$$n = [(b * n_b^{1.5} + s * n_s^{1.5})/P_w]^{2/3} \quad (\text{Eq. 5})$$

Where:

$b$  = the bottom width of the embedded channel (L)

$n_b$  = the Manning's roughness value for the embedded material ( $TL^{-1/3}$ )

$s$  = the wetted perimeter of the sides above the embedment (L)

$n_s$  = the Manning's roughness value for the sides ( $TL^{-1/3}$ )

$P_w$  = the total wetted perimeter (L)

### 2.1.2 Excess Discharge

Excess discharge is a method used when depth is difficult to measure or define because the size of the roughness elements relative to the depth is high. This is generally used for steeper slopes, greater than five percent, due to the small depth and large roughness associated with such slopes. The equation that defines critical unit discharge is found below in Equation 6.

$$q_{c-D50} = \frac{0.15g^{0.5}D_{50}^{1.5}}{S^{1.12}} \quad (\text{Eq. 6})$$

Where:

$q_{c-D50}$  = critical unit discharge to entrain the D50 particle size ( $L^2T^{-1}$ )

$g$  = gravitational acceleration ( $LT^{-2}$ )

$S$  = the channel bed slope (dimensionless)

The value computed using Equation 6 is then checked against the actual unit discharge as shown in Equation 7. Similar to the shear stress method, if the actual unit discharge exceeds the critical unit discharge, then mobility will occur.

$$q = Q/w_a \quad (\text{Eq. 7})$$

Where:

$w_a$  = active channel bed width (L)

HEC-26 uses the critical discharge method to determine mobility for one of the three example locations, namely, Bear Creek. The reason this report uses excess shear stress rather than critical discharge for this location is an attempt to see the water back up near the inlet. Using the excess discharge method, this is impossible to see even if it occurs because the critical unit discharge equation uses bed slope, not energy slope. In cases where headwater is likely to occur, or when the researcher desires to see its influence, if any, the excess shear stress method should be used.

## 2.2 Permissible Shear Stress

Permissible shear stress has to do with the sediment or object being moved and very little with the fluid moving it. The exception to this generalization is that the density of the fluid compared to that of the sediment is important. For uniformly graded material, the permissible shear stress equation is found in in Equation 8. Since natural bed material is not often uniformly graded, Equation 9 provides a suitable alternative to its less robust version.

$$\tau_p = F_* (\gamma_s - \gamma) D_{50}^{0.5} \quad (\text{Eq. 8})$$

$$\tau_p = F_* (\gamma_s - \gamma) D_{84}^{0.3} D_{50}^{0.7} \quad (\text{Eq. 9})$$

Where:

$F_*$  = the Shields parameter (or y-axis of the Shields diagram) for the D50 particle size as obtained from Table 7.1 in HEC-26 from Kilgore and Cotton (2005) ( $L^{0.5}$ )

$\gamma_s$  = the specific weight of the sediment ( $FL^{-3}$ )

$D_{84}$  = the sediment size for which 84 percent, by weight, of the bed is finer (L)

The specific weight of substrate is generally 165 pounds per cubic foot. HEC-26 states that it is between 156 and 165 pcf. Sample calculations for applied and permissible shear stress will be shown in the Methodology section.

### 3 METHODOLOGY

#### 3.1 HEC-26 Mobility and Stability

To determine mobility, one must first define what mobility is. Since this document reexamines the three design examples presented in HEC-26, we will define mobility the same way that it does. Per HEC-26, mobility occurs when the shear stress exerted on the bed exceeds the maximum permissible stress. For these design examples it is important to note that redesign is not required if the bed is mobile at every cross section for high passage flow ( $Q_H$ ) or if it is stable at every cross section for  $Q_H$  or peak discharge ( $Q_P$ ); rather, redesign is required only when the culvert bed is mobile or partly mobile ( $Q_P$ ) and the channel shows stability at any cross section (for  $Q_H$ ).

From HEC-26 directly, we understand that: “Interpretation of the shear stresses, or unit discharge, should conform to the following guidance:

1. If the maximum applied shear stress,  $\tau_a$ , or unit discharge for any channel cross-section is less than the permissible shear stress or critical unit discharge, respectively, then a redesign of the culvert to achieve a stable bed should be undertaken.
2. If the maximum applied shear stress,  $\tau_a$ , or unit discharge for all channel cross-sections is greater than the permissible shear stress or critical unit discharge, the bed may be considered mobile.
  - a. If the culvert shear stresses or unit discharges fall within the range observed in the

channel the culvert is adequately sized for the purposes of this step.

b. If the culvert shear stresses or unit discharges exceed the range observed in the channel the culvert is not adequately sized.”

The Tables below summarize the information quoted above and can be used as references to determine whether or not redesign is needed. The values used in the Tables are: “Y”, indicating *Yes*, there is mobility for all culvert or channel cross-sections, “N” indicating *No* Mobility for all culvert or channel cross-sections, and “P” indicating *Partial* mobility for all culvert or channel cross-sections Note that the only difference between the two tables is the second to last row. HEC-26 demands stability for peak hydraulic discharge as it conservatively assumes the bed will not replenish, and hence will not provide adequate substrate for fish passage.

Table 1: Summary of Mobility Possibilities and the Redesign Implications for  $Q_H$ .

	Culvert Mobility	Channel Mobility	Redesign needed
$Q_H$	P	P	Y
	P	Y	Y
	P	N	Y
	Y	P	Y
	Y	N	Y
	N	P	N
	N	Y	N
	Y	Y	N
	N	N	N

Table 2: Summary of Mobility Possibilities and the Redesign Implications for  $Q_P$ .

	Culvert Mobility	Channel Mobility	Redesign needed
$Q_P$	P	P	Y
	P	Y	Y
	P	N	Y
	Y	P	Y
	Y	N	Y
	N	P	N
	N	Y	N
	Y	Y	Y
	N	N	N

There are three case studies in the Appendices of HEC-26. This report reviews those case studies and shows how replenishment may conservatively be asserted. The next two sections review the equations used, the assumptions made, and the design process to help the designer understand each step.

### 3.2 Equations and Assumptions

As mentioned above in Section 2, both applied shear stress and permissible shear stress can be computed using derived and empirical equations respectively. The slope of the channel will be used for  $S_E$  for cross-sections upstream and downstream of the culvert as  $S_E$  mimics the channel bed slope closely for uniform flow. Although not strictly uniform flow, the assumption is that this approximation is acceptable. Near the culvert, however, rapid changes in geometry and flow type require that the energy slope be examined independently of the channel bed slope. For this reason, hand calculations for energy slope are important at the inlet and outlet of the culvert.

Before beginning the design procedure it is important to have five required variables: peak design flow ( $Q_P$ ), high passage design flow ( $Q_H$ ), low passage design flow ( $Q_L$ ), the bed material gradation, and cross-sectional surveys of the site. Permissible shear can be calculated from these variables (see Eq. 8 & 9).

### 3.3 North Thompson Fork

To illustrate the design process, this section will provide a walkthrough for North Thompson Fork as shown in Appendix H of HEC-26. The design criteria for this walkthrough are a 6.5' diameter CMP with a two foot embedment and a Manning's roughness of 0.06. With a peak design discharge of 103 cfs, the inlet cross-section maximum depth and energy slope become, using results from Equations 3 and 4:

$$Y_{\max} = 94.71 - 92.18 - 2.0 = 0.53 \text{ ft}$$

and

$$S_E = \left( \frac{Vn}{1.49R^{2/3}} \right)^2 = \left( \frac{2.67 \text{ ft/s} * 0.06 \text{ s/ft}^{1/3}}{1.49 * (0.53 \text{ ft})^{2/3}} \right)^2 = 0.02695 \text{ ft/ft}$$

It is important to note that these values only closely match the values found in HEC-26. They are, however, consistent enough to document. The assumptions made for this calculation are that the hydraulic radius is equal to the maximum depth and that the velocity used is the same velocity that is found in the culvert output table. The Manning's n that was used for the bed is the same as the one in the plan that HEC-RAS reads before execution. Using this bed roughness value and the standard CMP roughness of 0.024, individual composite roughness values were computed for the cross-section at the upstream and downstream end of the culvert using Equation 5.

The specific weight of substrate for this example has been chosen as 156 pcf (see pg 7-12). As calculated above, the maximum depth of the upstream invert cross-section is 0.53 ft. If it were not the cross-section immediately upstream of the culvert, its energy slope would be read directly from the HEC-26 XS output table. Since it is the upstream cross-section, we instead use Equation 4 to compute energy slope as shown above. The applied shear for the inlet can then be computed using Equation 2 as shown below.

$$\tau_a = \gamma Y_{max} S_E = 62.4 \text{ lb/ft}^3 * 0.53 \text{ ft} * 0.02695 = 0.89 \text{ lb/ft}^2$$

The second equation to step through of permissible shear stress is well covered by HEC-26, but it is covered here for completeness sake. The  $F_*$  factor comes from Table 7-1. The specific weight of substrate and of water have been previously defined for this case. The  $D_{84}$  and  $D_{50}$  must be determined from a pebble count; in this case, the information was provided in HEC-26 Table H.6. Using Equation 9, we get:

$$\tau_p = F_*(\gamma_s - \gamma)D_{84}^{0.3}D_{50}^{0.7} = 0.047(156 \text{ lb/ft}^3 - 62.4 \text{ lb/ft}^3)(0.56 \text{ ft})^{0.3}(0.16 \text{ ft})^{0.7} = 1.025 \text{ lb/ft}^2$$

Since the maximum permissible shear stress of 1.0 psf exceeds the applied shear stress of 0.89 psf this cross-section is not mobile. However, the entire reach must be checked to determine total channel mobility (Table 3).

Table 3: North Thompson Cross-Sectional Shear Stresses at  $Q_H=8.8$  cfs, embed=2 ft,  $n=0.060$

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Station (ft)	WSE (ft)	Bed elevation (ft)	$Y_{max}$ (ft)	Vel Chnl (fps)	E.G. Slope (ft/ft)	$\tau_{applied}$ (psf)	$\tau_{permissible}$ (psf)
600	103.37	102.69	0.68	2.43	0.02659	1.13	1.025
67	102.52	101.83	0.69	2.41	0.02543	1.09	1.025
472	99.42	98.79	0.63	2.93	0.04143	1.63	1.025
399	98.27	97.05	1.23	1.69	0.00891	0.68	1.025
342	97.01	96.44	0.57	3.46	0.07148	2.54	1.025
307	95.6	94.88	0.72	2	0.01694	0.76	1.025
286	94.82	94.32	0.5	3.29	0.07764	2.42	1.025
282.5	94.71	94.18	0.53	2.67	0.02695	0.89	1.025
259.5	Culvert						1.025
236.5	93.44	92.95	0.49	2.92	0.03579	1.09	1.025
233	93.44	92.9	0.54	2.5	0.02437	0.82	1.025
215	92.67	92.26	0.41	3.04	0.08027	2.05	1.025
172	91.32	90.59	0.73	1.98	0.01320	0.60	1.025
125	90.51	89.83	0.68	2.16	0.02212	0.94	1.025
57	88.86	88.2	0.66	2.52	0.02620	1.08	1.025
0	87.38	86.71	0.67	2.52	0.02605	1.09	1.025

Notes:

- (1) From profile output table. XS 259.5 is a placeholder for the centerline of the road and XS's 282.5 and 236.5 represent the physical inlet and outlet of the culvert. These were not surveyed as they are part of the culvert.
- (2) From profile output table. WSE for XS's 282.5 and 236.5 comes from the Culvert Output Table. The data is found in Culvert WS Inlet and Culvert WS Outlet respectively.
- (3) From the profile output table. The data for XS's 282.5 and 236.5 comes from the Culvert Output Table. They can be found by adding the embedment depth to Culv Inv El Up and Culv Inv El Dn.
- (4)  $Y_{max}$  can be found by subtracting columns (3) from (2). It can also be found in the profile output table.
- (5) From the profile output table using the title Vel Chnl. XS's 282.5 and 236.5 channel velocity can be found in the Culvert Output Table by Culv Vel US and Culv Vel DS.
- (6) From the profile output table. XS's 282.5 and 236.5 must be calculated using Manning's equation. Assumptions to use when calculating include: R is equal to  $Y_{max}$ , V is the value from Vel Chnl, and n is the same as the channel roughness.
- (7) Applied shear comes from Equation 2. Multiply the specific weight of water by columns (4) and (6).

(8) Permissible shear comes from the equation 9. Find  $F_*$  from Table 7-in HEC-26. Establish the specific weight of the substrate and the particle size distribution. For more uniformly graded material, only the  $D_{50}$  is needed (Equation 8).

A similar analysis to the one shown here was performed for six cases. For each culvert, the first culvert that met peak hydraulic criteria was tested, and then the final design as presented by HEC-26 was tested. The results are shown in the next section.



## 4 RESULTS

Analysis showed that of the three example culverts, conservatively only Bear Creek and Sickie Creek showed replenishment. Under closer examination, Bear Creek's replenishment was induced by a possibly incorrect hypothesis that deposition is longitudinally linearly continuous throughout the barrel. When examined in the software HY-8, it showed that the deposition at the outlet was due to a channel constriction and created a hydraulic jump a few feet upstream of the outlet.

The results are summarized in the Figures 3-12. The columns in each culvert Figure represent cross-sections of the channel or the inlet or outlet of the culvert. The rows represent different flows, ranging from  $Q_P$  down to  $Q_L$ . As  $Q_H$  is not readily apparent, it will be listed in the caption. The green cells indicate that for a given flow, the cross-section is mobile based on applied shear stress calculations. Likewise, the red cells indicate that for a given flow, the cross-section is immobile as permissible shear exceeds the applied shear stress there.

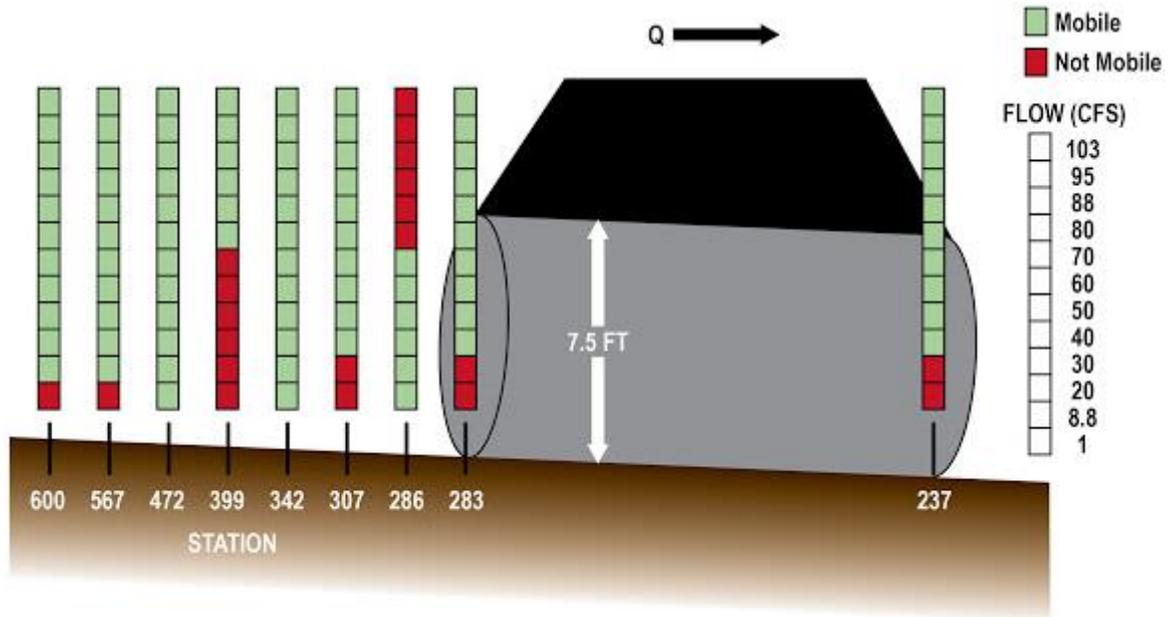


Figure 3: Model of 7.5' Culvert at North Thompson Fork. Green across a row indicates total reach mobility.  $Q_L=1$  cfs to  $Q_P=103$  cfs with  $Q_H=8.8$  cfs.

Figures 3 and 4 show spatial deposition for a range of flows at North Thompson Fork. Two differences are evident when comparing the two figures. First is the change in deposition at the outlet. This is likely due to the additional constriction presented by the downstream channel cross section. The second and debatably more interesting difference between the two figures is the immobility of material close to the outlet for the smaller culvert size. The theoretical explanation for this is that the water is heading up as it approaches the culvert and due to this effect, the energy slope near the inlet of the culvert is considerably flatter than normal. This leads to deposition near the inlet, but only for higher flows. As the flow recedes, the energy slope increases as the flow is not restricted anymore. The reason that this analysis shows that North Thompson Fork does not replenish is due not to the high flow immobility at cross-section 286, but rather the sediment continuity barrier at cross-section 399. Conservatively, we assume that the available sediment downstream of this cross-section is insufficient to replenish the culvert.

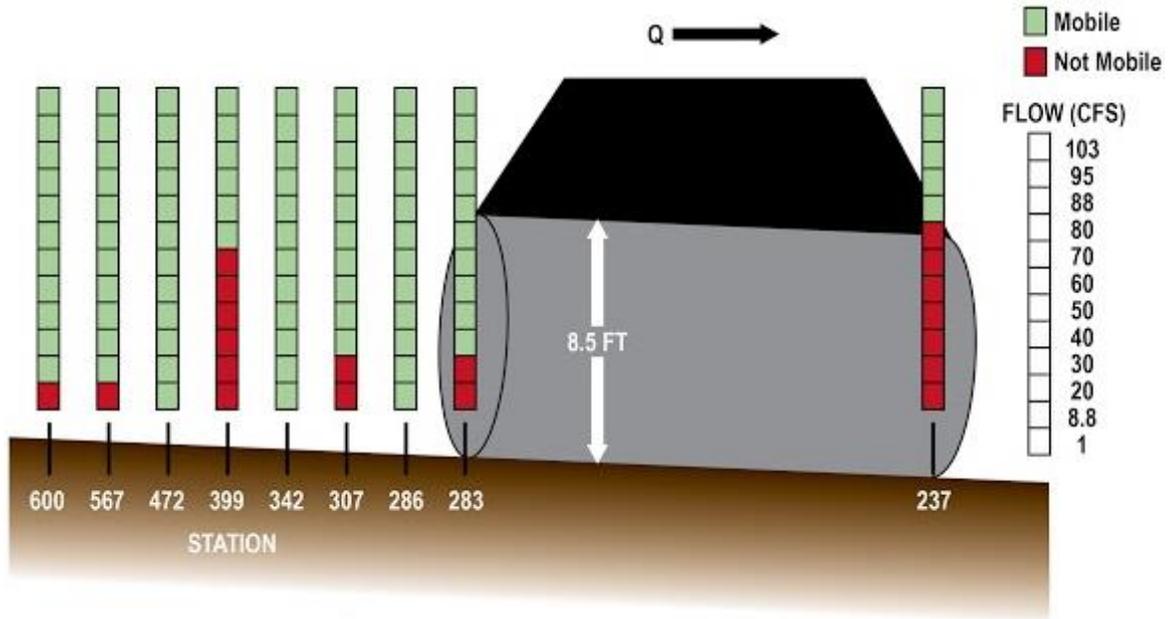


Figure 4: Sediment Mobility for a Range of Flows ( $Q_L=1$  cfs to  $Q_P=103$  cfs with  $Q_H=8.8$  cfs) for 8.5' Culvert at North Thompson Fork. Notice the difference in heading up with the larger diameter culvert.

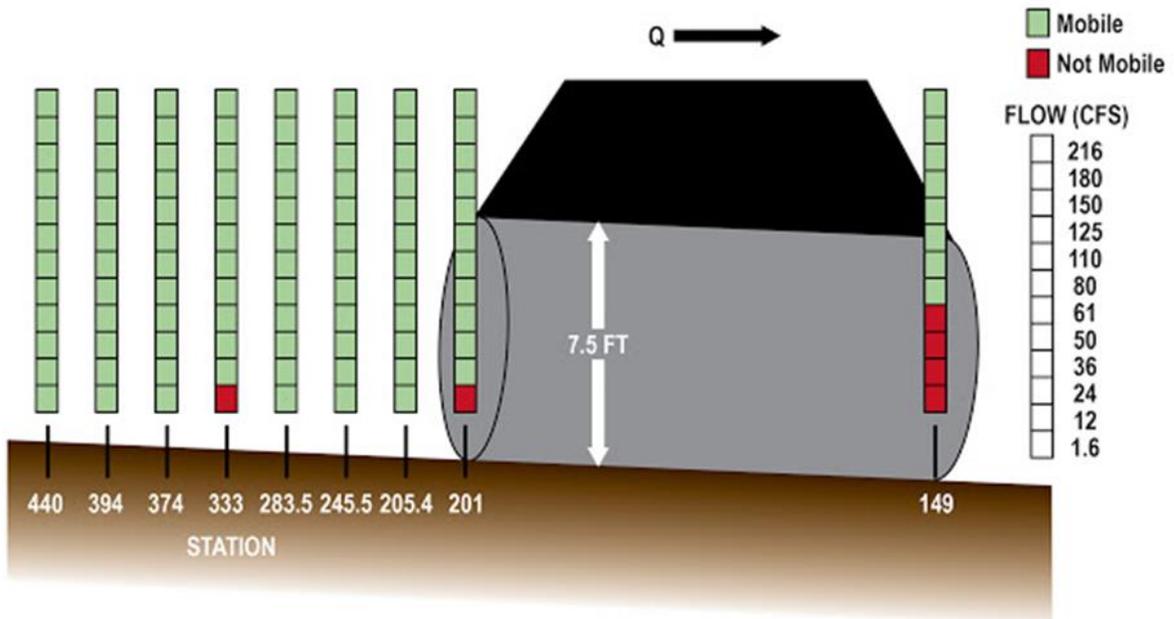


Figure 5: Sediment Mobility for a Range of Flows ( $Q_L=1.6$  cfs to  $Q_P=216$  cfs with  $Q_H=24$  cfs) for 7.5' Culvert at Bear Creek, AK.

Bear Creek presents an example of false confidence in replenishment. Notice in Figure 5 that the deposition is quite uncommon in the natural channel. However near the outlet, it occurs

with great frequency. The reason for this is the constriction in downstream cross-section. While in the field this constrictive cross section would potentially be altered to prevent flow constriction at the outlet, the user-entered cross-sections created by field surveys do not change based on flow magnitude or culvert size. This is particularly evident when considering Figure 6 where a dramatic increase in sediment immobility can be seen at the outlet.

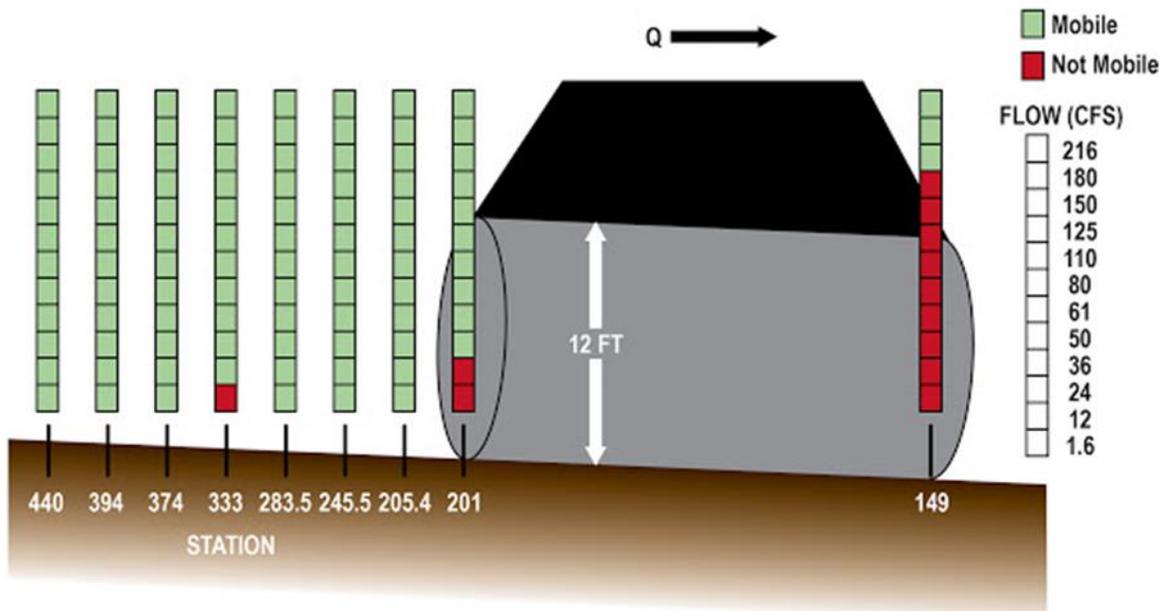


Figure 6: Sediment Mobility for a Range of Flows ( $Q_L=1.6$  cfs to  $Q_P=216$  cfs with  $Q_H=24$  cfs) for 12' Culvert at Bear Creek, AK.

The left most red dot in Figure 7 indicates the left ineffective flow boundary in RAS and the point left of the rightmost red dot is the right ineffective flow boundary. It is clear to see that much of the flow area is restricted by the downstream channel cross-section. This affects not only higher flows but lower flows as well. The bottom blue line indicates the water surface elevation for  $Q_H$  and the top line indicates it for  $Q_P$ .

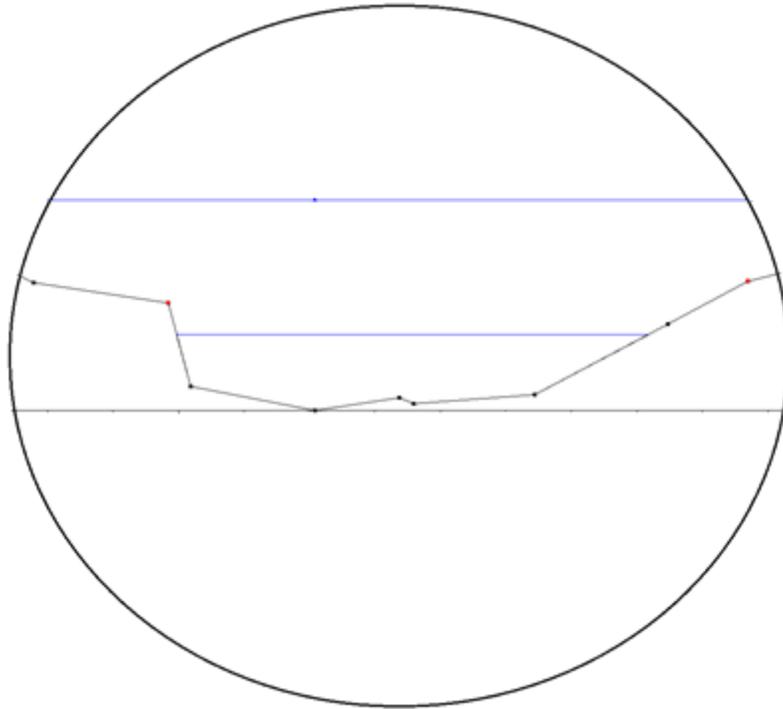


Figure 7: A View Looking at the Downstream Cross-section. Embedment shown is 4.43 feet. Ineffective flow area includes all but less than 8 feet of lateral span.

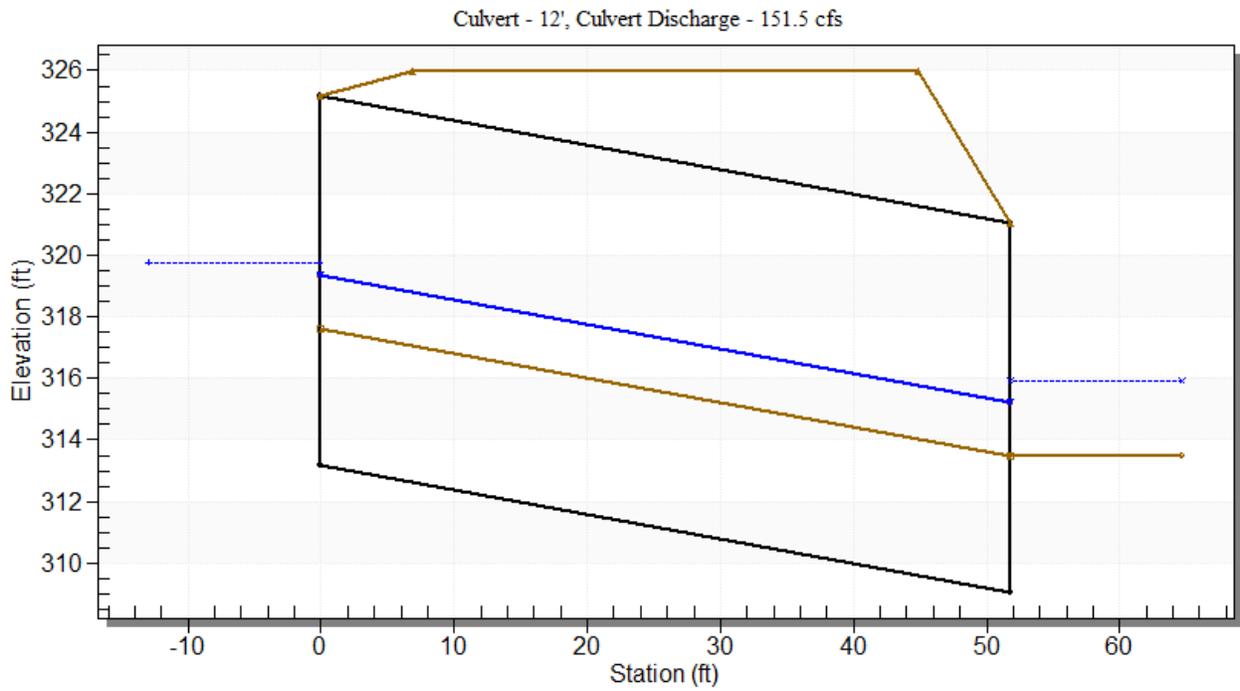


Figure 8: HY-8 Output File of the Water Surface Profile for Bear Creek. Q=151.5 cfs.

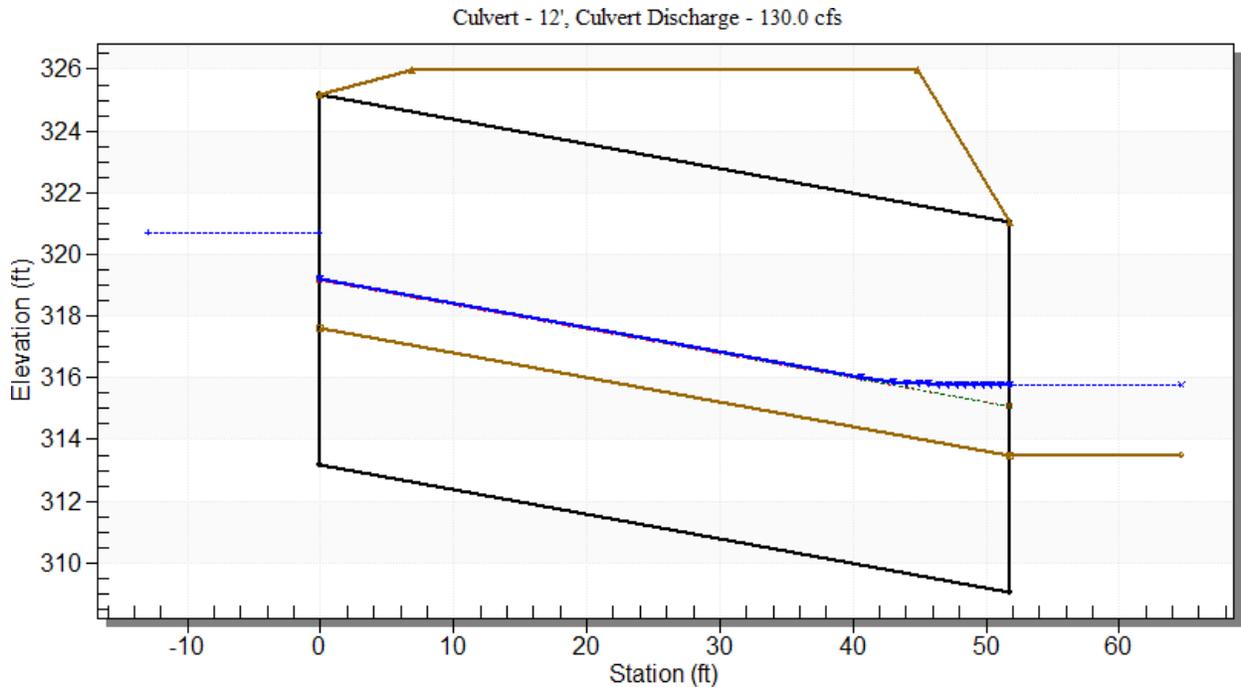


Figure 9: HY-8 Output File of the Water Surface Profile for Bear Creek. Q=130 cfs.

As the comparison of Figures 8 and 9 shows, the downstream channel constriction presents an issue for flows lower than 130 cfs. So although the boxes are red in a given analysis, it is important to check HY-8 to view the water surface profile. In the case of Bear Creek, this would likely create deposition behind the existing channel or scour the existing downstream XS or some combination of both. However, it would not likely replenish the entirety of the 52 foot culvert on a 7.9 percent grade.

The results for Sickie Creek revealed a significant finding that may be generalized to a more broad case. As a sand bed culvert, it is not surprising to view mobility for nearly all cross-sections of the channel. However, it is surprising is to see the immobility of fine grained material at such high flows for cross-sections (Figure 10). To understand why this happens, we examine the water surface profile again this time using HEC-RAS. Figure 11 shows this result. Note that in Figure 11, the flow direction is from right to left and the stationing is less than Figures 10 and

12 by 344 feet. Figures 10 and 11 ultimately show that even though the headwater does not submerge the inlet, the 7 foot culvert is small enough that the water backs up near the inlet and creates local inlet deposition.

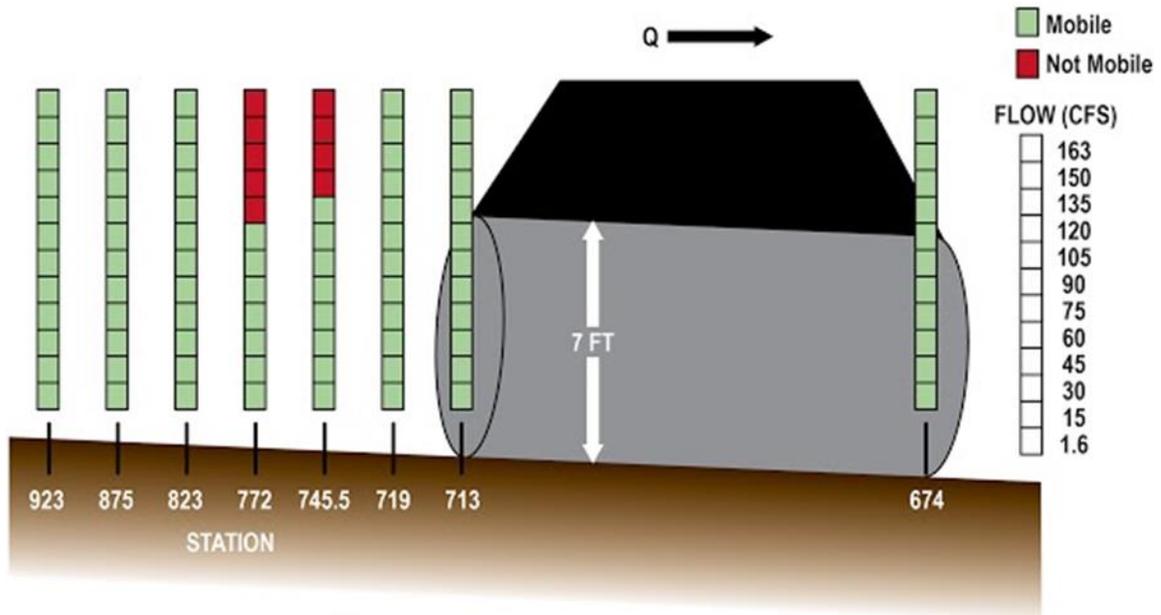


Figure 10: Sediment Mobility for a Range of Flows ( $Q_L=1$  cfs to  $Q_P=163$  cfs with  $Q_H=15$  cfs) for 7' Culvert at Sickle Creek, MI.

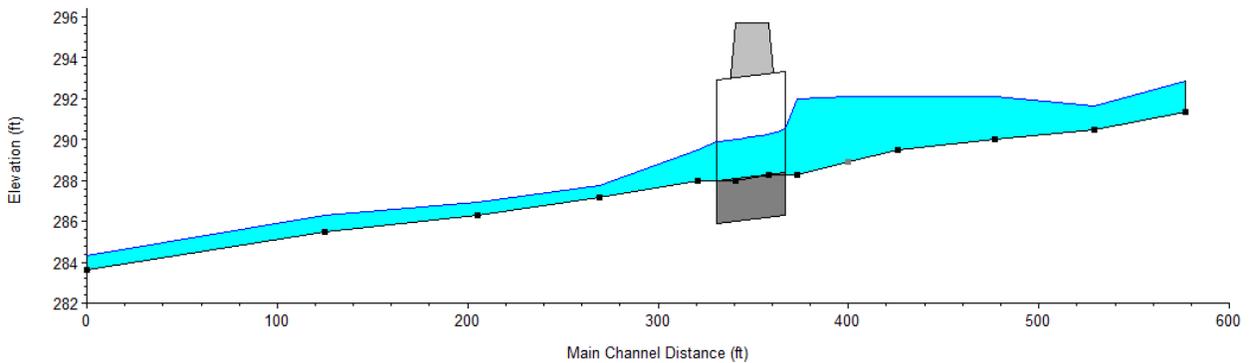


Figure 11: A Water Surface Profile for the 7 foot Culvert at Sickle Creek, MI. Note the flow direction is different from the other figures as well as the stationing is universally decreased by 344 feet in this figure.

When the culvert size is enlarged from 7 to 10 feet, the deposition no longer occurs (Figure 12). This is because the culvert is sized appropriately to prevent the dramatic heading up of water at the inlet. This analysis shows that even though replenishment will occur for either the

7 foot or the 10 foot culverts, if the designer is concerned about inlet deposition during high flows that they should still oversize the culvert. When not concerned with such temporary deposition, the 7 foot culvert will suffice without oversizing the culvert bed material. Culvert bed replenishment is shown in both Figures 10 and 12 as for fish passage flows the sediment continuity is not broken, neither is there deposition at the inlet prior to deposition at the outlet.

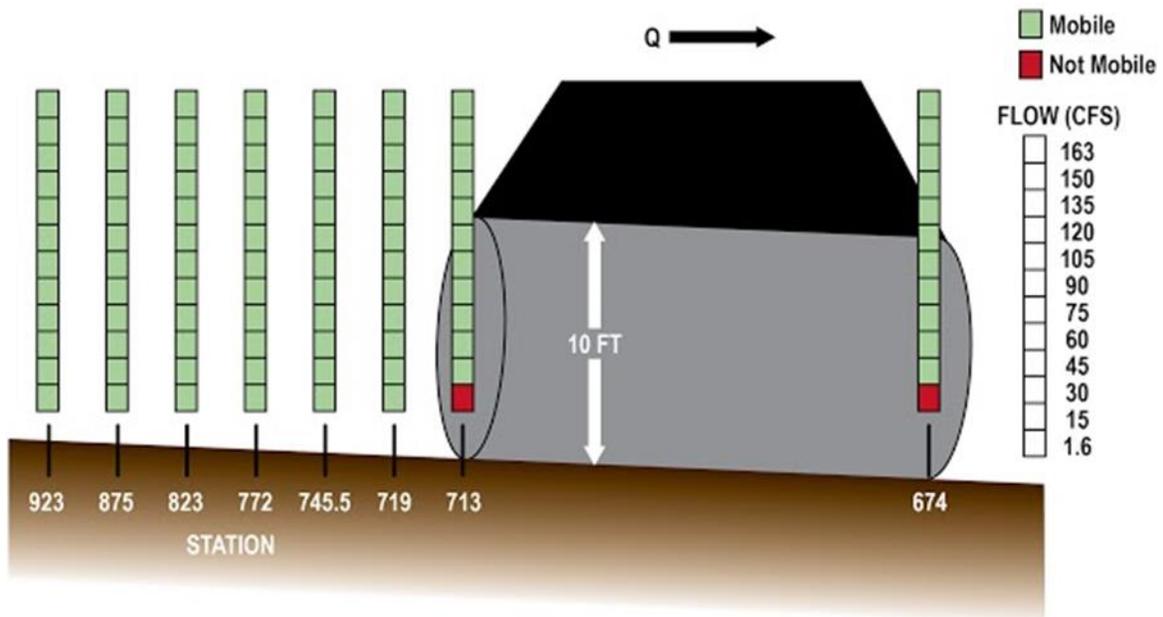


Figure 12: Sediment Mobility for a Range of Flows ( $Q_L=1$  cfs to  $Q_P=163$  cfs with  $Q_H=15$  cfs) for 10' Culvert at Sickie Creek, MI.

## 5 DISCUSSION OF RESULTS

As evidenced by the examples shown in the Results section, it is apparent that some beds do naturally replenish with sediment. For example, the sand bed at Sickie Creek definitively replenishes based on the following three replenishment criteria:

- 1) The channel shows no sediment transport discontinuity for flows where culvert deposition/replenishment occurs.
- 2) Sediment does not show deposition at the inlet prior to that of the outlet.
- 3) The water surface profile shows no hydraulic jumps.

Criterion 1 exists to allow sediment discontinuity for high flows where water may back up behind a culvert. The lack of sediment continuity only poses a problem for flows equal to or lower than the highest flow for which deposition occurs in the barrel because when deposition is not occurring in the barrel, sediment supply for bed replenishment is not a concern.

In the cases of North Thompson Fork and Bear Creek, deposition at the outlet is shown to vastly exceed the deposition at the inlet. Theoretically, this would be due to a gradually varied flow profile of M1, M3 or S1. While it may be natural for the designer to assume a linearly continuous deposition function based on an M1 profile, the research done in this project found that such dramatic increases in deposition from inlet to outlet were not due to an M1 profile, but rather an M3 or S1 profile which was due to the downstream channel cross-section posing a flow constriction. This constriction in flow creates a hydraulic jump and limits the transport capacity

immediately at the outlet. However, it is incomplete to state that replenishment will occur in such cases as Figures 5 and 6 without checking the water surface profile. It is for this reason that criterion 3 was implemented.

Lastly, the design in HEC-26 requires that a low-flow channel be constructed in the barrel particularly in cases where the embedded material has been oversized. Due to the large size of the riprap compared to the native material, low passage flow may be entirely interstitial due to the spaces in between the riprap that are not filled with native substrate or have been flushed out in the larger flows. HEC-26 states that to avoid creating this unintended barrier, baffles below the bed level may be used to cut off interstitial flow. However, this is an additional cost for channels where natural replenishment can be shown to occur.

## **6 RECOMMENDATIONS AND CONCLUSION**

### **6.1 Recommendations**

HEC-26 states that if bed mobility is shown for the entire culvert length for high passage flow along with total stream mobility and if the shear stresses in the culvert are within the range of those in the channel, then designing a larger, stable bed is unnecessary as the culvert poses no more a barrier than the natural stream. This reasoning is not extended for the peak discharge for two reasons: 1) AOP is not a concern at peak discharge and 2) ensuring that a bed exists at passage flows is a concern. The first reason is valid while the latter concern may be checked by following the procedure in this report. HEC-26 should treat peak discharge like high passage flow. This would recognize that bed mobility may occur for peak flow in the entire upstream reach. In the case of inlet deposition due to backwater and decreasing energy slope, the sediment deposits may be washed into the barrel at lower discharges.

To truly analyze sediment transport throughout a stream reach, an unsteady flow model with the conservation of mass equation for sediment would be required. While such models are available, the time required for their use has been prohibitive for culvert design. This may change in the future.

## 6.2 Conclusion

Although knowing whether sediment replenishment will occur in a given culvert can be challenging, the methods in this report describe a quantitative procedure to reach a conservative decision. Engineering judgment must still be used in the application of the produced results. When culvert shear stresses show that the bed is mobile for peak discharge, it is important to check the stream channel mobility as often it will be mobile also. Several flows should be run in HEC-RAS to ascertain where the sediment starts dropping out. If sediment throughput is shown, it provides a basis for a lower upfront cost as it may avoid cost of riprap and the culvert may be sized smaller due to a smaller required embedment depth.

As bed material provides roughness necessary for AOP, it is important that a natural bed exist for passage flows. To insure this condition, HEC-26 proposes oversizing the bed material to prevent blowout and forego the need for replenishment. This report states that oversizing culvert bed material to provide a stable bed at peak flow is not necessary when designing a culvert for aquatic organism passage (AOP) when the barrel can be proven to replenish. This report also outlines details of how to determine replenishment. This computational method provides justification for not oversizing the culvert bed material to guarantee necessary bed roughness for passage flows.

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