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APPENDIX J

DEGRADATION OF THE CHANNEL DOWNSTREAM FROM A DAM

J-1. Introduction. The rate and ultimate limit of channel degradation that can be expected downstream of a dam is dependent on the type of bed that comprises the channel. If the channel bed has a fairly uniform gradation and the largest particles present are easily capable of being transported at any time within the analysis time period, the stable slope method is recommended. For channel beds containing large enough particles in a significant amount to form an armor layer, the armor bed method is recommended. The concept of dominant discharge is used in both methods and this discharge is defined as a representative single discharge, when allowed to flow indefinitely, would produce a channel very similar to that formed by a naturally fluctuating flow. For an unregulated river, the dominant discharge is usually the bank full discharge or the peak discharge having a recurrence interval of 1 to 2 years. The channel hydraulic properties to be used in both methods should be the average properties of the cross sections near the dam site for the dominant discharge.

J-2. Stable Slope Method.

a. General. Based upon the assumption that the general character of the bed material does not change, the stable slope method, adapted from U. S. Bureau of Reclamation method [59], is used only when there is insufficient coarse material to form an armored layer, the gradation of the bed material is the same down to the depth of degradation, and the bed material depth is greater than the expected degradation limit. If a stable stream slope can be defined as that slope at which no bed material is transported, bed-load movement equations can be used to determine this slope by equating the bed-load movement to zero and solving for the slope. The bed-load equation selected for use should be tempered with judgment, compared with degradation limits of nearby dams with the same sediment/hydraulic characteristics, and comparisons should be made with other equations.

b. Volume of Erosion. If there is not a limit to the degradation length such as downstream structures or rock outcrops, the volume of expected eroded material must be estimated. It can be assumed that for reservoirs with little flow regulation, the amount of coarse sediments, of the size found on the channel bed, that is trapped by the reservoir is essentially the amount of sediment eroded downstream of the reservoir because of the stream's attempt to reach its transport potential. If the flow regulation is significant, the channel hydraulic and sediment properties for the dominant discharge must be used to calculate the sediment transport potential. Using an appropriate time interval, 1-5 years, the volume of sediment eroded can be estimated by multiplying the transport rate by the time interval. With this volume and the three slope method, which is discussed later, the new average channel can be estimated and its hydraulic properties can be used to estimate the sediment transport for the next time interval. The time interval increases as the change in bed elevation decreases. This procedure is continued until the design life of the reservoir is reached. The degradation length to be used is the lesser of the length computed as described or the distance to the nearest erosion preventing anomaly. The configuration of a degradation profile can be represented by the three slope method as shown in Figure J-1. The volume of eroded sediment can be represented by

$$Vol = At * B / 43{,}560 \qquad (J\text{-}1)$$

where

Vol = volume of material to be eroded in acre-feet

At = longitudinal area of degradation in square feet

B = channel width in feet

Solving for At

$$At = 43{,}560 * Vol / B \qquad (J\text{-}2)$$

From Figure J-1:

$$At = (39 * D^{**}2) / (64 * del\ S) \qquad (J\text{-}3)$$

where

D = depth of degradation immediately downstream of the dam

del S = difference between the existing and stable slope

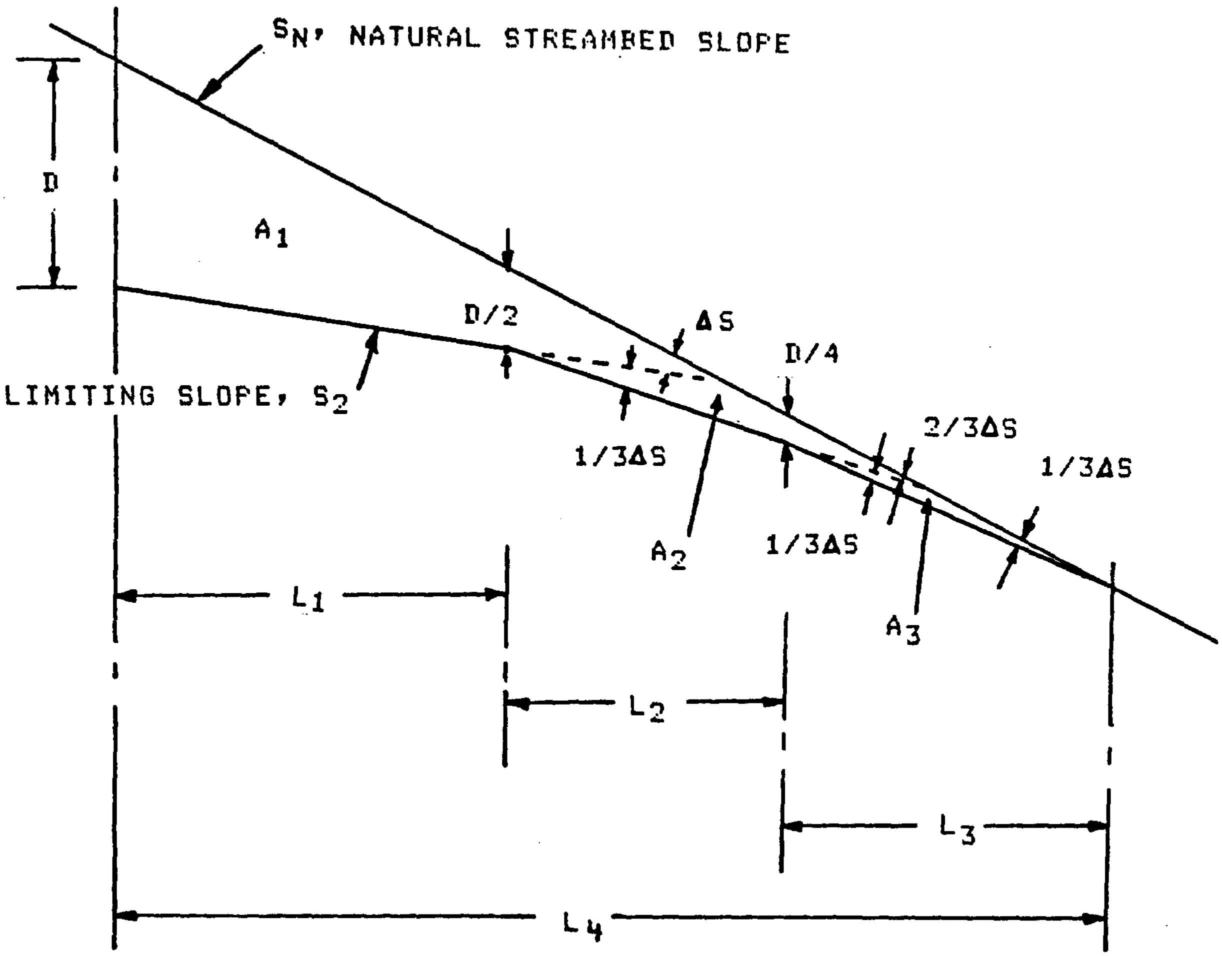
From Equations J-2 and J-3

$$43{,}560 * Vol / B = (39 * D^{**}2) / (64 * del\ S) \qquad (J\text{-}4)$$

$$D = 267.4 * SQRT[(Vol * del\ S) / B] \qquad (J\text{-}5)$$

From Figure J-1 the degradation reach length, L4, is:

$$L4 = 13 * D / (8 * del\ S) \qquad (J\text{-}6)$$



D = Depth of degradation at the dam

$\Delta S = S_n - S_2$ in ft/ft

$$A_1 = \frac{3D^2}{8\Delta S} \qquad L_1 = \frac{D}{2\Delta S}$$

$$A_2 = \frac{9D^2}{64\Delta S} \qquad L_2 = \frac{3D}{8\Delta S}$$

$$A_3 = \frac{3D}{32\Delta S} \qquad L_3 = \frac{3D}{4\Delta S}$$

$$A_4 = \frac{39D}{64\Delta S} \qquad L_4 = \frac{13D}{8\Delta S}$$

Figure J-1. Three slope method profile, [59]

c. Stable Slope. The stable slope, S , can be computed using the following formulas.

(1) Meyer-Peter, Muller formula is recommended for coarse sediment.

S = 0.19 * { [n / (d90**1/6)]**1.5 } * dm / R (J-7)

where

dm = effective size of bed material expressed as a weighted mean diameter, or d50, in mm

d90 = particle size of bed material at 90 percent finer, in mm

R = hydraulic radius, for width-depth ratio greater than 40, use water depth in feet

n = Manning n-value for channel roughness

(2) The Schoklitsch formula can also be used.

S = [(0.00021 * dm * B / Q)]**0.75 (J-8)

where

B = channel width

Q = dominant discharge

(3) Or the DuBoys formula.

S = tau-cr / (gma * R) (J-9)

where

gma = specific weight of water, in lb/cu ft

tau-cr = critical bed shear stress, in lb/sq ft, using dm and Figure J-2

d. Channel width. The channel width, B, is the average width of the channel when degradation has reached its maximum. If the channel width increases with time, bank material will contribute to the volume being eroded and the anticipated amount must be subtracted from "Vol" used in Equation J-1. The extent of width change can be estimated by using stable channel design criteria to determine an equilibrium width and comparing it with the existing average width.

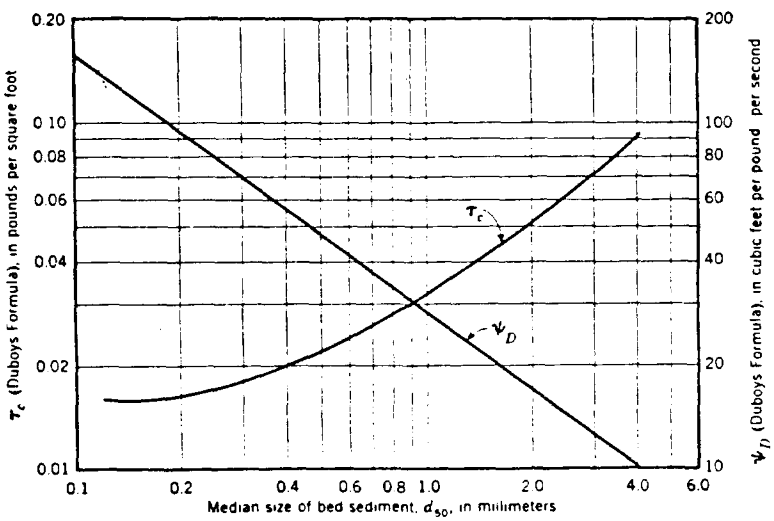


Figure J-2. DuBoys' relationship (from item 2, Appendix A, courtesy of The American Society of Civil Engineers)

J-3. Example 1.

a. Given.

Dominant discharge = 1500 cfs
Channel width = 400 ft
Mean channel depth = 2 ft
Existing stream bed slope = 0.0009
Anticipated volume trapped by reservoir in 100 years = 3000 acre-feet

dm of the Bed material = 0.5 mm
d90 of the bed material= 1.5 mm
Manning n-value = 0.03

b. Find. The stable channel slope, the depth of degradation and the length of the degrading reach.

(1) Using the Meyer-Peter and Muller formula, Equation J-7.

```
S = 0.19 * { [ .03/ (1.5)**1/6)]**1.5 } * .5 / 2.0
  = 0.00022
```

(2) Using the Schoklitsch formula, Equation J-8.

```
S = [ (0.00021*(.5)*(400)/1500.]**0.75
  = 0.00038
```

(3) Using DuBoys' formula, Equation J-9 and Figure J-2.

```
tau-cr = 0.022 lb/sq ft

     S = .022 / (62.4 * 2)
       = .00018
```

(4) Averaging the results from DuBoys' and Meyer-Peter, Muller but excluding Schoklitsch

```
    S = .0002

del S = 0.0009 - 0.0002
      = 0.0007
```

(5) From Equation J-5, the depth of degradation is

```
D = 267.4 * SQRT [(3000 * 0.0007) / 400 ]
  = 19.4 ft
```

(6) From Equation J-6, the length of the degradation reach is

```
L = 13 * 19.4 / (8 * .0007)
  = 45,036 ft  or 8.5 miles
```

J-4. Armor Bed Method. This method requires the determination of a minimum transportable representative particle size for the hydraulic conditions of the dominant discharge. This particle size will become the primary particle size comprising the armored bed. Laboratory and field investigations have shown that the tractive force, tau, exerted by moving water on the stream bed can be represented by:

$$\text{tau} = \text{gma} * R * S \tag{J-10}$$

and this force will transport sediment particles up to a certain mean diameter size. The relationship between tractive force and mean particle diameter is shown by Figure J-3. By rearranging Equations J-7 and J-8, respectively, the mean armoring diameter for the dominant discharge can be computed.

$$\text{dm} = 5.26 * S * R / [\,(n / \text{d90}^{**}1/6)^{**}1.5] \tag{J-11}$$

and

$$\text{dm} = 4762 * (S^{**}4/3) * Q / B \tag{J-12}$$

From the DuBoys' formula, the mean diameter can be found by determining "tau" and using Figure J-2. The depth of degradation of an armoring bed is shown graphically in Figure 4 [59] and

$$\text{Ya} = \text{Y} - \text{Yd} \tag{J-13}$$

where

Ya = thickness of armoring layer
Yd = depth of degradation (i.e., depth from original stream bed to top of armoring layer)
Y = depth from original stream bed to bottom top of armor layer

$$\text{Ya} = \text{Y} * [\text{del P}] \tag{J-14}$$

Where [del P] is the decimal percentage of material larger than the armoring layer obtained from the bed material sieve analysis. Combining Equations J-14 and J-13 gives:

$$\text{Yd} = \text{Ya} * \{(\,1 / [\text{del P}]) - 1.\} \tag{J-15}$$

The depth, Ya , is dependent on the particle size forming the armor layer and is generally considered to be 1 to 3 armoring particle diameter or 0.5 ft, whichever is smaller.

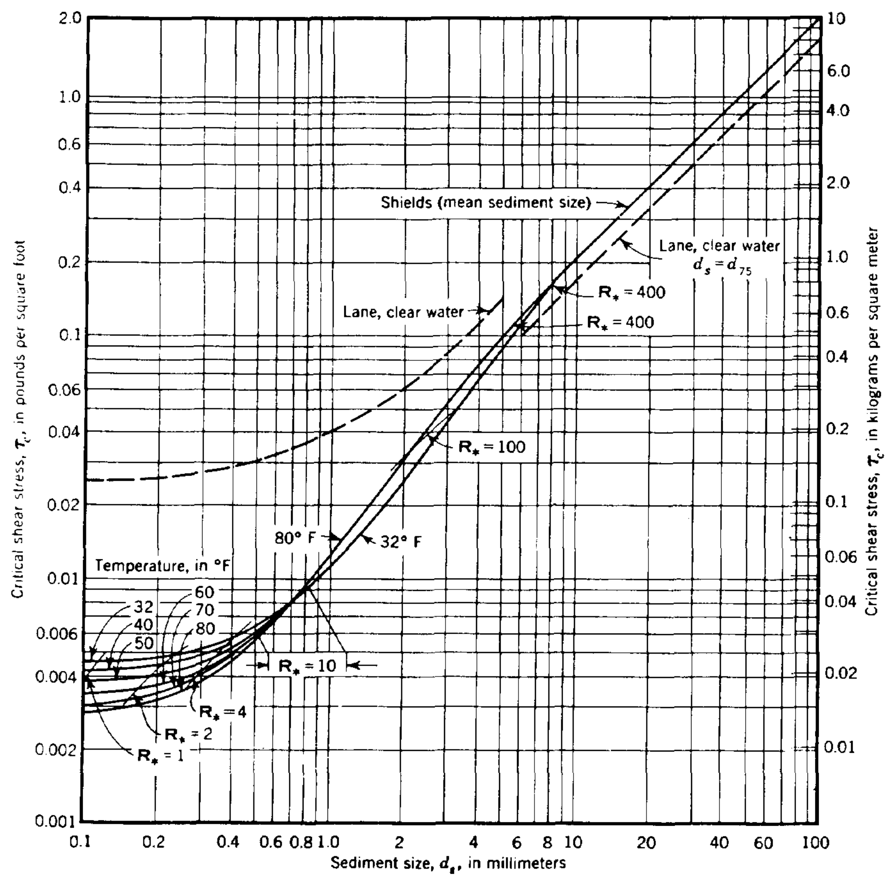


Figure J-3. Relationship of mean diameter and tractive force

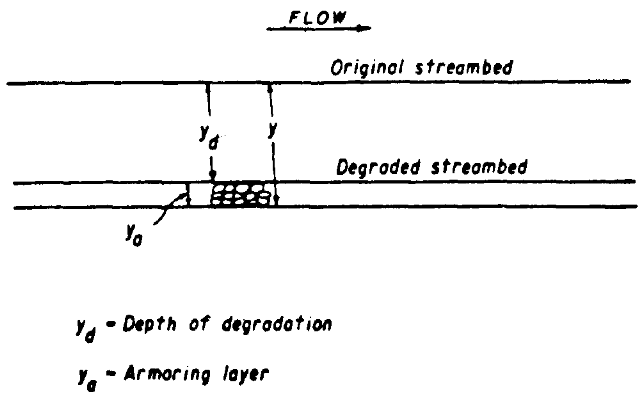


Figure J-4. Armoring Definition Sketch

J-5. Example 2.

a. Given.

Dominant discharge = 1000 cfs

Channel width = 75 ft

Hydraulic radius = 6 ft

Existing stream bed slope = 0.0015

Manning's n value = 0.03

Gradation of bed material is shown in Figure J-5.

b. Find. Find the depth of erosion require to produce an armor layer.

(1) The tractive force is calculated by Equation J-10.

$$\begin{aligned} \text{tau} &= 62.4 * 6 * 0.0015 \\ &= 0.562 \text{ lb/sq ft} \\ \text{or} &\quad 2{,}744 \text{ g/sq m} \end{aligned}$$

(2) From Figure J-3, dm = 27 mm

(3) From Equation J-11 and Figure J-5

dm = (5.26 * 0.0015 * 6)/[0.03/(40**1/6)]**1.5
= 22.9 mm

(4) From Equation J-12

dm = 4762 * (0.0015**4/3) * 1000 / 75
= 10.9 mm

(5) Using DuBoys's formula with tau = 0.562 lb/sq ft and extrapolating Figure J-2.

dm = 22.4 mm

(6) Throwing out 10.9 mm and averaging the rest,

dm = 24 mm

(7) The required armor layer thickness is

Ya = 3d
= 72 mm
= 0.236 ft < 0.5 ft

(8) From Figure J-5, del P = 0.20, expressed as a fraction

Yd = 0.236 * [(1/0.2) -1]
= 0.94 ft

J-6. Dominant Discharge. The methods described are based upon the dominant discharge being representative of equilibrium condition. However, if discharge is highly fluctuating and the peaks and troughs are significantly different from the dominant discharge, there could be scour and deposit along the stream that are transient in nature and would disappear and reappear as other flows pass through. The long term degradation will be as calculated but, if the fluctuation of the bed elevation along the degradation reach is important, the analysis should be made with a numerical modeling approach which simulates the actual hydrograph. An extreme event analysis should also be made to insure the structural integrity of the project and to evaluate downstream effects.

J-7. Bed Material Gradation. Particle size is the most important sediment controlling the property in degradation of a natural stream. Representative sizes are required for the study reach. That does not mean constant or average sizes, but rather sizes which will control the degradation process. The process is not uniform, therefore, the representative size will vary along the stream. Typically the coarses 5% of particles in the stream bed will control. Therefore, core and bulk samples should be taken at critical places.

J-8. Numerical Modeling Approaches. The degradation problem is too complex to rely on the simple analytical methods presented here for final design. More extensive analysis, such as provided by numerical modeling are required.

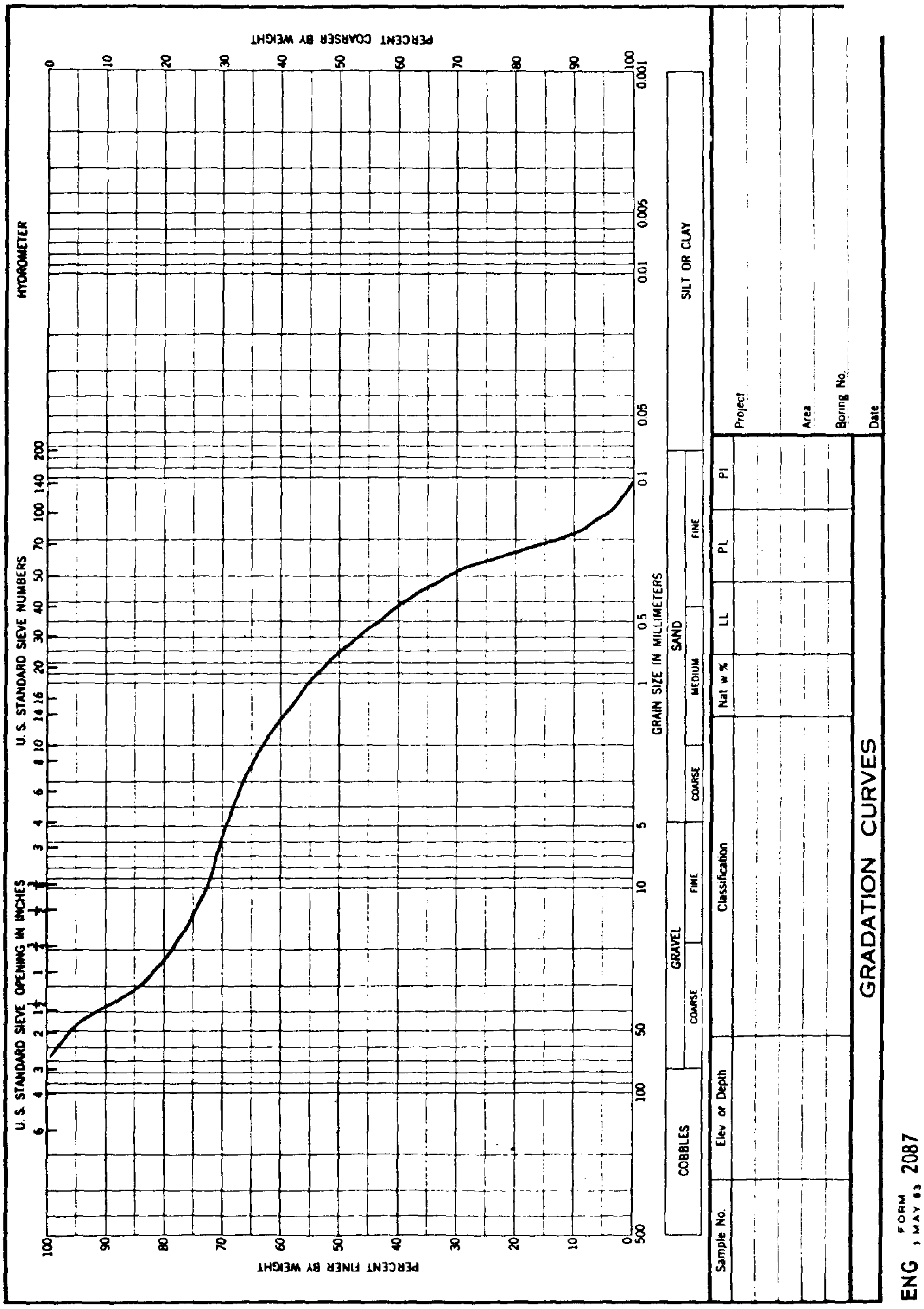


Figure J-5. Gradation of Bed Material