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DROP HEIGHT FOR CHANNEL EROSION CONTROL

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Abstract: Grade control by drop structure is a common practice to design a steep channel. For a given design discharge, the drop height is determined by the pre-selected permissible flow Froude number or flow velocity. Design parameters for the energy dissipation over a drop include channel lining roughness, approach flow Froude number, drop number, and downstream jump in the stilling basin. All these design parameters shall be collectively optimized to provide a safe and functional structure. This paper reviews the current design procedure and then presents a methodology to determine the drop height by maximizing the energy dissipation. Design parameters include the limiting Froude number and channel roughness. The sensitivity test conducted in this study suggests that the limiting Froude number for drop structure designs be between 0.6 and 0.8. The optimal dissipation rate can be 80 to 85 percent of the specific energy associated with the approach flow.

Key words: *drop, jump, channel design, dissipation, Froude number.*

INTRODUCTION

A steep channel tends to produce unstable flows. An unstable supercritical flow involves roll waves, oblique jumps, or cross waves between banks (Guo 1999a). A high velocity flow erodes and scours the channel bed and embankments. To mitigate the degradation problems on the channel bed, a drop structure is often installed across the channel bed to create a backwater pool upstream of the structure and a dissipation pool downstream of the structure (ASCE and WEF, 1982). The vertical height over a drop structure represents the improvement on the channel bed slope. Drop structures can be built with gabions, sheet piling, concrete walls with footings, and riprap (City of Tucson, 1989). In practice, a series of low head drops is more preferable to a single drop with a high head (Little and Murphy, 1982). Drop structures are susceptible to bank and bottom erosion failures, including the piping from seepage and bypassing flows and the scour near the foundation. Most of drop structures need additional bank and bottom protection because a drop induces abrupt changes to the flow. As recommended, the permissible flow velocity over a drop structure is directly related to the soil type in a grass channel (Chow 1959). For instance, the permissible flow velocity of 5.0 feet per second (fps) is recommended for soil Types A and B, and 7 fps for soil Types C and D (City of Denver in 2001, Clark County in 1999, City and County of Sacramento in 1992). The concept of permissible flow velocity was derived from the critical shear stress, not from the energy dissipation through a vertical drop. Therefore, this study presents an investigation on the limiting flow Froude number as a criteria to maximize the energy dissipation over a drop structure. The sensitivity test indicates that the maximal energy dissipation rate over a drop can be directly related to flow Froude number and channel roughness. To achieve the maximal dissipation rate, the limiting flow Froude number for drop design is recommended to be 0.6 to 0.8

DROP HEIGHT

The location a drop structure should be selected in a reasonably straight channel reach with neither upstream nor downstream curved within 100 to 200 feet of the structure. The foundation material must provide required supporting strength to resist sliding force and overturning moment.

The width of a drop structure has to be wide enough to pass the design discharge. The height of a drop structure is governed by the design flow condition, available construction material, required structural stability, and cost. From hydraulic point view, the height of a drop illustrated in Figure 1 is calculated as (Guo 1997):

$$H = (S_o - S_n)L \quad (1)$$

in which H = drop height, S_n = proposed channel bed slope, S_o = existing channel bed slope, and L = length of reach.

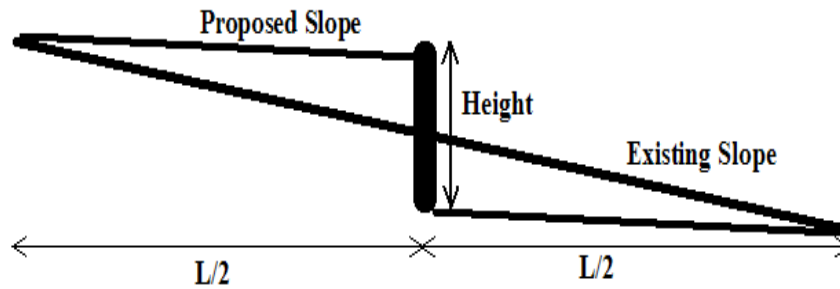


Figure 1 Illustration of Drop Height and Reach Length

The proposed channel slope depends on the permissible flow velocity and can be determined by re-arranging Manning's equation as:

$$S_n = \frac{N^2 U^2}{k^2 R^{4/3}} \quad (2)$$

in which N = Manning's roughness, U = permissible flow velocity, R = hydraulic radius, and k= unit conversion coefficient, equal to 1.486 for English units and one for metric units. The relationship between the permissible velocity and its flow Froude number is defined as:

$$F = \frac{U}{\sqrt{gD}} \quad (3)$$

$$U = \frac{Q}{A} \quad (4)$$

$$D = \frac{A}{T} \quad (5)$$

in which F = Froude number, g=gravitational acceleration, D = hydraulic depth, Q = design discharge, and T = top width. Substituting Eq 3 into Eq 2 yields

$$S_n = \frac{N^2 D g}{k^2 R^{4/3}} F^2 \quad (6)$$

Aided by Eq 4, the drop height is calculated as:

$$H = (S_o - \frac{N^2 D g}{k^2 R^{4/3}} F^2) L \quad (7)$$

The height of a drop structure represents the energy dissipation for the selected reach length, L. Using the trapezoidal channel in Figure 2 as an example, Eq 3 becomes

$$F^2 = \frac{Q^2 T}{g A^3} = \frac{Q^2 [B + Y(Z_1 + Z_2)]}{g [BY + \frac{1}{2} Y^2 (Z_1 + Z_2)]^3} \quad (8)$$

in which B = bottom width, Z₁ = left side slope, and Z₂ = right side slope. For the selected variables: Q, B, Z₁, and Z₂, Eq 8 is solved for flow depth, Y, when the limiting Froude number, F, is assigned. Having known the flow depth, Y, the proposed slope can be calculated by Eq 6 and the drop height can be determined using Eq 7.

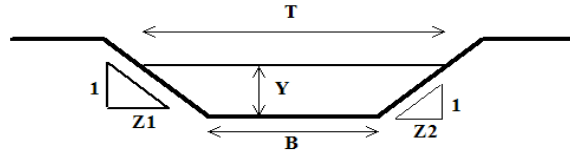


Figure 2 Cross Sectional Parameters for Trapezoidal Channel

MAXIMAL DISSIPATION RATE

In addition to the limiting Froude number and design discharge discussed above, it is also important to choose the reach length, L. It is recommended that a vertical drop be limited to seven feet because of the public safety and construction cost. With the specified design parameters, Eq 7 implies that the greater the design flow rate is, the higher the drop height will be. For convenience, Eq 5 is converted into its dimensionless form (Guo 1999b) using the normal depth as the characteristic length. The dimensionless form of Eq 5 is:

$$H_* = (S_o - N_*^2 F^2 \frac{D_*}{R_*^{4/3}}) L_* \quad (9)$$

The dimensionless variables in Eq 9 are defined as:

$$H_* = \frac{H}{Y} \quad (10)$$

$$L_* = \frac{L}{Y} \quad (11)$$

$$N_* = (\frac{N^2 g}{k^2 Y^{1/3}})^{0.5} \quad (12)$$

$$R_* = \frac{R}{Y} \quad (13)$$

$$D_* = \frac{D}{Y} \quad (14)$$

Similarly, the limiting Froude number in Eq 3 becomes

$$F_* = \frac{Q_*^2 T_*}{A_*^3} \quad (15)$$

The dimensionless variables in Eq 15 are defined as:

$$Q_* = \frac{Q}{\sqrt{gY^5}} \quad (16)$$

$$T_* = \frac{T}{Y} \quad (17)$$

$$A_* = \frac{A}{Y^2} \quad (18)$$

The dimensionless variable, H_* , represents the energy dissipation to approach normal flow depth ratio. From the hydraulic point of view, the higher the value of H_* is, the more efficient the drop structure is. As a result, the objective for the design of drop structure is set to be

$$\text{Max } H_* = \text{Max} \left(S_o - N_*^2 F_*^2 \frac{D_*}{R_*^{4/3}} \right) L_* \quad (19)$$

The solution for Eq 19 is subject to the selected design parameters.

DESIGN EXAMPLE AND SENSITIVITY

To illustrate the design procedure, a trapezoidal channel is employed to maximize the drop height. The design parameters include $B=10$ feet, $Z_1=Z_2=4$, $S_o=0.05$, $N=0.045$, and $Q=1000$ cfs. As indicated in Eq 19, the dissipation rate depends on the limiting Froude number that is normalized by the approach normal flow depth. For example, the sensitivity test may start with a range of the approach flow depths. Next, calculate the dimensionless variables using Eq's 9 through 18. As shown in Table 1, the highest dissipation rate, H_* , is found to be 0.8 when $F=0.60$.

Y feet	L*	Q*	T*	D*	R*	A*	F*	N*	Sn	H*	H feet
3.51	28.46	7.61	10.85	0.63	0.62	6.85	1.40	0.1390	0.0455	0.13	0.45
3.79	26.37	6.29	10.64	0.62	0.61	6.64	1.20	0.1372	0.0327	0.46	1.73
4.15	24.11	5.03	10.41	0.62	0.60	6.41	1.00	0.1352	0.0222	0.67	2.78
4.62	21.64	3.84	10.16	0.61	0.59	6.16	0.80	0.1328	0.0138	0.78	3.62
5.30	18.87	2.73	9.89	0.60	0.58	5.89	0.60	0.1298	0.0074	0.80	4.26
6.40	15.63	1.70	9.56	0.58	0.57	5.56	0.40	0.1258	0.0032	0.73	4.68
8.78	11.39	0.77	9.14	0.56	0.55	5.14	0.20	0.1193	0.0007	0.56	4.93

Table 1. Drop Heights for $Q=1000$ cfs, $N=0.045$, $B=10$ feet, $Z_1=Z_2=4.0$

As indicated in Eq 9, the lining roughness is also a key factor in determination of dissipation rate over a drop. A drop structure is usually protected by routed riprap blanket. As recommended, Manning's coefficient ranges from 0.040 to 0.045 for grouted rocks and riprap (Chow in 1959, Henderson in 1966, and Barnes in 1967). In this study, an investigation on the sensitivity of Manning's roughness was also conducted with $N=0.045$ and 0.04 . Figure 3 indicates that $H^* = 0.85$ at $F=0.8$ when $N=0.04$. The trend in Figure 3 shows that the smoother the lining material is, the higher the maximal the limiting Froude number can be. Of course, a stable channel does not sustain the flow with a high Froude number. Therefore, this study does not extend this test to Manning's roughness less than 0.04 . In this study, numerical tests were also performed to cover a wide range of design parameters, including channel widths, side slopes, and flow rates. In general, it is concluded that the maximal dissipation rate for trapezoidal channels varies in a very narrow range from 0.8 to 0.85 when the limiting Froude number varies between 0.6 and 0.8 . Of course, Eq 19 can produce the tailored maximal dissipation rate when the design parameters are given.

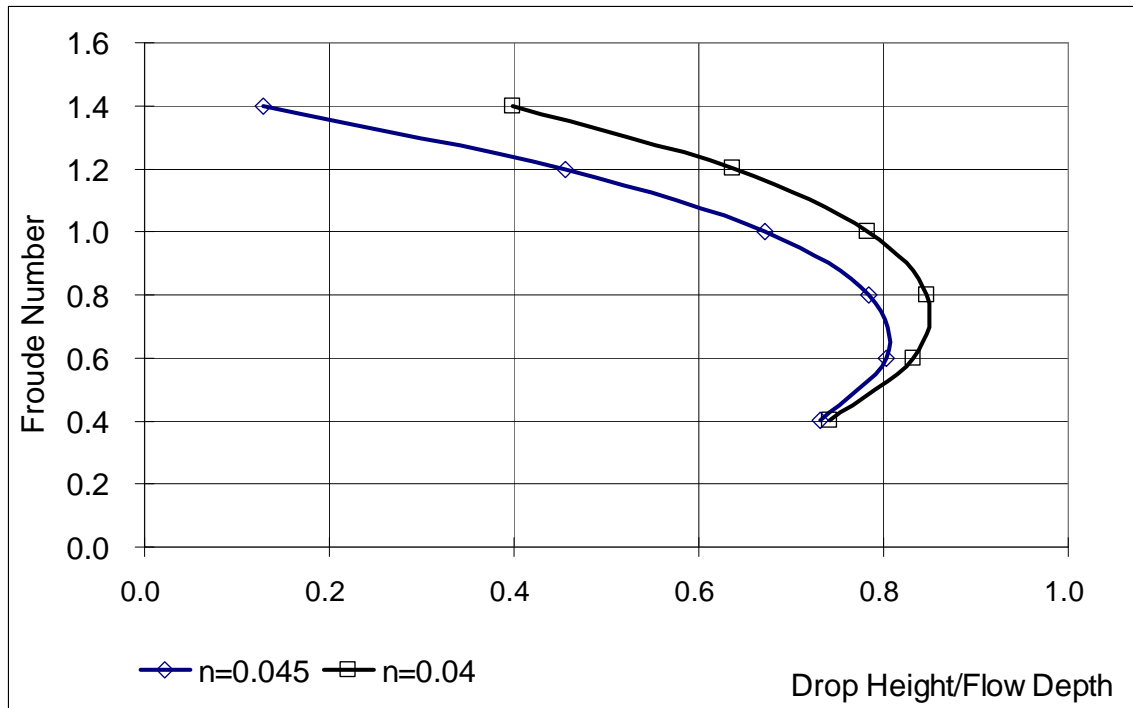


Figure 3 Maximal Dissipation Rates and Limiting Froude Numbers

CONCLUSIONS

Design parameters for sizing a drop structure include flow rate, water depth, flow velocity, storage capacity upstream of the drop, seepage flow, and downstream plunging flow into the stilling basin. All these flow variables are related to the selected drop height. Therefore, the very first step in design of a drop structure is the selection of the best drop height. In current practice, the drop height is determined using the permissible flow velocity. As an alternative, this study presents an approach to maximize the dissipation rate using the drop height as the decision variable. Eq 19 indicates that the maximal dissipation rate over a drop depends on the limiting Froude number and the lining roughness. Based on the sensitivity tests conducted in this study,

the maximal dissipation rate over a drop structure is ranged from 80 to 85% of the specific energy associated with the approach normal flow. The corresponding limiting Froude number for the maximal dissipation rate is found to be between 0.6 and 0.8. In practice, Eq 19 provides the on-site drop height for the specified design condition. With a recommended drop height by Eq 19, the engineer needs to examine the detailed hydraulic analyses, including upstream backwater profile, downstream plunging pool, soil particles on the channel bed, materials for footings and foundation, and under-drains to relieve the uplift force. Of course, the final check is the safety and future maintenance.

APPENDIX I: REFERENCES

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APPENDIX II

B = bottom width

D = hydraulic depth

F = Froude number

g=gravitational acceleration

H = drop height

L = length of reach
N = Manning's roughness
k = unit conversion coefficient, equal to 1.48 for English units and one for metric units
Q = design discharge
R = hydraulic radius
 S_n = proposed channel bed slope,
 S_o = existing channel bed slope,
T = top width
U = cross sectional average velocity,
 Z_1 = left side slope,
 Z_2 = right side slope
* = superscript for dimensionless variable.