Drop Height For Channel Erosion Control

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Introduction

In 2004, the author offered a training seminar on "*Flood Channel Design*". A question has been raised in the class several times as to how a permissible velocity recommended for drop structure designs was translated into its limiting flow Froude number. The *Urban Storm Drainage Criteria Manual* (USDCM), 2001, recommends that a drop height be designed with a permissible velocity of 5 fps or flow Froude number of 0.6 for soil types A and B and of 7 fps or flow Froude number of 0.8 for soil types C and D. This paper presents an investigation on the energy dissipation for a flow overtopping a vertical drop and then identifies the optimal flow Froude number to achieve the highest dissipation. It was found that the maximal dissipation rate is related to flow Froude number and channel roughness. Using Manning's coefficients of 0.04 and 0.045 for riprap and gabion linings, it is found that the optimal dissipation rate can be 80 to 85 percent of normal depth when the flow Froude number ranges between 0.6 and 0.8.

Drop Height

When a channel is too steep for the design condition, roll waves occur between banks (Guo 1999a). Erosion and scour occur to the channel bed and embankments. To mitigate the channel aggradation and degradation problems, 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 site of a drop structure should be located 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 a hydraulic point of view, the height of a drop illustrated in Figure 1 is calculated as (Guo 1997):

$$H = (S_o - S_n)L \tag{1}$$

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

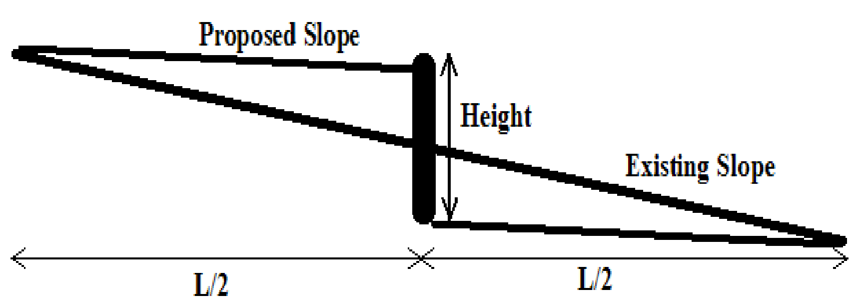

Figure 1 Illustration of Drop Height and Reach Length

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

$$S_n = \frac{N^2U^2}{2.22R^{4/3}} \quad (2)$$

in which N = Manning's roughness, U = cross sectional average velocity in fps, and R = hydraulic radius in ft. 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

$$S_n = \frac{N^2Dg}{2.22R^{4/3}}F^2 \quad (6)$$

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

$$H = (S_o - \frac{N^2Dg}{2.22R^{4/3}}F^2)L \quad (7)$$

The height of a drop structure represents the energy dissipation for the selected reach length, L. In current practice, a value of 0.8 is recommended for the limiting Froude number (City of Denver in 2001, and Clark County in 1999). Using the trapezoidal channel in Figure 2 as an example, Eq 3 becomes

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

in which B = bottom width, Z_1 = left side slop, and Z_2 = right side slope. For the selected variables: B, Z_1, and Z_2, Eq 8 is solved for flow depth, Y, for the specified F and Q. Having known the flow depth, Y, the proposed slope can then be calculated by Eq 2 or Eq 6 and the drop height is determined by Eq 1 or Eq 7.

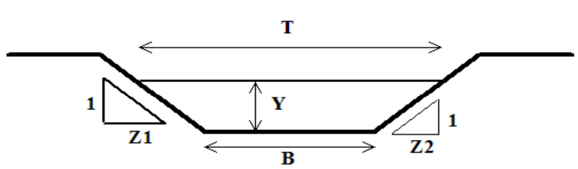

Figure 2 Cross Sectional Parameters for Trapezoidal Channel

Maximal Dissipation Rate
In addition to Froude number and design discharge discussed above, it is also important to properly choose the reach length, L. It is recommended that a vertical drop be limited to seven feet *(Editor's Note: The USDCM recommends a maximum drop height of three feet in urban areas for safety reasons)* because of expensive construction costs on retaining walls and footings. Eq 7 represents the criteria of erosion control by reducing the flow Froude number. From the hydraulic point of view, the higher the value of H, the more efficient the drop structure will be. As a result, the objective for the design of drop structure is set to be

$$Max\,H = L * Max\,(S_o - \frac{N^2 Dg}{2.22R^{4/3}}F^2) = Min\ (\frac{N^2 Dg}{2.22R^{4/3}}F^2) \qquad (9)$$

The solution for Eq 9 is subject to the selected design parameters.

Design Example and Sensitivity
To illustrate the design procedure, a trapezoidal channel is employed for the design of drop height. The design parameters include: L=100 ft, B=10 feet, Z_1=Z_2=4, S_o= 0.05, and Q=1000 cfs. As recommended by Chow (1959), Henderson (1966), and Barnes (1967), Manning's coefficient ranges from 0.040 to 0.045 for grouted rocks and riprap. In this study, Manning's coefficient is set to be N=0.045. As indicated in Eq 9, the dissipation rate depends on the flow Froude number. As an example, let us set the erosion control criteria with F= 0.8.

$$F^2 = 0.8^2 = \frac{1000^2[10 + Y(4+4)]}{32.2[10Y + \frac{1}{2}Y^2(4+4)]^3} \qquad (10)$$

By trial and error, the flow condition includes: Y= 4.62 ft, A=131.6 ft^2, R=2.74 ft, T=46.9 ft, and U=7.6 fps. Substituting the above variables into Eq 2 yields

$$S_n = \frac{0.045^2 * 7.6^2}{2.22 * 2.74^{4/3}} = 0.0138 \qquad (11)$$

Eq 6 provides the same result. With a new channel slope, use Eq 1 to calculate the drop height as:

$$H = (S_o - S_n)L = (0.05-0.0138)*100 = 3.62 \text{ ft} \qquad \text{or } H/Y=0.78 \qquad (12)$$

Of course, Eq 7 provides the same drop height as Eq 1. Eq 12 indicates that for this case, Fr=0.8 produces energy dissipation at 78% of the normal flow depth.

A good hydraulic design is the one that optimizes the integrated performance among design variables. At this point, a question is raised as to whether Eq 12 provides the maximal dissipation. For a given design condition, the flow Froude number in Eq 7 is the only design variable. Therefore, a sensitivity study was conducted to investigate the drop heights for Froude numbers ranging from 0.4 to 1.4. The results are plotted in Figure 3. For this example, the above flow condition can be further improved to increase the dissipation rate to 80% of normal depth or H/Y= 0.8 when reducing the flow Froude number to 0.6.

Furthermore, a similar analysis was performed to investigate the impact of Manning's coefficient. Consider N=0.04. As shown in Figure 3, the maximal dissipation can be H/Y= 0.85 at F=0.8. The trend in Figure 3 shows that the smoother the lining material is, the higher the flow Froude number can be. Of course, a stable channel does not sustain flows with a high Froude number. Therefore, the analysis in Figure 3 with N=0.03 is not recommended for designs.

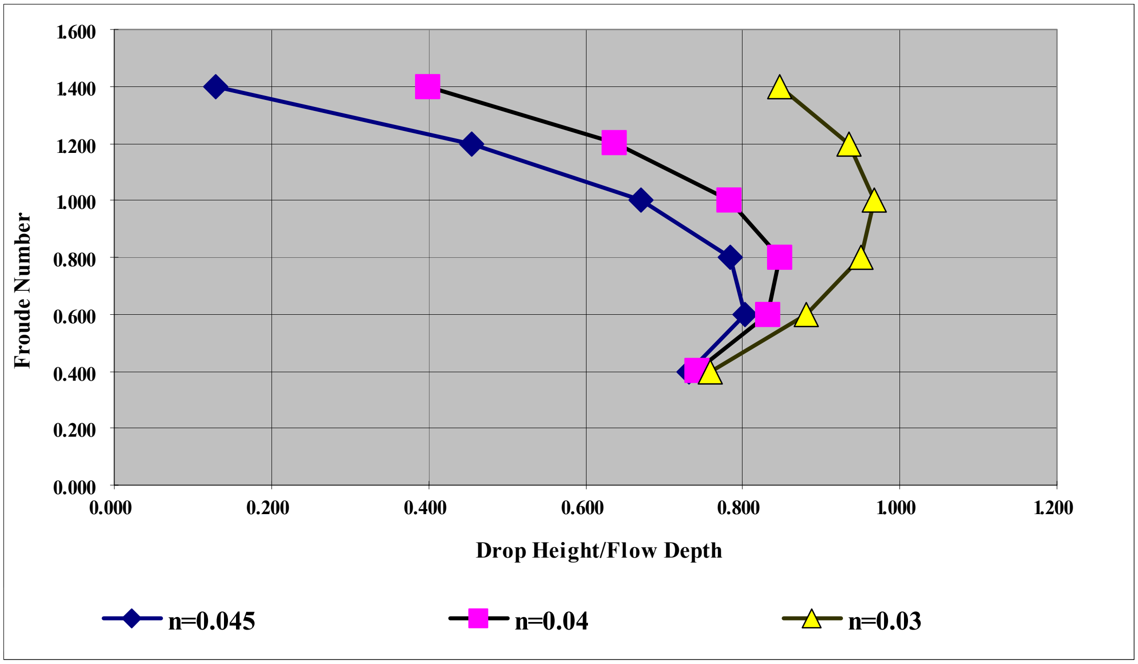

Figure 3 Maximal Dissipation Rates and Limiting Froude Numbers

Conclusions

The vertical drop height represents the improvement on the channel bed slope. Drop structures can be built with sheet piling, concrete walls with footings, and riprap. In urban drainage design, it is more desirable to use a series of low head drops than a high drop (Little and Murphy, 1982). Sediment erosion control applied to an erodable channel can be achieved by reducing flow velocity or flow Froude number. Design parameters include flow rate, water depth, flow velocity, headwater difference, storage capacity upstream of the submerged dam, seepage and uplift forces applied to the footings of the drop structure, and channel flow regime, i.e subcritical flow or supercritical flow. Among these variables, the design target dictates the type and height of the drop structure. This study presents an approach to determine the drop height by maximizing the dissipation to flow depth ratio. For a selected channel cross sectional geometry, Eq 9 indicates that the maximal dissipation rate over a drop depends on the flow Froude number and lining roughness.

Based on the sensitivity tests conducted in this study, the maximal dissipation rate over a drop structure ranges from 80 to 85 percent of the normal depth. The corresponding flow Froude number for the maximal dissipation rate ranges from 0.6 to 0.8. These findings agree with the current practice and recommendation. In practice, Eq 9 can be customized for the design condition. With a recommended drop height by Eq 9, the engineer needs to further examine flow hydraulics, channel morphologic, soil particles on the channel bed for the selection of building materials and design of underdrains.

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 slop,
Z_2 = right side slope