CITY OF LONGMONT
STORM DRAINAGE CRITERIA MANUAL

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SECTION 700 OPEN CHANNELS

701 INTRODUCTION

Presented in this section is the technical criteria for the hydraulic evaluation and hydraulic design of open channels including natural channels, grass, concrete or rock lined channels, and roadside ditches. A separate section is also provided for the design of riprap for channel linings and for erosion protection at culvert/storm sewer outlets. Some of the information in this section was obtained from the USDCM including the recently revised section on riprap. The individuals using this MANUAL are assumed to posses a working knowledge of hydraulics and have stormwater drainage evaluation experience. The user is encouraged to review the many referenced materials for additional information.

The open channel is generally the primary facility for the major drainage system (except for the roadside ditch). The selection of the type, capacity, and location for a major drainage channel will have a significant effect on the requirements for the minor system (refer to Section 304.3 for a discussion of the initial and major drainage systems). If the historic or natural drainage path is selected for the open channel route, the construction costs for the major system can be minimized. The historic route along with minimum alteration of the existing channel is recommended for all drainageways (refer to Section 303.1 Policy - Basin Transfer). In some instances, however, the land use of the property can be improved by relocating or straightening the natural drainage path, thereby improving the economic aspects of the project. Altering the channel alignment and shape may require the addition of grade control sections to control the flow velocities.

702 CHANNEL TYPES

The channels in the Boulder County area are defined as natural or artificial. Natural channels include all water courses that have developed by the erosion process such as St. Vrain Creek, Dry Creek, Boulder Creek, Left Hand Creek, and Fourmile Creek. Artificial channels are those constructed or significantly altered by human effort and include irrigation ditches and canals, roadside ditches, and grassed channels through the many subdivisions.

702.1 Natural channels

The hydraulic properties of natural channels vary along channel reach and can be either controlled to the extent desired or altered to meet given requirements. The initial decision to be made regarding natural channels is whether or not the channel is to be protected from erosion due to high velocity flows, or protected from excessive silt deposition due to low velocities.

Many natural channels in urbanizing or urbanized areas have mild slopes, are reasonably stable, and are not in a state of serious degradation or aggredation. However, if a natural channel is to be used for carrying storm runoff from an urbanized area, the altered nature of the runoff peaks and volumes from urban development can and will cause erosion. Hydraulic analyses will be required for natural channels in order to identify the erosion tendencies. Some onsite modification of the natural channel may be required to assure a stabilized condition.

The investigations necessary to assure that the natural channels will be adequate are different for every waterway. The engineer/designer must prepare cross sections of the channel, define the water surface profile for the initial and major design flood, investigate the bed and bank material to determine erosion tendencies, and study the bank slope stability of the channel under flow conditions. Supercritical flow does not normally occur in natural channels, but calculations must be made to assure that the results do not reflect supercritical flow.

702.2 Grass Lined Channels

Grass lined channels are the most desirable of the artificial channels. The grass will stabilize the body of the channel, consolidate the soil mass of the bed, check the erosion on the channel surface, and control the movement of soil particles along the channel bottom. The channel storage, the lower velocities, and the greenbelt multiple-use-benefits obtained create significant advantages over other artificial channels.

The presence of grass in channels creates turbulence which results in loss of energy and increased flow retardance. Therefore, the designer must give full consideration to sediment deposition and scour, as well as hydraulics. Unless existing development restricts the availability of right-of-way, only channels lined with grass will be considered acceptable.

702.3 Concrete Lined Channels

Concrete lined channels will be permitted only where ROW restrictions within existing development prohibit grass lined channels. The lining must be designed to withstand the various forces and actions which tend to overtop the bank, deteriorate the lining, erode the soil beneath the lining, and erode unlined areas.

If the project constraints dictate the use of a concrete channel, such use shall be allowed only upon approval by the City Engineer.

702.4 Rock Lined Channels

Rock lined channels are constructed from ordinary riprap or wire enclosed riprap (see Section 705). The rock lining increases the turbulence resulting in a loss of energy and increased flow retardance. The rock lining also permits a higher design velocity and therefore a steeper design slope than for grassed lined channels. Rock linings are also used for erosion control at culvert/storm sewer outlets, at sharp channel bends, at channel confluences, and at locally steepened channel sections.

If the project contraints dictate the use of a riprap or wire enclosed riprap lining, such use shall allow only upon approval of the City Engineer. Riprap for the purposes of local erosion control is permitted, subject to the criteria in this MANUAL.

702.5 Other Lining Types

The use of synthetic fabrics in construction and geotechnical engineering has increased tremendously in the last decade or more. The use of fabrics for drainage construction (i.e., erosion control liners) has actually taken place over the past several years. The placement of a slope revetment mat is a method of erosion control and the subject of discussion in this section.

The mattresses generally consist of double layers of woven fabric forms placed on the slope to be protected and filled with concrete or grout. This type of forming system is a simple, fast, and economical technique for the placement of concrete for slope protection both above and below the water without the need for dewatering. The performance characteristics and cost advantages make the process adaptable for stabilizing and protecting shorelines, levees, dikes, canals, holding basins, and similar erosion control projects.

The systems make use of the pressure injection of fluid fine-aggregate concrete into flexible fabric forms. Controlled bleeding of mixing water through the porous fabric produces all the desirable features of low water/cement ratio mortar - rapid stiffening, high strength, and exceptional durability.

For normal installations, the fabric forms, prefabricated to job specifications and dimensions, are simply spread over the terrain, which has received minimal grading. The fabric form is then pumped full of mortar. This same concept can be used where slide problems are caused by eroding of the toe of the slopes, and where access if difficult for placement of riprap. See Figure-701 for typical sections of mattresses.

There are several manufacturers of synthetic fabrics for erosion protection (see Reference-38). Included in this category of channel lining are the products which consist of discrete blocks on a continuous fabric backing.

The use of synthetic fabrics for lining of channels within Boulder County is restricted to areas where the ROW constraints prohibit the use of a grass lined section. Such use shall be allowed only upon approval of the City Engineer. In addition, synthetic fabric materials used as a mulch to improve grass growth will be restricted in use to areas outside of the "regularly" inundated portion of the channel (refer to Section 704.6).

703 HYDRAULICS OF OPEN CHANNELS

An open channel is a conduit in which water flows with a free surface. The hydraulics of an open channel can be very complex, encompassing many different flow conditions from steady state uniform flow to unsteady, rapidly varied flow. Most of the problems in storm water drainage involve uniform, gradually varied or rapidly varied flow states. An example of these flow conditions is illustrated in Figure-702. The calculations for uniform and gradually varied flow are relatively straight forward and are based upon similar assumptions (i.e., parallel streamlines). Rapidly varied flow computation, (i.e., hydraulic jumps and flow over spillways) however, can be very complex and the solutions are generally emperical in nature.

Presented in this section are the basic equations and computational procedures for uniform, gradually varied and rapidly varied flow. The user is encouraged to review the many hydraulics textbooks available including References-7, -8, and -39 for a more detailed discussion.

703.1 Uniform Flow

Open channel flow is said to be uniform if the depth of flow is the same at every section of the channel. For a given channel geometry, roughness, discharge and slope, there is only one possible depth for maintaining uniform flow; the normal depth. For a prismatic channel (i.e., uniform cross section) the water surface will be parallel to the channel bottom for uniform flow.

Uniform flow rarely occurs in nature and is difficult to achieve in a laboratory, because not all of the parameters remain exactly the same. However, channels are designed assuming uniform flow as an approximation, which is adequate for planning purposes.

The computation of uniform depth for Boulder County shall be based upon the Manning's formula as follows:

$$Q = (1.49/n)\ AR^{2/3}S^{1/2} \qquad (701)$$

Where Q = Discharge in cfs

n = Roughness coefficient (Table-706)

A = Area in square feet

R = Hydraulic radius, A/P

P = Wetted perimeter, feet

S = Slope of the energy grade line (EGL)

For prismatic channels, the EGL slope and the bottom slope are assumed to be the same.

For convenience, tables have been prepared using the Manning's formula for various uniform cross sections to compute uniform flow conditions given any four of the following parameters: D, b, Q, n, and S. For Trapezoidal sections, Table-701 can be used and for circular sections, Table-702 can be used. The use of the tables is illustrated by the following example:

<u>Example No. 8:</u> <u>Uniform Flow for Trapezoidal Channel</u>

<u>Given:</u> Channel bottom width b = 10-feet
Side slopes (Z) = 4:1
Slope (S) = 0.005
Discharge Q = 400 cfs

<u>Find:</u> Normal depth D, compute the following parameters:

Step 1: Estimate roughness coefficient, n = 0.032 for this example as a typical starting value.

Step 2: $Qn/b^{8/3}S^{1/2} = (400)(0.032)/(10)^{8/3} \times (.005)^{1/2} = 0.39$

Step 3: Enter Table-701 with the value of 0.39 under the Column for Z = 4 and read the corresponding value of D/b, interpolate if necessary

D/b = 0.328

Step 4: Compute normal depth D

$D = (0.328)(b) = (0.328)(10)$

$D = 3.28$-feet

Step 5: Compute the velocity, velocity head and specific energy (see Reference-7)

Flow Area at D = 3.28, $A = 75.8\ ft^2$

$V = Q/A = 400\ cfs/75.8\ ft^2$

$V = 5.28$ fps

Velocity head $(h_v) = V^2/2g = (5.28)^2/2(32.2) = 0.43$

Specific energy $(e) = D+h_v = 3.28 + 0.43$

$e = 3.71$-feet

Step 6: Compute hydraulic radius (R) and check assumed n-value using Figure-705.

$R = 2.05$ for $D = 3.28$

$RV = (2.05)(5.28) = 10.8$

From Figure-705 for Retardance C, read the value of 0.032, which is equal to the assumed value. If the computed n-value was different (i.e., $\pm$ 0.001), another n-value would be selected and steps 1 to 6 repeated. Also note that since the problem was to determine the normal depth, Retardance curve "C" was used. If the maximum velocity is to be found, curve "D" would be used (see Section 704.2).

The above parameters are important in the hydraulic evaluation of open channels as will be seen in subsequent sections. The designer should be aware that roughness greater than that assumed will cause the same discharge to flow at a greater depth, or conversely that flow at the computed depth will result in less discharge. In addition, obstructions in the channel cause an increase in depth above normal and must be taken into account by providing for freeboard (see Section 704).

703.2 Uniform/Critical Flow

The critical state of flow through a channel is characterized by several important conditions:

1. The specific energy is a minimum for a given discharge

2. The discharge is a maximum for a given specific energy

3. The specific force is a minimum for a given discharge

4. The velocity head is equal to half the hydraulic depth in a channel of small slope

5. The Froude Number is equal to 1.0

If the critical state of flow exists throughout an entire reach, the channel flow is critical and the channel slope is at critical slope S-sub c. A slope less than S-sub c will cause subcritical flow. A slope greater than S-sub c will cause supercritical flow. A flow at or near the critical state is unstable, because minor changes in specific energy, such as from channel debris, will cause a major change in depth.

The criteria of minimum specific energy for critical flow results in the definition of the Froude Number (F) as follows:

$$F = V/\sqrt{gD} \qquad (702)$$

Where F = Froude Number

V = Velocity (fps)

g = Acceleration of gravity (ft/sec^2)

D = Hydraulic Depth (ft) = A/T

A = Channel flow area (ft^2)

T = Top width of flow area (ft)

When F is equal to 1.0, the flow is critical. The Froude Number should be calculated for the design of all open channels to check the flow state (see Example-9).

The computation of the critical flow state for trapezoidal and circular section can be performed with the use of Figure-703. The use of the Figure is illustrated by the following example:

<u>Example No. 9:</u> <u>Critical Flow Computation for Trapezoidal Channel</u>

<u>Given:</u> Channel conditions for Example No. 8

<u>Find:</u> Froude Number and critical flow state

Step 1: Calculate Froude Number

$D = A/T = 75.8/36.2 = 2.09$-feet

$F = V/\sqrt{gD} = 5.28/\sqrt{(32.2)(2.09)} = 0.64$

Since F is less than 1.0, the flow is subcritical

Step 2: Calculate section factor Z

$Z = Q/\sqrt{g} = 400 \text{ cfs}/\sqrt{32.2} = 70.5$

Step 3: $Z/b^{5/2} = 70.5/10^{5/2} = 0.22$

Step 4: Enter Figure-703 with $Z/b^{5/2} = 0.22$ for channel side slope ($z = 4$) and read the value for y/b

$y/b = 0.26$

Step 5: Calculate critical depth

$y = (0.26)(b) = (0.26)(10) = 2.6$-feet

The remaining channel parameters (i.e., S, A, V, h_v, e) can be computed from the channel geometry and using Table-701.

$S = 0.0166$ ft/ft

$A = 53.0\ ft^2$

$V = 7.54$ fps

$h_v = 0.88$ ft

$e = 3.48$

Note that the specific energy, e, for critical flow is less than the specific energy at normal depth.

703.3 Gradually Varied Flow

The most common occurrence of gradually varied flow in storm drainage is the backwater created by culverts, storm sewer inlets, or channel constrictions. For these conditions, the flow depth will be greater than normal depth in the channel and the water surface profile must be computed using backwater techniques.

Backwater computation can be made using the method presented in Chow (Reference-7). Many computer programs are available for computation of backwater curves. The most general and widely used program is HEC-2, water-surface profiles, developed by the U.S. Army Corps of Engineers (Reference-2) and is the program recommended for floodwater profile computations in Boulder County. This program will compute water-surface profiles for natural and man-made channels.

For prismatic channels, the backwater calculation can be computed manually using the Direct Step Method (Reference-7). For an irregular non-uniform channel, the Standard Step Method is used, which is a more tedious iterative process. The use of HEC-2 is recommended for non-uniform channel analysis. The Direct Step Method can be used for prismatic channels in Boulder County and is illustrated by the following example:

Example No. 10: Direct Step Backwater Calculation

Given: Channel condition in Examples No. 8 and No. 9, a culvert with a headwater depth of 5.0-feet at the entrance.

Find: Water surface profile from the culvert upstream to where the flow depth reaches normal depth.

Step 1: Set up Table-703. Fill in the parameters at the top of the table.

Step 2: Starting with y = 5.00-feet (culvert headwater) compute Columns 2, 3, and 4 from the channel geometry.

Step 3: Compute Columns 5 through 12 as follows:

Col. 5: Velocity head, (alpha assumed equal to 1.0).

Col. 6: Specific energy in feet obtained by adding Column 1 and 5.

Col. 7: Change in specific energy in feet equal to the difference between the E value in Column 6 and that of the previous step (not applicable for first row).

Col. 8: Friction slope computed using the equation at the bottom of the table.

Col. 9: Average friction slope between this row and previous row (not applicable for the first row).

Col. 10: Difference between the bottom slope and average friction slope of Column 9 (not applicable for first row).

Col 11: Length of the reach in feet between consecutive rows, computed by the equation at the bottom of the table (not applicable for the first row).

Col. 12: Accumulated distance from the starting point.

Step 4: Decrease Column 1 depth (Y) by small amount (i.e., 2 to 4%) and enter in Column 1 row 2. Repeat steps 2 and 3 for the new depth.

Step 5: Continue steps 2, 3, and 4 until the depth in Column 1 equals the normal depth (± 0.05 feet). The plot of the depth (Column 1) versus distance (Column 23) is the water surface profile.

703.4 Rapidly Varied Flow

Rapidly varied flow (RVF) is characterized by very pronounced curvature of the streamlines. The change in curvature may become so abrupt that the flow profile is virtually broken, resulting in a state of high turbulence. Whereas there are several mathematical solutions to some cases of RVF, the practical hydraulician has generally relied on empirical solutions of specific problems. The two cases of RVF (weir flow and hydraulic jump) occurring commonly in storm drainage will be discussed in this section.

1. Weir Flow
   The common use of weirs in storm drainage analysis is for spillway outlets in detention ponds (Section 1200 Detention). The general form of the equation for horizontal crested weirs is (Reference-40).

$$Q = CLH^{3/2} \qquad (703)$$

Where Q = discharge (cfs)

C = weir coefficient

L = horizontal length (feet)

H = total energy head (feet)

Another common weir is the v-notch, whose equation is as follows (Reference-40)

$$Q = 2.5 \tan(\theta/2)H^{5/2} \qquad (704)$$

Where θ = angle of the notch at the apex (degrees)

When designing or evaluating weir flow, the effects of submergence must be considered. A single check on submergence can be made by compairing the tailwater to the headwater depth as illustrated in the figure on Table-704 (Reference-39). The coefficients to be used with Equation 703 are also listed on Table-704.

2. Hydraulic Jump

In urban hydraulics, the jump may occur at grade control structures (i.e., check drops), inside of storm sewers or concrete box culverts, or at the outlet of an emergency spillway for detention ponds. The evaluation of hydraulic jumps is important since there is a loss of energy and erosive forces associated with a jump. For hard-lined facilities such as pipes or concrete channels, the forces and the change in energy can effect the structural stability or the hydraulic capacity. For grass lined channels, the erosive forces must be controlled otherwise serious damages will result. The control is usually obtained by check drops or grade control structures which confine the erosive forces to a riprap protected area.

The analysis of the jump inside of storm sewers is approximate due to the lack of data for circular, elliptical or arch sections. The jump can be approximately located by intersecting the energy grade line of the supercritical and subcritical flow reaches. The primary concerns are: (1)can the pipe withstand the forces which may separate the joint or damage the pipe wall, and (2)will the jump effect the hydraulic characteristics. Since the storm sewers in Boulder County are restricted to concrete pipe and the velocities are limited to 15 fps (Section 800), then the hydraulic jump need only to be located and the impact on the pipe capacity determined for storm sewer analysis as discussed above. The effect on pipe capacity can be determined by evaluating the energy grade line taking into account the energy lost by the jump. In general, for Froude Numbers less than 2.0, the loss of energy is less than 10 percent.

For long box culverts, with a concrete bottom, the concerns of the jump are the same as for storm sewers. However, the jump can be adequately defined for box culverts/sewers and for spillways using the jump characteristics of rectangular sections. A detailed evaluation of the hydraulic jump is beyond the scope of this MANUAL and the user is refered to References-7 and -50 for computational procedures. The calculations are to be included with the required submittals (see Section 200).

The hydraulic jump conditions at vertical check drops (Section 1100) have been defined using experimental data (Reference-7). The aerated free-falling nappe in a vertical check drop will reverse the curvature and turn smoothly into supercritical flow on the apron (see Figure-704), which may form a hydraulic jump downstream. Using the experimental data, the flow geometry can be described by functions of the drop number (D-sub n) defined as:

$$D_n = (q^2 / gh^3) \tag{705}$$

Where q is the discharge per unit width of the crest of overfall (cfs/ft), g is the acceleration of gravity, and h is the height of drop (feet). The functions are:

$$L_d/h = 4.3\, D_n^{0.27} \tag{706}$$

$$d_p/h = 1.00\, D_n^{0.22} \tag{707}$$

$$d_1/h = 0.54\, D_n^{0.425} \tag{708}$$

$$d_2/h = 1.66\, D_n^{0.27} \tag{709}$$

Where L-sub d is the drop length (the distance from the drop wall to the position of the depth d-sub 1), y-sub p is the pool depth under the nappe, d-sub 1 is the depth at the toe of the nappe or the beginning of the hydraulic jump, and d-sub 2 is the tailwater depth sequent to d-sub 1. L is the length of the hydraulic jump and may be determined as outlined for stilling basins in References-7 or -50. From these equations, the drop length and design tailwater depth may be determined. The above equations are contingent upon the length of the spillway crest being approximately the same width as the approach channel.

The above equations, in conjunction with recent research performed under the jurisdiction of the Urban Drainage and Flood Control District were used to develop standard dimensions for check drops which are discussed in Section 1100.

704 DESIGN STANDARDS

The design standards for open channel cannot be presented in a step by step fashion because of the wide range of options available to the engineer. Certain planning and conceptual criteria are particularly useful in the preliminary design of a channel. These criteria, which have the greatest effect on the performance and cost of the channel, are discussed below.

704.1 Natural Channels

The design criteria and evaluation techniques for natural channels are:

1. The channel and overbank areas shall have adequate capacity for the 100-year storm runoff.

2. Natural channel segments which have a Froude Number greater than 0.95 for the 100-year flood peak shall be protected from erosion.

3. The water surface profiles shall be defined so that the floodplain can be zoned and protected.

4. Filling of the flood fringe reduces valuable channel storage capacity and tends to increase downstream runoff peaks. Filling of the flood fringe is subject to the restriction of floodplain regulations.

5. Roughness factors (n), which are representative of unmaintained channel conditions, shall be used for the analysis of water surface profiles.

6. Roughness factors (n), which are representative of maintained channel conditions, shall be used to determine velocity limitations.

7. Erosion control structures, such as riprap check drops or check dams, may be required to control flow velocities, including the initial storm runoff.

8. Plan and profile drawings of the floodplain shall be prepared. Appropriate allowances for future bridges or culverts, which can raise the water surface profile and cause the floodplain to be extended, shall be included in the analysis.

With most natural waterways, grade control structures should be constructed at regular intervals to decrease the thalweg slope and to control erosion. However, these channels should be left in as near a natural condition as possible. For that reason extensive modifications should not be undertaken unless they are found to be necessary to avoid excessive erosion with subsequent deposition downstream. Also, modification of the channel within the normal high water line will require a US Army Crops of Engineers Section 404 permit for many of the streams in Boulder County.

The usual rules of freeboard depth, curvature, and other guidelines which are applicable to artificial channels do not necessarily apply to natural channels. All structures constructed along the channel shall be elevated to a minimum of 1-foot above the 100-year water surface. There are significant advantages which may occur if the designer incorporates into his planning the overtopping of the channel and localized flooding of adjacent areas which are laid out and developed for the purpose of being inundated during the major storm runoff. The freeboard criteria can be used to advantage in gaging the adequacy of a natural channel for future changes in runoff.

If a natural channel is to be utilized as a drainageway for a development (i.e., historic 100-year flood peaks in excess of 100 cfs), then the applicant shall meet with the County Engineer to discuss the concept and to obtain the requirements for planning and design documentation. Approval of the concept and design will be made in accordance with the requirements of Section 200.

704.2 Grass Lined Channels

Key parameters in grass lined channel design include velocity, slopes, roughness coefficients, depth, freeboard, curvature, cross section shape, and lining materials. Other factors such as water surface profile computation, erosion control, drop structures, and transitions also play an important role. A discussion of these parameters is presented below.

1. Flow Velocity and Capacity
The maximum normal depth velocity for the 100-year flood peak shall not exceed 7.0-feet per second for grass lined channels, except in sandy soil where the maximum velocity shall not exceed 5.0-feet per second. The Froude Number (turbulence factor) shall be less than 0.8 for grass lined channels. Grass lined channels having a Froude Number greater than 0.8 shall not be permitted. The minimum velocity, wherever possible, shall be greater than 2.0-feet per second for the initial storm runoff. All grass lined channels shall be designed to convey the 100-year flood.

2. Longitudinal Channel Slopes
Grass lined channels normally will have slopes of 0.2 percent to 0.6 percent. Where the natural topography is steeper than desirable, drop structures shall be utilized to maintain design velocities (see Section 1100).

3. Freeboard
Except where localized overflow in certain areas is desirable for additional ponding benefits or other reasons, the freeboard shall be:

$$H_{FB} = 1.0 + V^2/2g \qquad (710)$$

Where H_{FB} = freeboard height (feet)

V = average channel velocity (fps)

g = acceleration of gravity = 32.2 ft/sec^2

The minimum freeboard shall be 1.5-feet above the computed water surface elevation. Freeboard shall not be obtained by the construction of levees.

An approximation of the superelevation, h (ft), at a channel bend with velocity V (fps), centerline radius of curvature r-sub c (ft), and topwidth of channel, Tw (ft), can be obtained from the following equation:

$$h = V^2 Tw/gr_c \qquad (722)$$

The freeboard shall be measured above the superelevation water surface.

4. Curvature
The center line curvature shall have a radius twice the top width of the design flow, but not less than 100-feet.

5. Roughness Coefficient
The variation of Manning's "n" with the retardance and the product of mean velocity and hydraulic radius as presented in Figure-705 shall be used in the capacity computation. Refer to Example No. 8, Section 703.1 for illustration of the use of Figure-705.

Retardance curve C shall be used to determine the channel capacity, since a mature channel (i.e., substantial vegetation with minimal pervious maintenance) will have a higher Manning's "n" value. However, a recently constructed channel will have minimal vegetation and the retardance will be less than the mature channel. Therefore, retardance curve D shall be used to determine the limiting velocity in a channel.

6. Cross Sections
The channel shape may be almost any type suitable to the location and to the environmental conditions. Often the shape can be chosen to suit open space and recreational needs (refer to Figures-706 and -707). However, limitations within which the design must fall for the major storm design flow include:

a. Trickle Channel
The base flow shall be carried in a trickle channel. The minimum capacity shall be 1.0 percent to 3.0 percent of the 100-year flow, but not less than 1 cfs. Trickle channel shall be constructed of concrete or other approved materials to minimize erosion, to facilitate maintenance and to aesthetically blend with the adjacent vegetation and soils.

b. Bottom Width
The minimum bottom width shall be consistent with the maximum depth, and velocity criteria. The minimum width shall be 4-feet to accommodate the trickle channel.

c. Right-of-Way Width
The minimum right-of-way width shall include freeboard and a twelve foot (12') wide maintenance access.

d. Flow Depth
The maximum design depth of flow (outside the trickle channel area) for the 100-year flood shall be limited to 5.0-feet in grass lined channels.

e. Maintenance/Access Road
Maintenance access shall be provided for all major drainageways with a minimum width of 12-feet.

f. Side Slopes
Side slopes shall be 4 (horizontal) to 1 (vertical) or flatter. Slopes as steep as 3:1 may be used in existing developed areas subject to additional erosion protection (Section 705) and approval from the City Engineer.

7. Grass

The grass species chosen must be sturdy, drought resistant, easy to establish and able to spread. A thick root structure is necessary to control weed growth and erosion. A mixture of native and introduced grass species has been found to be satisfactory in establishing an erosion-resistant channel lining. The Soil Conservation Service and local landscape architects can provide assistance in selecting grass mixtures which have been successful.

Some of the grass generally suitable for waterway use include White Dutch Clover, several Wheatgrass species, several Grama species, two Brome species and Perennial Ryegrass. If a landscaped park setting is desirable and an irrigation system is provided, Kentucky Bluegrass provides an excellent cover, but requires extensive water and maintenance.

Newly constructed channels need a protective cover consisting of mulch and grass seeding immediately after completion. If possible, seed the disturbed areas with permanent grass seed mix. To provide quick ground cover the seed mix should include a perennial ryegrass. The perennial ryegrass germinates quickly and will not compete with the sod-forming grasses later on. When immediate seeding of permanent grass is not practical, an annual crop may be planted with the perennial grass seeded later in the stubble or residue. Rye, oats, or ryegrass gives a fair temporary protection for waterways, though the crop should be clipped before it matures to seed.

Seed quality is important. Grass seed may range from 20 to 100 percent purity. Seeding rates are aimed at planting a given number of pure live seed per square foot. For additional information on seeding rates, the reader is referred to the Soil Conservation Service Technical Guide, Section IV, June 1976.

Disturbed areas should be seeded by drilling. The drill must be a specially adapted power drawn grass drill. In areas where access is a problem a hydraulic seeder may be used. Seeding rates should be doubled if hydraulic equipment is used. All areas seeded should be mulched to prevent erosion and hold moisture in the soil surface. Cutting of the grass should be planned so that it is at least about 6-inches high in November and June. Cutting practices should encourage the establishment and spread of the grass.

General rules for an effective grass lining for a waterway are as follows:

a. Strip and stockpile topsoil during construction. Use stockpiled materials in the surface preparation prior to seeding operations.

b. Prepare a good, firm seedbed and use a crop residue or a mulch to protect the waterway and grass seedlings during establishment.

c. Allow one year for grass to show an adequate stand.

d. Select a simple grass mixture that best fits the conditions of the waterway.

e. Use good quality seed.

f. Use grass origins and strains known to be adaptable.

g. Plant at the best date for the particular grass.

h. Use planting equipment and methods that give uniform distribution and proper placement of seed.

i. Water grass as required to supplement rainfall until established.

j. Fertilize according to the needs of the grass and soil as shown by soil tests.

k. Overseed or repair bare spots with sod chunks or mulch as necessary.

l. Avoid using the waterway as a road or damaging the sod with tillage implements.

m. Mow when grass can make good regrowth and restore food reserves in the roots.

8. Water Surface Profiles

Computation of the water surface profile shall be presented for all open channels utilizing standard backwater methods, taking into consideration losses due to changes in velocity of channel cross section, drops, waterway openings, or obstructions. The energy gradient shall be shown on all preliminary drawings. Refer to Section 703 for additional information.

704.3 Concrete Lined Channels

The criteria for the design and construction of concrete lined channels is presented below:

1. Hydraulics

a. Freeboard

Adequate channel freeboard above the designed water surface shall be provided and shall be not less than that determined by the following:

$$H_{FB} = 2.0 + 0.025V\,(d)^{1/3} \qquad (711)$$

Where H_{FB} = freeboard height (feet)

V = velocity (fps)

d = depth (feet)

Freeboard shall be in addition to superelevation, standing waves, and/or other water surface disturbances. These special situations should be addressed in the Design Report submitted with the construction drawings and specifications (Section 200).

Concrete side slopes shall be extended to provide freeboard. Freeboard shall not be obtained by the construction of levees.

b. Superelevation
Superelevation of the water surface shall be determined at all horizontal curves and design of the channel section adjusted accordingly (see Section 704.2.3).

c. Velocities
Flow velocities shall not exceed 8 fps or result in a Froude Number greater than 0.9 (see Section 703.2) during the 100-year flood for non-reinforced linings. Flow velocities shall not exceed 18 fps for reinforced linings during the 100-year flood.

d. N-Values
Refer to Table-706 for range of values, with the high value used for capacity determination and the low value used for velocity consideration.

2. Concrete Materials

a. Cement Type: II, IIA, or III

b. Minimum cement content: 550 lbs/C.Y.

c. Maximum water-cement ratio: 0.50 (6 gals. per sack)

d. Maximum aggregate size: 1-1/2 inches

e. Air content range: 4-7 percent

f. Slump: 2-4 inches

g. Minimum compressive strength (f'_c): 3250 psi at 28 days

3. Concrete Lining Section

a. Reinforced linings shall have a minimum thickness of 7-inches.

b. The side slopes shall be a maximum of 1-1/2 horizontal to 1 vertical or be a structurally reinforced retaining wall if steeper.

4. Concrete Joints

a. Channels shall be continously reinforced without transverse joints. Expansion joints shall be installed where new concrete lining is connected to a rigid structure or to existing concrete lining which is not continuously reinforced.

b. Longitudinal joints, where required, shall be constructed on the side walls at least 1-foot vertically above channel invert.

c. All joints shall be designed to prevent differential movement.

d. Construction joints are required for all cold joints and where the lining thickness changes.

5. Concrete Finish
The surface of the concrete lining shall be provided with a wood float finish. Excessive working or wetting of the finish shall be avoided.

6. Concrete Curing
All concrete shall be cured by the immediate application of a liquid membrane-forming curing compound (white pigmented) upon completion of the concrete finish.

7. Reinforcement Steel
a. Steel reinforcement shall be grade 60 deformed bars. Wire mesh shall not be used.

b. Ratio of longitudinal steel area to concrete cross sectional area shall be greater than .005.

c. Ratio of transverse steel area to concrete cross sectional area shall be greater than .0025.

d. Reinforcing steel shall be placed at the center of the section with a minimum clear cover of 3-inches adjacent to the earth.

8. Earthwork
The following areas shall be compacted to at least 90 percent of maximum density as determined by ASTM D-1557 (Modified Proctor):

a. The 12-inches of subgrade immediately beneath concrete lining (both channel bottom and side slopes).

b. Top 12-inches of maintenance road.

c. Top 12-inches of earth surface within 10-feet of concrete channel lip.

d. All fill material.

9. Bedding
Provide 6-inches of granular bedding in accordance with design procedures in Section 705.3.

10. Underdrain
Longitudinal underdrains as required shall be provided on 10-foot centers and shall daylight at the check drops. A check valve shall be provided at the outlet to prevent backflow into the drain.

11. Safety Requirements

a. A 6-foot high vinyl coated chain link fence shall be installed to prevent access wherever the 100-year channel lining depths exceed 3-feet. Gates, with top latch, shall be placed at 250-feet intervals and staggered where fence is required on both sides of the channel.

b. Ladder-type steps shall be installed not more than 400-feet apart on alternating sides of the channel. Bottom rung shall be placed approximately 12-inches vertically above channel invert.

704.4 Rock Lined Channels

Channel linings constructed from ordinary riprap, grouted riprap, or wire encased rock to control channel erosion have been found to be cost effective where channel reaches are relatively short (less than 1/4 mile). Situations for which riprap linings might be appropriate area: 1) where major flows, such as the 100-year flood are found to produce channel velocities in excess of allowable non-eroding values (5-feet per second for sandy soil conditions and 7-feet per second in erosion resistant soils); 2) where channel side slopes must be steeper than 3:1; 3) for low flow channels, and 4) where rapid changes in channel geometry occur such as channel bends and transitions. Design criteria applicable to these situations are presented in Section 705. Section 705.4 emphasizes requirements associated with ordinary riprap, while Section 705.5 contains additional design considerations specifically related to wire enclosed rock. Both Sections 705.4 and 705.5 are valid only for subcritical flow conditions where the Froude Number is 0.8 or less.

704.5 Roadside Ditches

The criteria for the design of roadside ditches is similar to the criteria for grass lined channels with modifications for the special purpose of minor storm drainage. The criteria is as follows (refer to Figure-708):

1. Capacity
   Roadside ditches shall have adequate capacity for the 5-year storm runoff peaks. Capacity shall be as defined in Table-705. Where the storm runoff exceeds the capacity of the ditch, a storm sewer system shall be required.

2. Flow Velocity
   The maximum velocity for the 5-year flood peak shall not exceed 5.0-feet per second for Type I ditch and 7.0-feet per second for Type II or III ditch. The capacity limitations of Table-705 are based on a maximum Froude Number of 0.8 for Types I, II, and 0.9 for Type III.

3. Longitudinal Slope
   The slope shall be limited by the average velocity of the 5-year flood peaks. Check drops may be required where street slopes are in excess of 2.5 percent.

4. Freeboard
   No freeboard is required.

5. Curvature
   The minimum radius of curvature shall be 25-feet.

6. Roughness Coefficient
Manning's "n" values presented in Figure-705 have been used in the capacity computation for roadside ditches.

7. Grass Lining
The grass lining shall be in accordance with Section 704.2.7.

8. Driveway Culverts
Driveway culverts shall be sized to pass the 5-year ditch flow capacity without overtopping the driveway. The minimum size culvert shall be a 22" x 13" CMPA (18" equivalent round pipe) with flared end sections. More than one culvert may be required.

704.6 Other Channel Linings

The criteria for the design of channels with linings other than grass, rock, or concrete will be dependent on the manufacturers recommendations for the specific product. The applicant will be required to submit the technical data in support of the proposed material. Additional information or calculations may be requested by the City Engineer to verify assumptions or design criteria. The following minimum criteria will also apply.

1. Flow Velocity
The maximum normal depth velocity will be dependent on the construction material utilized. The Froude number shall be less than 0.8.

2. Freeboard
Defined by Equation 710.

3. Curvature
The center line curvature shall have a minimum radius twice the top width of the design flow but not less than 100-feet.

4. Roughness Coefficient
A Manning's "n" value range shall be established by the manufacturers data with the high value used to determine depth/capacity requirements and the low value used to determine Froude Number and velocity restrictions.

5. Cross Sections
Same as for grassed lined channels, Section 704.2.6.

705 RIPRAP

The information for this section was obtained from the USDCM revision dated November 15, 1982 and modified for the specific requirements of Boulder County.

Riprap has proven to be an effective means to deter erosion along channel banks, in channel bottoms, upstream and downstream from hydraulic structures, at bends, at bridges, and in other areas where erosive tendencies exist. Riprap is a popular choice for erosion protection because the initial installation costs are often less than alternative methods for preventing erosion. However, the designer needs to bear in mind that there are additional costs associated with riprap erosion proctection since riprap installations require frequent inspection and maintenance. Wire enclosed riprap (gabion) in most cases requires complete renovation every 10 to 15 years.

The use of very light (VL) or light (L) types of riprap in an urbanized area has been found to be susceptable to vandalism. The lighter rock is easily displaced by hand and has been completely removed from the project site in some cases.

705.1 Ordinary Riprap

Ordinary riprap, or simply riprap, refers to a protective blanket of large loose stones, which are usually placed by machine to achieve a desired configuration. The terms ordinary riprap has been introduced to differentiate loose stones from grouted riprap and wire enclosed rock, which are discussed later.

Many factors govern the size of the rock necessary to resist the forces tending to move the riprap. For the riprap itself, this includes the size and weight of the individual rocks, the shape of the stones, the gradation of the particles, the blanket thickness, the type of bedding under the riprap, and the slope of the riprap layer. Hydraulic factors affecting riprap include the velocity, current direction, eddy action and waves.

Experience has shown that riprap failures result from undersized individual rocks in the maximum size range, improper gradation of the rock which reduces the interlocking of individual particles and improper bedding for the riprap which allows leaching of channel particles through the riprap blanket.

1. Rock Properties

   Rock used for riprap or wire enclosed riprap should be hard, durable, angular in shape, and free from cracks, overburden, shale and organic matter. Neither breadth nor thickness of a single stone should be less than 1/3 the length and rounded stone should be avoided. The rock should sustain a loss of not more than 40 percent after 500 revolutions in an abrasion test (Los Angeles machine - ASTM C-535-69) and should sustain a loss of not more than 10 percent after 12 cycles of freezing and thawing (AASHTO test 103 for ledge rock procedure A). Rock having a minimum specific gravity of 2.65 is preferred; however, in no case should rock have a specific gravity less than 2.50. In lieu of testing requirements, rock obtained from City approved quarries may be used.

   Classification and gradation for riprap are shown in Table-707 and are based on minimum specific gravity of 2.50 for the rock. Because of the relatively small size and weight, riprap types VL and L must be buried with native top soil and revegetated to protect the rock from vandalism.

2. Grouted Riprap

   Grouted riprap provides a relatively impervious channel lining which is less subject to vandalism than dumped riprap. Grouted riprap requires less routine maintenance by reducing silt and trash accumulation and is particularly useful for lining low flow channels and steep banks. The appearance of grouted riprap is enhanced by exposing the tops of individual stones and by cleaning the projecting rocks with a wet broom. Grouted riprap should meet all the requirements for ordinary riprap except that the smallest rock fraction (smaller than the 10% size) should be eliminated from the gradation. A reduction of riprap size by one size designation is permitted for grouted rock (i.e., from Type M to Type L).

As with ordinary riprap, grouted riprap should be placed on an adequate bedding. The recommended minimum grout specifications include entrained air, a 28-day strength of at least 2400 pounds per square inch, and a high slump (5- to 7-inches) in order to penetrate either the full depth of the riprap layer or at least 2-feet where the riprap layer is thicker than 2-feet. Concrete having maximum aggregate size of 3/4-inches may be substituted for grout when using Type M riprap or larger riprap. Weep holes should be provided at least every 4- to 6-feet at the toe of channel slopes and channel drops to reduce uplift forces on the grouted channel lining.

The grout shall be delivered to the place of final deposit by means that will insure uniformity and prevent segregation of the grout. Placing of grout shall be obtained by pumping under pressure through a 2-inch maximum diameter hose to insure complete penetration of the grout into the rock layer. A vibrator is to be employed near the nozzle during placement to aid the flow of the grout. The excess grout shall be removed by a thorough washing to leave a clean rock face exposed. The grouted riprap should resemble a hand placed stone wall or fireplace rock. Grout shall fill the voids to within approximately 4-inches of the riprap surface.

705.2 Wire Enclosed Rock

Wire enclosed rock must be approved for use by the County prior to construction for public facilities. Wire enclosed rock refers to rocks that are bound together in a wire basket so that they act as a single unit, usually referred to as a gabion. One of the major advantages of wire enclosed rock is that it provides an alternative in situations where available rock sizes are too small for ordinary riprap. Another advantage is the versatility that results from the regular geometric shapes of wire enclosed rock. The rectangular blocks and mats can be fashioned into almost any shape that can be formed with concrete. The durability of wire enclosed rock is generally limited by the service life of the galvanized binding wire which, under normal conditions, is considered to be about 15 years. Water carrying silt, sand, or gravel can reduce the service life of the wire; also water which rolls or otherwise moves cobbles and large stones breaks the wire with a hammer and anvil action and considerably shortens the life of the wire. The wire has been found to be susceptible to corrosion by various chemical agents and is particularly affected by high sulfate soils. If corrosive agents are known to be in the water or soil, a plastic coated wire should be specified.

Wire enclosed rock is not maintenance free and must be periodically inspected to determine whether the wire is sound. If breaks are found while they are still relatively small, they may be patched by weaving new strands of wire into the wire cage. Wire enclosed rock installations have been found to attract vandalism. Flat mattress surfaces seem to be particularly susceptible to having wires cut and stones removed. Where possible, mattress surfaces should be buried, as it has been found that wire enclosed rock buried under a few inches of soil is less prone to vandalism. Wire enclosed rock installations require inspection at least once a year under the best circumstances and may require inspection every three months in vandalism prone areas. Mattresses on sloping surfaces must be securely anchored to the surface of the soil (see Section 705.5).

Rock filler for the wire baskets should meet the rock property requirements for ordinary riprap. Minimum rock sizes and basket dimensions are shown in Table-708. The maximum stone size should not exceed 2/3 the basket depth or 12-inches, whichever is smaller.

705.3 Bedding Requirements

Long term stability of riprap and gabion erosion protection is strongly influenced by proper bedding conditions. A large percentage of all riprap failures are directly attributable to bedding failures. A properly designed bedding provides a buffer of intermediate sized material between the channel bed and the riprap to prevent piping of channel particles through the voids in the riprap. Two types of bedding are in common use: 1) a granular bedding filter and 2) filter fabric.

1. Granular Bedding

Two methods for establishing gradation requirements for granular bedding are described in this section. The first, a one or two layer bedding, shown in Table-709 is adequate for most ordinary riprap, grouted riprap or wire encased riprap applications. The second utilizes a design procedure developed by Terzaghi, which is referred to as the T-V (Terzaghi-Vicksburg) design (References-51 and -52). The T-V filter criteria establishes an optimum bedding gradation for a specific channel soil. The latter requires channel soil information, including a gradation curve, while the Type I and Type II bedding specifications given in Table-709 are applicable whether or not soil information is available.

The Type I and Type II bedding specifications shown in Table-709 were developed using the T-V filter criteria and the fact that bedding which will protect an underlying noncohesive soil with a mean grain size of 0.045 mm will protect anything finer. Since the T-V filter criterion provides some latitude in establishing bedding gradations, it was possible to make the Type I and Type II bedding specifications conform with Colorado Division of Highways aggregate specifications. The Type I bedding in Table-709 is designed to be the lower layer in a two layer filter for protecting fine grained soils and has a gradation identical to Colorado Division of Highways concrete sand specification AASHTO M-6 (Section 703.1). Type II bedding, the upper layer in a two layer filter, is equivalent to Colorado Division of Highways Class A filter material (Section 703.9) except that it permits a slightly larger maximum rock fraction. When the channel is excavated in course sand and gravel (50 percent or more by weight retained on the No. 40 sieve), only the Type II filter is required, otherwise a two layer bedding (Type I topped by Type II) is required. Alternatively, a single 12-inch layer of Type II bedding can be used except at drop structures. For required bedding thickness see Table-710. At drop structures a combination of filter fabric and Type II bedding is acceptable as an alternative to a two layer filter.

The specifications for the T-V inverse filter relate the gradation of the protective layer (filter) to that of the bed material (base) by the following inequalities:

$$D_{15(filter)} \leq 5\, d_{85(base)} \quad (712)$$

$$4\, d_{15(base)} \leq D_{15(filter)} \leq 20\, d_{15(base)} \quad (713)$$

$$D_{50(filter)} \leq 25\, d_{50(base)} \quad (714)$$

where the capital "D" refers to the filter gain size and the lower case "d" to the base grain size. The subscripts refer to the percent by weight which is finer than the grain size denoted by either "D" or "d". For example, 15 percent of the filter material is finer than D-sub 15(filter) and 85 percent of the base material is finer than d-sub 85(base). Application of the T-V filter criteria is described in example No. 11, Section 705.7.

2. Filter Fabric

Filter fabric is not a complete substitute for granular bedding. Filter fabric provides filtering action only perpendicular to the fabric and has only a single equivalent pore opening between the channel bed and the riprap. Filter fabric has a relatively smooth surface which provides less resistance to stone movement. As a result, filter fabric is restricted to slopes no steeper than 2.5h to 1v. Tears in the fabric greatly reduce its effectiveness so that direct dumping of riprap on the filter fabric is not recommended and care must be exercised during construction. Nonetheless, filter fabric has proven to be an adequate replacement for granular bedding in many instances. Filter fabric provides an adequate bedding for channel linings along uniform mild sloping channels where leaching forces are primarily perpendicular to the fabric.

At drop structures and sloped channel drops, where seepage forces may run parallel with the fabric and cause piping along the bottom surface of the fabric, special care is required in the use of filter fabric. Seepage parallel with the fabric might be reduced by folding the edge of the fabric vertically downward about 2-feet (similar to a cutoff wall) at 12-foot intervals along the installation, particularly at the entrance and exit of the channel reach. Filter fabric should be lapped a minimum of 12-inches at roll edges with upstream fabric being placed on top of downstream fabric at the lap.

Fine silt and clay may clog the openings in the filter fabric, preventing free drainage and increasing failure potential due to uplift. For this reason, a double granular filter is recommended for fine silt and clay channel beds. See Figure-709 for details on acceptable use of filter fabric as bedding.

705.4 Ordinary Riprap Channel Linings

Design criteria applicable to ordinary and grouted riprap channel linings are presented in this

The Manning's roughness coefficient (n) for hydraulic computations may be estimated for ordinary riprap using:

$$n = .0395\, d_{50}^{\ 0.17}$$

in which d_{50} = the mean stone size in feet.

This equation does not apply to grouted riprap (n = .023 to .030), or to very shallow flow (hydraulic radius is less than or equal to 2 times the maximum rock size) where the roughness coefficient will be greater than indicated by the formula (see Table-706).

1. Rock Size and Lining Dimensions

Table-711 summarizes riprap requirements for a stable channel lining based on the following relationship which resulted from Smith and Murray's model studies (Reference-53).

$$VS^{0.17}/(d_{50}^{\ 0.5}(S_s - 1)^{0.66}) = 4.5 \qquad (715)$$

in which, V = mean channel velocity in feet per second

S = longitudinal channel slope in feet per foot

S_s = specific gravity of rock (minimum S_s = 2.50)

d_{50} = rock size in feet for which 50% of the riprap by weight is smaller.

Using the riprap classification of Table-707 for the d-sub 50 values and specific gravity of 2.5, Equation 715 was rearranged to relate specifically to the riprap rock type (i.e., VL, L, M, H, and VH). Acceptable ranges of velocity and slope within the channel design criteria (i.e., velocity, Froude Number) was established and a direct relationship between the rock type and the flow parameters was developed. Table-711 presents the riprap requirements for channel linings as a function of slope and velocity.

Table-711 recognizes that rock size does not need to be increased for steeper channel side slopes, provided the side slopes are no steeper than 2h:1v (Reference-53). Rock lined side slopes steeper than 2h:1v are not acceptable because of stability, safety, and maintenance considerations. Proper bedding is required both along the side slopes and the channel bottom for a stable lining. The riprap blanket thickness should be at least 1.75 times d-sub 50 (at least 2.0 times d-sub 50 in sandy soils) and should extend up the side slopes at least 1-foot above the design water surface. At the upstream and downstream termination of a riprap lining, the thickness should be increased 50 percent for at least 3-feet to prevent under cutting.

2. Toe Protection

Where only the channel sides are to be lined, additional riprap is needed to provide for long term stability of the lining. In this case, the riprap blanket should extend at least 3-feet below the existing channel bed and the thickness of the blanket below the existing channel bed increased to at least 3 times d-sub 50 to accommodate possible channel scour during floods (see Figure-710). For sandy soils, consult specific criteria for channels on sandy soils.

3. Channel Bends

The potential for erosion increases along the outside bank of a channel bend due to the acceleration of flow velocities on the outside part of the bend. Thus, it is often necessary to provide erosion protection in channels which otherwise would not need protection. In erosion resistant soils, extra protection is not required along bends where the radius is greater than 2 times the top width (as measured for the major flows) but in no case less than 100-feet.

For bank protection requirements in sandy soils, consult the specific criteria for channels on sandy soils. However, for channels in erosion resistant soils not requiring riprap protection along straight sections, channel bends with radii smaller than stated above require Type L or SM9 riprap protection. Such riprap needs to be covered with native soil and revegetated in accordance with Section 704.2.7. The minimum allowable radius for a riprap lined bend is 1.2 times the top width of the design flow water surface and in no case less than 50-feet. The riprap protection should be placed along the outside of the bank and should extend downstream from the bend a distance equal to the length of the bend.

Where the mean channel velocity exceeds the allowable non-eroding velocity so that riprap protection is required for straight channel sections, increase the rock size by one category (e.g., Type L to Type M) around bends having a radius less than the greater of the following: 2 times the top width, or 100-feet. The minimum allowable radius for a riprap lined bend in this case is also 1.2 times the top width of the design flow water surface.

4. Transitions

Scour potential is amplified by turbulent eddies in the vicinity of rapid changes in channel geometry such as at transitions and bridges. Table-711 may be used for selecting riprap protection for subcritical transitions (Froude Numbers 0.8 or less) by increasing the channel velocity by twenty percent (20%). Since the channel velocity varies through a transition, the maximum velocity in the transition should be used in selecting riprap size after it has been increased by 20%.

Protection should extend upstream from the transition entrance at least 5-feet and extend downstream from the transition exit at least 10-feet.

705.5 Wire Enclosed Riprap Channel Linings

The geometric properties of wire enclosed rock permit placement in areas where ordinary riprap is either difficult or impractical to place. Proper design and construction is important to successful operation and lifetime performance. Figure-711 depicts some of the more common ways wire enclosed rock is configured along channel banks. However, wire enclosed riprap lining shall not be used for areas exposed to annual floods, and ordinary riprap is recommended whenever feasible.

The roughness coefficient for slope mattress linings varies from 0.025 to 0.033 depending on the predominant rock size. An n-value of 0.028 is recommended (see Table-706) based on a rock size of 4-inches. For gabion linings a larger value of n = .035 is recommended due to the larger rock size.

If wire enclosed rock lining is used, the toe must be protected by placing riprap at the toe. This is needed to protect against frequently occurring abrasion (see Figure-710).

Where channel side slopes must exceed 2h to 1v, gabion baskets (G36) may be stacked to form a retaining wall as well as erosion protection along the channel banks as shown in Figure-711. Adjacent baskets should be tied together with heavy gauge wire and adequate protection against channel bed degradation must be provided at the toe of the lining. Stacked baskets must be sloped, or stepped into the bank as shown in Figure-711. Vertical stacking is not acceptable.

Channel linings should be tied to the channel banks with gabion (G36) counterforts at least every 12-feet. Counterforts should be keyed at least 12-inches into the existing banks with slope mattress linings (see Figure-711) and should be keyed at least 3-feet by turning the counterfort gabions end-wise when the lining is designed to serve as a retaining wall.

Mattresses and flat gabions on channel side slopes need to be tied to the banks by 2-inch diameter steel pipes driven 4-feet into tight soil (clay) and 6-feet into loose soil (sand) (See Figure-711). The pipes should be located at the inside corners of basket diaphragms along an upslope (highest) basket wall, so that the stakes are an integral part of the basket. The exact spacing of the stakes depends upon the configuration of the baskets, however, the following is the suggested minimum spacing: Stakes every 6-feet along and down the slope, for slopes 2.5 to 1 and steeper and every 9-feet along and down the slope for slopes flatter than 2.5 to 1. Counterforts are optional with slope mattress linings. Slope mattresses staking, however, is required, whether or not counterforts are used.

705.6 <u>Erosion Protection at Conduit Outlets</u>

Scour resulting from highly turbulent rapidly decelerating flow is a common problem at conduit outlets. The following riprap protection is suggested for outlet Froude Numbers up to 2.5 (i.e., (Q/D ** 2.5) or (Q/WH ** 1.5) up to 14 where the outlet of the conduit slope is parallel with the channel gradient and the conduit outlet invert is flush with the riprap channel protection. Here Q is the discharge in cubic feet per second, D is the diameter of a circular conduit in feet and W and H are the width and height of a rectangular conduit in feet.

1. <u>Configuration of Protection</u>
   Figure-712 illustrates a typical riprap basin at a conduit outlet. The additional thickness of the riprap just downstream from the outlet is to assure protection from extreme flow conditions which might cause rock movement in this region. Note that protection is required under the conduit barrel and an end slope is provided to accommodate degradation of the downstream channel.

2. <u>Rock Size</u>
   The required rock size may be selected from Figure-713 for circular conduits and from Figure-714 for rectangular conduits. Figure-713 is valid for (Q/D ** 2.5) of 6.0 or less and Figure-714 is valid for (Q/WH ** 1.5) of 8.0 or less. The parameters in these two figures are:

a. (Q/D ** 1.5) or (Q/WH ** 0.5) in which Q is the design discharge in cubic feet per second and D is a circular conduit diameter in feet and W and H are the width and height of a rectangular conduit in feet.

b. Y-sub t/D or Y-sub t/H in which Y-sub t is the tailwater depth in feet, D is the diameter of a circular conduit and H is the height of a rectangular conduit in feet. In cases where Y-sub t is unknown or a hydraulic jump is suspected downstream of the outlet, use Y-sub t/D = Y-sub t/H = 0.40 when using Figures-713 and -714.

c. The riprap size requirements in Figures-713 and -714 are based on the non-dimensional parametric equations-716 and -717 (References-54 and -55).

Circular Culvert:

$$(d_{50}/D)(Y_t/D)^{1.2} \ / \ (Q/D^{2.5}) = 0.023 \qquad (716)$$

Rectangular Culvert:

$$(d_{50}/D)(Y_t/H) \ / \ (Q/WH^{1.5}) = 0.014 \qquad (717)$$

The rock size requirements were determined assuming that the flow in the culvert barrel is not supercritical. Equations 716 and 717 can be used when the flow in the culvert is less than pipe full and is supercritical if the value of D or H is modified for use with Figures-713 and -714. Whenever the flow is supercritical in the culvert, substitute the average depth (D-sub a) for D and average height (H-sub a) for H, in which D-sub a is defined as:

$$D_a = 1/2(D + Y_n) \qquad (718)$$

in which maximum D_a shall not exceed D, and

$$H_a = 1/2(H + Y_n) \qquad (719)$$

in which maximum H_a shall not exceed H, and

D_a = A parameter to be used in Figure-713 whenever the culvert flow is supercritical.

D = Diameter of a circular culvert in feet.

H_a = A parameter to be used in Figure-714 whenever the culvert flow is supercritical.

H = Height of a rectangular culvert in feet.

Y_n = Normal depth of supercritical flow in the culvert.

3. <u>Extent of Protection</u>

The length of the riprap protection downstream from the outlet depends on the degree of protection desired. To prevent all erosion, the riprap must be continued until the velocity has been reduced to an acceptable value. For purposes of outlet protection during major floods the acceptable velocity is set at 5.5 fps for very erosive soils and 7.7 fps for erosion resistant soils. The rate at which the velocity of a jet from a conduit outlet decreases is not well known. For the procedure recommended here, the velocity decrease is assumed to be related to the angle of lateral expansions, θ, of the jet. The velocity is related to the expansion factor, (1/(2tan θ)), which may be determined directly using Figures-715 or -716.

Assuming that the expanding jet has a rectangular shape:

$$L = (1/(2 \tan \theta))(A_t/Y_t - W) \quad (720)$$

In which:

L = length of protection in feet,

W = width of the conduit in feet (use diameter for circular conduits),

Y_t = tailwater depth in feet,

θ = the expansion angle of the culvert flow.

$$A_t = Q / V \quad (721)$$

Q = design discharge in cubic feet per second

V = the allowable non-eroding velocity in the downstream channel in feet per second.

A_t = required area of flow at allowable velocity in square feet.

In certain circumstances, Equation 720 may yield unreasonable results. Therefore in no case should L be less than 3D or 3H, nor does L need to be greater than 10D or 10H whenever the Froude parameter (Q/WH ** 1.5) or (Q/D ** 2.5) is less than 8 or 6 respectively. Whenever the Froude parameter is greater than these maximums, increase the maximum L required by one-fourth D or H for each whole number the Froude parameter is greater than 8 or 6 for rectangular or circular pipe respectively.

4. <u>Multiple Conduits</u>

The procedures outlined in the sections above can be used to design outlet erosion protection for multi-barrel culvert installations by hypothetically replacing the multiple barrels with a single hydraulically equivalent rectangular conduit. The dimensions of the equivalent conduit may be established as follows: First, distribute the total discharge, Q, among the individual conduits. Where all the conduits are hydraulically similar and identically situated, the flow can be assumed to be equally distributed, otherwise, the flow through each barrel must be computed. Next, compute the Froude parameter (Q-sub i)/((D-sub i) **2.5) (circular conduit) or (Q-sub i)/(W-sub i)((H-sub i) **1.5) (rectangular conduit), where the subscript i indicates the discharge and dimensions associated with an individual conduit. If the installation includes dissimilar conduits, select the conduit with the largest value of the Froude parameter to determine the dimensions of the equivalent conduit. Make the height of the equivalent conduit, H-sub e, equal to the height, or diameter, of the selected individual conduit. The width of the equivalent conduit, W-sub e, is determined by equating the Froude parameter from the selected individual conduit with the Froude parameter associated with the equivalent conduit, (Q-sub e)/(W-sub e)((H-sub e) **1.5).

705.7 Examples

Example No. 11: Design of Granular Bedding

Given: Sandy-silt channel bed with gradation shown by the solid line in Figure-717.

Find: The gradation band for granular bedding required to protect the given sany-silt channel bed.

Step 1: From the gradation curve read:

d_{15}(base) = .016 mm

d_{50}(base) = .051 mm

d_{85}(base) = 0.10 mm

Step 2: The upper limit of D sub-15 (filter) = 5 x d sub-85(base) (Equation 712)
(5 x .1 = .5 mm).

Step 3: The upper limit of D sub-15(filter) = 20 x d sub-15(base) (Equation 713)
(20 x .016 = .32 mm).

Since .32 mm < .5 mm, requirement 2 controls. The upper limit for D sub-15(filter) = .32 mm.

Step 4: The lower limit for D-sub 15(filter) = 4 x d-sub 15 (Equation 713)
(4 x .016 = .064 mm).

Step 5: The upper limit for D-sub 15(filter) = 25 x d-sub 50 (Equation 714)
(25 x .051 = 1.28 mm).

Step 6: Plot the results from Steps 2 through 5 as shown on Figure-717.

Step 7: Sketch the upper and lower limits of the gradation requirements for the lowest layer of the bedding. Use the shape of the sandy-silt gradation curve and the plotted points to establish the limits as shown by the dashed lines on Figure-717.

Step 8: Establish a gradation for the lowest bedding layer which fits within the gradation band from Step 7.

Step 9: Repeat Steps 1 through 8 using the gradation curve from Step 8 as the base to establish the required gradation band for the second layer of the bedding. Usually two layers are sufficient.

Step 10: Set the granular bedding thickness of each layer to the thickness of each layer specified in Table-710.

<u>Example No. 12</u>: <u>Single Conduit Outlet Protection</u>

<u>Given</u>: 72-inch (6-ft) diameter culvert at S-sub o = 0.010 ft/ft and n = 0.012.

$D = 6$ ft

$Q = 500\ ft^3/s$ (pipe full flow)

Tailwater depth (normal depth downstream) = 3.0 ft.

Allowable channel velocity downstream = 5.5 ft/s.

Step 1: Determine the required type of riprap for erosion protection.

First check to see if culvert is supercritical. Since the pipe is flowing full D-sub a = D = 6 ft

Then,

$Y_t/D = 3.0/6.0 = 0.5$

$Q/D^{1.5} = 500/6^{1.5} = 34$

From Figure-713 -- Type VH riprap will be required

From Table-707 -- $d_{50} = 24$ in

Step 2: Determine the expansion factor $1/(2\tan\theta)$.

$Q/D^{2.5} = 500/6^{2.5} = 5.67$

From Figure-715 -- $1/(2\tan\theta) = 2.8$

Step 3: Determine the length of riprap protection

$A_t = 500/5.5 = 91\ ft^2$ (721)

$L = 2.8\ (91/3 - 6) = 68$ ft (720)

Step 4: Check if maximum or minimum limit governs

Since $Q/d^{2.5}$ is less than 6.0, then

$L_{max} = 10D = 10(6) = 60$ ft

Therefore, use 60-feet for basin length.

Step 5: Determine the maximum riprap depth

From Figure-712 maximum depth = 2 d_{50} = 2(2) = 4 ft.

Example No. 13: Multiple Conduit Outlet Protection Similar Pipes

Given: Triple 36 inch (3-foot) culvert at S sub-o = 0.010 ft/ft n = 0.012

$Q = 270\ ft^3/s$

Tailwater depth = 2.1 ft

Allowable channel velocity downstream = 7.7 ft/s

Step 1: Determine flow in each conduit and determine if they are flowing at supercritical depths.

$Q = 270/3 = 90\ ft^3/s$

Critical depth at 90 ft^3/s = 1.02 ft

Normal depth Y_n at 90 ft^3/s is pipe full flow.

Therefore, flow is subcritical and no adjustment is needed to the diameter when using Figure-714.

Step 2: Compute Froude Parameter

$F = Q/(D^{2.5}) = 90/(3^{2.5}) = 5.77.$

Step 3: Set height of equivalent rectangular conduit

$H_e = D = 3$ ft

Step 4: Calculate the width of an equivalent rectangular culvert W-sub e by equating Froude Parameters using H-sub e = 3.0 ft.

$Q/(W_e)(H_e^{1.5}) = 5.77$

or

$W_e = 270/(5.77)(3^{1.5}) = 9$ ft

Step 5: Determine type of riprap

$Y_t/H_e = 2.1/3.0 = 0.7$

$Q/(W_e)(H_e^{0.5}) = 270/(9)(3^{0.5}) = 17.3$

From Figure-714 -- Type L riprap

From Table-707 -- d_{50} = 9 in

Step 6: Determine the expansion factor

$Q/(W_e)(H^{1.5}) = 270/(9)(3^{1.5}) = 5.77$

From Figure-716 -- $1/(2\tan \theta) = 4.3$

Step 7: Calculate length of protection

$A_t = (270/7.7) = 35.1 \text{ ft}^2$ (721)

$L = 4.3(35.1/2.1 - 9.0) = 33 \text{ ft}$ (720)

Step 8: Check if maximum or minimum limits govern

Since $Q/(D^{2.5})$ is less than 6.0, then

$L_{max} = 10H = 10(3) = 30 \text{ ft}$

Therefore, use L = 30 ft for basin length.

Step 9: Determine maximum riprap depth

From Figure-712, maximum depth is $2d_{50} = 2(.75) = 1.50$.

<u>Example No. 14</u>: <u>Multiple Conduit Outlet Protection-Dissimilar Pipes</u>

<u>Given</u>: Double 36-inch (3 ft) culvert

Single 48-inch (4 ft) culvert

All pipes at S_o = 0.030 ft/ft and n = 0.012

All outlet inverts are at the same elevation (± 0.25 ft). This procedure can be applied only to such cases. If inverts are not at the same elevation, then concrete energy dissipator is recommended.

$Q = 315 \text{ ft}^3/\text{s}$

Headwater depth = 8 ft

Tailwater depth = 3.0 ft

Allowable channel velocity downstream = 7.7 ft/s

Step 1: Determine the flow in each conduit

Assume inlet control governs

$HW/D_1 = 8/4 = 2$; $HW/D_2 = 8/3 = 2.67$

From highway culvert nomographs for circular pipe having a square edged headwall type entrance

$Q_1 = 145 \text{ ft}^3/s$; $Q_2 = 85 \text{ ft}^3/s$

Step 2: Determine if any of the pipes are flowing at supercritical depths.

Critical depth for a 48 in circular pipe at 145 ft^3/s is 3.5 ft. Normal depth (Y-sub n), is 1.80 ft. Therefore, this pipe is flowing supercritical and inlet control assumption in Step 2 is also valid.

Step 3: Since the culverts are at supercritical flow, determine the modified pipe heights.

For the 48 in pipe

$$D_a = 1/2\ (4.0 + 2.12) = 3.06 \text{ ft} \qquad (718)$$

for the 36 in pipe

$$D_a = 1/2(3.0 + 1.80) = 2.40 \text{ ft}$$

Step 4: Compute Froude Parameters and determine equivalent rectangular height

$$F_1 = 145/(3.06^{2.5}) = 8.85$$

$$F_2 = 85/(2.40^{2.5}) = 9.53$$

F-sub 2 governs, therefore use H-sub a = D-sub a = 2.40 ft. Note that because D-sub a is less than the tailwater and the pipe is flowing at supercritical depth, a hydraulic jump downstream of outlet is suspected. Also note that F-sub 1 and F-sub 2 exceeds the upper limit of 6.0 for circular pipe and the use of riprap or Figures-713 and -714 would not normally be acceptable. However, for the sake of illustrating the procedure this example utilizes these two Figures for rock size selection.

Step 5: Calculate width of equivalent rectangular culvert W-sub e for the 3-foot pipe by equating Froude Parameters using

$$H_e = 2.40 \text{ ft.}$$

$$Q/(W_e)(H_e^{1.5}) = 9.53$$

$$W_e = 315/(9.53)(2.4^{1.5}) = 8.9 \text{ ft.}$$

Step 6: Determine type of riprap

$Y_t/H_e = 3.0/2.40 > 1.0$

Tailwater is greater than approach flow and a hydraulic jump is suspected, therefore in accordance with Paragraph 705.6.2, set Y-sub t/H sub-e = 0.40 for use with Figure-714.

$Q/(W_e)(H_e^{0.5}) = 315/(8.9)(2.40^{0.5}) = 22.8$

From Figure-714 -- Type M riprap

From Table-707 -- $d_{50} = 12$

Note the qualification in Step 4 of this example

Step 7: Determine expansion factor $1/(2\tan\theta)$.

$Q/(W_e)(H_e^{1.5}) = 9.53$

$Y_t/H_e = 2.4/1.76 = 1.36$

Note that the value of these two parameters is beyond the range of Figure-716. Never-the-less, a value of $1/(2\tan\theta)$ is chosen using

$Q/(W_e)(H_e^{1.5}) = 6$

and

$Y^t/H_e = 1.0$

Set $1/(2\tan\theta) = 5.6$

Step 8: Determine length of protection

$A_t = 315/7.7 = 40.9\ ft^2$ (721)

$L = 5.6\ (40.9/3.0 - 8.9) = 26.5$ feet (720)

Step 9: Check if maximum limit governs using the tallest culvert of the three. Since the Froude Parameter for the controlling circular pipe is greater than 6, the upper limit must be increased by one-fourth for each whole Froude Paramter greater than 6. Thus,

$L_{max} = (10 + 0.25\ (9.53 - 6))H$

or

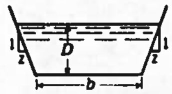
$L_{max} = 10.9H$

$L_{max} = 10.9(4.0) = 43.6$ ft

Since the basin length in Step 8 is less than L-sub max, use basin length L = 26.5 ft.

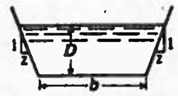
UNIFORM FLOW FOR TRAPEZOIDAL CHANNELS

Values of $\frac{Qn}{b^{8/3}S^{1/2}}$



D/b[1]	z=0	z=¼	z=½	z=¾	z=1	z=1¼	z=1½	z=1¾	z=2	z=2½	z=3	z=4
.02	.00213	.00215	.00216	.00217	.00218	.00219	.00220	.00220	.00221	.00222	.00223	.00225
.03	.00414	.00419	.00423	.00426	.00429	.00431	.00433	.00434	.00437	.00440	.00443	.00449
.04	.00661	.00670	.00679	.00685	.00690	.00696	.00700	.00704	.00707	.00715	.00722	.00735
.05	.00947	.00964	.00980	.00991	.0100	.0101	.0102	.0103	.0103	.0104	.0106	.0109
.06	.0127	.0130	.0132	.0134	.0136	.0137	.0138	.0140	.0141	.0143	.0145	.0149
.07	.0162	.0166	.0170	.0173	.0176	.0177	.0180	.0182	.0183	.0186	.0190	.0196
.08	.0200	.0206	.0211	.0215	.0219	.0222	.0225	.0228	.0231	.0235	.0240	.0250
.09	.0240	.0249	.0256	.0262	.0267	.0271	.0275	.0279	.0282	.0289	.0296	.0310
.10	.0283	.0294	.0305	.0311	.0318	.0324	.0329	.0334	.0339	.0348	.0358	.0375
.11	.0329	.0342	.0354	.0364	.0373	.0380	.0387	.0394	.0400	.0413	.0424	.0448
.12	.0376	.0393	.0408	.0420	.0431	.0441	.0450	.0458	.0466	.0482	.0497	.0527
.13	.0425	.0446	.0464	.0480	.0493	.0505	.0516	.0527	.0537	.0556	.0575	.0613
.14	.0476	.0501	.0521	.0542	.0559	.0573	.0587	.0599	.0612	.0636	.0659	.0705
.15	.0528	.0559	.0585	.0608	.0628	.0645	.0662	.0677	.0692	.0721	.0749	.0805
.16	.0582	.0619	.0650	.0676	.0699	.0720	.0740	.0759	.0776	.0811	.0845	.0912
.17	.0638	.0680	.0717	.0748	.0775	.0800	.0823	.0845	.0867	.0907	.0947	.103
.18	.0695	.0744	.0786	.0822	.0854	.0883	.0910	.0936	.0961	.101	.105	.115
.19	.0753	.0809	.0857	.0900	.0936	.0970	.100	.103	.106	.112	.117	.128
.20	.0813	.0875	.0932	.0979	.102	.106	.110	.113	.116	.123	.129	.141
.21	.0873	.0944	.101	.106	.111	.115	.120	.123	.127	.134	.142	.156
.22	.0935	.101	.109	.115	.120	.125	.130	.134	.139	.147	.155	.171
.23	.0997	.109	.117	.124	.130	.135	.141	.146	.151	.160	.169	.187
.24	.106	.116	.125	.133	.139	.146	.152	.157	.163	.173	.184	.204
.25	.113	.124	.133	.142	.150	.157	.163	.170	.176	.187	.199	.222
.26	.119	.131	.142	.152	.160	.168	.175	.182	.189	.202	.215	.241
.27	.126	.139	.151	.162	.171	.180	.188	.195	.203	.218	.232	.260
.28	.133	.147	.160	.172	.182	.192	.201	.209	.217	.234	.249	.281
.29	.139	.155	.170	.182	.193	.204	.214	.223	.232	.250	.267	.302
.30	.146	.163	.179	.193	.205	.217	.227	.238	.248	.267	.286	.324
.31	.153	.172	.189	.204	.217	.230	.242	.253	.264	.285	.306	.347
.32	.160	.180	.199	.215	.230	.243	.256	.269	.281	.304	.327	.371
.33	.167	.189	.209	.227	.243	.257	.271	.285	.298	.323	.348	.396
.34	.174	.198	.219	.238	.256	.272	.287	.301	.315	.343	.369	.422
.35	.181	.207	.230	.251	.270	.287	.303	.318	.334	.363	.392	.450
.36	.190	.216	.241	.263	.283	.302	.319	.336	.353	.384	.416	.477
.37	.196	.225	.251	.275	.297	.317	.336	.354	.372	.406	.440	.507
.38	.203	.234	.263	.289	.311	.333	.354	.373	.392	.429	.465	.536
.39	.210	.244	.274	.301	.326	.349	.371	.392	.412	.452	.491	.568
.40	.218	.254	.286	.314	.341	.366	.389	.412	.433	.476	.518	.600
.41	.225	.263	.297	.328	.357	.383	.408	.432	.455	.501	.545	.634
.42	.233	.279	.310	.342	.373	.401	.427	.453	.478	.526	.574	.668
.43	.241	.282	.321	.356	.389	.418	.447	.474	.501	.553	.604	.703
.44	.249	.292	.334	.371	.405	.437	.467	.496	.524	.579	.634	.739
.45	.256	.303	.346	.385	.422	.455	.487	.519	.548	.607	.665	.778
.46	.263	.313	.359	.401	.439	.475	.509	.541	.574	.635	.696	.816
.47	.271	.323	.371	.417	.457	.494	.530	.565	.600	.665	.729	.856
.48	.279	.333	.384	.432	.475	.514	.552	.589	.626	.695	.763	.897
.49	.287	.345	.398	.448	.492	.534	.575	.614	.652	.725	.797	.939
.50	.295	.356	.411	.463	.512	.556	.599	.639	.679	.758	.833	.983
.52	.310	.377	.438	.496	.548	.599	.646	.692	.735	.820	.906	1.07
.54	.327	.398	.468	.530	.590	.644	.696	.746	.795	.891	.984	1.17
.56	.343	.421	.496	.567	.631	.690	.748	.803	.856	.963	1.07	1.27
.58	.359	.444	.526	.601	.671	.739	.802	.863	.922	1.04	1.15	1.37
.60	.375	.468	.556	.640	.717	.789	.858	.924	.988	1.12	1.24	1.49
.62	.391	.492	.590	.679	.763	.841	.917	.989	1.06	1.20	1.33	1.60
.64	.408	.516	.620	.718	.809	.894	.976	1.05	1.13	1.28	1.43	1.72
.66	.424	.541	.653	.759	.858	.951	1.04	1.13	1.21	1.37	1.53	1.85
.68	.441	.566	.687	.801	.908	1.01	1.10	1.20	1.29	1.47	1.64	1.98
.70	.457	.591	.722	.842	.958	1.07	1.17	1.27	1.37	1.56	1.75	2.12
.72	.474	.617	.757	.887	1.01	1.13	1.24	1.35	1.45	1.66	1.87	2.27
.74	.491	.644	.793	.932	1.07	1.19	1.31	1.43	1.55	1.77	1.98	2.41
.76	.508	.670	.830	.981	1.12	1.26	1.39	1.51	1.64	1.88	2.11	2.57
.78	.525	.698	.868	1.03	1.18	1.32	1.46	1.60	1.73	1.98	2.24	2.73
.80	.542	.725	.906	1.08	1.24	1.40	1.54	1.69	1.83	2.10	2.37	2.90
.82	.559	.753	.945	1.13	1.30	1.47	1.63	1.78	1.93	2.22	2.51	3.07
.84	.576	.782	.985	1.18	1.36	1.54	1.71	1.87	2.03	2.34	2.65	3.25
.86	.593	.810	1.03	1.23	1.43	1.61	1.79	1.97	2.14	2.47	2.80	3.44
.88	.610	.839	1.07	1.29	1.49	1.69	1.88	2.07	2.25	2.60	2.95	3.63
.90	.627	.871	1.11	1.34	1.56	1.77	1.98	2.17	2.36	2.74	3.11	3.83
.92	.645	.898	1.15	1.40	1.63	1.86	2.07	2.28	2.48	2.88	3.27	4.04
.94	.662	.928	1.20	1.46	1.70	1.94	2.16	2.38	2.60	3.03	3.43	4.25
.96	.680	.960	1.25	1.52	1.78	2.03	2.27	2.50	2.73	3.17	3.61	4.48
.98	.697	.991	1.29	1.58	1.85	2.11	2.37	2.61	2.85	3.33	3.79	4.70

Values of $\frac{Qn}{b^{8/3}S^{1/2}}$



D/b[1]	z=0	z=¼	z=½	z=¾	z=1	z=1¼	z=1½	z=1¾	z=2	z=2½	z=3	z=4
1.00	.714	1.02	1.33	1.64	1.93	2.21	2.47	2.73	2.99	3.48	3.97	4.93
1.05	.759	1.10	1.46	1.80	2.13	2.44	2.75	3.04	3.33	3.90	4.45	5.55
1.10	.802	1.19	1.58	1.97	2.34	2.69	3.04	3.37	3.70	4.34	4.96	6.21
1.15	.846	1.27	1.71	2.14	2.56	2.96	3.34	3.72	4.09	4.82	5.52	6.91
1.20	.891	1.36	1.85	2.33	2.79	3.24	3.68	4.09	4.50	5.32	6.11	7.68
1.25	.936	1.45	1.99	2.52	3.04	3.54	4.03	4.49	4.95	5.86	6.73	8.48
1.30	.980	1.54	2.14	2.73	3.30	3.85	4.39	4.90	5.42	6.42	7.39	9.34
1.35	1.02	1.64	2.29	2.94	3.57	4.18	4.76	5.34	5.90	7.01	8.10	10.2
1.40	1.07	1.74	2.45	3.16	3.85	4.52	5.18	5.80	6.43	7.65	8.83	11.2
1.45	1.11	1.84	2.61	3.39	4.15	4.88	5.60	6.29	6.98	8.30	9.62	12.2
1.50	1.16	1.94	2.78	3.63	4.46	5.26	6.04	6.81	7.55	9.02	10.4	13.3
1.55	1.20	2.05	2.96	3.88	4.78	5.65	6.50	7.33	8.14	9.74	11.3	14.4
1.60	1.25	2.15	3.14	4.14	5.12	6.06	6.99	7.89	8.79	10.5	12.2	15.6
1.65	1.30	2.27	3.33	4.41	5.47	6.49	7.50	8.47	9.42	11.3	13.2	16.8
1.70	1.34	2.38	3.52	4.69	5.83	6.94	8.02	9.08	10.1	12.2	14.2	18.1
1.75	1.39	2.50	3.73	4.98	6.21	7.41	8.57	9.72	10.9	13.0	15.2	19.5
1.80	1.43	2.62	3.93	5.28	6.60	7.89	9.13	10.4	11.6	14.0	16.3	20.9
1.85	1.48	2.74	4.15	5.59	7.01	8.40	9.75	11.1	12.4	15.0	17.4	22.4
1.90	1.52	2.86	4.36	5.91	7.43	8.91	10.4	11.8	13.2	15.9	18.7	24.0
1.95	1.57	2.99	4.59	6.24	7.87	9.46	11.0	12.5	14.0	17.0	19.9	25.6
2.00	1.61	3.12	4.83	6.58	8.32	10.0	11.7	13.3	14.9	18.0	21.1	27.2
2.10	1.71	3.39	5.31	7.30	9.27	11.2	13.1	15.0	16.8	20.3	23.9	30.8
2.20	1.79	3.67	5.82	8.06	10.3	12.5	14.6	16.7	18.7	22.8	26.8	34.7
2.30	1.89	3.96	6.36	8.86	11.3	13.8	16.2	18.6	20.9	25.4	30.0	38.8
2.40	1.98	4.26	6.93	9.72	12.5	15.3	17.9	20.6	23.1	28.3	33.4	43.3
2.50	2.07	4.58	7.52	10.6	13.7	16.8	19.8	22.7	25.6	31.3	37.0	48.0
2.60	2.16	4.90	8.14	11.6	15.0	18.4	21.7	25.0	28.2	34.5	40.8	53.0
2.70	2.26	5.24	8.80	12.6	16.3	20.1	23.8	27.4	31.0	37.9	44.8	58.4
2.80	2.35	5.59	9.49	13.6	17.8	21.9	25.9	29.9	33.8	41.6	49.1	64.0
2.90	2.44	5.95	10.2	14.7	19.3	23.8	28.2	32.6	36.9	45.3	53.7	70.1
3.00	2.53	6.33	11.0	15.9	20.9	25.8	30.6	35.4	40.1	49.4	58.4	76.4
3.20	2.72	7.12	12.5	18.3	24.2	30.1	35.8	41.5	47.1	58.0	68.9	90.3
3.40	2.90	7.97	14.2	21.0	27.9	34.8	41.5	48.2	54.6	67.7	80.2	105
3.60	3.09	8.86	16.1	24.0	32.0	39.9	47.8	55.5	63.0	78.2	92.8	122
3.80	3.28	9.81	18.1	27.1	36.3	45.5	54.6	63.5	72.4	89.6	107	141
4.00	3.46	10.8	20.2	30.5	41.1	51.6	61.9	72.1	82.2	102	122	160
4.50	3.92	13.5	26.2	40.1	54.5	68.8	82.9	96.9	111	136	164	217
5.00	4.30	16.7	33.1	51.5	70.3	89.2	108	126	145	181	216	287

[1] For D/b less than 0.04, use of the assumption $R = D$ is more convenient and more accurate than interpolation in the table.

WRC ENG.

REFERENCE: Hydraulic and Excavation Tables
Bureau of Reclamation 1957

UNIFORM FLOW FOR CIRCULAR SECTIONS

d = Depth of flow
D = Diameter of pipe
A = Area of flow
R = Hydraulic radius

Q = Discharge in second-feet by Manning's formula
n = Manning's coefficient
S = Slope of the channel bottom and of the water surface

$\frac{d}{D}$	$\frac{A}{D^2}$	$\frac{R}{D}$	$\frac{Qn}{D^{8/3}S^{1/2}}$	$\frac{Qn}{d^{8/3}S^{1/2}}$	$\frac{d}{D}$	$\frac{A}{D^2}$	$\frac{R}{D}$	$\frac{Qn}{D^{8/3}S^{1/2}}$	$\frac{Qn}{d^{8/3}S^{1/2}}$
0.01	0.0013	0.0066	0.00007	15.04	0.51	0.4027	0.2531	0.239	1.442
0.02	0.0037	0.0132	0.00031	10.57	0.52	0.4127	0.2562	0.247	1.415
0.03	0.0069	0.0197	0.00074	8.56	0.53	0.4227	0.2592	0.255	1.388
0.04	0.0105	0.0262	0.00138	7.38	0.54	0.4327	0.2621	0.263	1.362
0.05	0.0147	0.0325	0.00222	6.55	0.55	0.4426	0.2649	0.271	1.336
0.06	0.0192	0.0389	0.00328	5.95	0.56	0.4526	0.2676	0.279	1.311
0.07	0.0242	0.0451	0.00455	5.47	0.57	0.4625	0.2703	0.287	1.286
0.08	0.0294	0.0513	0.00604	5.09	0.58	0.4724	0.2728	0.295	1.262
0.09	0.0350	0.0575	0.00775	4.76	0.59	0.4822	0.2753	0.303	1.238
0.10	0.0409	0.0635	0.00967	4.49	0.60	0.4920	0.2776	0.311	1.215
0.11	0.0470	0.0695	0.01181	4.25	0.61	0.5018	0.2799	0.319	1.192
0.12	0.0534	0.0755	0.01417	4.04	0.62	0.5115	0.2821	0.327	1.170
0.13	0.0600	0.0813	0.01674	3.86	0.63	0.5212	0.2842	0.335	1.148
0.14	0.0668	0.0871	0.01952	3.69	0.64	0.5308	0.2862	0.343	1.126
0.15	0.0739	0.0929	0.0225	3.54	0.65	0.5404	0.2882	0.350	1.105
0.16	0.0811	0.0985	0.0257	3.41	0.66	0.5499	0.2900	0.358	1.084
0.17	0.0885	0.1042	0.0291	3.28	0.67	0.5594	0.2917	0.366	1.064
0.18	0.0961	0.1097	0.0327	3.17	0.68	0.5687	0.2933	0.373	1.044
0.19	0.1039	0.1152	0.0365	3.06	0.69	0.5780	0.2948	0.380	1.024
0.20	0.1118	0.1206	0.0406	2.96	0.70	0.5872	0.2962	0.388	1.004
0.21	0.1199	0.1259	0.0448	2.87	0.71	0.5964	0.2975	0.395	0.985
0.22	0.1281	0.1312	0.0492	2.79	0.72	0.6054	0.2987	0.402	0.965
0.23	0.1365	0.1364	0.0537	2.71	0.73	0.6143	0.2998	0.409	0.947
0.24	0.1449	0.1416	0.0585	2.63	0.74	0.6231	0.3008	0.416	0.928
0.25	0.1535	0.1466	0.0634	2.56	0.75	0.6319	0.3017	0.422	0.910
0.26	0.1623	0.1516	0.0686	2.49	0.76	0.6405	0.3024	0.429	0.891
0.27	0.1711	0.1566	0.0739	2.42	0.77	0.6489	0.3031	0.435	0.873
0.28	0.1800	0.1614	0.0793	2.36	0.78	0.6573	0.3036	0.441	0.856
0.29	0.1890	0.1662	0.0849	2.30	0.79	0.6655	0.3039	0.447	0.838
0.30	0.1982	0.1709	0.0907	2.25	0.80	0.6736	0.3042	0.453	0.821
0.31	0.2074	0.1756	0.0966	2.20	0.81	0.6815	0.3043	0.458	0.804
0.32	0.2167	0.1802	0.1027	2.14	0.82	0.6893	0.3043	0.463	0.787
0.33	0.2260	0.1847	0.1089	2.09	0.83	0.6969	0.3041	0.468	0.770
0.34	0.2355	0.1891	0.1153	2.05	0.84	0.7043	0.3038	0.473	0.753
0.35	0.2450	0.1935	0.1218	2.00	0.85	0.7115	0.3033	0.477	0.736
0.36	0.2546	0.1978	0.1284	1.958	0.86	0.7186	0.3026	0.481	0.720
0.37	0.2642	0.2020	0.1351	1.915	0.87	0.7254	0.3018	0.485	0.703
0.38	0.2739	0.2062	0.1420	1.875	0.88	0.7320	0.3007	0.488	0.687
0.39	0.2836	0.2102	0.1490	1.835	0.89	0.7384	0.2995	0.491	0.670
0.40	0.2934	0.2142	0.1561	1.797	0.90	0.7445	0.2980	0.494	0.654
0.41	0.3032	0.2182	0.1633	1.760	0.91	0.7504	0.2963	0.496	0.637
0.42	0.3130	0.2220	0.1705	1.724	0.92	0.7560	0.2944	0.497	0.621
0.43	0.3229	0.2258	0.1779	1.689	0.93	0.7612	0.2921	0.498	0.604
0.44	0.3328	0.2295	0.1854	1.655	0.94	0.7662	0.2895	0.498	0.588
0.45	0.3428	0.2331	0.1929	1.622	0.95	0.7707	0.2865	0.498	0.571
0.46	0.3527	0.2366	0.201	1.590	0.96	0.7749	0.2829	0.496	0.553
0.47	0.3627	0.2401	0.208	1.559	0.97	0.7785	0.2787	0.494	0.535
0.48	0.3727	0.2435	0.216	1.530	0.98	0.7817	0.2735	0.489	0.517
0.49	0.3827	0.2468	0.224	1.500	0.99	0.7841	0.2666	0.483	0.496
0.50	0.3927	0.2500	0.232	1.471	1.00	0.7854	0.2500	0.463	0.463

WRC ENG.

REFERENCE: **Hydraulic and Excavation Tables**
Bureau of Reclamation 1957

STANDARD FORM SF-7

FLOW PROFILE COMPUTATION

(Direct step method)

DIRECT STEP BACKWATER CALCULATION EXAMPLE 10

Q= 400 n= .032 S_0 = 0.005 α = 1.0 y_c = 2.60 y_n = 3.28

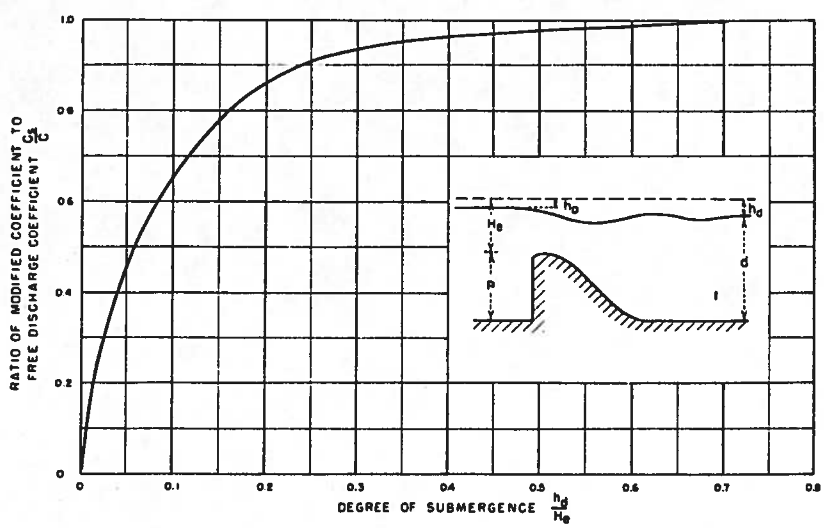
y (1)	A (2)	R (3)	V (4)	$\alpha V^2/2g$ (5)	E (6)	ΔE (7)	S_f (8)	$\overline{S}_f$ (9)	$S_0-\overline{S}_f$ (10)	ΔX (11)	X (12)
5.00	150.0	2.93	2.67	0.111	5.111	—	0.0007871	—	—	—	—
4.80	140.2	2.83	2.85	0.126	4.926	0.185	0.0009392	0.0008632	0.0041368	45	45
4.60	130.6	2.73	3.06	0.146	4.746	0.180	0.0011358	0.0010375	0.0039625	45	90
4.40	121.4	2.62	3.29	0.168	4.568	0.178	0.0013867	0.0012613	0.0037388	48	138
4.20	112.6	2.52	3.55	0.196	4.396	0.172	0.0017004	0.0015436	0.0034565	50	188
4.00	104.0	2.42	3.85	0.230	4.230	0.166	0.0021105	0.0019055	0.0030946	54	242
3.80	95.8	2.32	4.18	0.271	4.071	0.159	0.0026315	0.0023710	0.0026290	60	302
3.60	87.8	2.21	4.56	0.323	3.923	0.148	0.0033407	0.0029861	0.0020139	73	375
3.40	80.2	2.11	4.99	0.387	3.787	0.136	0.0042545	0.0037976	0.0012024	113	488
3.30	76.6	2.06	5.22	0.423	3.723	0.064	0.0048067	0.0045306	0.0004694	136	624

$$S_f = \frac{n^2 V^2}{2.22 R^{4/3}} \qquad \Delta X = \frac{\Delta E}{S_0 - \overline{S}_f}$$

TABLE 703

WEIR FLOW COEFFICIENTS

SHAPE	COEFFICIENT	COMMENTS
Sharp Crested	-	
Projection Ratio (H/P = 0.4)	3.4	H ≥1.0
Projection Ratio (H/P = 2.0)	4.0	H ≥1.0
Broad Crested	-	
w/Sharp U/S Corner	2.6	Minimum Value
w/Rounded U/S Corner	3.1	Critical Depth
Triangular Section	-	
A) Vertical U/S Slope	-	
1:1 D/S Slope	3.8	H ≥0.7
4:1 D/S Slope	3.2	H ≥0.7
10:1 D/S Slope	2.9	H ≥0.7
B) 1:1 U/S Slope	-	
1:1 D/S Slope	3.8	H ≥1.0
3:1 D/S Slope	3.5	
Trapezoidal Section		
1:1 U/S Slope, 2:1 D/S Slope	3.4	H ≥1.0
2:1 U/S Slope, 2:1 D/S Slope	3.4	H ≥1.0
Road Crossings		
Gravel	3.0	H ≥1.0
Paved	3.1	H ≥1.0



ADJUSTMENT FOR TAILWATER

WRC ENG.	REFERENCE: King & Brater, Handbook of Hydraulics, McGraw Hill Book Company, 1963

ROADSIDE DITCH CAPACITIES

SLOPE (%)	DITCH TYPE I		DITCH TYPE II		DITCH TYPE III	
	VEL. (fps)	Q (cfs)	VEL. (fps)	Q (cfs)	VEL. (fps)	Q (cfs)
0.5	0.7	6	0.7	6	2.5	22
1.0	1.6	14	1.6	14	3.5	31
1.5	2.4	22	2.4	22	4.4	39
2.0	3.2	29	3.2	29	Not Permitted	
2.5 (3)	4.0	36	4.0	36	Not Permitted	

NOTES:

1. See Figure-708 for geometry of roadside ditch.
2. Velocity and capacity are based upon the SCS Retardance Curve "C".
3. Maximum permissible slope for roadside ditch is 2.5%. Slope limitation is based on a maximum Froude number of 0.8 for Type I & II and 0.9 for Type III ditch.
4. Linearly interpolate for intermediate slopes.

REFERENCE: Caculations by WRC Engineering, Inc.

MANNING'S n-VALUES FOR OPEN CHANNELS

CHANNEL TYPE	N-VALUE RANGE	RECOMMENDED VALUE
A. Earth Lined (ditches/canals)		
1. Clean, Weathered	.018 to .025	.022
2. Clean, Gravel	.022 to .030	.025
3. Some Weeds	.022 to .033	.027
4. Non-Maintained	.030 to .040	.035
B. Grass Lined (man-made)		
1. RV >10 (see Fig.-705)	.029 to .034	.032 (1)
2. RV < 10	.032 to .100	See Fig.-705
C. Natural Streams	.025 to 0.100	Note (2)
D. Riprap Lined		
1. Ordinary Riprap	$n = .0395\ d_{50}^{0.17}$	(Sect. 705.4)
2. Gabions		0.035
3. Grouted Riprap	.023 to .030	0.027
4. Slope Mattress	.025 to .033	.028
E. Concrete Lined		
1. Float Finished/Wood Forms	.013 to .016	Note (3)
2. Slip Formed	.013 to .016	Note (3)
3. Gunite	.016 to .023	Note (3)

NOTES:

1. Use as starting value to estimate channel capacity (see Section 703.1).
2. Refer to Chow, V.T., Open Channel Hydraulics, McGraw-Hill Book Co., 1959, Table-5-6.
3. High value used for capacity determination and low value used for velocity consideration (refer to Section 704.3.1d.)

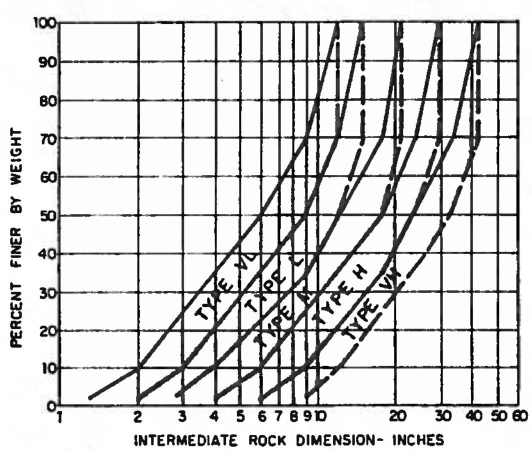
REFERENCE: Chow, V.T., Open Channel Hydraulics, McGraw Hill Book Company, 1959

CLASSIFICATION AND GRADATION OF ORDINARY RIPRAP

RIPRAP DESIGNATION	% SMALLER THAN GIVEN SIZE BY WEIGHT	INTERMEDIATE ROCK DIMENSION (INCHES)	d_{50}* (INCHES)
Type VL	70-100	12	
	50-70	9	
	35-50	6	6**
	2-10	2	
Type L	70-100	15	
	50-70	12	
	35-50	9	9**
	2-10	3	
Type M	70-100	21	
	50-70	18	
	35-50	12	12
	2-10	4	
Type H	100	30	
	50-70	24	
	35-50	18	18
	2-10	6	
Type VH	100	42	
	50-70	33	
	35-50	24	24
	2-10	9	

*d_{50} = Mean particle size

**Bury types VL and L with native top soil and revegetate to protect from vandalism.



WRC ENG.

REFERENCE: USDCM, DRCOG, March 1969 (Rev 11-15-82)

STANDARD GABION BASKETS (ENGLISH SIZES)

DRAINAGE MANUAL DESIGNATION	LETTER CODE OF SIZE	LENGTH	WIDTH	DEPTH	NUMBER OF DIAPHRAGMS	CAPACITY CUBIC YARDS	MINIMUM ROCK DIMENSION
	A	6'	x 3'	x 3'	1	2	4"
G36	B	9'	x 3'	x 3'	2	3	4"
	C	12'	x 3'	x 3'	3	4	4"
	D	6'	x 3'	x 1'-6"	1	1	4"
G18	E	9'	x 3'	x 1'-6"	2	1.5	4"
	F	12'	x 3'	x 1'-6"	3	2	4"
	G	6'	x 3'	x 1'	1	0.66	4"
G12	H	9'	x 3'	x 1'	2	1	4"
	I	12'	x 3'	x 1'	3	1.33	4"
			SLOPE MATTRESS				
SM9	T	10'	x 6'-6"	x 0'-9"	5	1.80	3"
	U	12'	x 6'-6"	x 0'-9"	6	2.16	3"

WRC ENG.

REFERENCE: "Maccaferri Gabion", Maccaferri Gabions, Inc. New York

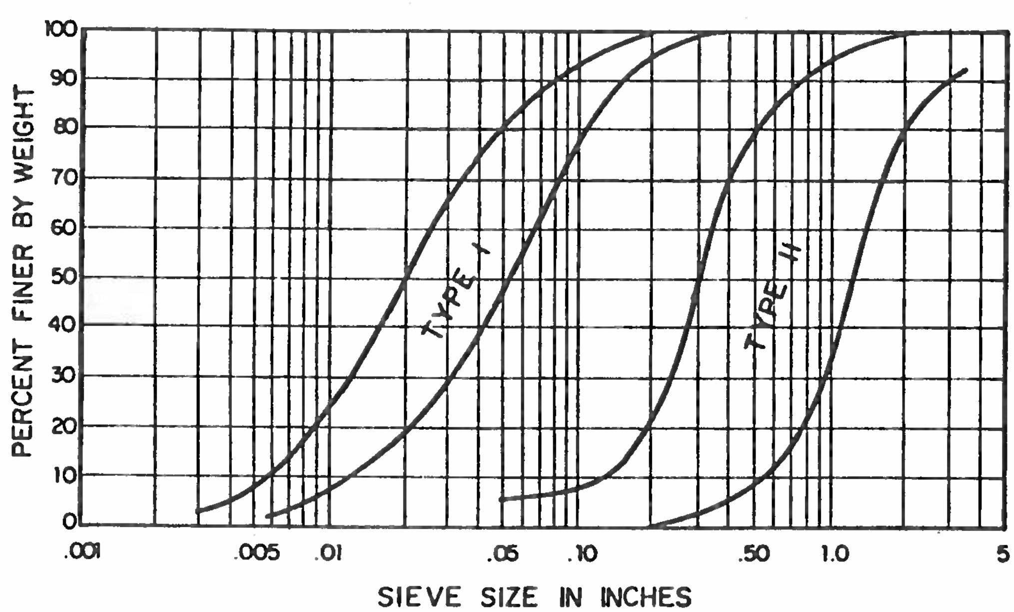
GRADATION FOR GRANULAR BEDDING

U. S. STANDARD SIEVE SIZE	PERCENT WEIGHT BY PASSING TYPE I	SQUARE MESH SIEVES TYPE II
3"	-	90 - 100
1-1/2"	-	-
3/4"	-	20 - 90
3/8"	100	-
#4	95 - 100	0 - 20
#16	45 - 80	-
#50	10 - 30	-
#100	2 - 10	-
#200	0 - 2	0 - 3

NOTES: 1. For earth with less than 50% passing #40 sieve both Type I and Type II are required.

2. For earth with more than 50% passing #40 sieve, only Type II is required.

FILTER GRADATION LIMITS



THICKNESS REQUIREMENTS FOR GRANULAR BEDDING

RIPRAP DESIGNATION	MINIMUM BEDDING THICKNESS (INCHES) FINE GRAINED SOILS TYPE I	FINE GRAINED SOILS TYPE II	COURSE GRAINED SOILS TYPE II
VL, L	4	4	6
M	4	4	6
H	4	6	8
VH	4	6	8

1. Fine grained soils require a two layer filter as noted. A single layer of 12" Type II bedding may be substituted except at check drops.

2. For fine or coarse grained soils the filter requirements may be substituted with a single 4" or 6" layer of Type II bedding and a filter fabric (see fig. 709).

3. Fabric shall not be placed on slopes greater than 2.5:1 where riprap is to be constructed.

4. A course grained soil is defined as having 50% or more by weight retained on the #40 sieve.

RIPRAP REQUIREMENTS FOR CHANNEL LININGS **

REQUIREMENTS FOR CHANNEL LININGS **

$VS^{0.17}/(S_s-1)^{0.66}$* (FEET 1/2 PER SECOND)	ROCK TYPE ***
1.4 to 3.2	VL
3.3 to 3.9	L
4.0 to 4.5	M
4.6 to 5.5	H
5.6 to 6.4	VH

* Use S sub-s = 2.5 unless the source of rock and the density are known at the time of design. V-in fps and S in ft/ft.

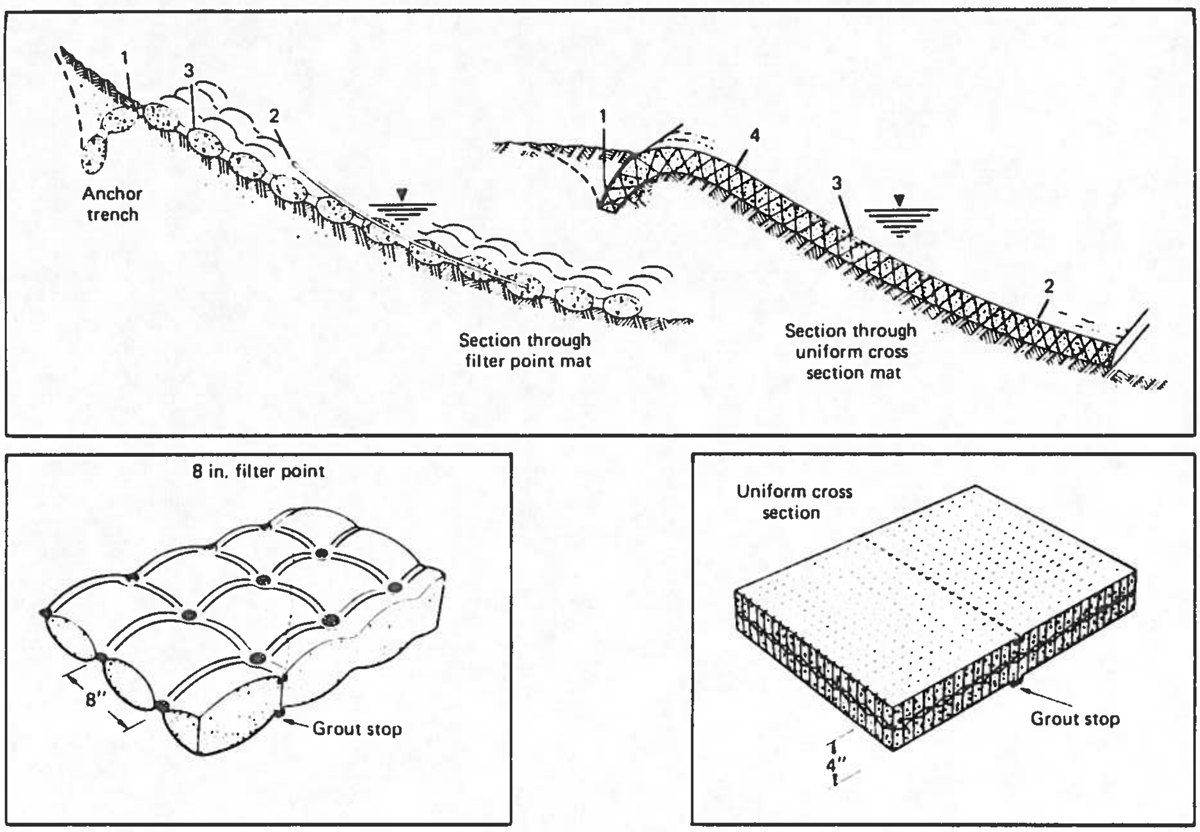
** Table valid only for Froude number of 0.8 or less and side slopes no steeper than 2h:1v.

*** Type VL and L riprap shall be buried after placement to reduce vandalism.

SM9 slope mattress with toe protection may be substituted for Type VL or L riprap.

G12 gabion with toe protection may be substituted for Type M and Type H riprap.

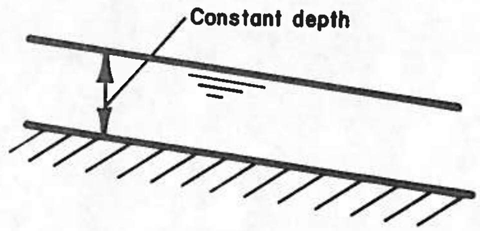
TYPICAL EROSION CONTROL MATTRESSES



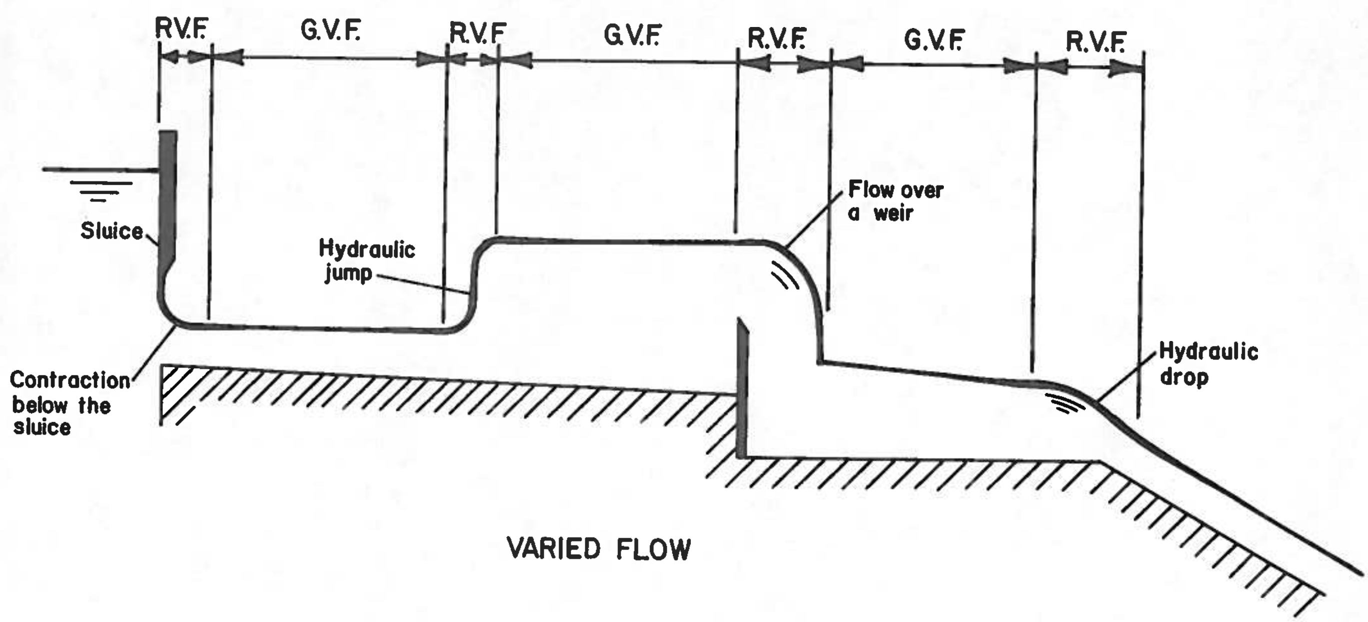
NOTE: Numbers refer to sequence of mortar injection.

WRC ENG. | REFERENCE: Koerner & Welsh, Construction and Geotechnical Engineering Using Synthetic Fabrics, John Wiley & Sons, Inc. 1980

FLOW CONDITIONS



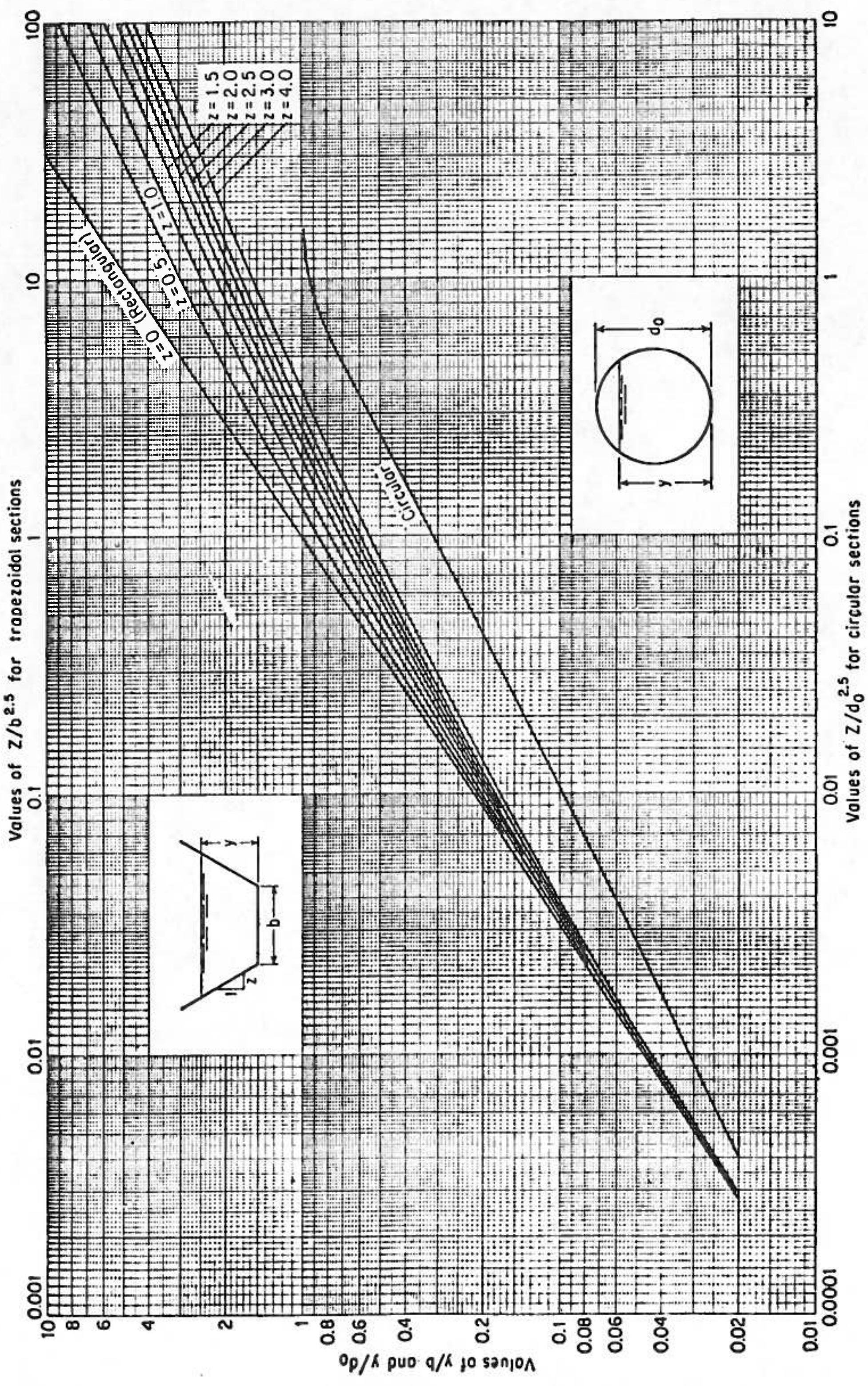
UNIFORM FLOW
Flow in a laboratory channel



VARIED FLOW

REFERENCE: Chow, V. T., Open-Channel Hydraulics
McGraw Hill Book Company 1959

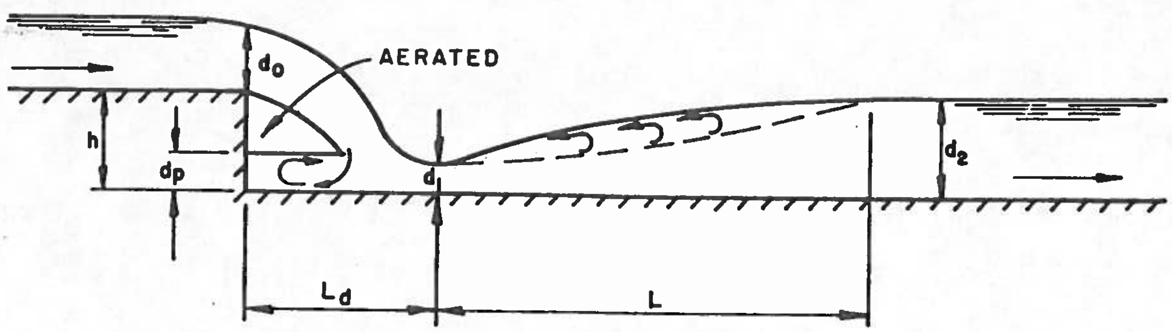
CRITICAL DEPTH FOR TRAPEZOIDAL AND CIRCULAR SECTIONS



NOTE: $Z = Q/\sqrt{g}$

WRC ENG.	REFERENCE: Chow, V. T., Open Channel Hydraulics McGraw Hill Book Company 1959

FLOW GEOMETRY OF A STRAIGHT DROP SPILLWAY

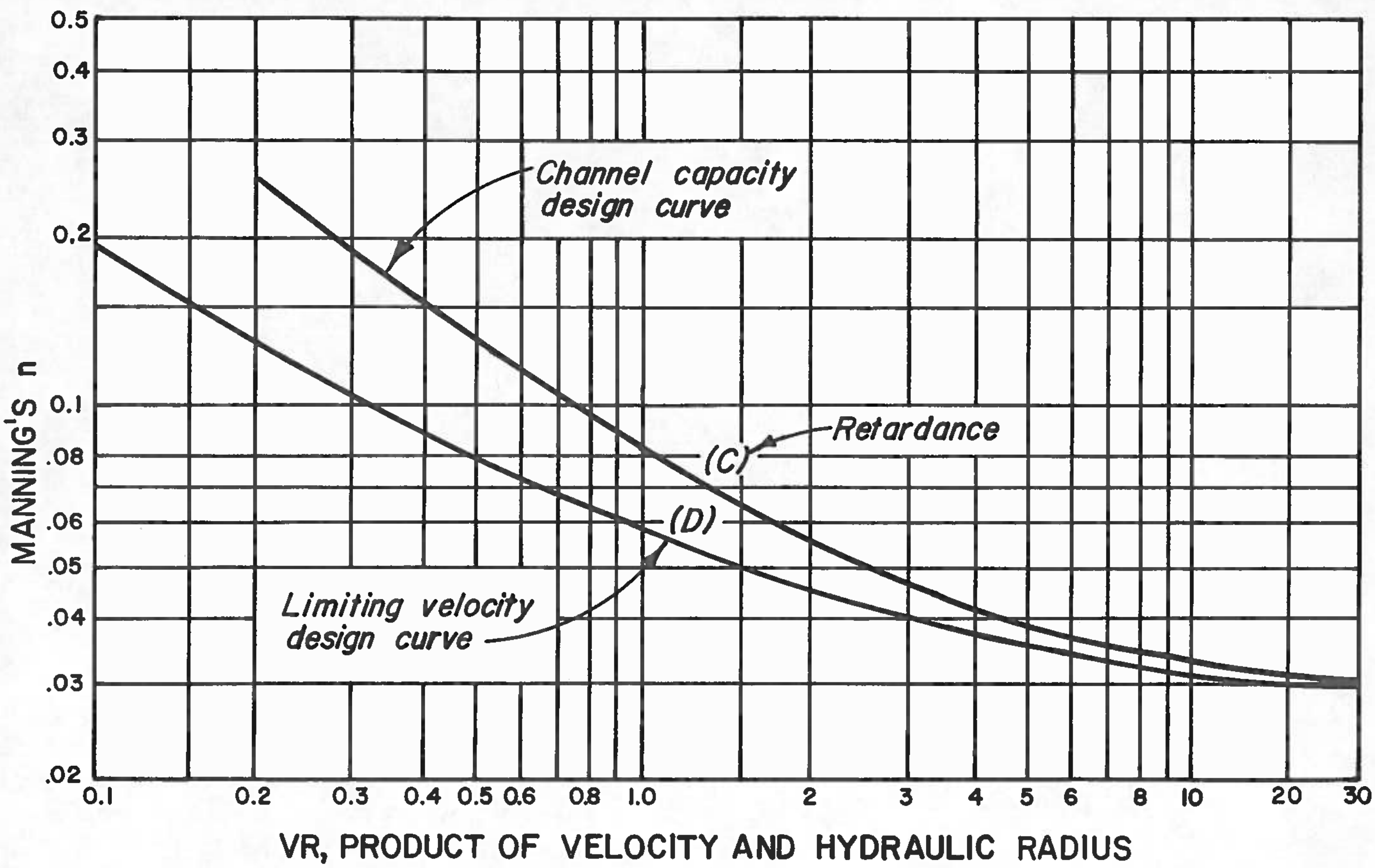


WRC ENG.

REFERENCE:

Chow, V.T., Open-Channel Hydraulics
McGraw Hill Book Company, 1959

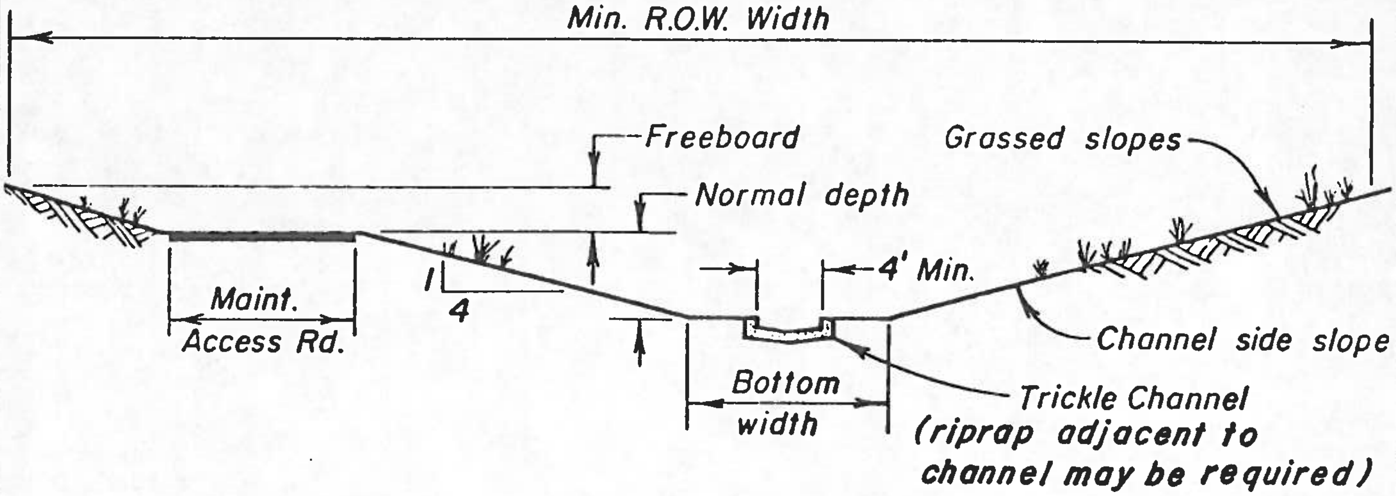
ROUGHNESS COEFFICIENT FOR GRASSED CHANNELS



From "Handbook of Channel Design For Soil and Water Conservation," U.S. Department of Agriculture, Soils Conservation Service, No. SCS-TP-61 March, 1947, Rev. June, 1954

WRC ENG.	REFERENCE: See figure for credit

TYPICAL GRASSED LINED CHANNEL SECTION TYPE A



NOTES:

1. Bottom Width: Consistent with maximum allowable depth and velocity requirements, shall not be less trickle channel width.

2. Trickle Channel: Minimum capacity to be 1% to 3% of 100-year flow but not less than 1 cfs. Channel to be constructed of concrete or other approved materials.

3. Normal Depth: Normal depth at 100-year flow shall be such that the product of hydraulic depth (A/T) and the 100-year flow velocity (V_{max} = 7 fps) be less than 35 cfs/ft.

4. Freeboard: Freeboard to be a minimum of 1-foot

5. Maintenance/Access Road: Minimum width to be 12-feet.

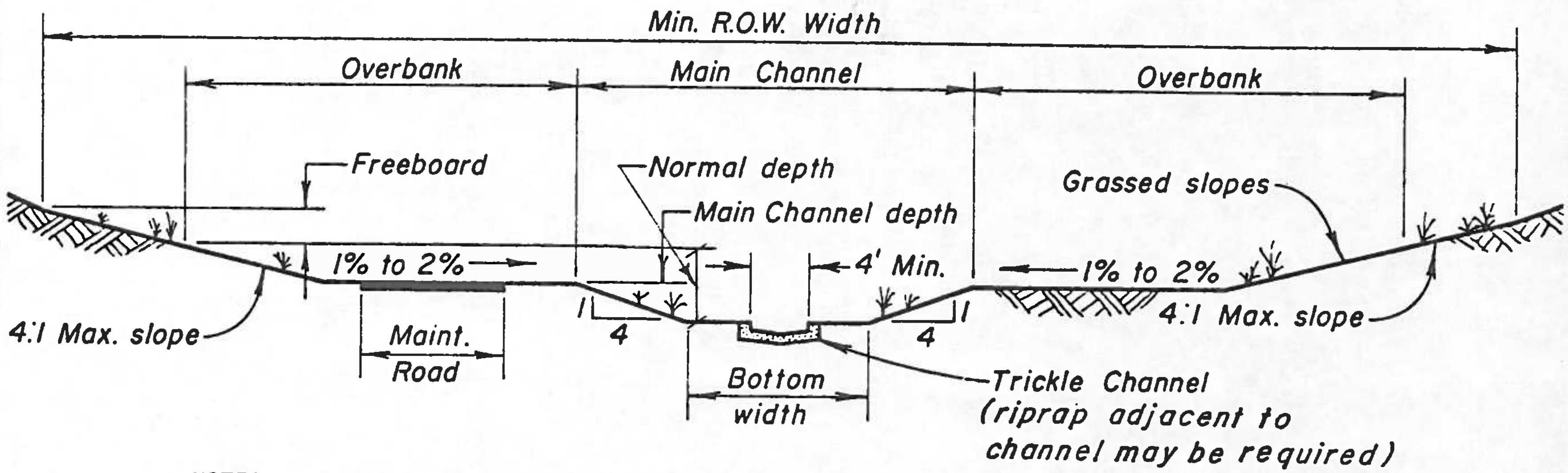
6. ROW Width: Minimum width to include freeboard and maintenance access road.

7. Channel Side Slope: Maximum side slope for grassed channels to be 4:1.

8. Froude Number: Maximum value shall not exceed 0.8 for initial and major floods.

9. The maximum flow velocity to be 7 fps for erosion resistant soils or 5 fps for sandy soils.

TYPICAL GRASSED LINED CHANNEL SECTION TYPE B



NOTES:

1. Main Channel: Capacity to be less than 20% of 100-year at Main Channel depth. Maximum 100-year flow velocity is 7 fps.

2. Trickle Channel: Minimum capacity to be 1% to 3% of 100-year flow but not less than 1 cfs. Channel to be constructed of concrete or other approved materials.

3. Normal Depth: Flow depth for 100-year flow shall be such that the product of hydraulic depth (A/T) and the 100-year flow velocity (V_{max} = 7 fps) be less than 35 cfs/ft.

4. Freeboard: Freeboard to be a minimum of 1-foot.

5. Maintenance/Access Road: Minimum width to be 12-feet.

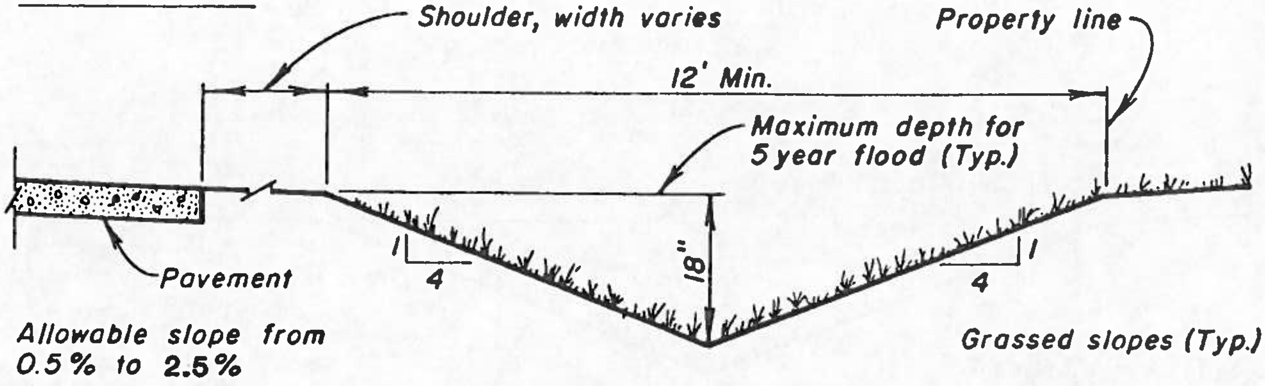
6. ROW Width: Minimum width to include freeboard and maintenance access road.

7. Overbank: Flow in excess of main channel to be carried in this area. Area may be used for recreation purposes.

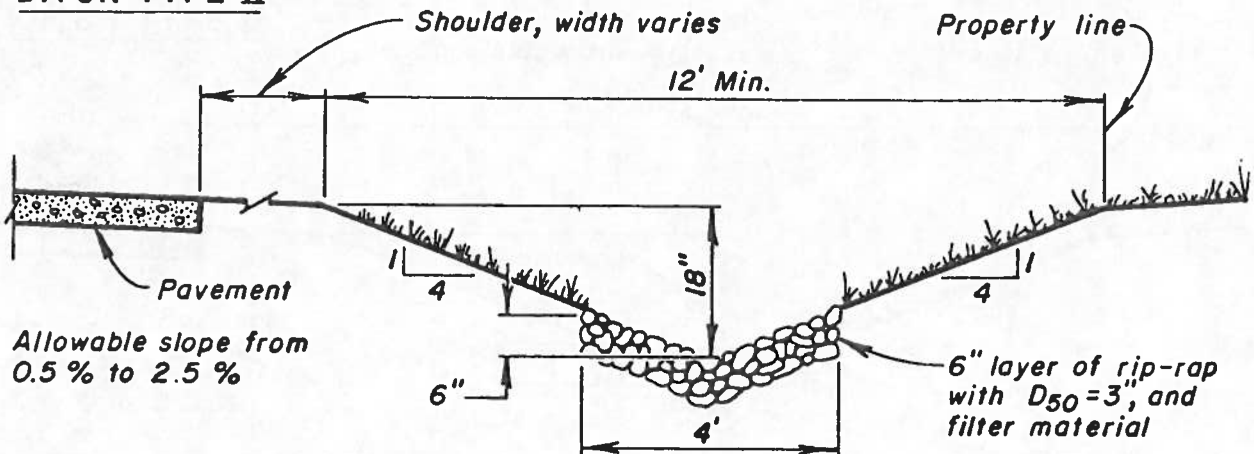
8. Froude Number: Maximum value shall not exceed 0.8 for initial and major floods.

ROADSIDE DITCH SECTIONS

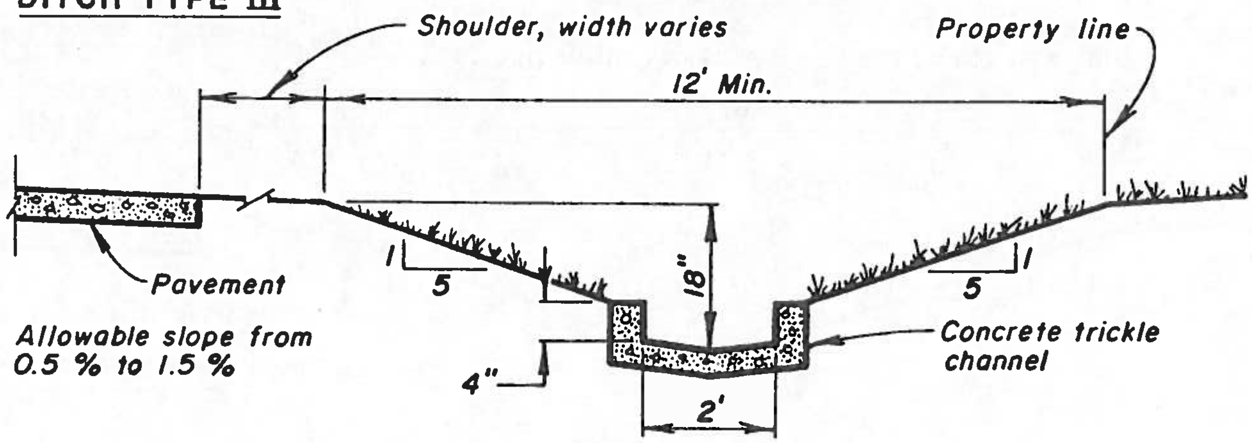
DITCH TYPE I



DITCH TYPE II



DITCH TYPE III

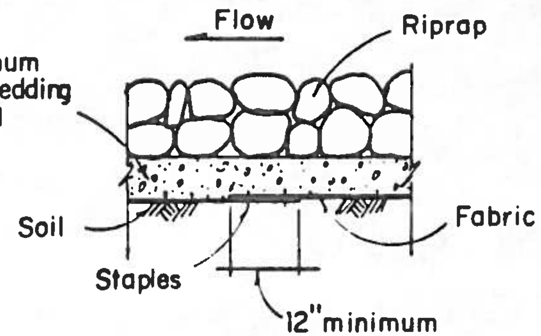


NOTE:
1. See Table-705 for capacity of roadside ditch.
2. For street slopes greater than maximum allowable, check drops (2' maximum height) will be required.

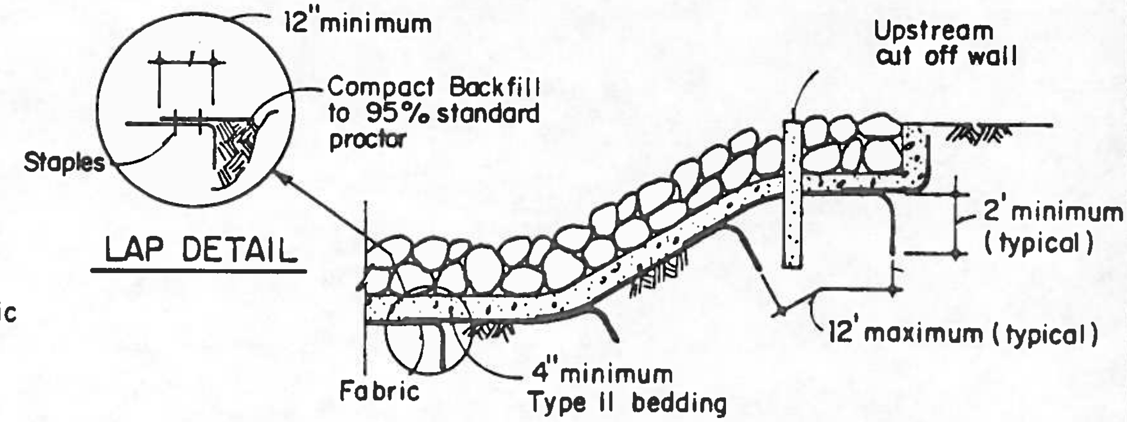
WRC ENG.	REFERENCE: Prepared by WRC Engineering, Inc.

FILTER FABRIC PLACEMENT DETAILS

NOTE: Always place fabric starting downstream and work upstream

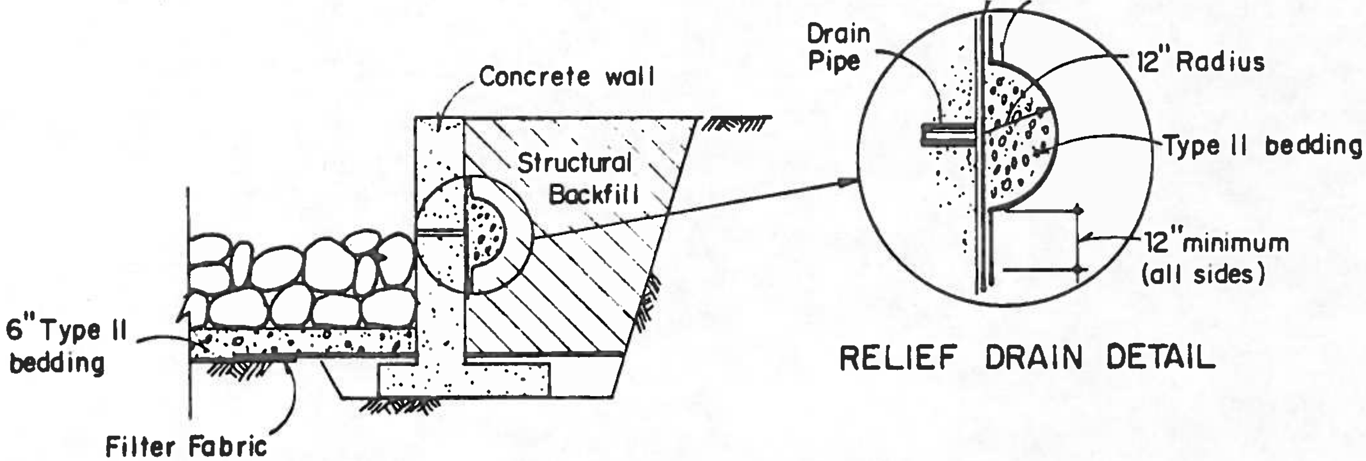


(A) TYPICAL LAP DETAIL AND FILTER FABRIC PLACEMENT



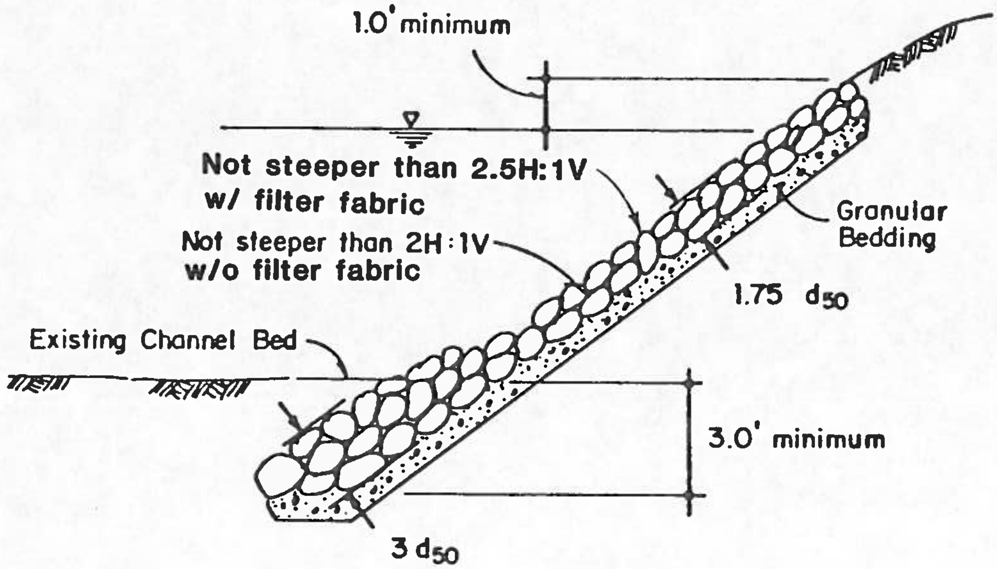
(B) RIPRAP CHUTE DROP

NOTE: Some soils may require a hydraulic cut off to prevent piping failure of drops

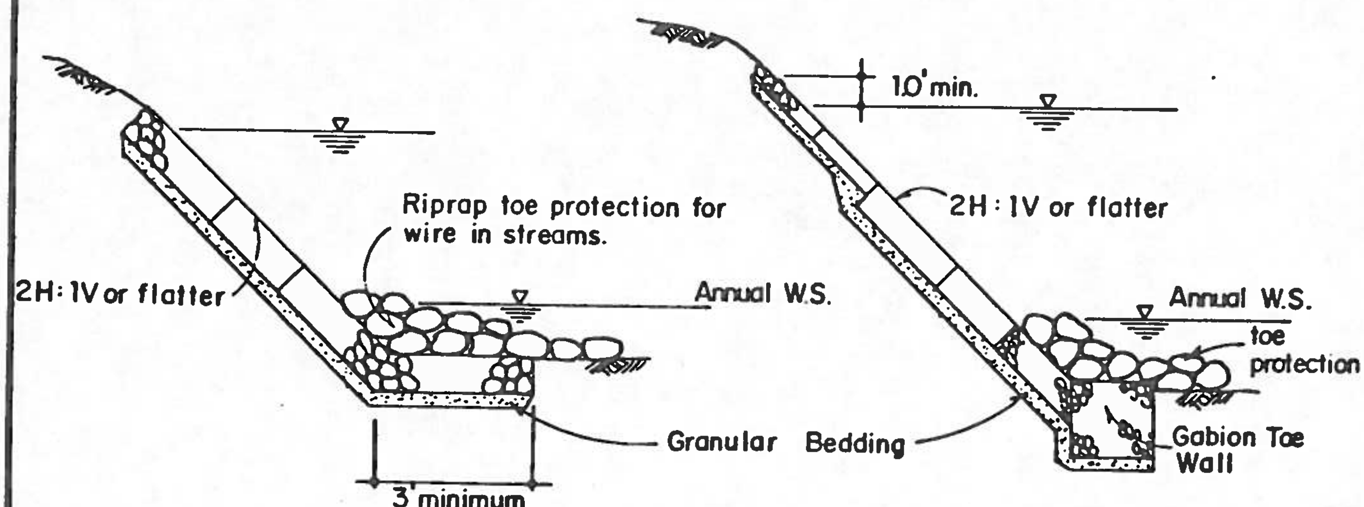


(C) VERTICAL DROP

TOE PROTECTION FOR ROCK LINED CHANNELS

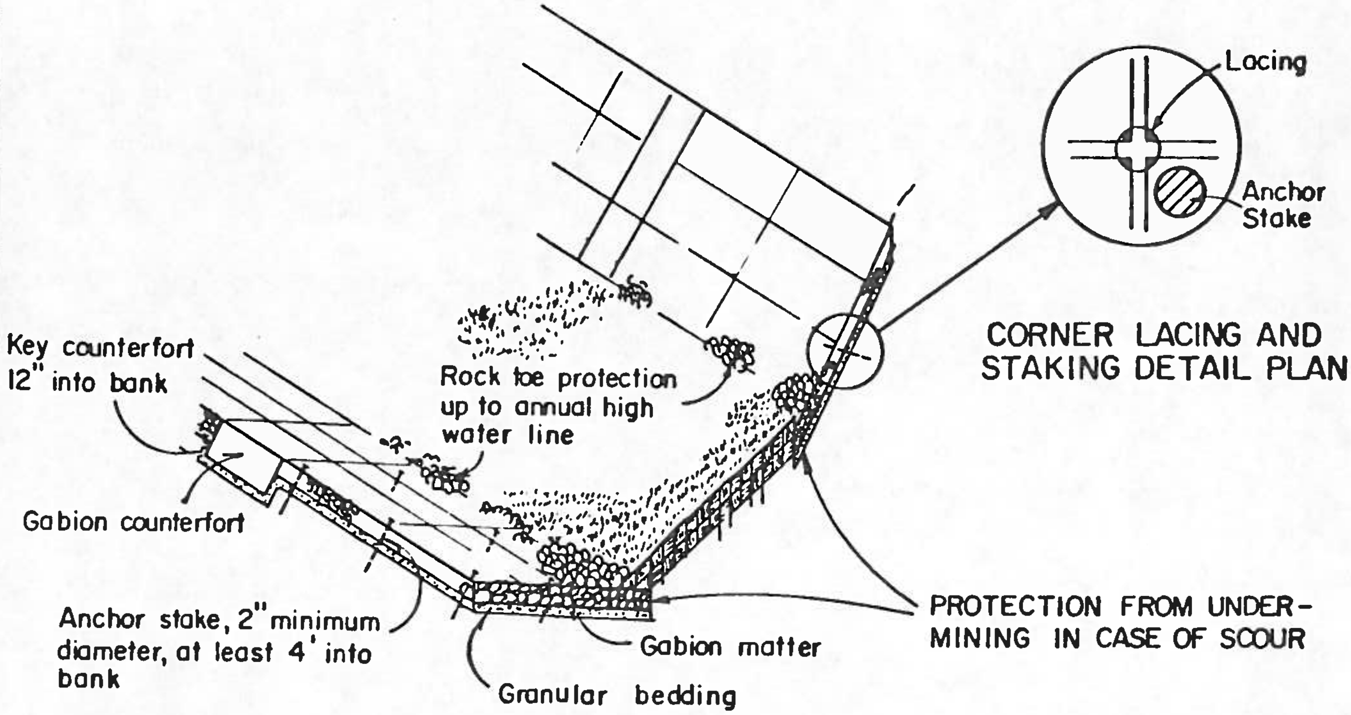


(A) RIPRAP CHANNEL LINING

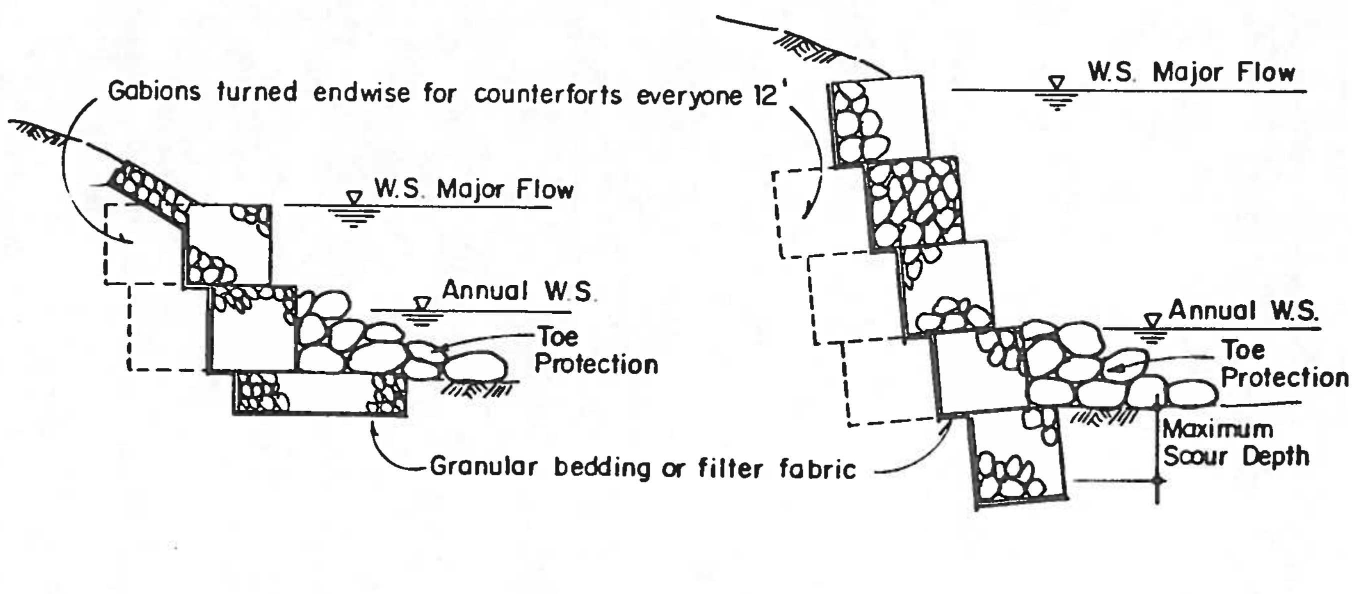


(B) WIRE ENCLOSED ROCK LINING

GABION AND SLOPE MATTRESS LINING CONFIGURATIONS



SLOPE MATTRESS LINING



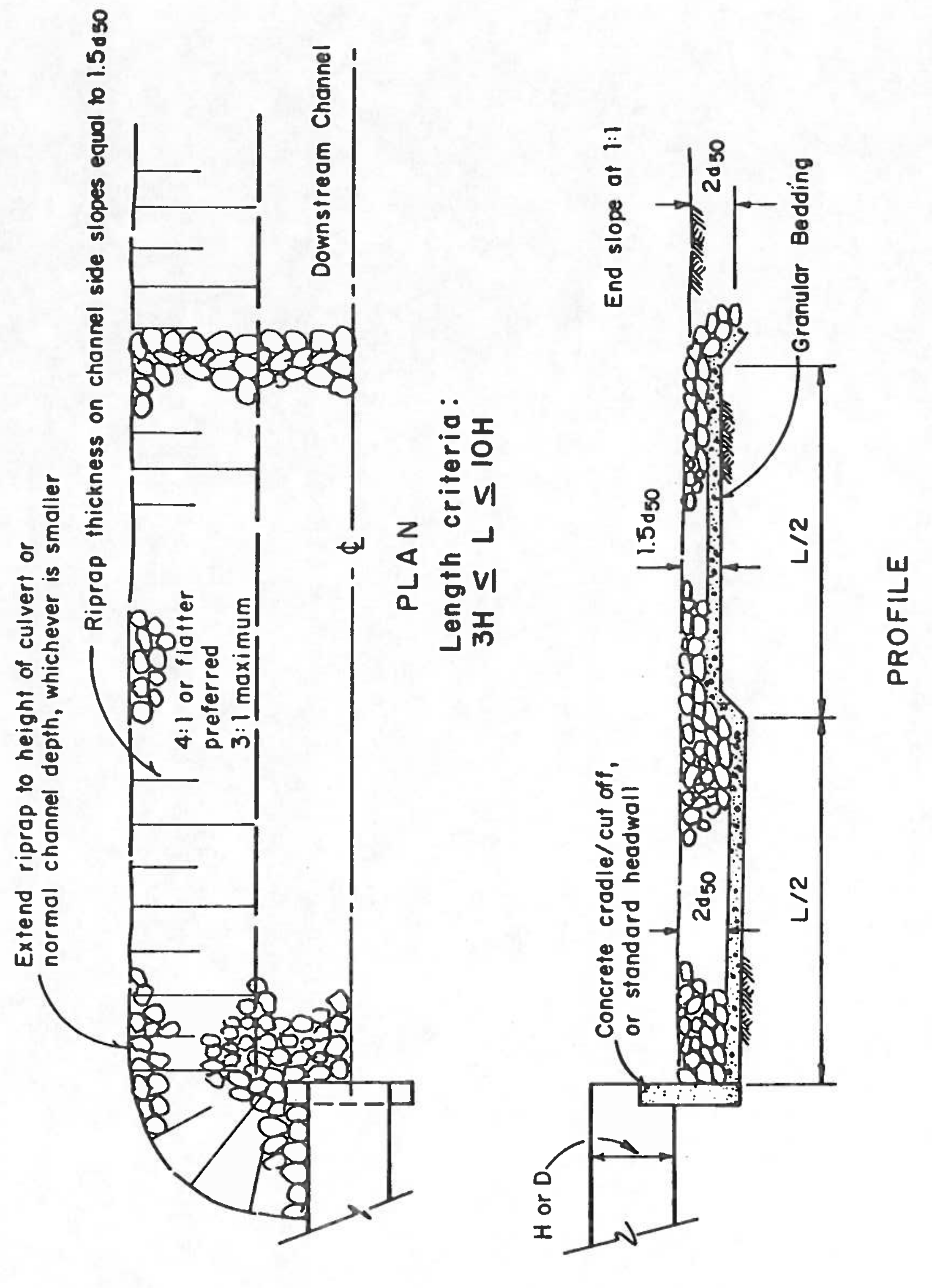
GABION LINING

WRC ENG.	REFERENCE: USDCM, DRCOG, March 1969 (Revised 11-15-82)

BOULDER COUNTY
STORM DRAINAGE CRITERIA MANUAL

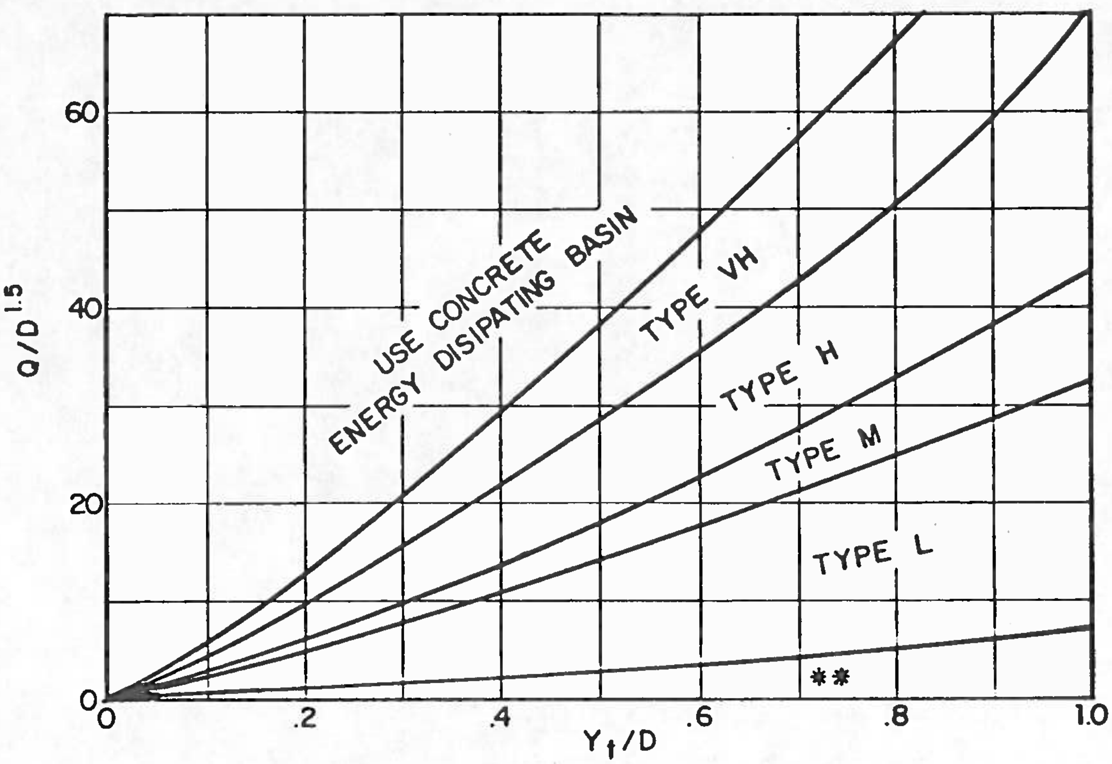
FIGURE 712

CONDUIT OUTLET EROSION PROTECTION



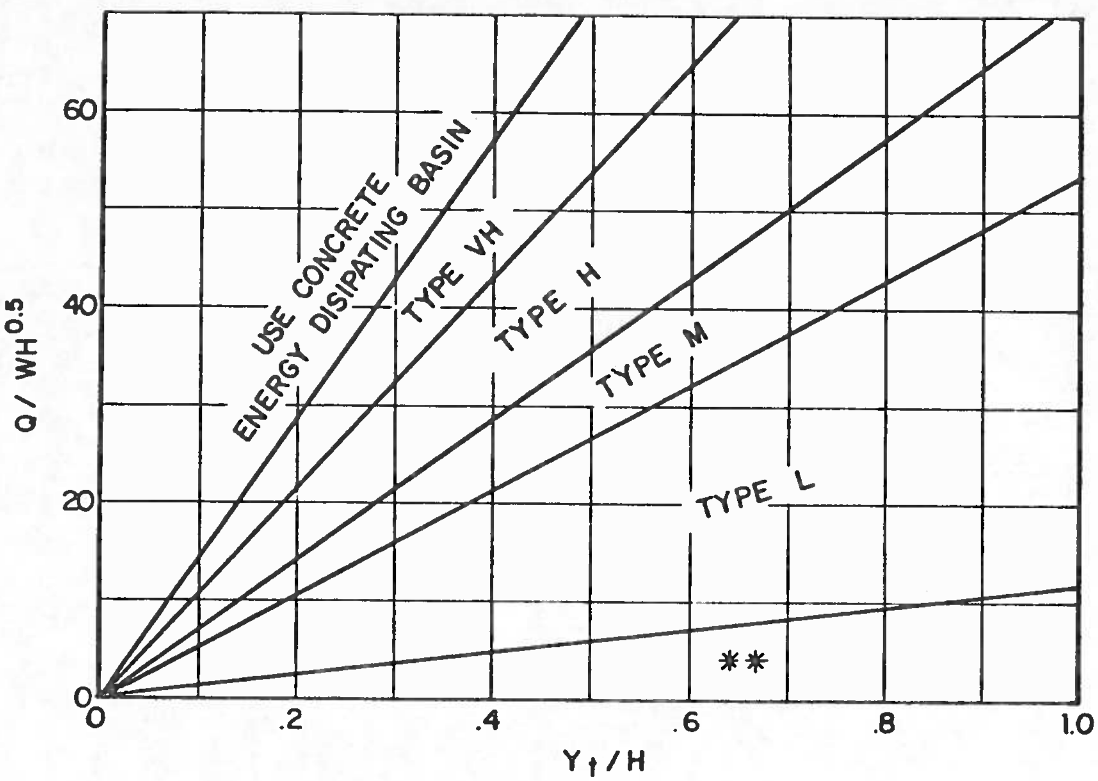
WRC ENG.	REFERENCE: USDCM, DRCOG, March 1969 (Revised 11-15-82)

RIPRAP EROSION PROTECTION AT CIRCULAR CONDUIT OUTLET



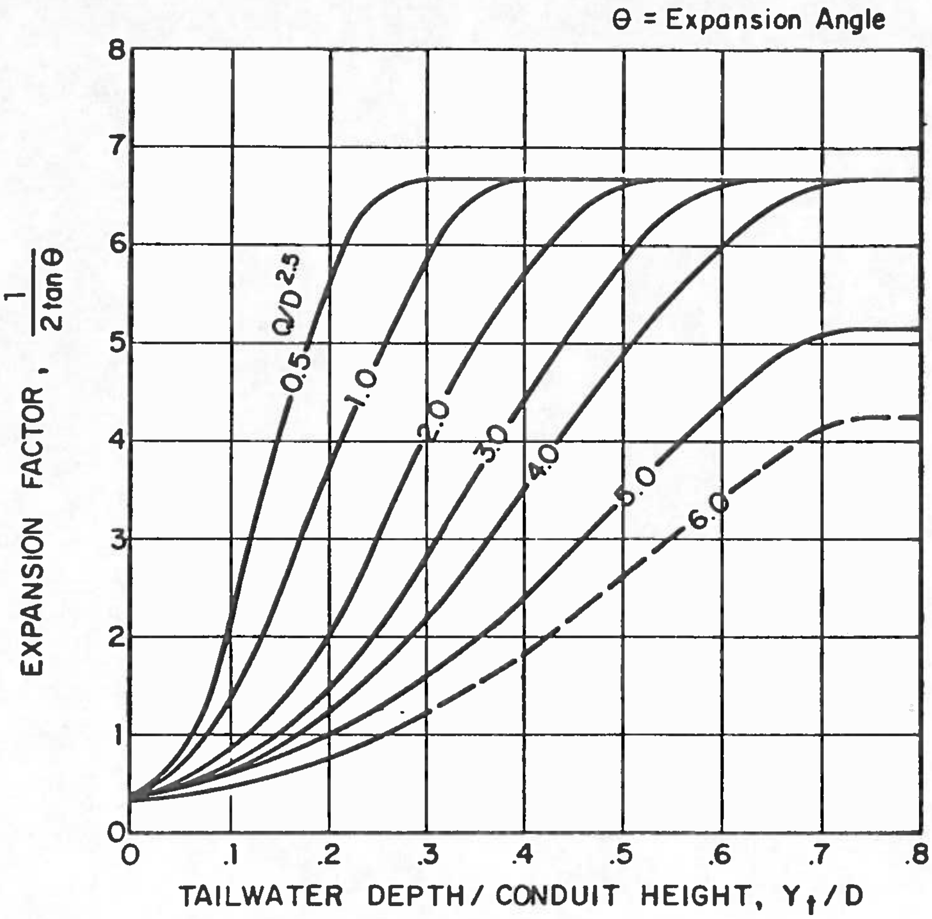
Use D_a instead of D whenever flow is supercritical in the barrel.
** Use Type L for a distance of 3D downstream.

RIPRAP EROSION PROTECTION AT RECTANGULAR CONDUIT OUTLET

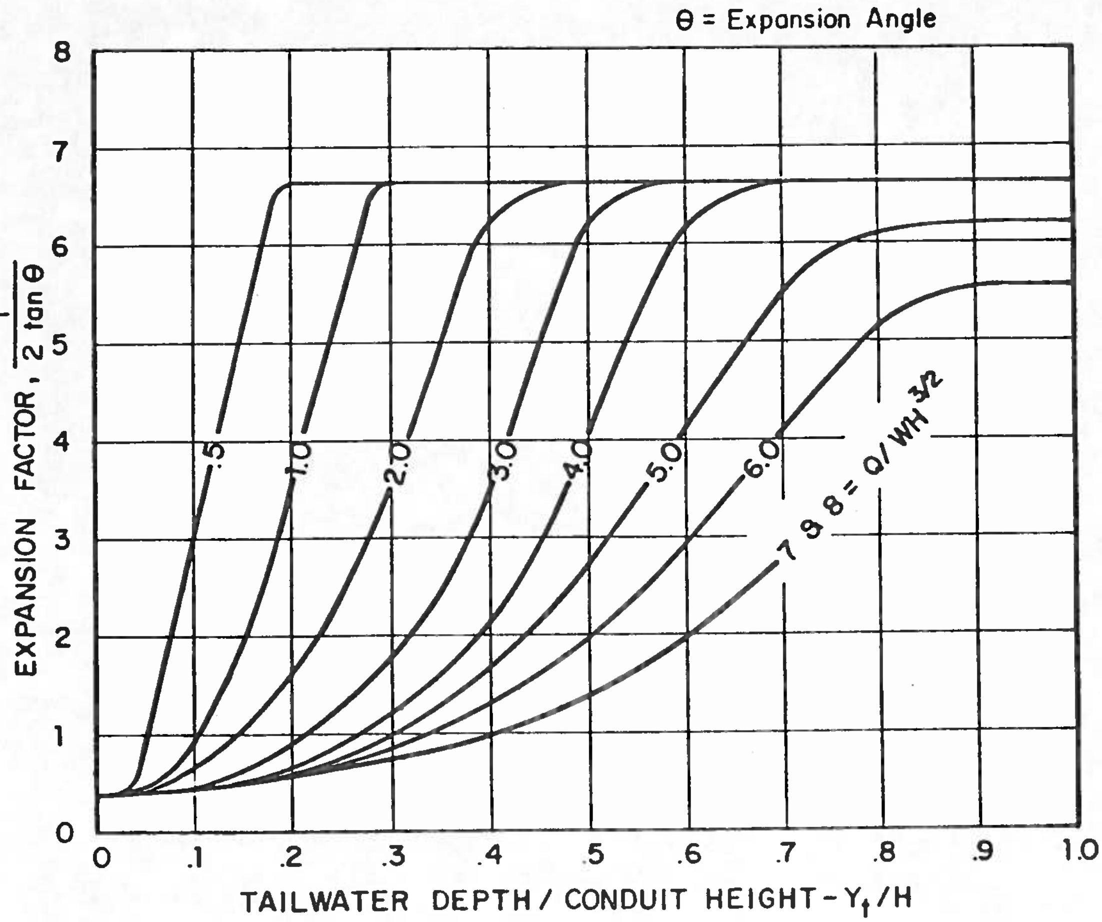


Use H_a instead of H whenever culvert has supercritical flow in the barrel.
**Use Type L for a distance of 3H downstream.

EXPANSION FACTOR FOR CIRCULAR CONDUITS

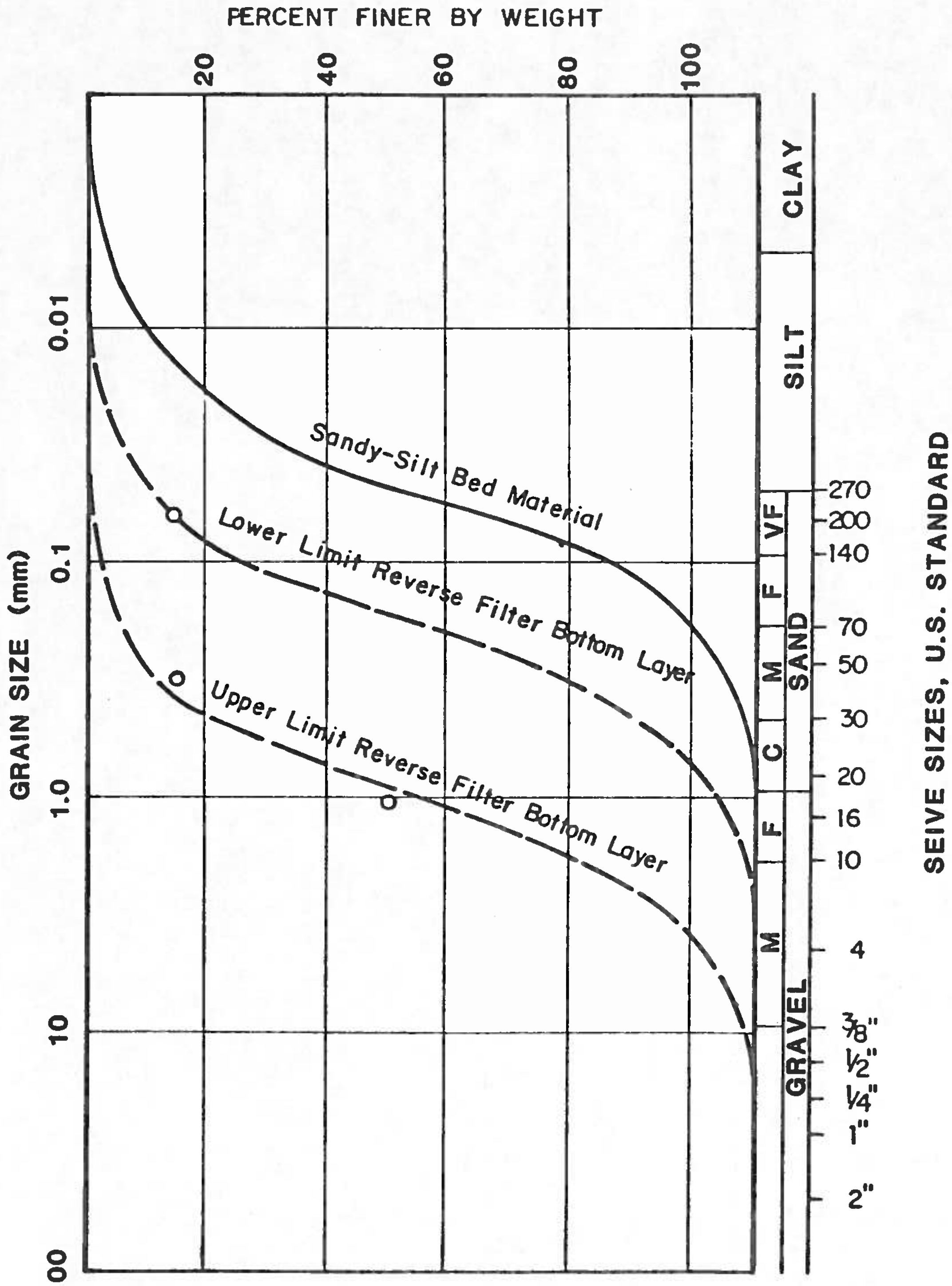


EXPANSION FACTOR FOR RECTANGULAR CONDUITS



WRC ENG.	REFERENCE:	USDCM, DRCOG, March 1969 (Revised 11-15-82)

EXAMPLE GRANULAR FILTER DESIGN



WRC ENG.	REFERENCE: USDCM, DRCOG, March 1969 (Revised 11-15-82)