CHAPTER 5
OPEN CHANNELS

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Chapter Five - Open Channels
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5.1 Overview

5.1.1 Introduction

Consideration of open channel hydraulics is an integral part of projects in which natural channels and improvements to channels are a concern. Natural open channels are encouraged for use, especially in the major drainage system, and can have advantages in terms of cost, capacity, multiple use (i.e., recreation, wildlife habitat, etc. Disadvantages include right-of-way needs for modifications to channels and maintenance requirements.

Where natural channels are not well defined, runoff flow paths can usually be determined and used as the basis for location and construction of channels. In most cases the well-planned use of natural channels and flow paths in the development of a drainage system may obviate the need for an underground storm drain system.

For any open channel conveyance, channel stability must be evaluated to determine what measures are needed so as to avoid bottom scour and bank cutting. This chapter emphasizes procedures for performing uniform flow calculations that aid in the evaluation of appropriate channel linings, grade controls and other protections. Allowable velocities are provided, along with procedures for evaluating channel capacity using Manning's equation.

Even where streams retain a relatively natural state, streambanks may need to be stabilized while vegetation recovers. To preserve riparian characteristics of channels, channel improvement or stabilization projects should minimize the use of visible concrete, riprap or other hard stabilization materials.

Hydraulic analysis software such as HEC-RAS may be useful when preparing preliminary and final channel designs.

Significant alignment revisions to natural channels will require a Corps of Engineers 404 permit and are typically discouraged. However, sometimes when options are limited such as may happen for new major roadway projects, roadway widening, major channel improvements, or flood control projects significant channel alignments are necessary.

For any open channel conveyance, channel stability must be evaluated to determine what measures are needed to avoid bottom scour and bank cutting. Channels shall be designed for long term stability, but be left in as near a natural condition as possible. The use of open, natural channels is especially encouraged in the major drainage system and can have advantages in terms of cost, capacity, multiple use (i.e., recreation, wildlife habitat, etc.). Even where streams retain a relatively natural state, streambanks may need to be stabilized due to urbanization. To preserve riparian characteristics of channels, channel improvement or stabilization projects should minimize the use of visible concrete, riprap or other hard stabilization materials.

The design and construction of any constructed open channel and its associated overbank areas shall be designed to manage the 100-year storm. Open channels shall be maintained by the developer or a property owners' association unless an alternative ownership or maintenance arrangement has been approved by the Director, Planning Commission and City Council.

5.1.2 Natural Channels

Natural channels are carved or shaped by nature prior to urbanization. Often, natural channels have mild slopes and are relatively stable. With increased flows due to urbanization, natural channels may experience erosion and may need grade control checks and localized bank protection to provide stabilization.

5.1.3 Constructed Channels

Constructed channels are discouraged, however they may be required due to a major road projects, flood control, or other desired channel improvement. Constructed channels include the following or a combination of the following type of channels.

5.1.3.1 Grass-lined Channels

Grass-lined channels are the most desirable type of constructed channel. Vegetative linings stabilize the channel body, consolidate the soil mass of the bed, check erosion on the channel surface, and control the movement of soil particles along the channel bottom. Conditions to keep in mind are:

- Flow conditions in excess of the maximum shear stress for bare soils,
- Lack of the regular maintenance,
- Lack of nutrients and inadequate topsoil,
- Excessive shade,
- High velocities, and
- Right-of-way limitations For grass-lined channels, proper seeding, mulching, and soil preparation are required during construction to assure establishment of a healthy stand of grass. Soil testing should be performed and

the results evaluated by an agronomist or similar expert to determine soil treatment requirements for pH, nitrogen, phosphorus, potassium, and other factors. In many cases, temporary erosion control measures are required to provide time for the seeding to establish a viable vegetative lining. Commercially available turf reinforcement products can be used to control erosion while vegetation is being established and to increase the erosion resistance of established vegetation.

Most channel realignment type channel projects are grass lined with grade controls as necessary to prevent head cutting or bank destabilization (i.e. maintain adequate slopes and velocities).

Wetland bottom channels are a subset of grass-lined channels that are designed to encourage the development of wetlands and other riparian species in the channel bottom. In low flow areas, the banks may need protection against undermining (UDFCD, 1990).

5.1.3.2 Low Flow Liner

Under continuous baseflow conditions when the slope is too low (e.g. < 2%), a low flow liner could be used to handle the continuous low flows. Vegetation could then be maintained for handling larger flows. The low flow liner allows for easier maintenance and reduces erosion caused by a meandering low flow channel. Low flow liners can be concrete, open block, or other hard armored material. Concrete low flow liners are discouraged as they convey pollutants from urban runoff directly to local streams and lakes. Low flow liners for channels with large riverine cross sections may be earthen if properly designed for velocity. Low flow liner capacity should be roughly 1 to 5 percent of the design flow.

5.1.3.3 Rock-lined Channels

Rock riprap, including clean rubble, is a common type of rock-lined channel. It presents a rough surface that can dissipate energy and mitigate increases in erosive velocity. These linings are usually less expensive than rigid concrete linings and have self-healing qualities that reduce maintenance. They typically require use of filter fabric and allow the infiltration and exfiltration of water. The growth of grass and weeds through the lining may present maintenance problems. The use of rock-lined channels may be restricted where right-of-way is limited, since the higher roughness values create larger cross sections. Wire-enclosed (gabion) rock and grouted riprap are other examples of commonly used rock- lined channels. If using wire-enclosed rock use with coated wires.

5.1.3.4 Concrete Channels

Concrete channels are used where smoothness offers a higher capacity for a given cross-sectional area. Higher velocities, however, create the potential for scour at channel lining transitions. A concrete lining can be destroyed by flow undercutting the lining, channel headcutting, or the buildup of hydrostatic pressure behind the rigid surfaces. Filter fabric may be required to prevent soil loss through pavement cracks. When properly designed, concrete linings may be appropriate where the channel width is restricted. Concrete channels have a high construction cost and high rehabilitation cost.

5.1.4 Maintenance

Open channels shall be maintained by the developer or a property-owners' association unless an alternative ownership/maintenance arrangement has been approved by the Director of Public Works and Utilities, Planning Commission and the City Council. Changes in channel alignment require a 404 permit which may require a monitoring plan over a number of years as determined by the Corp of Engineers. Sureties and as-built plans may be required to ensure proper construction. If within a floodplain area they require a floodplain permit and potentially a Letter of Map Revision. Revisions within minimum corridors may require to be mitigated.

5.2 Symbols and Definitions

To provide consistency within this chapter, as well as throughout this manual, the following symbols will be used. These symbols were selected because of their wide use in open channel publications.

Table 5-1 Symbols and Definitions

Symbol	Definition	Units
A	Cross-sectional area	ft^2
b	Bottom width	ft
C_x	Correction factor	–
D	Depth of flow	ft
d_{avg}	Average flow depth in the main flow channel	ft
dx	Diameter of stone for which x percent, by weight, of the gradation is finer	ft
Fr	Froude number	–
g	Acceleration of gravity	32.2 ft/s^2
h	Superelevation	ft
K_1	Correction term reflecting bank angle	–
L	Length of channel	ft
L_p	Length of downstream protection	ft
n	Manning's roughness coefficient	–
P	Wetted perimeter	ft
Q	Discharge rate	cfs
R	Hydraulic radius ft	
r_c	Mean radius of the bend	ft
S	Slope	ft/ft
S_f	Friction slope or energy grade line slope	ft/ft
SF	Stability factor	–
S_s	Specific gravity of the riprap material	lb/ft^2
Tw	Top width	ft
V or v	Velocity of flow	ft/s
W_{50}	Weight of the median particle	lb
y_c	Critical depth	ft
y_n	Normal depth	ft
Z	Critical flow section factor	–
θ	Bank angle with the horizontal	degrees
Φ	Riprap materials angle of repose	degrees

5.3 Hydraulic Terms

5.3.1 Introduction

An open channel is a channel or 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 stormwater drainage involve uniform, gradually varied or rapidly varied flow states. The calculations for uniform and gradually varied flow are relatively straight forward and are based upon similar assumptions (e.g., parallel streamlines).

This section will present the basic equations and computational procedures for uniform, gradually varied, and rapidly varied flow. Many proprietary and non-proprietary computer software packages are available that may be used to evaluate the hydraulics of open channels.

5.3.2 Steady and Unsteady Flow

Flow in open channels is classified as steady flow or unsteady flow. Steady flow occurs when discharge or rate of flow at any cross section is constant with time. In unsteady flow the discharge or rate of flow varies from one cross section to another, with time.

5.3.3 Uniform Flow and Normal Depth

Open channel flow is said to be uniform if the depth of flow is the same at every section. For a given channel geometry, roughness, slope, and discharge, there is only one possible depth for maintaining uniform flow. This depth is referred to as normal depth.

True uniform is difficult to observe in the field because not all of the parameters remain the same. However, channel capacities are often based on assuming uniform flow. This approximation is generally adequate for drainage purposes. The engineer must be aware that uniform flow computation provides only an approximation of what will occur.

Manning's Equation, presented below, is recommended for evaluating uniform flow conditions in open channels.

$$Q = (1.49/n)\,A\,R^{2/3}\,S^{1/2} \tag{5.1}$$

Where:	Q	=	discharge rate for design conditions (cfs)
	n	=	Manning's roughness coefficient
	A	=	cross-sectional area (ft^2)
	R	=	hydraulic radius A/P (ft)
	P	=	wetted perimeter (ft)
	S	=	slope of the energy grade line (EGL) (ft/ft)

The Manning's “n” value is an important variable in open channel flow computations. Variation in this variable can significantly affect discharge, depth, and velocity estimates. Since Manning's n values depend on many different physical characteristics of natural and constructed channels, care and good engineering judgment must be exercised in the selection process.

For prismatic (e.g., trapezoid, rectangular) channels, in the absence of backwater conditions, the slope of the energy grade line, water surface and channel bottom are equal.

Since normal depth is computed so frequently, special tables and figures (see Table 5-2 and Figure 5-1) have been developed using the Manning’s formula for various uniform cross sections to eliminate the need for trial and error solutions, which are time consuming. Table 5-2 is applicable only for trapezoidal channels.

5.3.4 Critical Flow

Critical flows are atypical in Lincoln, but may occur with hydraulic structures such as weirs or in a steep underground pipe.

Critical flow in an open channel or covered conduit with a free water surface is characterized by the following conditions:

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

- The discharge is a maximum for a given specific energy.
- The specific force is a minimum for a given discharge.
- The velocity head is equal to half the hydraulic depth in a channel of small slope.
- The Froude number is equal to 1.0.
- The velocity of flow in a channel of small slope is equal to the celerity of small gravity waves in shallow waters

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_c." A slope less than "S_c" will cause subcritical flow, while a slope greater than "S_c" will cause supercritical flow. Under subcritical flow, surface waves propagate upstream as well as downstream, and control of subcritical flow depth is always downstream. Under supercritical flow, surface disturbance can propagate only in the downstream direction, and control of supercritical flow depth is always at the upstream end of the critical flow region. A flow at or near the critical state is not stable. In design, if the depth is found to be at or near critical, the shape or slope should be changed to achieve greater hydraulic stability.

The criteria of minimum specific energy for critical flow results in the definition of the Froude number, which is expressed by the following equation:

$$Fr = v / (gD)^{0.5} \tag{5.2}$$

Where:			
	Fr	=	Froude number
	v	=	mean velocity of flow (ft/s)
	g	=	acceleration of gravity (32.2 ft/s^2)
	D	=	hydraulic depth (ft) - defined as the cross sectional area of water normal to the direction of channel flow divided by free surface width.

Since the Froude number is a function of depth, the equation indicates there is only one possible critical depth for maintaining a given discharge in a given channel. When the Froude number equals 1.0, the flow is critical. The Froude number should be calculated for the design of open channels to check the flow state. The computation of critical flow for trapezoidal and circular sections can be performed with the use of Figure 5-2 (Chow, 1959).

5.3.5 Gradually Varied Flow

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

Many computer programs are available for computation of backwater curves. The most general and widely used program is, HEC-RAS, River Analysis System, developed by the U.S. Army Corps of Engineers (USACE, 1995) and is the program recommended for floodwater profile computations. HEC-RAS will compute water surface profiles for natural and constructed channels. The HY-8 is a program developed for the Federal Highway Administration that can also be used to perform backwater calculations for both natural and constructed channels.

For prismatic channels, the backwater calculation can be computed manually using the direct step method, as presented by Chow (1959). The use of HEC-RAS is recommended for non-uniform channel analysis. The reader is directed to the HEC-RAS documentation for proper use of the model.

5.3.6 Rapidly Varied Flow

Rapidly varied flow is characterized by pronounced curvature of streamlines. The change in curvature may become so abrupt that the flow profile is virtually broken, resulting in high turbulence. Empirical solutions are usually relied on to solve specific, rapidly varying flow problems. Hydraulic jump is an example of rapidly varied flow that commonly occurs in urban storm drainage.

5.3.6.1 Hydraulic Jump

Hydraulic jumps occur when a supercritical flow rapidly changes to subcritical flow. The result is usually an abrupt rise of the water surface with an accompanying loss of kinetic energy. The hydraulic jump is an effective energy dissipation device which is often used to control erosion at drainage structures.

In urban hydraulics, the jump may occur at grade control structures, inside of or at the outlet of storm drains or concrete box culverts, or at the outlet of an emergency spillway for detention ponds. The evaluation of a hydraulic jump should consider the high energy loss and erosive forces that are associated with the jump. For rigid-lined facilities such as pipes or concrete channels, the forces and the change in energy can affect the structural stability or the hydraulic capacity. For grass-lined channels, unless the erosive forces are controlled, serious damage can result. Control of jump location is usually obtained by check dams or grade control structures that confine the erosive forces to a protected area. Flexible material such as riprap may afford the most effective protection.

5.3.6.1.1 Storm Drains

The analysis of the hydraulic jump inside storm sewers is approximate. The jump can be approximately located by intersecting the energy grade line of the super- critical and subcritical flow reaches. The primary concerns are whether the pipe can withstand the forces which may separate the joint or damage the pipe wall, and whether the jump will affect the hydraulic characteristics. 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. French (1985) provides semi- empirical procedures to evaluate the hydraulic jump in circular and other non-rectangular channel sections. "Hydraulic Analysis of Broken Back Culverts", Nebraska Department of Roads, January 1998 provides guidance for analysis of hydraulic jump in pipes.

5.3.6.1.2 Box Culverts

For long box culverts with a concrete bottom, the concerns about jump are the same as for storm sewers. However, the jump can be adequately defined for box culverts/drains and for spillways using the jump characteristics of rectangular sections. The relationship between variables for a hydraulic jump in rectangular sections can be expressed as:

$$D_2 = -(D_1/2) + [(D_1^2/4) + (2v_1^2 D_1/g)]^{1/2} \tag{5.3}$$

Where:

	D_2	=	depth below jump (ft)
	D_1	=	depth above jump (ft)
	v_1	=	velocity above jump (ft/s)
	g	=	acceleration due to gravity (32.2 ft/s^2)

Additional details on hydraulic jumps can be found in HEC-14 (1983), Chow (1959), Peterska (1978), and French (1985)

5.3.6.1.3 Vertical Drop Structures

Chow (1959) used experimental data to determine hydraulic jump conditions at vertical drop structures. The aerated free-falling nappe in a vertical check drop structure will reverse the curvature and turn smoothly into supercritical flow on the apron, which may form a hydraulic jump downstream. Based on the relationships developed by Chow, the length of the hydraulic jump can be determined. A good approximation of the hydraulic jump length is six times the sequent depth (UDFCD, 1990). The reader is referred to Chow for a more detailed presentation.

5.4 General Open Channel Design Criteria

5.4.1 Introduction

In general, the following criteria should be used for constructed open channel design:

- Trapezoidal cross sections are preferred and triangular shapes should be avoided.
- Channel side slopes shall be stable throughout the entire length and side slope shall depend on the channel material. A maximum of 4H:1V is recommended for vegetation and 2H:1V for riprap, unless otherwise justified by calculations.
- If relocation of a stream channel is unavoidable, the cross-sectional shape, meander, pattern, roughness, sediment transport, and slope should generally conform to the existing conditions insofar as practicable, after giving consideration to increased flows from urbanization. Energy dissipation may be necessary.
- Streambank stabilization should be provided, when appropriate, as a result of any stream disturbance such as encroachment and should include both upstream and downstream banks as well as the local site.
- A low flow liner may be needed for grass-lined channels.
- Earthen Low flow liners may need to be used in the design of channels with large cross sections.
- Computation of water surface profiles shall be presented for all open channels utilizing standard backwater methods, taking into consideration losses due to changes in velocity, drops, and obstructions. The hydraulic and energy grade lines shall also be shown on preliminary and construction drawings. When potential erosion and flood capacity problems are identified, modifications to the channel may be necessary.

5.4.2 Channel Transitions

The following criteria should be considered at channel transitions:

- Transition to channel sections should be smooth and gradual.
- A straight line connecting flow lines at the two ends of the transition should not make an angle greater than 12.5 degrees with the axis of the main channel.
- Transition sections should be designed to provide a gradual transition to avoid turbulence and eddies.
- Energy losses in transitions should be accounted for as part of the water surface profile calculations.
- Scour downstream from rigid-to-natural and steep-to-mild slope transition sections should be accounted for through velocity-slowing and energy-dissipating devices.

5.4.3 Return Period Design Criteria

Natural channels and their overbank areas will have the 100-year storm contained within outlots.

The design and construction of constructed open channels shall be sized to handle the 100-year storm. The 100-year storm even shall not encroach on buildable lots and shall be contained in outlots.

When comprising the minor drainage system, open channels shall be sized to handle the 5-year storm in residential areas and the 10-year storm in downtown areas and industrial/commercial developments. For major drainage systems, open channels shall be sized to handle the 100-year storm.

5.4.3.1 Approximate Flood Limits Determination

Refer to Section 1.5.6 Flood Corridor Management for guidance on policy requirements for flood limit determination and minimum corridor requirements.

For cases when the design engineer can demonstrate that a complete backwater analysis is unwarranted, approximate methods may be used.

A generally accepted method for approximating the 100-year flood elevation is outlined as follows:

1. Divide the stream or tributary into reaches that may be approximated using average slopes, cross sections, and roughness coefficients for each reach.
2. Estimate the 100-year peak discharge for each reach using the appropriate hydrologic method (e.g. normal depth).
3. Compute normal depth for uniform flow in each reach using Manning's equation for the reach characteristics from Step 1 and peak discharge from Step 2.
4. Use the normal depths computed in Step 3 to approximate the 100-year flood elevation in each reach. The 100-

year flood elevation is then used to delineate the floodplain.

This approximate method is based on several assumptions and should not be used where not appropriate. Assumptions, include, but are not limited to, the following:

1. A channel reach is accurately approximated by average characteristics throughout its length.
2. The cross-sectional geometry, including area, wetted perimeter, and hydraulic radius, of a reach may be approximated using typical geometric properties that can be used in Manning's equation to solve for normal depth.
3. Uniform flow can be established and backwater effects are negligible between reaches.
4. Expansion and contraction effects are negligible.

As indicated, the approximate method is based on a number of restrictive assumptions that may limit the accuracy of the approximation and applicability of the method. The engineer is responsible for appropriate application of this method to get reliable results.

Where a complete backwater analysis is warranted, the engineer is encouraged to use the USACE HEC-RAS model.

5.4.4 Velocity Limitations

Sediment transport requirements must be considered for conditions of flow below the design frequency, minimum channel flow velocity for the 2-year storm shall be 2.0 feet per second. A low flow channel component within a larger channel can reduce maintenance by improving sediment transport in the channel. Channel flow velocities shall be non-erosive for the 2-, 10- and 100-year storms. Low flow liner design flow rate shall be 1% of the major storm flow rate and shall be non- erosive. Grade control structures, streambank protection, and construction and maintenance considerations shall be determined during design.

The final design of constructed open channels should be consistent with the velocity limitations for the selected channel lining. Maximum velocity values for selected lining categories are presented in Table 5-3. Velocity limitations for established vegetative linings are reported in Table 5-4.

Table 5-3 Maximum Design Velocities for Comparing Lining Materials (all values in feet per second)

Material	Clear Water	Water with Colloidal Silt	Water with Non-colloidal Silt, Sand or Gravel
Fine Sand (colloidal)	1.5	2.5	1.5
Sand Loam (noncolloidal)	1.45	2.5	2.0
Silt Loam (noncolloidal)	2.0	3.0	2.0
Alluvial Silt (noncolloidal)	2.0	3.5	2.0
Alluvial Silt (colloidal)	3.75	5.0	3.0
Firm Loam	2.5	3.5	2.25
Fine Gravel	2.5	5.0	3.75
Stiff Clay (very colloidal)	3.75	5.0	3.0
Graded Loam to Cobbles(noncol)	3.75	5.0	5.0
Graded Silt to Cobbles (colloidal)	3.75	5.0	3.0
Coarse Gravel	4.0	6.0	6.5
Cobbles and Shingles	5.0	5.5	6.5
Shales and Hard Pans	6.0	6.0	5.0

Source: Fortier and Scoby, 1926.

Somewhat typical for Lincoln would be 5.0 ft/sec (alluvial colloidal silt material with flow having colloidal silt.

Table 5-4 Maximum Velocities for Vegetative Channel Linings

Vegetation Type	Slope Range (%)[1]	Maximum Velocity[2] (ft/s)	
		Erosion Resistant Soils	Easily Eroded Soils
Bermuda grass	0-5	8	6
	5-10	7	5
	>10	6	4
Kentucky bluegrass	0-5	7	5
Buffalo grass	5-10	6	4
	>10	5	3
Grass mixture	0-5[1]	5	4
	5-10	4	3
Kudzu, alfalfa	0-5[3]	3.5	2.5
Annuals	0-5	3.5	2.5
Sod		4.0	4.0
Lapped sod		5.5	5.5

Source: USDA, TP-61, 1954.
[1]Do not use on slopes steeper than 10 percent except for side-slope in combination channel.
[2]Use velocities exceeding 5 ft/s only where good stands can be established and maintained.
[3]Do not use on slopes steeper than 5 percent except for side-slope in combination channel.

5.4.5 Grade Control Structures

Grade control structures are used to prevent streambed degradation. This is accomplished in two ways. First, the structures provide local base levels that prevent bed erosion and subsequent slope increases. Second, some structures provide controlled dissipation of energy between upstream and downstream sides of the structure. Structure choice depends on existing or anticipated erosion, cost, and environmental objectives. Design guidance for grade control structures is provided in Section 5.10.

Examples of grade control structures include:

Check Structures - A check structure is a structure that extends across a channel and has a surface that is flush with the channel invert or that extends a foot or two above the invert. Because check structures are intended to prevent scouring of the bed, they should be placed close enough together to control the energy grade line and prevent scour between structures. Check structures may be notched at the lowest flow point location to concentrate low flows to improve aquatic habitat and water quality or for aesthetic reasons. In highly visible locations, check structures extending above the channel invert may be constructed of, or faced with, materials such as natural stone that create an attractive appearance. Check structures may also be modified to allow for passage of boats or fish, if desired.

Drop Structures, Chutes, and Flumes - Drop structures provide for a vertical drop in the channel invert between the upstream and downstream sides, whereas chutes and flumes provide for a more gradual change in invert elevation. Because of the high energies that must be dissipated, pre-formed scour holes or plunge pools are required below these structures.

The design of hydraulic structures, such as drop structures, must consider safety of the general public, especially if multiple uses may occur or are allowed (i.e., boating and fishing). There are certain hazards that can be associated with drop structures, such as the “reverse roller” phenomenon which can trap an individual and result in drowning. As a result, it may be necessary to sign locations accessible by the public to warn of the danger associated with the hydraulic structure.

5.4.6 Streambank Protection

Streambanks subject to erosion are protected by stabilizing eroding soils, planting vegetation, covering the banks with various materials, or building structures to deflect stream currents away from the bank. Placement and type of bank protection vary, depending on the cause of erosion, environmental objectives, and cost. Section 5-11 identifies different streambank protection measures that are recommended for bank stability.

5.4.7 Construction and Maintenance Considerations

Open channels shall be maintained by the developer or a property-owners' association unless an alternative ownership/maintenance arrangement has been approved by the Director of Public Works and Utilities, Planning Commission and the City Council.

An important step in the design process involves identifying whether special provisions are warranted to properly construct or maintain proposed facilities.

Open channels can lose hydraulic capacity without adequate maintenance. Maintenance may include repairing erosion damage, mowing grass, cutting brush, and removing sediment or debris. Brush, sediment, or debris can reduce design capacity and can harm or kill vegetative linings, thus creating the potential for erosion damage during large storm events. Maintenance of vegetation should include mowing, the appropriate application of fertilizer, irrigation during dry periods, and reseeding or resodding to restore the viability of damaged areas. Extra sizing may be used to account for future vegetation growth.

Implementation of a successful maintenance program is directly related to the accessibility of the channel system and the easements necessary for maintenance activities. The easement cross-section must accommodate the depth and width of flow from the 100-year storm. The width must also be designed to allow for access of maintenance equipment.

Both natural and construed channels may require maintenance plans. Constructed channels require 404 permits, City approval, potentially floodplain permits and may require sureties.

5.5 Natural Channel Design Criteria

Natural channels in the Lincoln area are sometimes found to have erodible banks and bottoms which tend to result in steep vertical banks. Other channels may have mild slopes and are reasonably stable. Natural channels are preferred to be used in urbanized and to-be-urbanized areas to convey stormwater runoff, it can be assumed that there will be increased flow peaks and volumes that will result in increased channel erosion. As such, an hydraulic analysis during the planning and design phase is necessary to address the potential for erosion, and will usually result in the need for some stabilization measures.

The following criteria and analysis techniques are recommended for natural channel evaluation and stabilization:

- The channel and over-bank areas must have adequate capacity for the 100-year post-development storm runoff.
- The water surface profiles must be defined and delineated so that the 100-year flood extents can be identified and managed. Plan and profile drawings should be prepared of the 100-year flood extents, and allowances should be made for future bridges or culverts.
- Filling of the floodplain is subject to the restriction of floodplain regulations.
- Manning's n roughness factors representative of maintained channel conditions should be used. Table 5-5 provides representative values of the roughness factor in natural streams.
- Erosion control structures such as drop structures and grade control checks should be provided as necessary to control flow velocities and channel erosion.
- Outlots are to be designed to be wide enough to accommodate the 100-year flood extents. If within a floodplain follow all floodplain regulations and provide pertinent information on the plans.

Table 5-5 Uniform Flow Values of Roughness Coefficient - n

Type Of Channel And Description	Minimum	Normal	Maximum
Minor streams (top width at flood stage < 100 ft)			
a. Streams on Plain			
1. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
2. Same as above, but more stones and weeds	0.030	0.035	0.040
3. Clean, winding, some pools and shoals	0.033	0.040	0.045
4. Same as above, but some weeds and some stones	0.035	0.045	0.050
5. Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
6. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
Floodplains			
a. Pasture, no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated area			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush 1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees	0.040	0.060	0.080
3. Medium to dense brush	0.070	0.100	0.160
d. Trees			
1. Dense willows, straight	0.110	0.150	0.200
2. Cleared land, tree stumps, no sprouts	0.030	0.040	0.050
3. Same as above, but with heavy growth of sprouts	0.050	0.060	0.080
4. Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5. Same as above, but with flood stage reaching branches	0.100	0.120	0.160
Major Streams (top width at flood stage > 100 ft).			
a. Regular section with no boulders or brush	0.025	.....	0.060
b. Irregular and rough section	0.035	.....	0.100

Natural channels should be left in as near a natural condition as feasible. However, with most natural channels, grade control structures may need to be constructed at regular intervals to limit channel degradation and to maintain what is expected to be the final stable longitudinal slope after full urbanization of the watershed. In addition, the engineer is reminded that modification of the channel typically requires a US Army Corps of Engineers Section 404 permit.

Use of natural channels in the drainage system requires thoughtful planning, as they offer multiple-use opportunities.

Certain criteria pertaining to constructed channels, such as freeboard depth and curvature, may not apply to natural channels in order to meet some of the multi-purpose objectives. Special consideration shall be given to transitions from “hard” to “soft” stabilization materials.

5.6 Grassed-Lined Channel Design Criteria

Grass-lined channels are encouraged when designing constructed channels. Advantages include: channel storage, lower velocities, provision of wildlife habitat, and aesthetic and recreational values. Design considerations include velocity, longitudinal slopes, roughness coefficients, depth, freeboard, curvature, cross-section shape, and channel lining material (vegetation and low flow liner considerations).

5.6.1 Design Velocity and Froude Number

It is recommended that the maximum normal depth velocity for grass-lined channels during the major design storm (i.e., 100-year) not exceed 7.0 feet per second for erosion-resistant soils and 5.0 per second for easily eroded soils. These velocity limitations assume a well-maintained, good stand of grass. The Froude number should not exceed 0.8 for erosion-resistant soils and 0.6 for easily eroded soils (UDFCD, 1990).

5.6.2 Longitudinal Slopes

Grass-lined channels should have longitudinal slopes of less than 1 percent, but will ultimately be dictated by velocity and Froude number considerations. In locations where the natural topography is steeper than desirable, grade control structures should be implemented.

5.6.3 Roughness Coefficients

Table 5-6 provides guidance for roughness coefficients for grass-lined channels. The roughness coefficient for grass-lined channels depends on length and type of vegetation and flow depth. Roughness coefficients are smaller for higher flow depths due to the fact that at higher depths the grass will lay down to form a smoother bottom surface.

Table 5-6 Manning's Roughness Coefficients for Grass-Lined Channels - n
n - Value with Flow Depth Ranges

Grass Type	Length	0.0-1.5 ft	>3.0 ft
Bermuda grass, Buffalo grass, Kentucky bluegrass	Mowed to 2 inches	0.035	0.030
	Length 4 to 6 inches	0.040	0.030
Good stand any grass	Length of 12 inches	0.070	0.035
	Length of 24 inches	0.100	0.035
Fair stand any grass	Length of 12 inches	0.060	0.035
	Length of 24 inches	0.070	0.035

Source: UDFCD, 1990.

5.6.4 Freeboard

A minimum freeboard of 1 foot should be provided between the water surface and top of bank, or adjacent buildable lots or the elevation of the lowest opening of adjacent structures. In some areas, localized overflow may be desirable for additional ponding/storage benefits.

5.6.5 Curvature

It is recommended that the centerline curves of channels have a radius of two to three times the design flow top width or at least 100 feet.

5.6.6 Cross-sections

Channel shape may be almost any type suitable to the site-specific conditions, and can be designed to meet multi-purpose uses, such as recreational needs and wildlife habitat. However, limitations to the design include the following:

- Side slopes should be 4 (horizontal) to 1 (vertical) or flatter. Slopes as steep as 3H:1V may be considered in areas where development already exists and there are right-of-way limitations.
- The bottom width should be designed to accommodate the hydraulic capacity of the cross-section, recognizing
- the limitations on velocity and depth. Width must be adequate to allow necessary maintenance (ASCE, 1992).
- Maintenance/access roads should be provided for along all major drainageways. Low flow liners or underdrain pipes should be provided on grass-lined channels to minimize erosion. As an alternative, low flow channels can be provided (low flow channels are particularly applicable for larger conveyances). Figure 5-3 shows typical cross-sections suitable for grass-lined channels. Low flow liners should be designed to carry base flow originating from lawn watering, low intensity rainfall events, and snow melt.

5.6.7 Grass Species

Seed mixes for the channel lining should be selected to be sturdy, easy to establish, and able to spread and develop a strong turf layer after establishment. A thick root structure is necessary to control weed growth and erosion. Seed mixes should meet all state and local seed regulations. Refer to Chapter 30 of the City of Lincoln Standard Specifications.

5.7 Wetland Bottom Channel Design Criteria

Wetland bottom channels should be considered as the design approach in circumstances where existing wetland areas are affected or natural channels are modified. In fact, the USACE may mandate the use of wetland bottom vegetation in the channel design as mitigation for wetland damages elsewhere. Wetland bottom channels are in essence grass-lined channels, with the exception that wetland-type vegetation is encouraged in the channel bottom (this is usually accomplished by removing the low flow liner and slowing velocities). Increased water quality and habitat benefits are realized with the implementation of wetland bottom channels; however, they can become difficult to maintain (i.e., mow) and may be potential mosquito breeding areas.

Due to the abundant vegetation associated with wetland channels, flow conveyance will decrease and channel bottom agradation will increase. Consequently, channel cross-sections and right-of-way requirements will be larger than those associated with grass-lined channels.

The recommended procedures for wetland bottom channel design are quite similar to the design of grass-lined channels. For wetland channel design, the engineer must accommodate two flow roughness conditions to account for channel stability during a "new channel" condition and channel capacity during a "mature channel" condition.

5.7.1 Design Velocity

It is recommended that the maximum normal depth velocity for wetland bottom "new channel" conditions during the major design storm (i.e., 100-year) not exceed 7.0 feet per second for erosion resistant soils and 5.0 per second for easily eroded soils. The Froude number should not exceed 0.8 for erosion resistant soils and 0.6 for easily eroded soils under "new channel" conditions.

5.7.2 Longitudinal Slopes

The longitudinal slopes of wetland bottom channels should be dictated by velocity and Froude number considerations under "new channel" conditions.

5.7.3 Roughness Coefficients

As previously mentioned, wetland bottom channel design requires consideration of two roughness coefficient scenarios. To determine longitudinal slope and initial cross-section area, a "new channel" coefficient should be used. To determine design water surface, and final cross-section area, a "mature channel" coefficient should be used. The "mature channel" coefficient will likely be a composite coefficient. The following provides guidance for roughness coefficients for wetland bottom channels:

- New channel condition, use n = 0.030
- Mature channel condition, calculate a composite based on the following relation and Figure 5-4 (UDFCD
- 1990):

$$n_C = (n_0 p_0 + n_w p_w)/(p_0 + p_w) \tag{5.5}$$

Where:
n_c = composite Manning's n
n_0 = Manning's n for areas above wetland (refer to Table 5.5)
n_w = Manning's n for the wetland area (see Figure 5-4)
p_0 = wetted perimeter of channel above wetland area
p_w = wetted perimeter of wetland area (approximated as bottom width plus 10 feet)

5.7.4 Design Depth

As a preliminary design criteria, the maximum design depth of flow for the major storm runoff should not exceed 5.0 feet in areas of the channel cross-section outside the low flow channel area. Scour potential should also be analyzed when determining the design depth.

5.7.5 Freeboard

A minimum freeboard of 1 foot should be provided between the water surface and top of bank or the elevation of the lowest opening of adjacent structures. Freeboard should be determined based on the major storm water surface elevation under "mature channel" conditions.

5.7.6 Curvature

It is recommended that the centerline curves of channels have a radius of two to three times the design flow top width or at least 100 feet.

5.7.7 Cross-sections

Channel shape may be almost any type suitable to the site-specific conditions, and can be designed to meet multi-purpose uses, such as recreational needs and wildlife habitat. However, limitations to the design include the following:

- Side slopes should be 4 (horizontal) to 1 (vertical) or flatter.
- It is recommended that the low flow channel be designed to convey the minor storm (i.e., 5- or 10-year storm) runoff.
- The bottom width should be designed to accommodate the hydraulic capacity of the cross-section, recognizing the limitations on velocity and depth. It is recommended that bottom widths not be less than 8.0 feet.
- Side slope banks of low flow channels should be lined with riprap or turf reinforcement material (at 2.5H:1V or
- 3H:1V) to minimize erosion. Figure 5-5 shows a typical cross-section suitable for wetland bottom channels.

5.8 Rock-Lined Channel Design

Rock-lined channels constructed from riprap, grouted riprap, or wire-enclosed (gabion) rock can be cost effective at controlling erosion along short channel reaches. These rock-lined channels might be appropriate in the following scenarios:

- Where major flows generate velocities in excess of allowable non-eroding values.
- Where right-of-way restrictions necessitate channel side slopes to be steeper than 3H:1V.
- Where rapid changes in channel geometry occur such as at channel bends and transitions.
- For low flow channels.

For hydraulic calculations, the following equation can be used for Manning's n values for riprap (this equation does not apply to situations involving very shallow flow where the roughness coefficient will be greater):

$$\mathbf{n = 0.0395\,(d_{50})^{1/6}} \tag{5.6}$$

Where:			
	n	=	Manning's roughness coefficient for stone riprap
	d_{50}	=	Diameter of stone for which 50 percent, by weight, of the gradation is finer (ft)

A Manning's n value of 0.035 can be used for wire-enclosed rock and a value of 0.023 to 0.030 can be used for grouted riprap.

Riprap requirements for a stable channel lining can be based on the following relationship (UDFCD 1984):

$$\mathbf{VS^{0.17}/d_{50}{}^{0.5}(S_s - 1)^{0.66} = 4.5} \tag{5.7}$$

Where:			
	V	=	Mean channel velocity (ft/s)
	S	=	Longitudinal channel slope (ft/ft)
	S_S	=	Specific gravity of rock (minimum S_S = 2.5)
	d_{50}	=	Diameter of stone for which 50 percent, by weight, of the gradation is finer (ft)

Rock sizing requirements are based on rock having a specific gravity of at least 2.5. Gradation and classification for riprap are shown in Tables 5-8 and 5-9.

Table 5-8 Rock Riprap Gradation Limits

Stone Size Range (ft.)	Stone Weight Range (lb)	Percent of Gradation Smaller Than
1.5 d_{50} to 1.7 d_{50}	3.0 W_{50} to 5.0 W_{50}	100
1.2 d_{50} to 1.4 d_{50}	2.0 W_{50} to 2.75 W_{50}	85
1.0 d_{50} to 1.15 d_{50}	1.0 W_{50} to 1.5 W_{50}	50
0.4 d_{50} to 0.6 d_{50}	0.1 W_{50} to 0.2 W_{50}	15

Table 5-9 Riprap Gradation Classes

Riprap Class	Rock Size[1] (ft.)	Rock Size[2] (lbs.)	Percent of Riprap Smaller Than
Facing	1.30	200	100
	0.95	75	50
	0.40	5	10
Light	1.80	500	100
	1.30	200	50
	0.40	5	10
1/4 ton	2.25	1000	100
	1.80	500	50
	0.95	75	10
½ ton	2.85	2000	100
	2.25	1000	50
	1.80	500	5
1 ton	3.60	4000	100
	2.85	2000	50
	2.25	1000	5
2 ton	4.50	8000	100
	3.60	4000	50
	2.85	2000	5

[1] Assuming a specific gravity of 2.65.
[2] Based on AASHTO gradations.

Rock-lined side slopes steeper than 2H:1V are considered unacceptable because of stability, safety, and maintenance considerations. Proper bedding is required along both the side slopes and channel bottom. The riprap blanket thickness should be at least 2 times d_{50} and should extend up the side slopes at least one foot above the design water surface. The upstream and downstream flanks require special treatment to prevent undermining. Details on these considerations are presented in section 5.11.2.

5.9 Concrete Channels

Concrete linings are used where smoothness offers a higher capacity for a given cross-sectional area. When properly designed, rigid linings may be appropriate where the channel width is restricted. Use of concrete linings is not encouraged due to the lack of water quality benefits as well as the propensity for higher velocities, which create the potential for scour at channel lining transitions.

5.10 Grade Control Structures

The most common use of channel drop structures or grade control structures is to control the longitudinal slope of grass-lined channels to keep design velocities within acceptable limits. Baffle chute drops, grouted sloping boulder drops, and vertical riprap drops are all examples of possible structures to use. The focus of this section will be on vertical riprap drops. Chapter 7 of this Manual provides guidance for more substantial energy dissipator structures used for larger flows and channel transitions.

The design of hydraulic structures, such as drop structures, must consider safety of the general public, especially when multiple uses are allowed (i.e., boating and fishing). There are certain hazards that can be associated with drop structures, such as the "reverse roller" phenomenon which can trap an individual and result in drowning. As a result, it may be necessary to sign locations accessible by the public to warn of the danger associated with the hydraulic structure and should be evaluated on a project by project basis.

5.10.1 Vertical Riprap Drops

An example of a vertical riprap drop is presented in Figure 5-6. The design of the drop is based upon the height of the drop and the normal depth and velocity of the approach and exit channels. The channel should be prismatic from the upstream channel through the drop to the downstream channel. The maximum recommended side slope for the stilling basin area is 4:1. Flatter side slopes are encouraged when available right-of-way exists. When riprap is grouted, the stilling basin side slopes can be steepened to 3:1. The riprap should extend up the side slopes to a depth 1 foot above the normal depth projected upstream from the downstream channel. For safety considerations, the maximum fall recommended at any one drop structure is 4 feet from the upper channel bottom to the lower channel bottom, excluding the low flow liner. Table 5-10 is a design chart to be used in conjunction with Figure 5-6 for sizing of the riprap basin and retaining wall structure. Rock-filled wire baskets may be a likely alternative to be considered by the designer for some structures.

5.10.1.1 Approach Depth

The upstream and downstream channels will normally be grass-lined trapezoidal channels with low flow liners to convey normal low flow water. The maximum normal depth, y_n, is 5 feet and the maximum normal velocity, v_n, is 7 ft/s for erosion-resistant soils and 5 ft/s for easily eroded soils.

5.10.1.2 Low Flow Liner

The low flow liner (shown as a concrete channel in Figure 5-6) ends at the upstream end of the upstream riprap apron. A combination cutoff wall and foundation wall is provided to give the end of the low flow liner additional support. The water is allowed to flow across the upstream apron and over the vertical wall. The low flow liner is ended at the upstream end of the apron to minimize the concentration of flows.

5.10.1.3 Approach Apron

A 10-foot long riprap apron (d_{50} = 12 inches is recommended) is provided upstream of the cutoff wall to protect against the increasing velocities and turbulence which result as the water approaches the vertical drop. Grouted riprap can also be used for the approach apron.

5.10.1.4 Crest Wall

The vertical wall should have the same trapezoidal shape as the approach channel. The wall distributes the flow evenly over the entire width of the drop structure, which minimizes flow concentrations that could adversely affect the riprap basin. The low flow liner flows pass through the wall via a series of notches in order to prevent ponding (see Figure 5-6).

The wall must be designed as a structural retaining wall, with the top of the wall above the upstream channel bottom. This is done to create a higher water surface elevation upstream, thereby reducing the draw-down effects normally caused by a sudden drop. The distance, P, that the top of the wall should be above the upstream channel, can be determined from Table 5-10 or from a backwater analysis.

5.10.1.5 Stilling Basin

The riprap stilling basin is designed to force the hydraulic jump to occur within the basin, and is designed for minimal scour. The floor of the basin is depressed an amount, B, below the downstream channel bottom, excluding the low flow liner. This is done to create a deeper downstream sequent depth which helps keep the hydraulic jump in the basin. This arrangement will cause ponding in the basin; however, a low flow liner can relieve all or some of the ponding.

The riprap basin can be sized using Table 5-10. To use the table, determine the required height of the drop, C, the normal velocity of the approach, v_n and the upstream and downstream normal depths, y_n and y_2, respectively. Both upstream and downstream channels must have the same geometry and y_n and y_2 must be equal to use Table 5-10. Select the appropriate riprap classification based on the row with the correct C, v_n, y_n, and y_2. The riprap should be placed on bedding and filter fabric and should extend up the channel side slopes a distance $y_2 + 1$ foot as projected from the downstream channel. The basin side slopes should be the same as those in the downstream channel (i.e., 4:1 or flatter).

When riprap is grouted to within approximately 4 inches of the riprap surface, then the rock size requirement can be reduced by one size from that specified in Table 5-10. However, if the grout has been placed such that much of the rock surface is smooth, a larger basin than specified in Table 5-10 would be required.

5.10.1.6 Exit Depth

The downstream channel design should be the same as the upstream channel, including a low flow liner. For concrete low flow liners, a cutoff wall similar to the one used for the upstream low flow liner should be used. This may also serve to control seepage and piping.

5.11 Stability and Bank Protection

5.11.1 Channel Stability Guidelines

The best way to avoid instability problems in urban stream channels and to maximize environmental benefits is to maintain streams in as natural a condition as possible, and when channel modification is necessary, to avoid altering channel dimensions, channel alignment, and channel slope as much as possible, except to account for impacts caused by urbanization. When channel modification is necessary, the following set of guidelines should be followed to minimize erosion problems and maximize environmental benefits:

- When channels must be enlarged, avoid streambed excavation that would significantly increase streambed slope or streambank height.
- When channel bottom widths are increased more than 25 percent, provide for a low flow channel to concentrate flows during critical low flow periods.
- Avoid channel realignment whenever feasible.

When unstable banks exist, several stabilization measures can be employed to provide the needed erosion protection and bank stability. The types of slope protection or revetment commonly used for bank stabilization include:

- turf reinforcement,
- rock riprap,
- wire-enclosed rock (gabions),
- pre-formed concrete blocks,
- grouted rock, and
- bioengineering methods
- poured-in-place concrete
- grout-filled fabric mattress

5.11.2 Rock Riprap

Placement of riprap is often used as bank or bed stabilization. Design of riprap size and thickness has been presented in numerous documents including those by Reese (1984 and 1988). Filter material is installed beneath riprap in all cases. Refer to the City of Lincoln standard specifications for material specification.

Filter Fabric Placement

To provide good performance, a properly selected cloth should be installed in accordance with manufacturer recommendations with due regard for the following precautions:

- Heavy riprap may stretch the cloth as it settles, eventually causing bursting of the fabric in tension. A 4-inch to 6-inch gravel bedding layer should be placed beneath the riprap layer for riprap gradations having d_{50} greater than 3.00 ft.
- The filter cloth should not extend into the channel beyond the riprap layer; rather, it should be wrapped around the toe material as illustrated in Figure 5-7.
- Adequate overlaps must be provided between individual fabric sheets.
- A sufficient number of folds should be included during placement to eliminate tension and stretching under settlement.
- Securing pins with washers are recommended at 2- to 5-ft intervals along the midpoint of the overlaps.
- Proper stone placement on the filter requires beginning at the toe and proceeding up the slope. Dropping stone from heights greater than 2 ft can rupture fabrics (greater drop heights are allowable under water).

5.11.2.1 Edge Treatment

The edges of riprap revetments (flanks, toe, and head) require special treatment to prevent undermining. The flanks of the revetment should be designed as illustrated in Figure 5-8. The upstream flank is illustrated in section (a) and the downstream flank is illustrated in section (b) of this figure. A more constructable flank section uses riprap rather than compacted fill.

Undermining of the revetment toe is one of the primary mechanisms of riprap failure. The toe of the riprap should be designed as illustrated in Figure 5-9. The toe material should be placed in a toe trench along the entire length of the riprap blanket.

Where a toe trench cannot be dug, the riprap blanket should terminate in a thick, stone toe at the level of the streambed (see alternate design in Figure 5-9). Care must be taken during the placement of the stone to ensure that the toe material does not mound and form a low dike; a low dike along the toe could result in flow concentration along the revetment face which could stress the revetment to failure. In addition, care must be exercised to ensure that the channel's design capability is not impaired by placement of too much riprap in a toe mound.

The size of the toe trench or the alternate stone toe is controlled by the anticipated depth of scour along the revetment. As scour occurs (and in most cases it will) the stone in the toe will launch into the eroded area. Observation of the performance of these types of rock toe designs indicates that the riprap will launch to a final slope of approximately 2:1.

The volume of rock required for the toe must be equal to or exceed one and one-half times the volume of rock required to extend the riprap blanket (at its design thickness and on a slope of 2:1) to the anticipated depth of scour. Dimensions should be based on the required volume using the thickness and depth determined by the scour evaluation. The alternate location can be used when the amount of rock required would not constrain the channel.

5.11.2.2 Construction Considerations

Construction considerations related to the construction of riprap revetments include bank slope or angle, bank preparation, and riprap placement.

The area should be prepared by first clearing all trees and debris, and grading the surface to the desired slope. In general, the graded surface should not deviate from the specified slope line by more than 6 inches. However, local depressions larger than this can be accommodated since initial placement of filter material and/or rock for the revetment will fill these depressions. In addition, any debris found buried near the edges of the revetment should be removed.

The common methods of riprap placement are hand placing; machine placing, such as from a skip, dragline, or some form of bucket; and dumping from trucks and spreading by bulldozer. Hand placement produces the best riprap revetment, but it is the most expensive method except when labor is unusually cheap. Steeper side slopes can be used with hand placed riprap than with other placing methods. Where steep slopes are unavoidable (when channel widths are constricted by existing bridge openings or other structures, and when rights-of-way are costly), hand placement should be considered.

In the machine placement method, sufficiently small increments of stone should be released as close to their final positions as practical. Rehandling or dragging operations to smooth the revetment surface tend to result in segregation and breakage of stone, and can result in an overly rough revetment surface. Stone should not be dropped from an excessive height as this may result in the same undesirable conditions. Riprap placement by dumping with spreading may be satisfactory provided the required layer thickness is achieved. Riprap placement by dumping and spreading is the least desirable method as a large amount of segregation and breakage can occur and is not recommended. In some cases, it may be economical to increase the layer thickness and stone size somewhat to offset the shortcomings of this placement method.

5.11.2.3 Design Procedure

The rock riprap design procedure outlined in the following sections is comprised of three primary sections: preliminary data analysis, rock sizing, and revetment detail design. The individual steps in the procedure are numbered consecutively throughout each of the sections.

<u>Preliminary Data</u>

1. Compile all necessary field data including (channel cross section surveys, soils data, aerial photographs, history of problems at site, etc.).
2. Determine design discharge.
3. Develop design cross section(s). Note: The rock sizing procedures described in the following steps are designed to prevent riprap failure from particle erosion.
4. Compute design water surface.
    a. When evaluating the design water surface, Manning's "n" shall be estimated. If a riprap lining is being designed for the entire channel perimeter, an estimate of the rock size may be required to determine the roughness coefficient "n".
    b. If the design section is a regular trapezoidal shape, and flow can be assumed to be uniform, use design procedures delineated in this chapter.
    c. If the design section is irregular or flow is not uniform, backwater procedures must be used to

determine the design water surface.

d. Any backwater analysis conducted must be based on conveyance weighing of flows in the main channel, right bank and left bank.

5. Determine design average velocity and depth.
   a. Average velocity and depth should be determined for the design section in conjunction with the computations of step 4. In general, the average depth and velocity in the main flow channel should be used.
   b. If riprap is being designed to protect channel banks, abutments, or piers located in the floodplain, average floodplain depths and velocities should be used.
6. Compute the bank angle correction factor

$$K_1 = [1 - (\sin^2\theta / \sin^2 \Phi)]^{0.5} \tag{5.8}$$

Where: θ = The bank angle with the horizontal
Φ = The riprap material's angle of repose

7. Determine riprap size required to resist particle erosion

$$d_{50} = 0.001\ V^3 / d_{avg}^{0.5} K_1^{\ 1.5}) \tag{5.9}$$

Where: d_{50} = The median riprap particle size, ft
V = The average velocity in the main channel, ft/s
davg = The average flow depth in the main flow channel ft,
K_1 = Bank angle correction factor

   a. Initially assume no corrections.
   b. Evaluate correction factor for rock riprap specific gravity and stability factor $C = C_{sg}C_{sf}$).

$$C_{sg} = 2.12 / S_s - 1)^{1.5}$$

Where: S_s = the specific gravity of the rock riprap

$$C_{sf} = (SF / 1.2)^{1.5}$$

Where: SF = the stability factor to be applied

8. If the entire channel perimeter is being stabilized, and an assumed d50 was used in determination of Manning's 'n' for backwater computations, return to step 4 and repeat steps 4 through 7.
9. Select final d50 riprap size, set material gradation, and determine riprap layer thickness.
10. Determine longitudinal extent of protection required.
11. Determine appropriate vertical extent of revetment.
12. Design filter layer.
    a. Determine appropriate filter material size and gradation.
    b. Determine layer thickness.
13. Design edge details (flanks and toe).

5.11.3 Wire-enclosed Rock

Wire-enclosed rock (gabion) revetments consist of rectangular wire mesh baskets filled with rock. The most common types of wire-enclosed revetments are mattresses and stacked blocks. The wire cages which make up the mattresses and gabions are available from commercial manufacturers.

Rock and wire mattress revetments consist of flat wire baskets or units filled with rock that are laid end to end and side to side on a prepared channel bed and/or bank. The individual mattress units are wired together to form a continuous revetment mattress.

Stacked block gabion revetments consist of rectangular wire baskets which are filled with stone and stacked in a stepped-back fashion to form the revetment surface. They are also commonly used at the toe of embankment slopes as toe walls which help to support other upper bank revetments and prevent undermining.

The rectangular basket or gabion units used for stacked configurations are more equidimensional than those typically used for mattress designs. That is, they typically have a square cross section. Commercially available gabions used in stacked configurations are available in various sizes but the most common have a 3-ft width and thickness.

Follow manufacturers recommended practice for design of gabions.

5.11.4 Pre-cast Concrete Blocks

Pre-cast concrete block revetments consist of pre-formed sections which interlock with each other, are attached to each other, or butt together to form a continuous blanket or mat. The concrete blocks which make up the mats differ in shape and method of articulation, but share certain common features. These features include flexibility, rapid installation, and provisions for the establishment of vegetation within the revetment.

Pre-cast revetments are bound using a variety of techniques. In some cases the individual blocks are bound to rectangular sheets of filter fabric (referred to as fabric carrier). Other manufacturers use a design which interlocks individual blocks. Other units are simply butted together at the site. The most common method is to join individual blocks with wire cable or synthetic fiber rope. Follow manufacturers recommended design procedure.

5.11.5 Grouted Rock

Grouted rock revetment consists of rock slope-protection having voids filled with concrete grout to form a monolithic armor. Grouted rock is not typically recommended due to maintenance and aesthetic concerns.

Components of grouted rock riprap design include layout of a general scheme or concept, bank preparation, bank slope, rock size and blanket thickness, rock grading, rock quality, grout quality, edge treatment, filter design, and pressure relief.

Grouted riprap designs are rigid monolithic bank protection schemes. When complete they form a continuous surface. A typical grouted riprap section is shown in Figure 5-10. Grouted riprap should extend from below the anticipated channel bed scour depth to the design high water level, plus additional height for freeboard.

During the design phase for a grouted riprap revetment, special attention needs to be paid to edge treatment, foundation design, and mechanisms for hydrostatic pressure relief.

<u>Bank And Foundation Preparation</u>

The area to be stabilized should be prepared by first clearing all trees and debris, and grading the surface to the desired slope. In general, the graded surface should not deviate from the specified slope line by more than 6 inches. However, local depressions larger than this can be accommodated since initial placement of filter material and/or rock for the revetment will fill these depressions.

Since grouted riprap is rigid but not extremely strong, support by the embankment must be maintained. To form a firm foundation, it is recommended that the bank surface be tamped or lightly compacted. Care must be taken during bank compaction to maintain a soil permeability similar to that of the natural, undisturbed bank material. The foundation for the grouted riprap revetment should have a bearing capacity sufficient to support either the dry weight of the revetment alone, or the submerged weight of the revetment plus the weight of the water in the wedge above the revetment for design conditions, whichever is greater.

<u>Bank Slope</u>

Bank slopes for grouted riprap revetments should not exceed 1.5:1. The soil stability slope will likely determine the maximum bank slope.

<u>Rock Size And Blanket Thickness</u>

Blanket thickness and rock size requirements for grouted riprap installation are interrelated. Figure 5-11 illustrates a relationship between the design velocity and the required riprap blanket thickness for grouted riprap designs. The median rock size in the revetment should not exceed 0.67 times the blanket thickness. The largest rock used in the revetment should not exceed the blanket thickness.

<u>Rock Grading</u>

Grouted riprap should meet all of the requirements for ordinary riprap except that the smallest rock fraction (i.e., smaller than the 10 percent size) should be eliminated from the gradation. A reduction of riprap size by one size designation is acceptable for grouted rock.

<u>Rock Quality</u>

Rock used in grouted rock slope-protection is usually the same as that used in ordinary rock slope-protection. However, the specifications for specific gravity and hardness may be lowered if necessary as the rocks are protected by the surrounding grout. In addition, the rock used in grouted riprap installations should be free of fines in order that penetration of grout may be achieved.

Grout Quality And Characteristics

Grout should consist of good strength concrete using a maximum aggregate size of 3/4 inch and a slump of 3 to 4 inches. Sand mixes may be used where roughness of the grout surface is unnecessary, provided sufficient cement is added to give good strength and workability.

The volume of grout required will be that necessary to provide penetration to the full depth of the riprap layer or at least 2 feet where the riprap layer is thicker than 2 feet. The finished grout should leave face stones exposed for one-fourth to one-third their depth and the surface of the grout should expose a matrix of coarse aggregate.

Edge Treatment

The edges of grouted rock revetments (the head, toe, and flanks) require special treatment to prevent undermining. The revetment toe should extend to a depth below anticipated scour depths or to bedrock. The toe should be designed as illustrated in Figure 5-10(a). After excavating to the desired depth, the riprap slope protection should be extended to the bottom of the trench and grouted. The remainder of the excavated area in the toe trench should be filled with ungrouted riprap. The ungrouted riprap provides extra protection against undermining at the bank toe.

To prevent outflanking of the revetment, various edge treatments are required. Recommended designs for these edge treatments are illustrated in Figure 5-10, parts (a), (b), and (c).

Filter Design

Filters are required under all grouted riprap revetments to provide a zone of high permeability to carry off seepage water and prevent damage to the overlying structure from uplift pressures. A 6-inch granular filter is required beneath the pavement to provide an adequate drainage zone. The filter can consist of well-graded granular material or uniformly-graded granular material with an underlying filter fabric. The filter should be designed to provide a high degree of permeability while preventing base material particles from penetrating the filter, thus causing clogging and failure of the protective filter layer.

Pressure Relief

Weep holes should be provided in the revetment to relieve hydrostatic pressure build-up behind the grout surface (see Figure 5-10(a)). Seeps should extend through the grout surface to the interface with the gravel underdrain layer. Weeps should consist of 2-inch minimum diameter pipes having a maximum horizontal spacing of 6 ft and a maximum vertical spacing of 10 ft. The buried end of the weep should be covered with wire screening or a fabric filter of a gage that will prevent passage of the gravel underlayer.

5.11.5.1 Construction

Construction details for grouted riprap revetments are illustrated in Figure 5-10. The following construction procedures should be followed:

1. Normal construction procedures include:
    a. Bank clearing and grading;
    b. Development of foundations;
    c. Placement of the rock slope protection;
    d. Grouting of the interstices;
    e. Backfilling toe and flank trenches; and
    f. Vegetation of disturbed areas.
2. The rock should be set immediately prior to commencing the grouting operation.
3. The grout may be transported to the place of final deposit by chutes, tubes, buckets, pneumatic equipment, or any other mechanical method which will control segregation and uniformity of the grout.
4. Spading and rodding are necessary where penetration is achieved by gravity flow into the interstices.
5. No loads should be allowed upon the revetment until good strength has been developed

5.11.6 Bioengineering Methods

Bioengineering combines mechanical, biological, and ecological concepts to construct "living" structures for bank and slope protection. Bioengineering methods use structural support to hold live plantings in place while the root structure grows and the plants are established. This is done through the use of sprigging, live crib walls, cut brush layers, live fascines, live stakes, and other methods.

Advantages of bioengineering include: natural appearance, the self-healing properties, habitat enrichment, and resistance to slope failure. Disadvantages include: labor-intensive installation, need for stability control until the roots are established, and dependence on materials to root and grow.

{provide more information}

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