Omaha Regional Stormwater Design Manual

Open Channels

Chapter 5

Revised June 2014

City of Omaha Environmental Quality Control Division
www.omahastormwater.org

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5.1 Overview

5.1.1 Introduction

Consideration of open channel hydraulics is an integral part of projects in which artificial channels and improvements to natural channels are a primary concern. 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.), and flow routing storage. Disadvantages include right-of-way needs 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 some cases, the well-planned use of natural channels and flow paths in the development of a major drainage system can reduce the need for underground storm sewer system facilities.

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 selection or evaluation of appropriate channel linings, depths, and grades for natural or man-made channels. Allowable velocities are provided, along with procedures for evaluating channel capacity using Manning's equation. Open channels shall be sized to handle the 100-year storm.

Hydraulic analysis software such as the Corps of Engineers HEC-RAS program may be useful when preparing preliminary and final channel designs.

For any open channel conveyance, channel stability must be evaluated to determine what measures are needed to avoid bottom scour and bank cutting. Channels should be left in, or restored to a natural-appearing condition that is feasible for the channel locale and setting, but must be designed for long-term stability. 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.), and flow-routing storage. The designer shall demonstrate, to the satisfaction of the Director of Public Works, that the natural condition, or an acceptable alternative channel design, will provide stable streambed and bank conditions.

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.

5.1.2 Channel Types

The main classifications of open channel types are natural, bio-technical vegetated, grass-lined, rock-lined, and concrete. Grass-lined channels include grass with mulch and/or sod, reinforced turf, and wetland bottom channel. Rock-lined channels include riprap, grouted riprap, and wire-enclosed rock.

5.1.2.1 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 (UDFCD, 1990). Natural channels must be designed to handle the flow required by this manual when using the actual shape (cross-section), slope, type of soil, and groundcover within the drainageway. In addition, there must be adequate undeveloped space on each side of the drainageway for maintenance vehicles and vegetative buffers. If only one side of the drainageway is accessible, a wider space is required on that side. The maintenance and buffer space shall not be included within the 10-year flow width, adjacent property owner's backyards, or in easements owned by a private property owner. The maintenance and buffer space may be included in the 100-year flow width as long as the land is level and clear enough for normal maintenance vehicles to use.

5.1.2.2 Grass-lined Channels

Channels vegetated with deeply-rooted grasses are the most desirable type of artificial 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 under which vegetative linings may not be acceptable, however, include but are not limited to:

1. Flow conditions in excess of the maximum shear stress for bare soils,
2. Lack of regular maintenance resources necessary to prevent domination by taller vegetation,
3. Lack of nutrients and inadequate topsoil,
4. Excessive shade,
5. High velocities, and
6. 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 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.

Sodding, when implemented, should be staggered, to avoid seams in the direction of flow. Lapped or shingle sod should be staggered and overlapped by approximately 25 percent. Staked sod is usually only necessary for use on steeper slopes to prevent sliding. Low flow areas may need to be concrete or rock-lined to minimize erosion and maintenance problems.

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).

Grass-lined channels may be landscaped with trees and other planting species if anticipated in the channel-design hydraulics, and if maintenance resources will be adequate to avoid domination by the taller vegetation that could diminish the effectiveness of a grass-lining.

5.1.2.3 Trickle Channel Linings

Under continuous baseflow conditions, if a vegetated lining cannot provide a stable streambed, a small concrete pilot or trickle channel could be used to handle the continuous low flows. Vegetation could then be maintained for handling larger flows. The trickle channel allows for easier maintenance and reduces erosion caused by a meandering low flow channel. Rock lining may also be used for trickle channels, but may require more maintenance and can encourage sediment deposition. Rock imbedded in concrete can obtain the best of both designs, but at greater cost. Trickle channel capacity should be roughly 1 to 5 percent of the design flow. Trickle flows may be conveyed in storm sewers (see Chapter 3).

5.1.2.4 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 rock and grouted riprap are other examples of commonly used rock-lined channels.

5.1.2.5 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.

5.1.2.6 Maintenance

Maintenance of open drainageways and channels is necessary to avoid reduction of hydraulic capacity, stability, and environmental functions. Provisions of maintenance will be consistent with the policies established in the Watershed Master Plan; in compliance with the applicable local codes and regulations; and implemented through advance formal agreements between the entities with jurisdiction or responsibility.

5.1.2.7 Tree Mitigation

Most projects which involve construction of, or within channels, will involve tree removal. As part of the planning and construction of such projects, mitigation for tree removals in accordance with City of Omaha and project permitting requirements, must be coordinated with the projects (s).

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.
d_x	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	—
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). Rapidly varied flow computations, such as hydraulic jumps and flow over spillways, however, can be very complex and the solutions are generally empirical in nature (Tulsa, 1993).

This section will present the basic equations and computational procedures for uniform, gradually varied, and rapidly varied flow. For more detailed discussion, the user is referred to references such as Chow's *Open-Channel Hydraulics* (1959) and French's *Open-Channel Hydraulics* (1985). 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 (Tulsa, 1993).

True uniform flow is difficult to observe in the field because not all of the parameters remain the same. However, channels are often designed 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.

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

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 man-made 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.

5.3.3.1 Uniform Flow and Normal Depth Example

A trapezoidal channel has a bottom width of 8 ft. and 4 to 1 side slopes. The grade is 0.005 ft. per ft. Manning's n is 0.035. What is the normal depth for discharge of 100 cfs?

Solve using Table 5-2:

1. Calculate:

$$\frac{Q \times n}{b^{2/3}\, s_0^{1/2}} = \frac{100 \times 0.035}{8^{2/3} \times 0.005^{1/2}} = 0.19$$

2. From Table 5-2 with the above value of side slope horizontal dimension, z, equal to 4, it is found that:

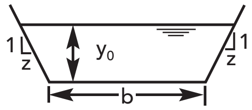
$$\frac{y_0}{b} = 0.235\ ; \text{ rearranging yields } y_0 = .235 \times b = 0.235 \times 8 = 1.88 \text{ ft.}$$

The designer should be aware that as the roughness coefficient increases, the same discharge will flow at a greater depth. Conversely, flow at the computed depth will result in less discharge if the roughness coefficient increases.

Table 5-2 Uniform Flow for Trapezoidal Channels by Manning Formula

Normal Depth For Uniform Flow $\frac{y_0}{b}$ = 0.02 to 0.64 (4)

Value of $\frac{Q \times n}{b^{2/3} s_0^{1/2}}$

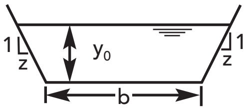


$\frac{y_0}{b}$	S=0	S= ¼	S= ½	S=¾	S=1	S=1 ¼	S=1 ½	S=2	S= 2 ½	S=3	S=4
0.02	0.00213	0.00215	0.00216	0.00217	0.00218	0.00219	0.00220	0.00221	0.00222	0.00223	0.00225
0.03	0.00414	0.00419	0.00423	0.00426	0.00429	0.00431	0.00433	0.00437	0.00440	0.00443	0.00449
0.04	0.00661	0.00670	0.00679	0.00685	0.00690	0.00696	0.00700	0.00707	0.00715	0.00722	0.00735
0.05	0.00947	0.00964	0.00980	0.00991	0.0100	0.0101	0.0102	0.0103	0.0104	0.0106	0.0109
0.06	0.0127	0.0130	0.0132	0.0134	0.0136	0.0137	0.0138	0.0141	0.0143	0.0145	0.0149
0.07	0.0162	0.0166	0.0170	0.0173	0.0176	0.0177	0.0180	0.0183	0.0186	0.0190	0.0196
0.08	0.0200	0.0206	0.0256	0.0262	0.0267	0.0271	0.0275	0.0282	0.0289	0.0296	0.0310
0.10	0.0283	0.0294	.0.305	0.0311	0.0313	0.0324	0.0329	0.0339	0.0348	0.0358	0.0375
0.11	0.0329	0.0342	0.0354	0.0364	0.0373	0.0380	0.0387	0.0400	0.0413	0.0424	0.0448
0.12	0.0376	0.0393	0.0408	0.0420	0.0431	0.0441	0.0430	0.0466	0.0482	0.0497	0.0527
0.13	0.0425	0.0446	0.0464	0.0480	0.0493	0.0505	0.0516	0.0537	0.0556	0.0575	0.0613
0.14	00.476	0.0501	0.0524	0.0542	0.0559	0.0573	0.0587	0.0612	0.0636	0.0659	0.0705
0.15	0.0528	0.0559	0.0583	0.0608	00628	0.0645	0.0662	0.0692	0.0721	0.0749	0.0805
0.16	0.0582	0.0619	0.0650	0.0676	0.0699	0.0720	0.0740	0.0776	0.0811	0.0845	0.0912
0.17	0.0638	0.0680	0.0717	0.0748	0.0775	0.0800	0.0823	0.0867	0.0907	0.0947	0.103
0.18	0.0695	0.0744	0.0786	0.0822	0.0854	0.0883	0.0910	0.0961	0.101	0.105	0.115
0.19	0.0753	0.0809	0.0857	0.0900	0.0936	0.0970	0.100	0.106	0.112	0.117	0.128
0.20	0.0813	0.0875	0.0932	0.0979	0.102	0.106	0.110	0.116	0.123	0.129	0.141
0.21	0.0673	0.0944	0.101	0.106	0.111	0.115	0.120	0.127	0.134	0.142	0.156
0.22	0.0935	0.101	0.109	0.115	0.120	0.125	0.130	0.139	0.147	0.155	0.171
0.23	0.0997	0.109	0.117	0.124	0.130	0.135	0.141	0.151	0.160	0.169	0.187
0.24	0.106	0.116	0.125	0.133	0.139	0.146	0.152	0.163	0.173	0.184	0.204
0.25	0.113	0.124	0.133	0.142	0.150	0.157	0.163	0.176	0.187	0.199	0.222
0.26	0.119	0.131	0.142	0.152	0.160	0.168	0.175	0.189	0.202	0.215	0.241
0.27	0.126	0.139	0.151	0.162	0.171	0.180	0.188	0.203	0.218	0.232	0.260
0.28	0.133	0.147	0.160	0.172	0.182	0.192	0.201	0.217	0.234	0.249	0.281
0.29	0.139	0.155	0.170	0.182	0.193	0.204	0.214	0.232	0.250	0.267	0.302
0.30	0.146	0.163	0.179	0.193	0.205	0.217	0.227	0.248	0.267	0.286	0.324
0.31	0.153	0.172	0.189	0.204	0.217	0.230	0.242	0.264	0.285	0.306	0.347
0.32	0.160	0.180	0.199	0.215	0.230	0.243	0.256	0.281	0.304	0.327	0.371
0.33	0.167	0.189	0.209	0.227	0.243	0.257	0.271	0.298	0.323	0.348	0.396
0.34	0.174	0.198	0.219	0.238	0.256	0.272	0.287	0.315	0.343	0.369	0.422
0.35	0.181	0.207	0.230	0.251	0.270	0.287	0.303	0.334	0.363	0.392	0.450
0.36	0.190	0.216	0.241	0.263	0.283	0.302	0.319	0.353	0.384	0.416	0.477
0.37	0.196	0.225	0.251	0.275	0.297	0.317	0.336	0.372	0.406	0.440	0.507
0.38	0.203	0.234	0.263	0.289	0.311	0.333	0.354	0.392	0.429	0.465	0.536
0.39	0.210	0.244	0.274	0.301	0.326	0.349	0.371	0.412	0.452	0.491	0.568
0.40	0.218	0.254	0.286	0.314	0.341	0.366	0.389	0.433	0.476	0.518	0.600
0.41	0.225	0.263	0.297	0.328	0.357	0.383	0.408	0.455	0.501	0.545	0.634
0.42	0.233	0.279	0.310	0.342	0.373	0.401	0.427	0.478	0.526	0.575	0.668
0.43	0.241	0.282	0.321	0.356	0.389	0.418	0.447	0.501	0.553	0.604	0.703
0.44	0.249	0.292	0.334	0.371	0.405	0.437	0.467	0.524	0.579	0.634	0.739
0.45	0.256	0.303	0.346	0.385	0.422	0.455	0.487	0.548	0.607	0.665	0.778
0.46	0.263	0.313	0.359	0.401	0.439	0.475	0.509	0.574	0.635	0.696	0.816
0.47	0.271	0.323	0.371	0.417	0.457	0.494	0.530	0.600	0.665	0.729	0.856
0.48	0.279	0.333	0.384	0.432	0.475	0.514	0.552	0.626	0.695	0.763	0.897
0.49	0.287	0.345	0.398	0.448	0.492	0.534	0.575	0.652	0.725	0.797	0.939
0.50	0.295	0.356	0.411	0.463	0.512	0.556	0.599	0.679	0.758	0.833	0.983
0.52	0.310	0.377	0.438	0.494	0.548	0.599	0.646	0.735	0.820	0.906	1.07
0.54	0.327	0.398	0.468	0.530	0.590	0.644	0.696	0.795	0.891	0.984	1.17
0.56	0.343	0.421	0.496	0.567	0.631	0.690	0.748	0.856	0.963	1.07	1.27
0.58	0.359	0.444	0.526	0.601	0.671	0.739	0.802	0.922	1.04	1.15	1.37
0.60	0.375	0.468	0.556	0.640	0.717	0.789	0.858	0.988	1.12	1.24	1.49
0.62	0.391	0.492	0.590	0.679	0.763	0.841	0.917	1.06	1.20	1.33	1.60
0.64	0.408	0.516	0.620	0.718	0.809	0.894	0.976	1.13	1.28	1.43	1.72

Source: UDFCD, 1990

Table 5-2 (continued) Uniform Flow for Trapezoidal Channels by Manning Formula

Normal Depth For Uniform Flow $\frac{y_0}{b}$ = 0.66 to 5.00 (4)

$\frac{y_0}{b}$	Value of $\frac{Q \times n}{b^{2/3} s_0^{1/2}}$										
0.66	0.424	0.541	0.653	0.759	0.858	0.951	1.04	1.21	1.37	1.53	1.85
0.68	0.441	0.566	0.687	0.801	0.908	1.01	1.10	1.29	1.47	1.64	1.98
0.70	0.457	0.591	0.722	0.842	0.958	1.07	1.17	1.37	1.56	1.75	2.12
0.72	0.474	0.617	0.757	0.887	1.01	1.13	1.24	1.45	1.66	1.87	2.27
0.74	0.491	0.644	0.793	0.932	1.07	1.19	1.31	1.55	1.77	1.98	2.41
0.76	0.508	0.670	0.830	0.981	1.12	1.26	1.39	1.64	1.88	2.11	2.57
0.78	0.525	0.698	0.868	1.03	1.18	1.32	1.46	1.73	1.98	2.24	2.73
0.80	0.542	0.725	0.906	1.08	1.24	1.40	1.54	1.83	2.10	2.37	2.90
0.82	0.559	0.753	0.945	1.13	1.30	1.47	1.61	1.93	2.22	2.51	3.07
0.84	0.576	0.782	0.985	1.18	1.36	1.54	1.71	2.03	2.34	2.65	3.25
0.86	0.593	0.810	1.03	1.23	1.43	1.61	1.79	2.14	2.47	2.80	3.44
0.88	0.610	0.839	1.07	1.29	1.49	1.69	1.88	2.25	2.60	2.95	3.63
0.90	0.627	0.871	1.11	1.34	1.56	1.77	1.98	2.36	2.74	3.11	3.83
0.92	0.645	0.898	1.13	1.40	1.63	1.86	2.07	2.48	2.88	3.27	4.04
0.94	0.662	0.928	1.20	1.46	1.70	1.94	2.16	2.60	3.03	3.43	4.25
0.96	0.680	0.960	1.25	1.52	1.78	2.03	2.27	2.73	3.17	3.61	4.48
0.98	0.697	0.991	1.29	1.58	1.85	2.11	2.37	2.85	3.33	3.79	4.70
1.00	0.714	1.02	1.33	1.64	1.93	2.21	2.47	2.99	3.48	3.97	4.93
1.05	0.759	1.10	1.46	1.80	2.13	2.44	2.75	3.33	3.90	4.45	5.55
1.10	0.802	1.19	1.58	1.97	2.34	2.69	3.04	3.70	4.34	4.96	6.21
1.15	0.846	1.27	1.71	2.14	2.56	2.96	3.34	4.09	4.82	5.52	6.91
1.20	0.891	1.36	1.85	2.33	2.79	3.24	3.68	4.50	5.32	6.11	7.68
1.25	0.936	1.45	1.99	2.52	3.04	3.54	4.03	4.95	5.86	6.73	8.48
1.30	.0980	1.54	2.14	2.73	3.30	3.85	4.39	5.42	6.42	7.39	9.34
1.35	1.02	1.64	2.29	2.94	3.57	4.18	4.76	5.90	7.01	8.10	10.2
1.40	1.07	1.74	2.45	3.16	3.85	4.52	5.18	6.43	7.65	8.83	11.2
1.45	1.11	1.84	2.61	3.39	4.15	4.88	5.60	6.98	8.30	9.62	12.2
1.50	1.16	1.94	2.78	3.63	4.46	5.26	6.04	7.55	9.02	10.4	13.3
1.55	1.20	2.05	2.96	3.88	4.78	5.65	6.50	8.14	9.74	11.3	14.4
1.60	1.25	2.15	3.14	4.14	5.12	6.06	6.99	8.79	10.5	12.2	15.6
1.65	1.30	2.27	3.33	4.41	5.47	6.49	7.50	9.42	11.3	13.2	16.8
1.70	1.34	2.38	3.52	4.69	5.83	6.94	8.02	10.1	12.2	14.2	18.1
1.75	1.39	2.50	3.73	4.98	6.21	7.41	8.57	10.9	13.0	15.2	19.5
1.80	1.43	2.62	3.93	5.28	6.60	7.89	9.13	11.6	14.0	16.3	20.9
1.85	1.48	2.74	4.15	5.59	7.01	8.40	9.75	12.4	15.0	17.4	22.4
1.90	1.52	2.86	4.36	5.91	7.43	8.91	10.4	13.2	15.9	18.7	24.0
1.95	1.57	2.99	4.59	6.24	7.87	9.46	11.0	14.0	17.0	19.9	25.6
2.00	1.61	3.12	4.83	6.58	8.32	10.0	11.7	14.9	18.0	21.1	27.2
2.10	1.71	3.39	5.31	7.30	9.27	11.2	13.1	16.8	20.3	23.9	30.8
2.20	1.79	3.67	5.82	8.06	10.3	12.5	14.6	18.7	22.8	26.8	34.7
2.30	1.89	3.96	6.36	8.86	11.3	13.8	16.2	20.9	25.4	30.0	38.8
2.40	1.98	4.26	6.93	972	12.5	15.3	17.9	23.1	28.3	33.4	43.3
2.50	2.07	4.58	7.52	10.6	13.7	16.8	19.8	25.6	31.3	37.0	48.0
2.60	2.16	4.90	8.14	11.6	15.0	18.4	21.7	28.2	34.5	408	53.0
2.70	2.26	5.24	8.80	12.6	16.3	20.1	23.8	31.0	37.9	44.8	58.4
2.80	2.35	5.59	9.49	13.6	17.8	21.9	25.9	33.8	41.6	49.1	64.0
2.90	2.44	5.95	10.2	14.7	19.3	23.8	28.2	36.9	45.3	53.7	70.1
3.00	2.53	6.33	11.0	15.9	20.9	25.8	30.6	40.1	49.4	58.4	76.4
3.20	2.72	7.12	12.5	18.3	24.2	30.1	35.8	47.1	58.0	68.9	90.3
3.40	2.90	7.97	14.2	21.0	27.9	34.8	41.5	54.6	67.7	80.2	105
3.60	3.09	8.86	16.1	24.0	32.0	39.9	47.8	63.0	78.2	92.8	122
3.80	3.28	9.81	18.1	27.1	36.3	45.5	54.6	72.4	89.6	107	141
4.00	3.46	10.8	20.2	30.5	41.1	51.6	61.9	82.2	12	122	160
4.50	3.92	13.5	26.2	40.1	54.5	688	82.9	111	136	164	217
5.00	4.39	16.7	33.1	51.5	70.3	89.2	108	145	181	216	287

Source: UDFCD, 1990

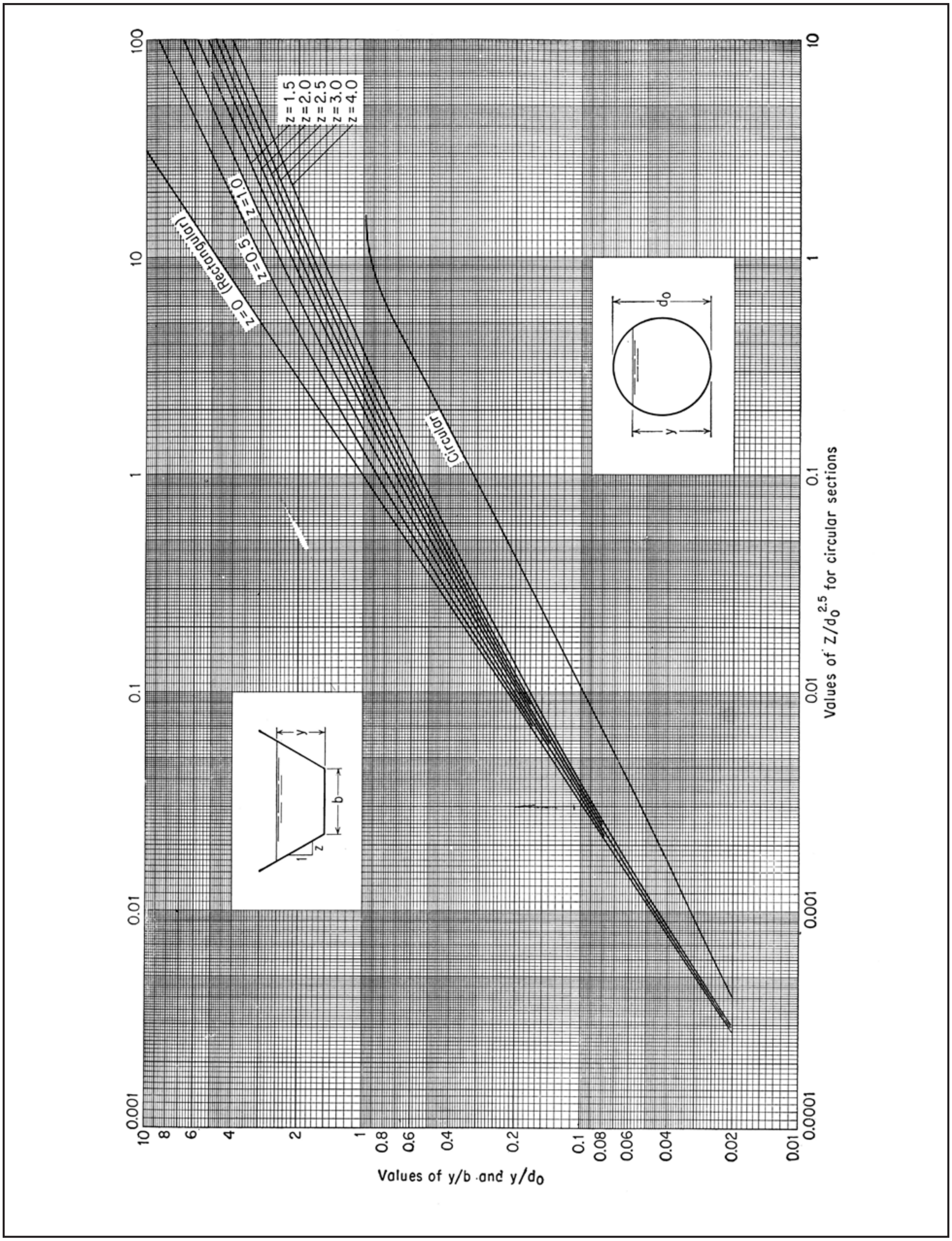


Figure 5-1 Normal Depth for Uniform Flow in Open Channels Source: Chow, 1959

5.3.4 Critical Flow

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:

$$\mathbf{Fr = v / (gD)0.5} \qquad \mathbf{(5.2)}$$

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, 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 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 man-made channels. Bridge Waterways Analysis Model (WSPRO) and HY-8 are

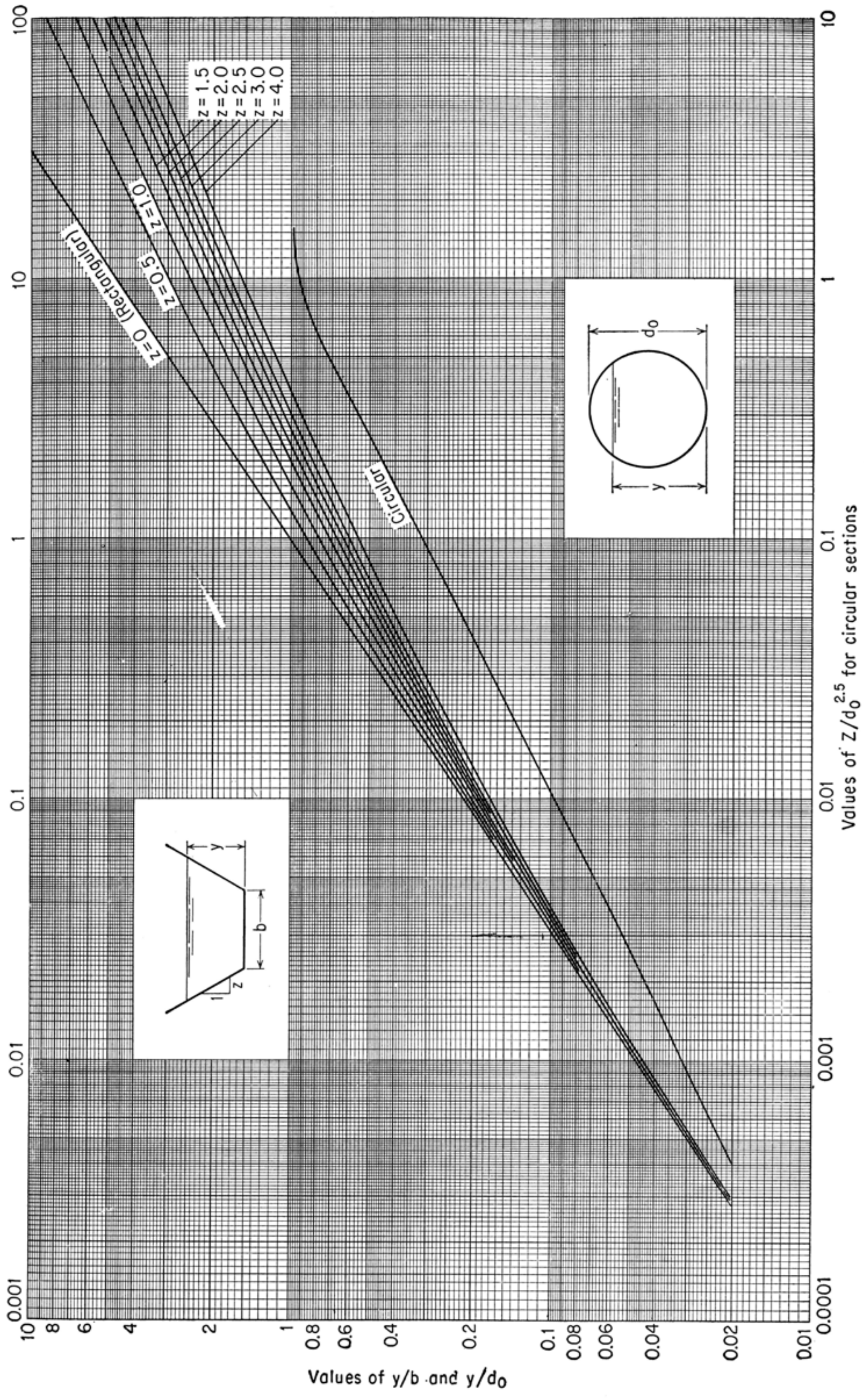


Figure 5-2 Critical Depth in Open Channels

Source: Chow, 1959

programs developed for the Federal Highway Administration that can also be used to perform backwater calculations for both natural and artificial channels.

For prismatic channels, the backwater calculation can be computed manually using the direct step method, as presented by Chow (1959). For an irregular nonuniform channel, the standard step method is recommended, although it is a more tedious and iterative process. 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 sewers or concrete box culverts, or at the outlet of an emergency (or auxillary) 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 can often afford the most effective protection.

5.3.6.1.1 Storm Sewers

Hydraulic jump may occur in storm sewers flowing in partially full (open channel) conditions. The analysis of the hydraulic jump inside storm sewers is approximate, because of 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 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:

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

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 open channel design:

1. Trapezoidal cross sections are preferred and triangular shapes should be avoided.
2. 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.
3. 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.
4. 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.
5. A low flow or trickle channel is recommended for all grass-lined channels.
6. Low flow sections shall be used in the design of channels with large cross sections.
7. New channels with bottom widths greater than 10 ft. shall be designed with a minimum bottom cross slope of 12 to 1 to discourage meandering.
8. Superelevation of the water surface at horizontal curves shall be accounted for by increased freeboard.
9. 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 (Tulsa 1993).

5.4.2 Channel Transitions

The following criteria should be considered at channel transitions:

1. Transition to channel sections should be smooth and gradual.
2. 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.
3. Transition sections should be designed to provide a gradual transition to avoid turbulence and eddies.
4. Energy losses in transitions should be accounted for as part of the water surface profile calculations.
5. 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

When comprising the major drainage system, open channels shall be sized to handle the 100-year flow. There shall be no buildings allowed within the calculated high water area based on the final shape and groundcover of the drainageway. An easement or other method of restricting building construction within the high water area is required. High water levels and limits should be determined by the designer using USACE HEC-RAS modeling.

5.4.4 Velocity Limitations

Sediment transport requirements must be considered for conditions of flow below the design frequency. A low flow channel component within a larger channel can reduce maintenance by improving sediment transport in the channel.

The final design of artificial 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. Higher design velocities may be approved by the Director of Public Works if supported by clearly conclusive soils and shear stress analyses.

Table 5-3 Maximum Design Velocities for Comparing Lining Materials (all values in ft./s.)

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 (non-colloidal)	1.45	2.5	2.0
Silt Loam (non-colloidal)	2.0	3.0	2.0
Alluvial Silt (non-colloidal)	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 (non-colloidal)	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

Table 5-4 Maximum Velocities For Vegetative Channel Linings

Vegetation Type	Slope Range (%)[1]	Maximum Velocity[1] (ft./s.)[2]	
		Erosion Resistant 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
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

[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.

Source: USDA, TP-61, 1954

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, the 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. Additional guidance can be found in the NRCS National Engineering Handbook, Section 11, Drop Spillways and Section 14, Chute Spillways.

Examples of grade control structures include:

Sills or Check Structures — A sill is a structure that extends across a channel and has a surface that is flush with the channel invert or that extends a ft. or two above the invert. Because sills 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. Sills 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, sills extending above the channel invert may be constructed of, or faced with, materials such as natural stone that create an attractive appearance. Sills 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 plunge pools and/or stabilization practices are required below these structures.

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.

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

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. 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 may include repairing erosion damage; mowing grass; cutting brush; removing sediment or debris; appropriate application of fertilizer; irrigation during dry periods; and reseeding or resodding to restore the viability of damaged areas. Ample sizing of channels should 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.

5.5 Natural Channel Design Criteria

Natural channels in the Omaha area are often found to have erodible banks and bottoms which tend to result in steep, vertical banks. Other channels may have mild slopes and be reasonably stable. If natural channels are 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 in the future. A 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 urbanized, fully developed storm runoff.
- Manning's n roughness factors, representative of highly-probable future channel conditions, shall be used. Table 5-5 provides representative values of the roughness factor in natural streams. Unless the drainageway is "improved" with engineering structures, and there is an agreement to maintain them, assume for purposes of hydraulic analysis that the stream will be irregular and rough, with a heavy stand of timber and dense underbrush within the drainageway.
- The water surface profiles must be defined and delineated so that the 100-year floodplain can be identified and managed. Plan and profile drawings should be prepared of the FEMA floodplain, and allowances should be made for future bridges or culverts.
- Filling of the floodplain is subject to the restriction of floodplain regulations.
- Erosion control structures such as drop structures and grade control checks should be provided as necessary to control flow velocities and channel erosion. Design should anticipate, and provide long-term stability for, a full range of flow conditions up to and including the 100-year storm event flow from urbanized, full development.

Natural channels should be left in as near a natural condition as feasible. However, with most natural channels, grade control structures will 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. Special consideration shall be given to transitions from "hard" to "soft" stabilization materials to minimize the potential for erosion at these locations. In addition, the engineer is reminded that modification of the channel may require 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 artificial channels, such as freeboard depth and curvature, may not apply to natural channels in order to meet some of the multi-purpose objectives. In performing designs which incorporate natural channels, channel width, and right-of-ways/easements shall be designed which designate the full extent of space to be occupied by channel maintenance and flood flows. The minimum easement/right-of-way width shall be the wider of the 100-year flow, or the width determined by a 3H:1V slope on each side of the channel projected up from the lowest point in the channel to the overbank ground surface. Whichever of these methods determines the required widest right-of-way width, the designated right-of-way width must include a 20-ft. minimum-width maintenance route and a 30-ft. minimum vegetated buffer width along each side of the channel. The 100 ft. of minimum width for maintenance and buffer purposes may be within the 100-year flow width if terrain is suitable, but no portion of the maintenance accesses shall be within the 10-year flow width. All portions of the maintenance accesses must be level and clear enough so normal maintenance vehicles can use it without difficulty. See Figure 5-3.

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

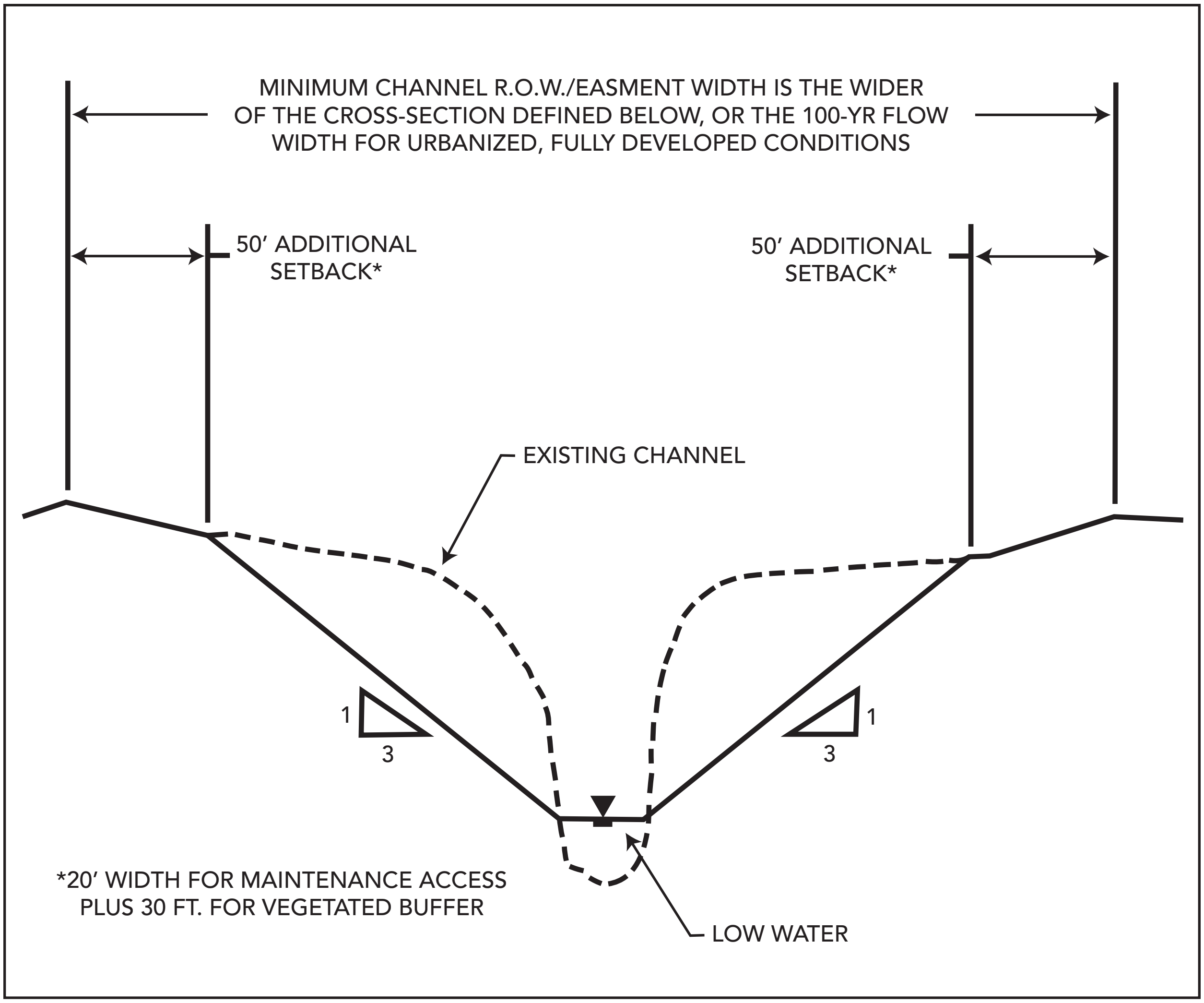


Figure 5-3 Channel ROW/Easement Width

5.6 Grass-Lined Channel Design Criteria

Grass-lined channels are encouraged when designing artificial 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 trickle channel 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 ft./s. 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). Unless there is field information to the contrary, assume the soils are easily eroded.

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, drop 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. depth	>3.0 ft. depth
Bermuda grass, Buffalo grass Kentucky bluegrass	Mowed to 2 in.	0.035	0.030
	Length 4 to 6 in.	0.040	0.030
Good stand any grass	Length to 12 in.	0.070	0.035
	Length to 24 in.	0.100	0.035
Fair stand any grass	Length to 12 in.	0.060	0.035
	Length to 24 in.	0.070	0.035

Source: UDFCD, 1990

5.6.4 Freeboard

A minimum freeboard of 1 ft. should be provided between the water surface and top of bank or the elevation of the lowest opening of adjacent structures. In some areas, planned localized overflow may be desirable for additional ponding/storage benefits. The elevation of the minimum height of any opening in an adjacent structure must be listed on the plat for each lot.

Superelevation of the water surface should be determined at horizontal curves. An approximation of the superelevation can be made from the following equation:

$$\mathbf{h = V^2 Tw / g r_c} \qquad \mathbf{(5.4)}$$

Where: h = superelevation (ft.)
V = velocity (ft./s.)
Tw = top width of channel (ft.)
g = acceleration due to gravity (32.2 ft./s.^{2})
r_c = centerline radius of curvature (ft.)

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 ft.

5.6.6 Cross-sections

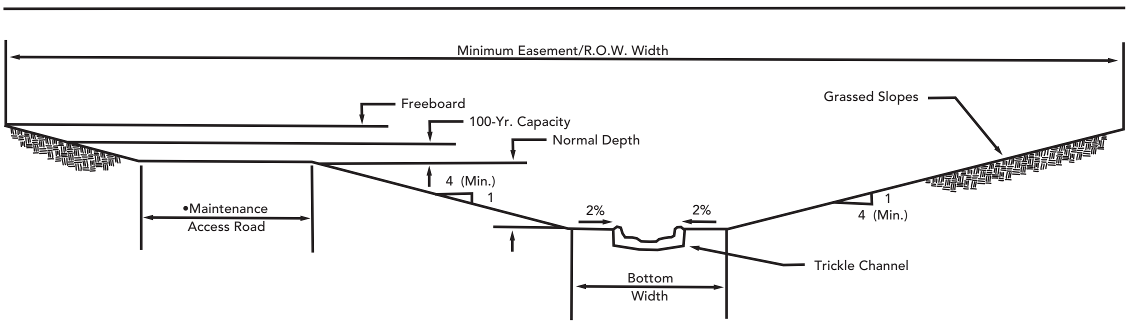
Channel shape may be almost any type suitable to the site-specific conditions, and can be designed to meet multi-purpose uses, such as recreational needs and wildlife habitat. However, limitations to the design include the following:

- 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.
- Trickle channels 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 5-4 shows typical cross-sections suitable for grass-lined channels. Trickle channels should be designed to carry base flow originating from lawn watering, low intensity rainfall events, and snow melt.

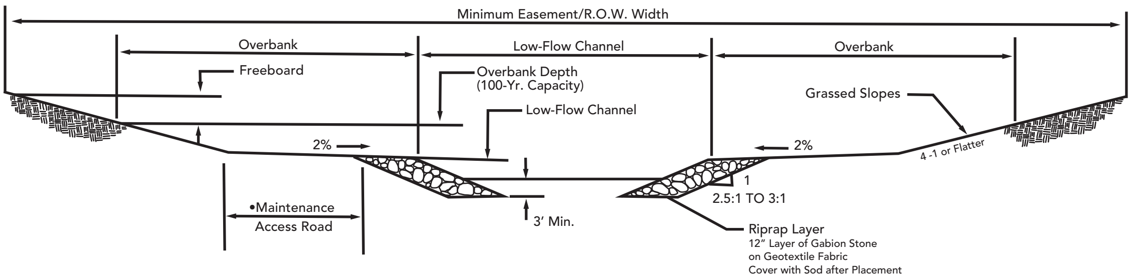
5.6.7 Grass Species

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 City of Omaha Standard Specifications.

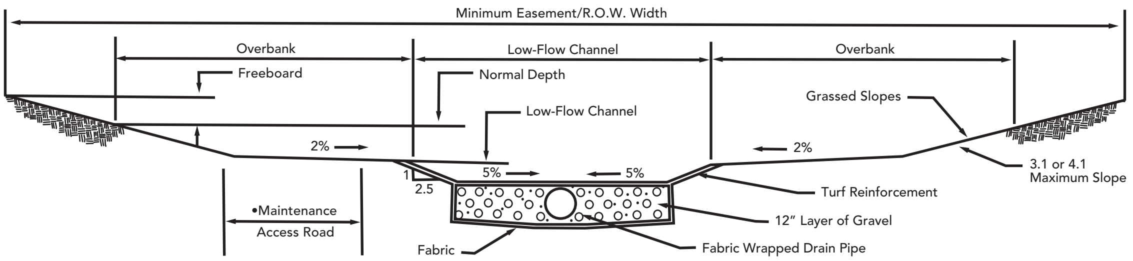
For additional guidance on seed mixes and seed rates the reader is referred to the local Natural Resources Conservation Service branch office and the P-MRNRD. Table 5-7 provides suggested seed mixtures.



WITH A TRICKLE FLOW CHANNEL



WITH A LOW-FLOW CHANNEL



•Maintenance Road may be
located on Top of Bank of the
Major Channel

WITH AN UNDERDRAIN

Figure 5-4 Typical Grass-Lined Channel Details

Source: UDFCD, 1990

Table 5-7 Suggested Seed Mixtures

Seeding Dates	Suggested Mixture	Lbs to Furnish 60 PLS /sq. ft. Per Ac.	Loams, Clayloams and Clays						Sands and Loamy Sand				Remarks
Warm Season Dominant			A	B	C	D	E	F	A	B	E	F	
October 1 — June 15	Big bluestem	4.0	X	0	—	—	X	—	X	—	X	—	For sands and loamy sands substitute sand bluestem for big bluestem, 1.8 lbs of prairie sandreed for sideoats grama and 0.2 lbs PLS sand lovegrass for tall fescue
	Sideoats grama	2.9	X	0	—	—	X	—	X	—	X	—	
	Switchgrass	0.7	X	0	—	—	X	—	X	—	X	—	
	Indiangrass	3.6	X	0	—	—	X	—	X	—	X	—	
	Tall fescue	2.1	X	0	—	—	X	—	X	—	X	—	
	Buffalograss (burs)	38.0	—	—	—	X	X	X	—	X	—	X	
	Blue grama	06	—	—	—	X	X	X	—	X	—	X	
	Buffalograss (burs)	32.3	0	—	—	X	X	X	—	X	—	X	
	Blue grama	0.6	0	—	—	X	X	X	—	X	—	X	
	Sideoats grama	2.7	0	—	—	X	X	X	—	X	—	X	
	Switchgrass	3.8	—	X	X	—	—	—	X	—	X	—	Wet area
Cool Season Dominant			A	B	C	D	E	F	A	B	E	F	
August 15 — April 30	Smooth brome	14.4	X	0	—	—	X	—	X	—	0	—	Add 10 lbs of western wheatgrass to replace 7.2 lbs of brome or 3.6 lbs of tall fescue
	Switchgrass	1.7	X	0	—	—	X	—	X	—	0	—	
	Tall fescue	7.3	X	X	0	—	X	—	0	—	0	—	
	Switchgrass	2.4	X	X	0	—	X	—	0	—	0	—	
	Perennial ryegrass	5.2	—	—	—	X	—	X	—	X	—	X	Less than 5 years
	Alfalfa	10.8	—	—	—	X	—	X	—	X	—	X	
	Red clover	3.9	—	—	—	X	—	X	—	X	—	X	Substitute 0.6 lbs PLS sand lovegrass to replace tall fescue for sands and loamy sands
	Birdsfoot trefoil	1.9	—	—	—	X	—	X	—	X	—	X	
	Tall fescue	6.3	—	—	—	X	—	X	—	X	—	X	

Source: LPSNRD, 1994

KEY:				
X	Best	A Dam, Diversion, Dike	D Heavy Traffic & recreation
O	Fair	B Channels	E Roadside
—	Poor	C Shoreline & Low Areas	F Residential & Development Sites

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 trickle channel 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 aggradation 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 ft./s. for erosion resistant soils and 5.0 ft./s. 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. Unless there is field information to the contrary, assume that the soils are easily eroded.

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 5-5 (UDFCD 1990):

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

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 5-5)
p_0 = wetted perimeter of channel above wetland area
p_w = wetted perimeter of wetland area (approximated as bottom width plus 10 ft.)

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 ft. 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 ft. 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.

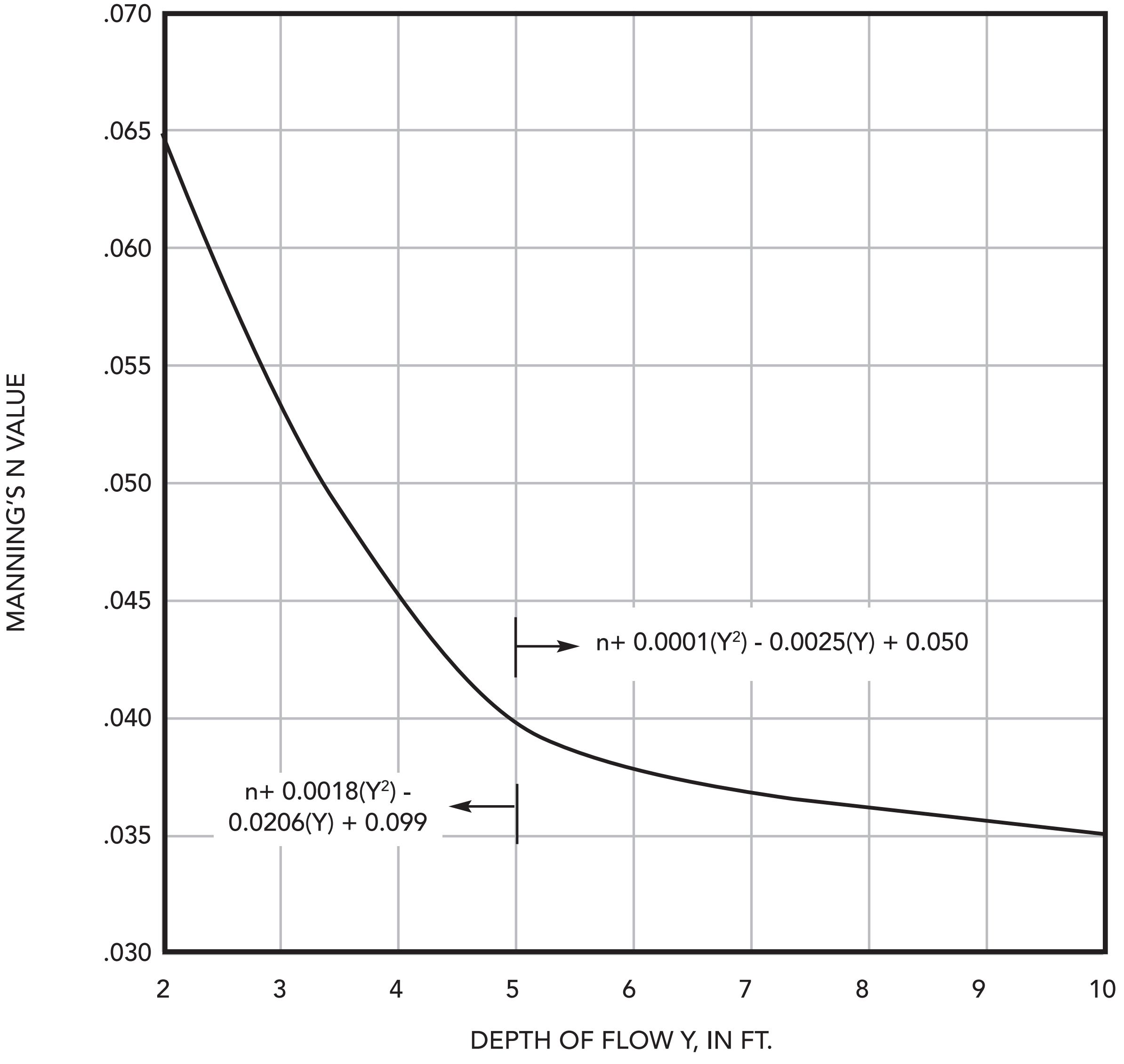
5.7.6 Curvature

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 ft.

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., 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 ft.
- 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. The second cross-section shown on Figure 5-4 may be suitable for wetland bottom channel design.



*Use normal depth, ignoring all backwater effects

Figure 5-5 Depth of Flow vs. Manning's n for Wetland Bottom

Source: UDFCD, 2001

5.8 Rock-Lined Channel Design

Rock-lined channels constructed from riprap, buried and vegetated riprap, grouted riprap, or wire-enclosed 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):

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

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):

$$\frac{VS^{0.17}}{d_{50}^{\;0.5}\,(S_s\ -\ 1)^{0.66}} = 4.5 \qquad \mathbf{(5.7)}$$

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	Stone Weight Range	Percent Of Gradation
(ft.)	(lb.)	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]	Rock Size[2]	Percent Of Riprap
	(ft.)	(lbs.)	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 1.75 times d_{50} and should extend up the side slopes at least one ft. 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. The guidance presented in this section for design of vertical riprap drops was obtained from the City of Tulsa Stormwater Management Manual (1993). Other design approaches exist which are also appropriate for vertical drops and other types of grade control structures. For example, the reader is referred to the SCS National Engineering Handbook for more detail on chute and sloping boulder drops. Also, Chapter 7 of this Manual provides guidance for other energy dissipator structures.

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 ft. above the normal depth projected upstream from the downstream channel. For safety considerations, the maximum fall recommended at any one drop structure is 4 ft. from the upper channel bottom to the lower channel bottom, excluding the trickle channel. 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 trickle channels to convey normal low flow water. The maximum normal depth, y_n, is 5 ft. 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 Trickle Channel

The trickle channel (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 trickle channel additional support. The water is allowed to flow across the upstream apron and over the vertical wall. The trickle channel is ended at the upstream end of the apron to minimize the concentration of flows.

5.10.1.3 Approach Apron

A 10-ft. long riprap apron (d_{50} = 12 in. 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 trickle 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 trickle channel. 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 trickle channel 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, vn 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 ft. 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 in. 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 trickle channel. For concrete trickle channels, a cutoff wall similar to the one used for the upstream trickle channel should be used. This may also serve to control seepage and piping.

5.10.1.7 Design Example

The following example demonstrates the use of Table 5-10 and Figure 5-6 for the sizing of riprap basin dimensions and selection of riprap.

Given a Q_{100} = 400 cfs and the following upstream and downstream channel dimensions:

- bottom width = 8 ft.
- longitudinal slope = 0.004 ft./ft.
- side slopes = 4:1
- y_c = 2.8 ft.
- y_n = 4 ft.
- v_n = 4.2 ft./s.
- channel drop, C = 3 ft.

From Table 5-10, for C = 3.0 ft., v_n = 4.2 ft./s. (assume v_n = 5 ft./s. on table), and y_n and y^2 = 4.0 ft., the following dimensions can be determined:

- P = 0.1 ft.
- B = 1.0 ft.
- A = 2.5 ft.
- LB = 20 ft.
- D = 5 ft.
- E = 4 ft.
- Riprap = d_{50} of 18 in.

Table 5-10 Vertical Riprap Channel Drop Design Chart

C (ft.)	v_n (ft./s.)	v_n & y^2 (ft.)	P (ft.)	B (ft.)	A (ft.)	LB (ft.)	D (ft.)	E (ft.)	Riprap d50 (in.)
2	5	4	0.1	0.6	2.0	20	4	3	12
2	5	5	*	0.8	2.5	25	5	4	18
2	5; 7	4	0.1	0.8	2.5	20	5	4	18
2	5; 7	5	*	0.8	2.5	25	5	4	18
3	5	4	0.1	1.0	2.5	20	5	4	18
3	5	5	*	1.0	2.5	25	5	4	18
3	5; 7	4	0.1	1.0	2.5	20	5	4	18
3	5; 7	5	*	1.0	2.5	25	5	4	18
4	5	4	0.1	1.2	3.5	20	7	5	18
4	5	5	*	1.2	3.5	25	7	5	18
4	5; 7	4	0.1	1.4	3.5	20	7	6	18
4	5; 7	5	*	1.4	3.5	25	7	6	18

* See Crest Wall elevation below

Crest Wall Elevation Chart

Approach Bottom width (ft.)	P (ft.) at V_n = 5 ft./s.	P (ft.) at V_n = 7 ft./s.
5	0.2	0.2
4	0.4	0.3
100	0.5	0.3

Notes:

1. See Figure 5-6 for definition of symbols.

2. Maximum allowable C = 4.0 ft.

3. This chart is for ordinary riprap structures only. Other types of drop structures require their own hydraulic analysis.

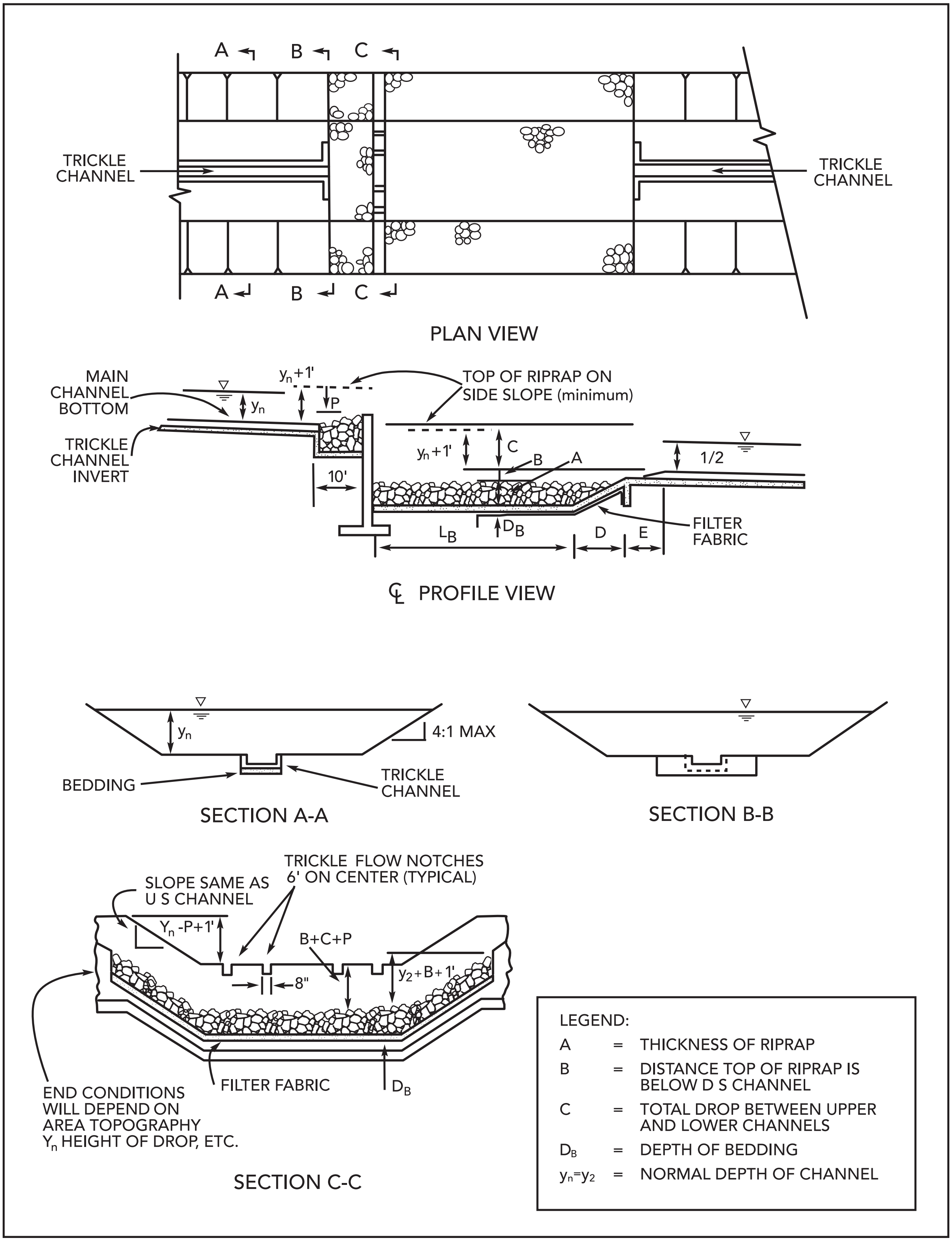


Figure 5-6 Vertical Riprap Channel Drop

Source: City of Tulsa, 1993

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 and rubble 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 Omaha 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-in. to 6-in. 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).

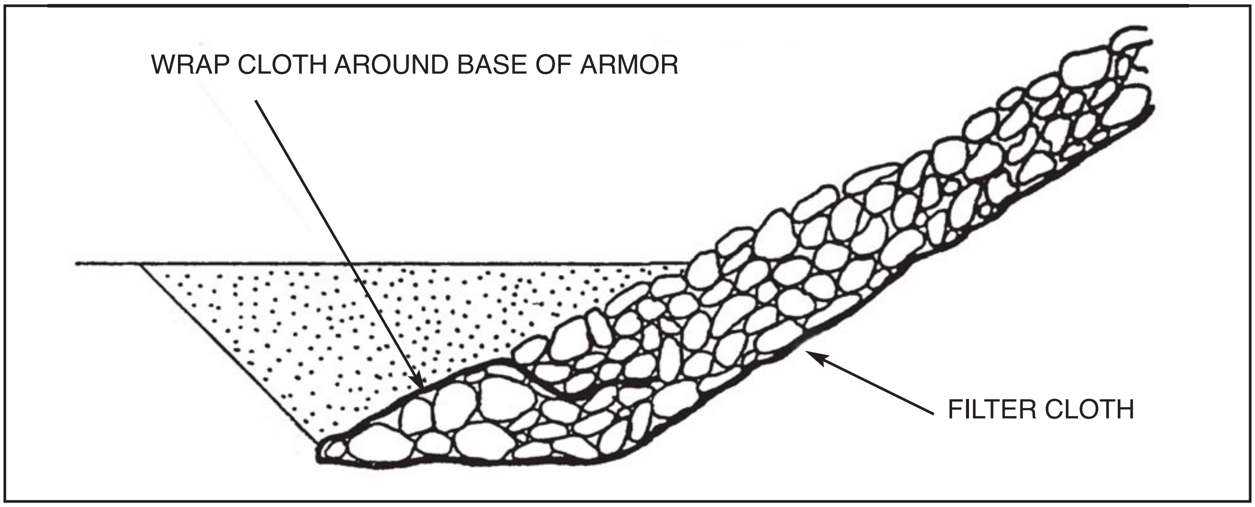


Figure 5-7 Filter Fabric Placement

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-A and the downstream flank is illustrated in Section B-B of this figure.

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 to a final slope configuration 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 trees and debris in accordance with the approved tree removal and mitigation plan for the project, 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 in. 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 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. 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.

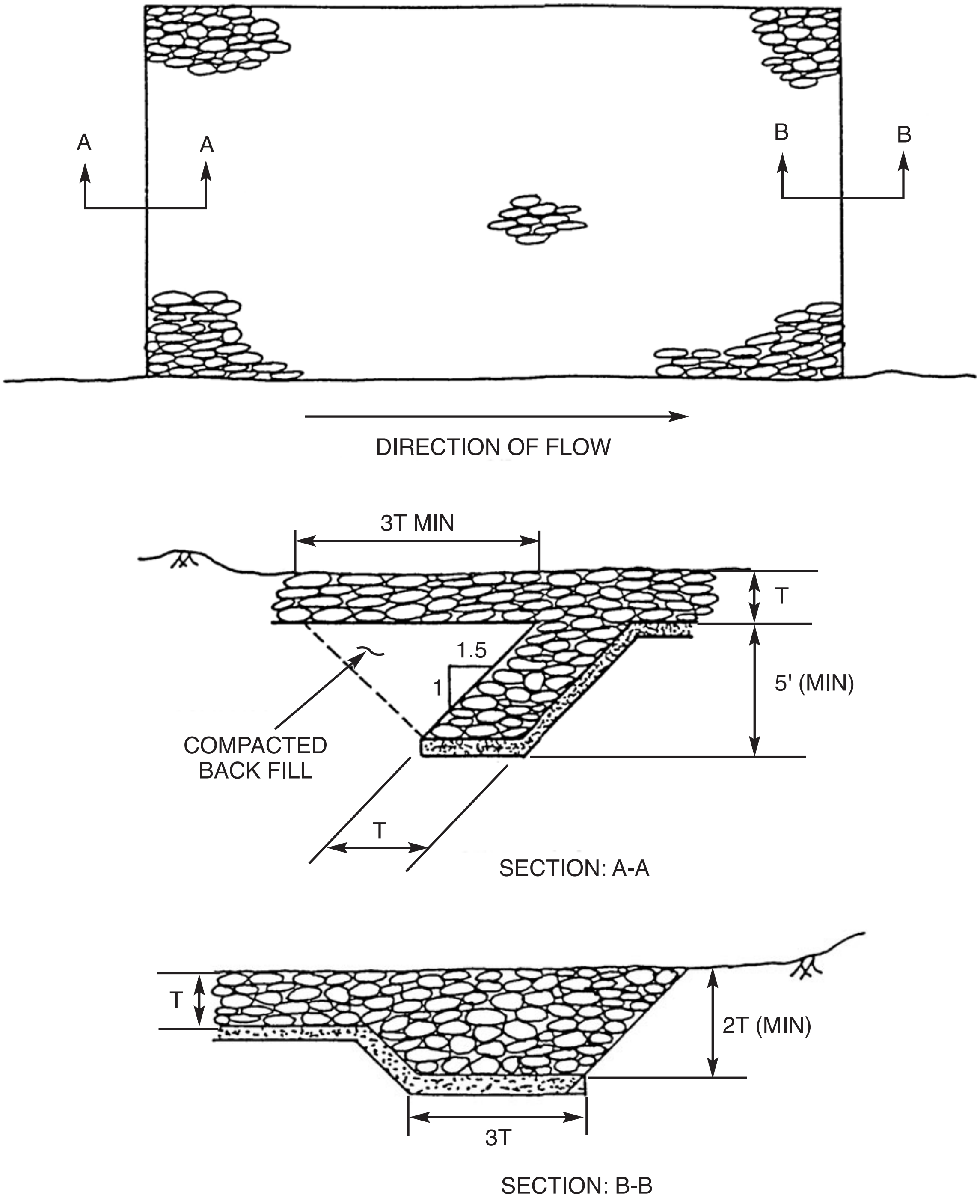


Figure 5-8 Typical Riprap Installation: Plan And Flank Details

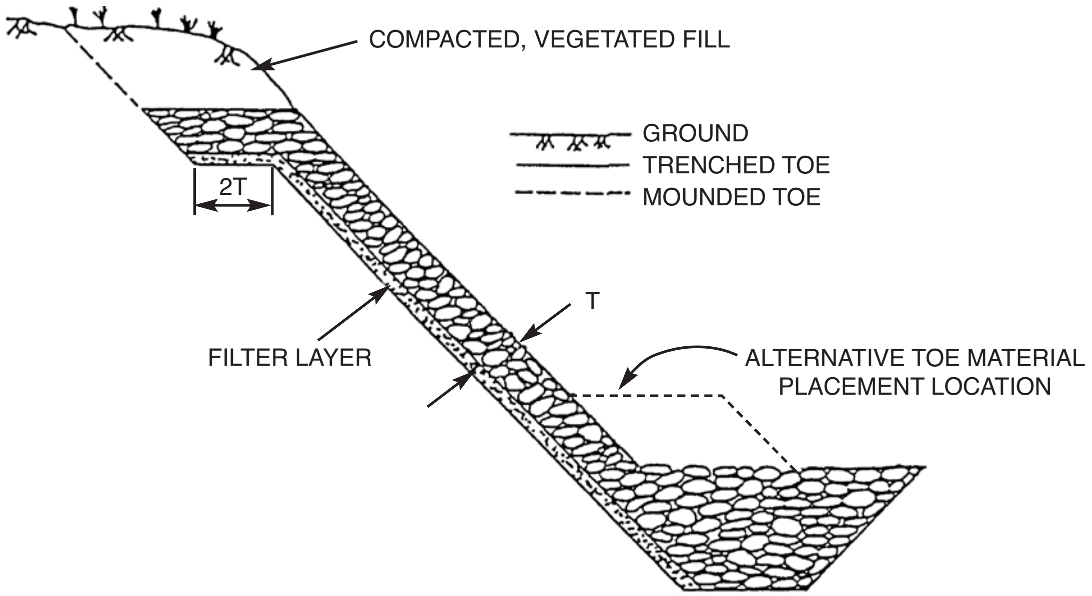


Figure 5-9 Typical Riprap Installation: End View (Bank Protection Only)

5.11.2.3 Design Procedure

The rock riprap design procedure outlined in the following steps 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.

Preliminary Data

Step 1 Compile all necessary field data including (channel cross section surveys, soils data, aerial photographs, history of problems at site, etc.).

Step 2 Determine design discharge.

Step 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.

Step 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.

Step 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.

Rock Sizing

Step 6 Compute the bank angle correction factor $K_1= [1 - (\sin^2 \Theta / \sin^2 \Phi)]0.5$. (5.8)

Where:

Θ = the bank angle with the horizontal
Φ = the riprap material's angle of repose

Step 7 Determine riprap size required to resist particle erosion $d_{50} = 0.001\ V^3 / d_{avg}^{0.5}K_1^{1.5}$. (5.9)

Where:

d_{50} = the median riprap particle size, ft. (for rock with a specific gravity, S_s, of 165 lb./ft.^{3})
V = the average velocity in the main channel, ft./s.
d_{avg} = the average flow depth in the main flow channel, ft.

Step 8 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

Multiply the correction factor C times the D_{50} size from Step 7.

Step 9 If the entire channel perimeter is being stabilized, and an assumed d_{50} was used in determination of Manning's "n", return to step 4 and repeat steps 4 through 7.

Step10 Select final d_{50} riprap size, set material gradation, and determine riprap layer thickness.

Revetment Detail Design

Step 11 Determine longitudinal extent of protection required.

Step 12 Determine appropriate vertical extent of revetment.

Step 13 Design filter layer.

(a) Determine appropriate filter material, size and gradation.

(b) Determine layer thickness.

Step 14 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 manufacturer's recommended procedures for design and installation 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 manufacturer's recommended design and installation procedures.

5.11.5 Grouted Rock

Grouted rock revetment consists of rock slope-protection having voids filled with concrete grout to form a monolithic armor.

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.

Bank And Foundation Preparation

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 in. 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. Filling depressions in the graded surface with filter material or rock can significantly increase the volume of those materials used.

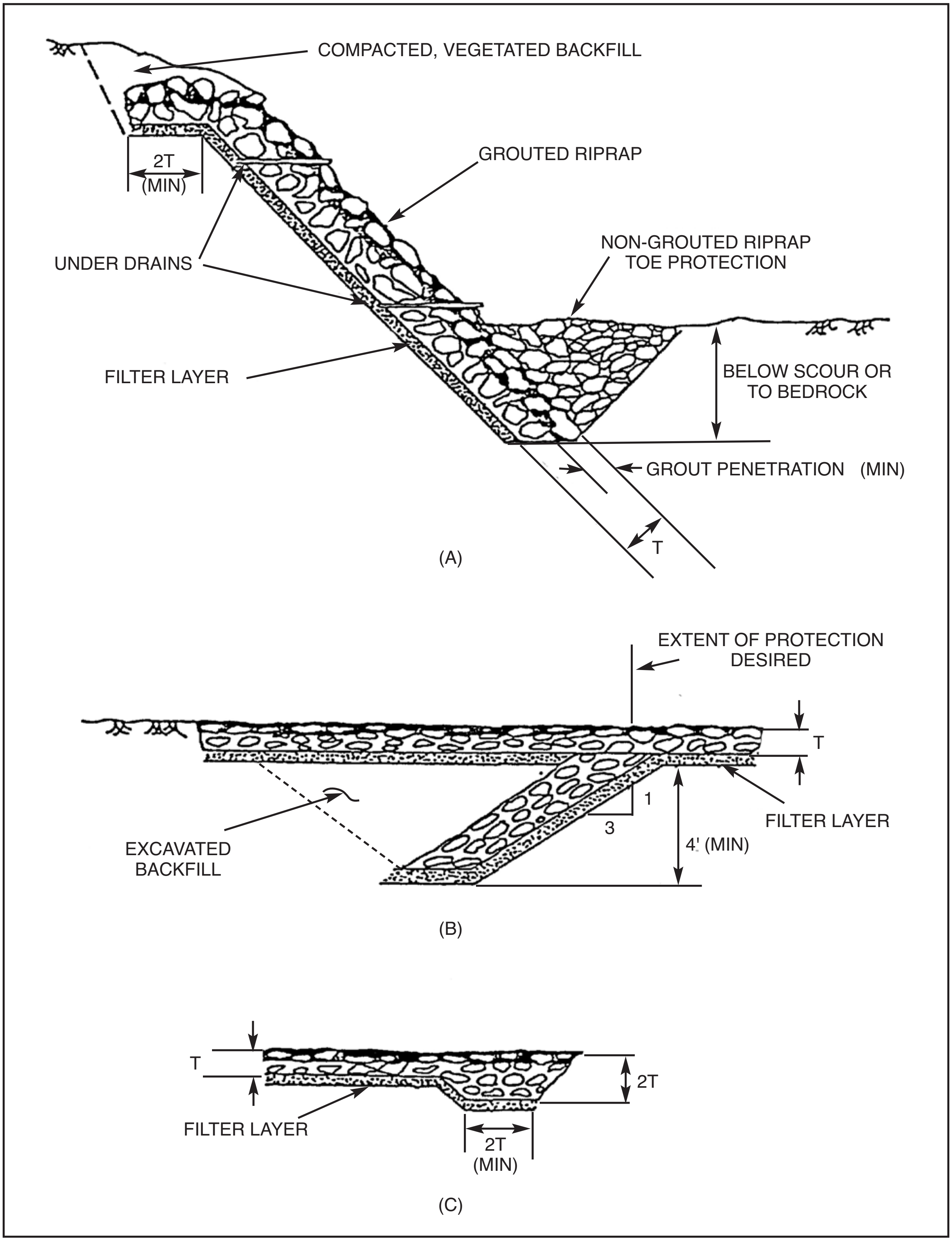


Figure 5-10 Grouted Riprap Sections: (A) Section; (B) Upstream Flank; and (C) Downstream Flank

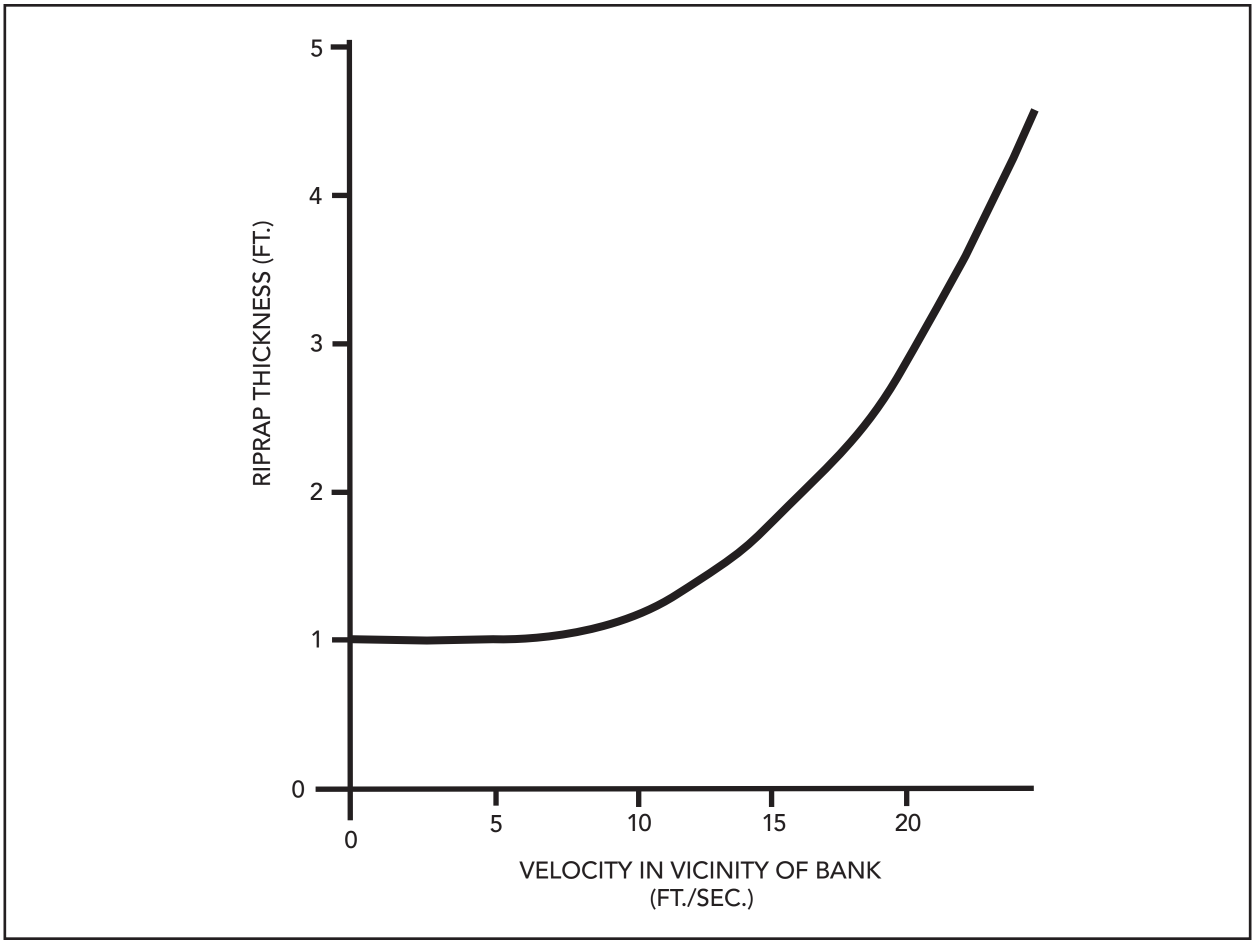


Figure 5-11 Required Blanket Thickness As A Function Of Flow Velocity

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.

Bank Slope

Bank slopes for grouted riprap revetments should not exceed 1.5:1. The actual maximum bank slope at a given site must be determined based on the stability of the site soils and the necessary factor of safety.

Rock Size And Blanket Thickness

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.

Rock Grading

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.

Rock Quality

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 in. and a slump of 3 to 4 in. 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 ft. where the riprap layer is thicker than 2 ft. 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-in. 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-in. 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:

Step 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.

Step 2 The rock should be set immediately prior to commencing the grouting operation.

Step 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.

Step 4 Spading and rodding are necessary where penetration is achieved by gravity flow into the interstices.

Step 5 No loads should be allowed upon the revetment until the grout has cured for at least one week.

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. Bioengineering is gaining in popularity throughout the country.

Soil-bioengineered bank stability systems have not been fully standardized, the decision of whether and how to use the practices for a given site requires careful consideration. Two excellent references for detailed bioengineering design guidelines entitled “Stream Restoration: Principles, Processes, and Practices, Final Manuscript Draft, 1998” and “Part 650, Engineering Field Handbook, Chapter 16, Streambank and Shoreline Protection, 1996”, are published by the Natural Resources Conservation Service. These documents provide background on fundamental concepts necessary for planning, designing and applying bio-engineering techniques on many streams. Expertise in soils, biology, plant sciences, landscape architecture, geology, engineering and hydrology may be required for projects where the stream is large or the erosion is severe (NRCS Stream Corridor Restoration Final Manuscript Draft 1998). Several examples of bio-engineering techniques are presented in Figures 5-12 through 5-18.

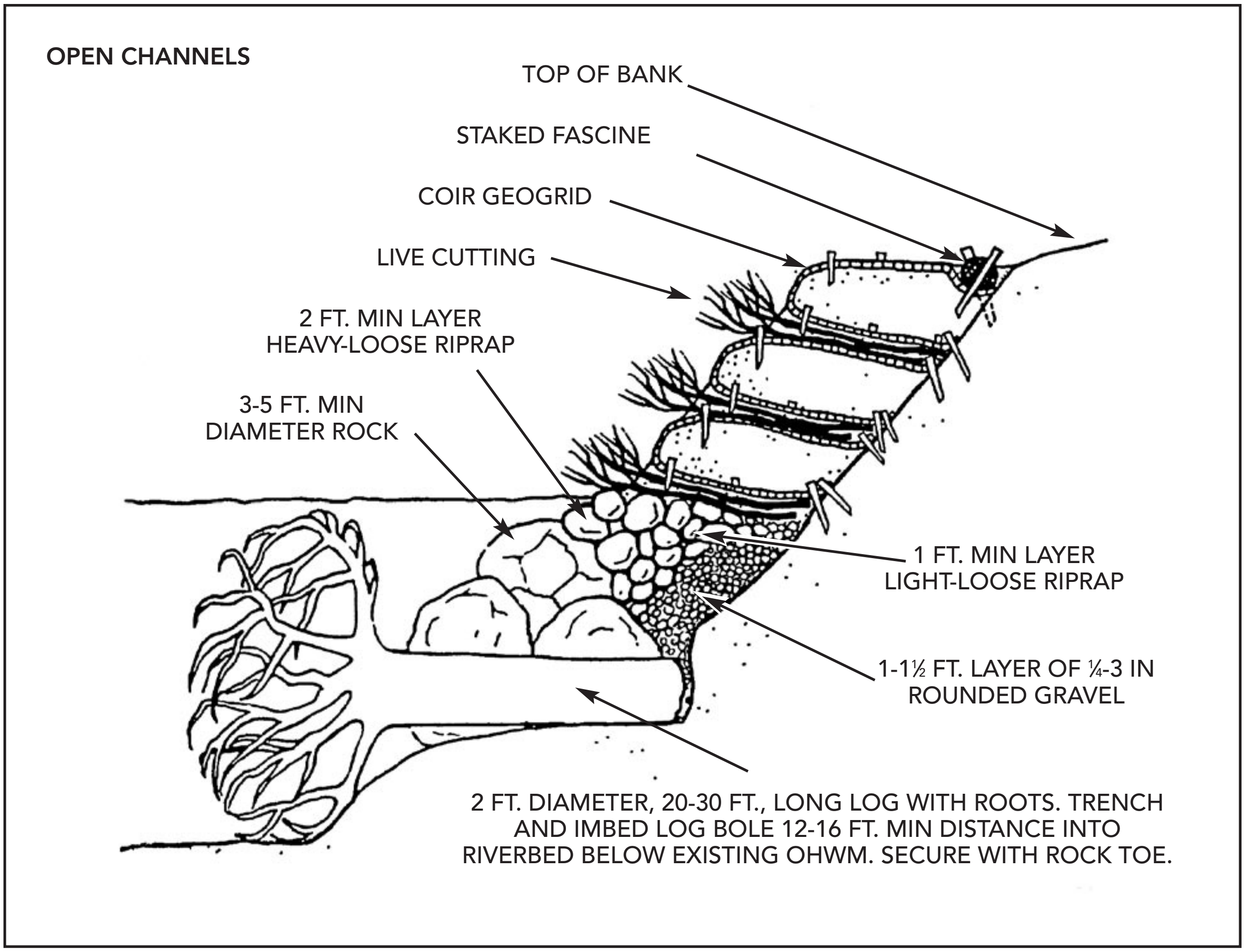


Figure 5-12 Integrated System With Large Woody Debris

Source: NRCS, 1996

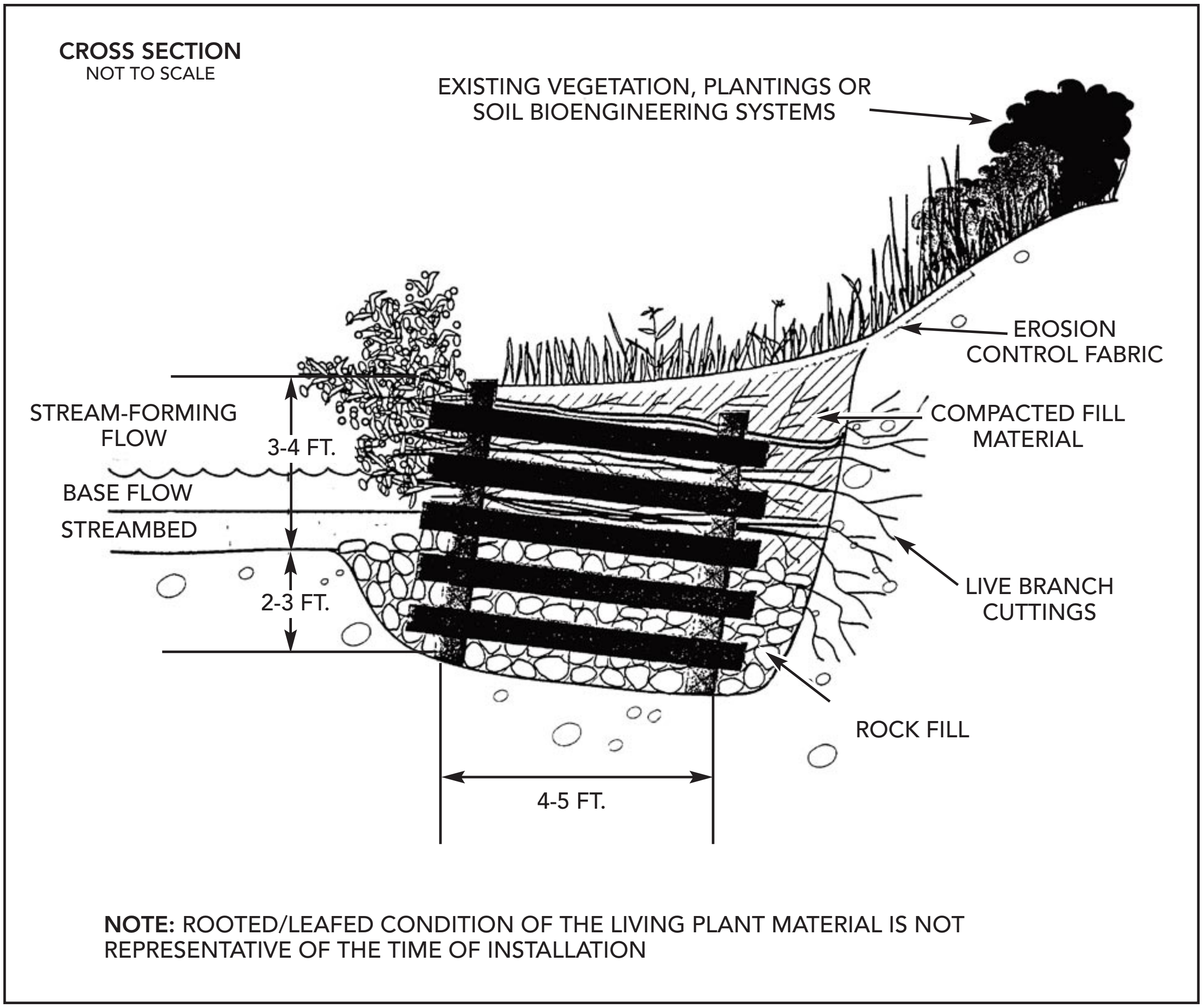
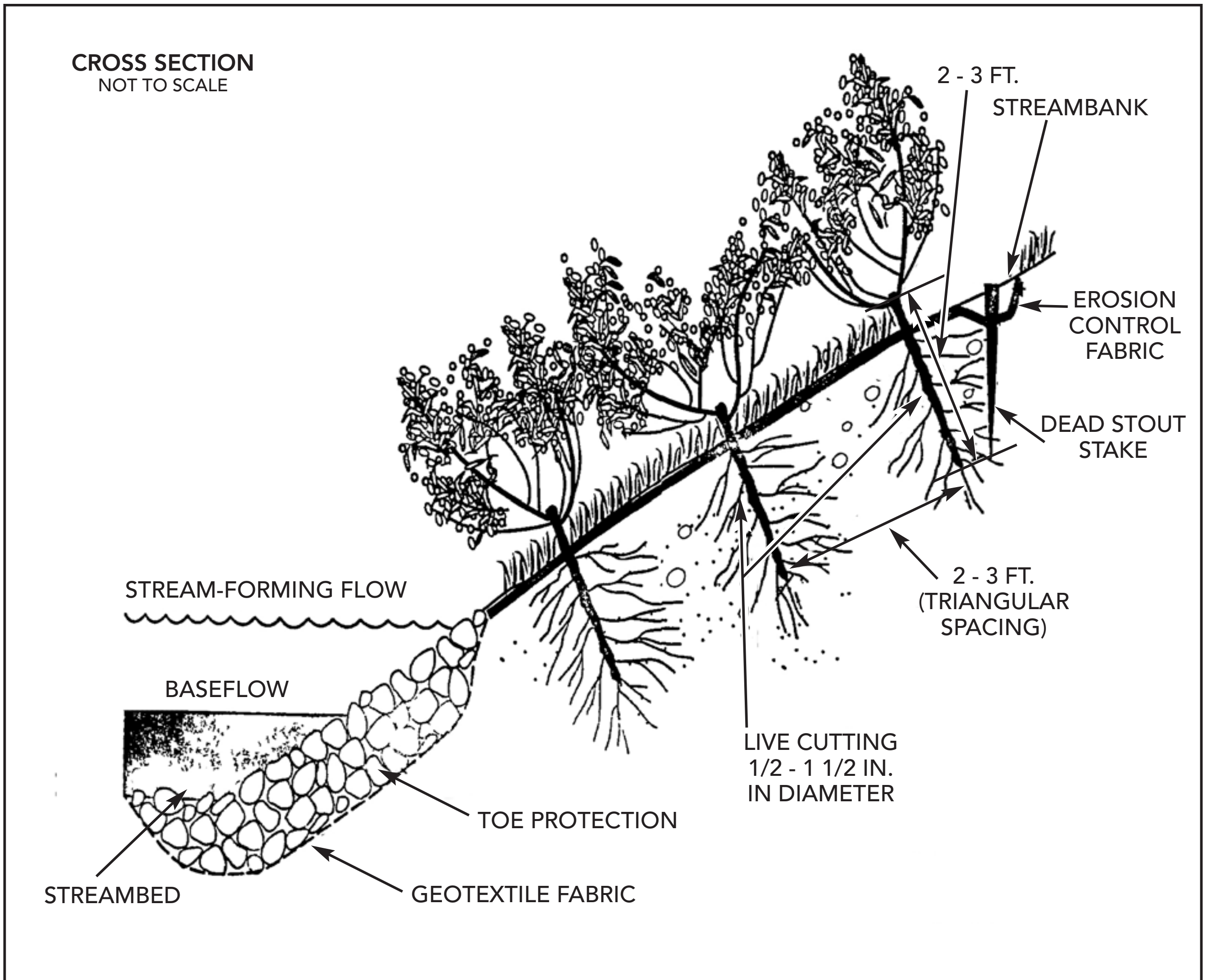


Figure 5-13 Live Cribwall Details Source: NRCS, 1996



NOTE: ROOTED/LEAFED CONDITION OF THE LIVING PLANT MATERIAL IS NOT REPRESENTATIVE OF THE TIME OF INSTALLATION

Figure 5-14 Live Stake Details

Source: NRCS, 1996

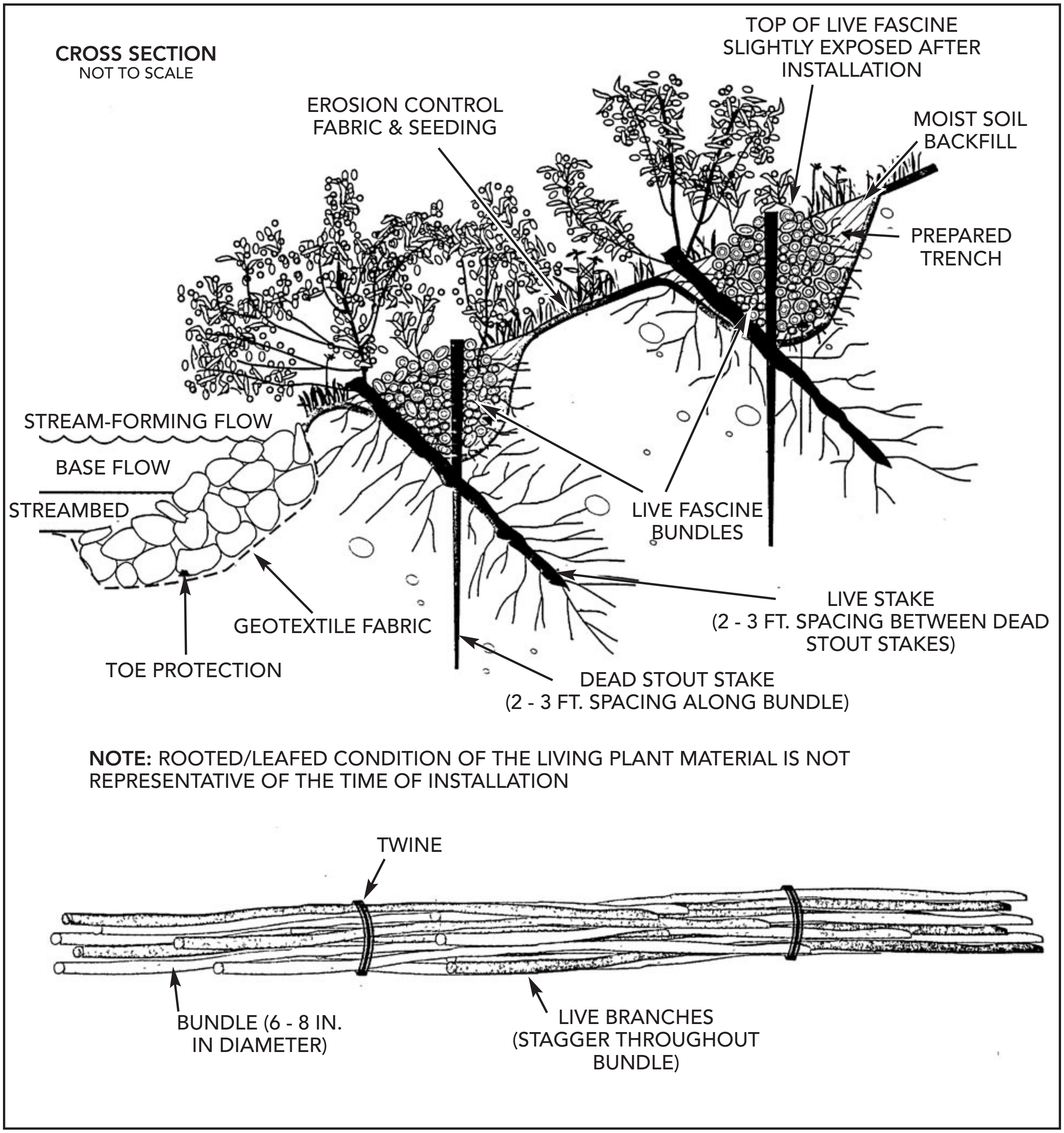


Figure 5-15 Live Fascine Details

Source: NRCS, 1996

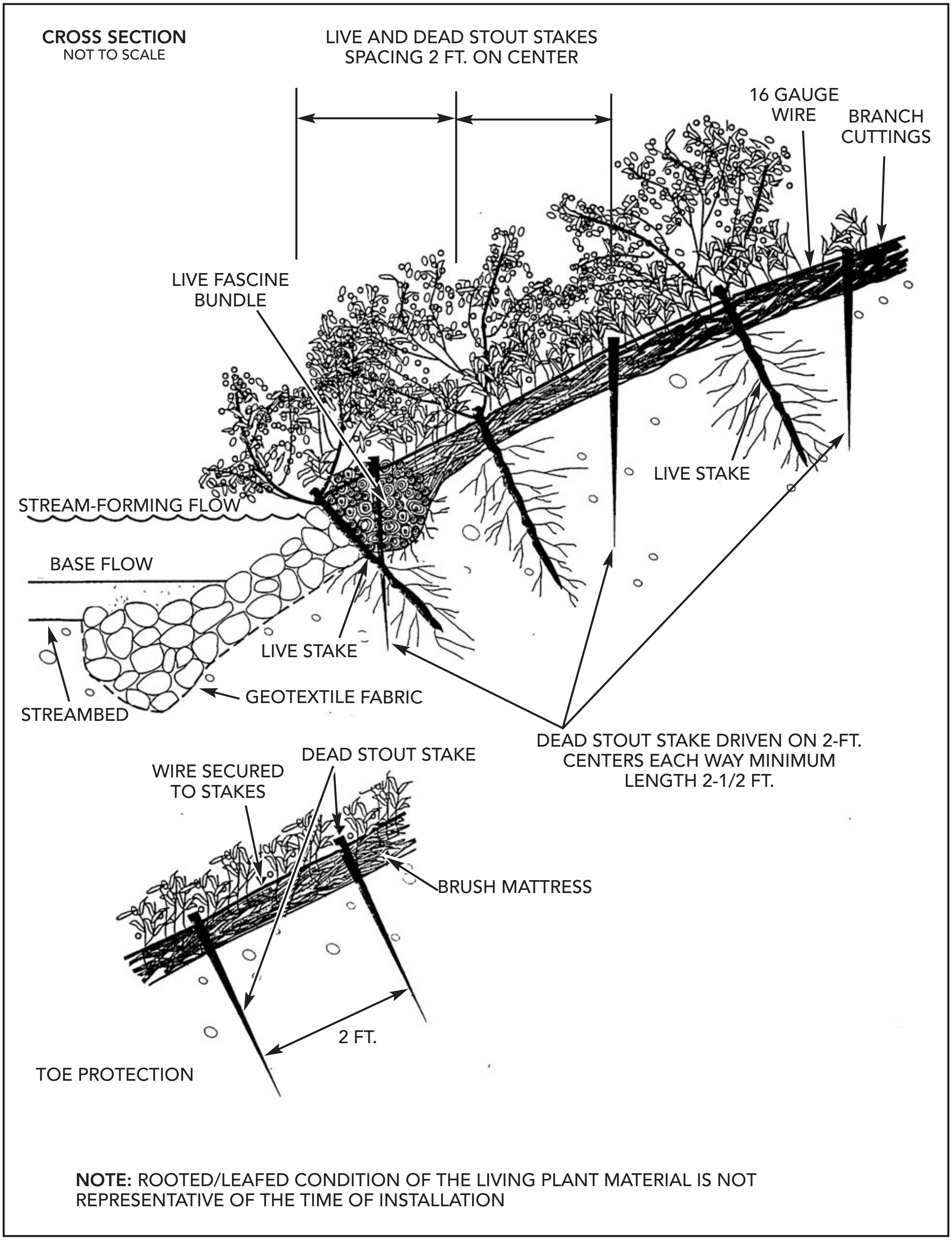


Figure 5-16 Brushmattress Details Source: NRCS, 1996

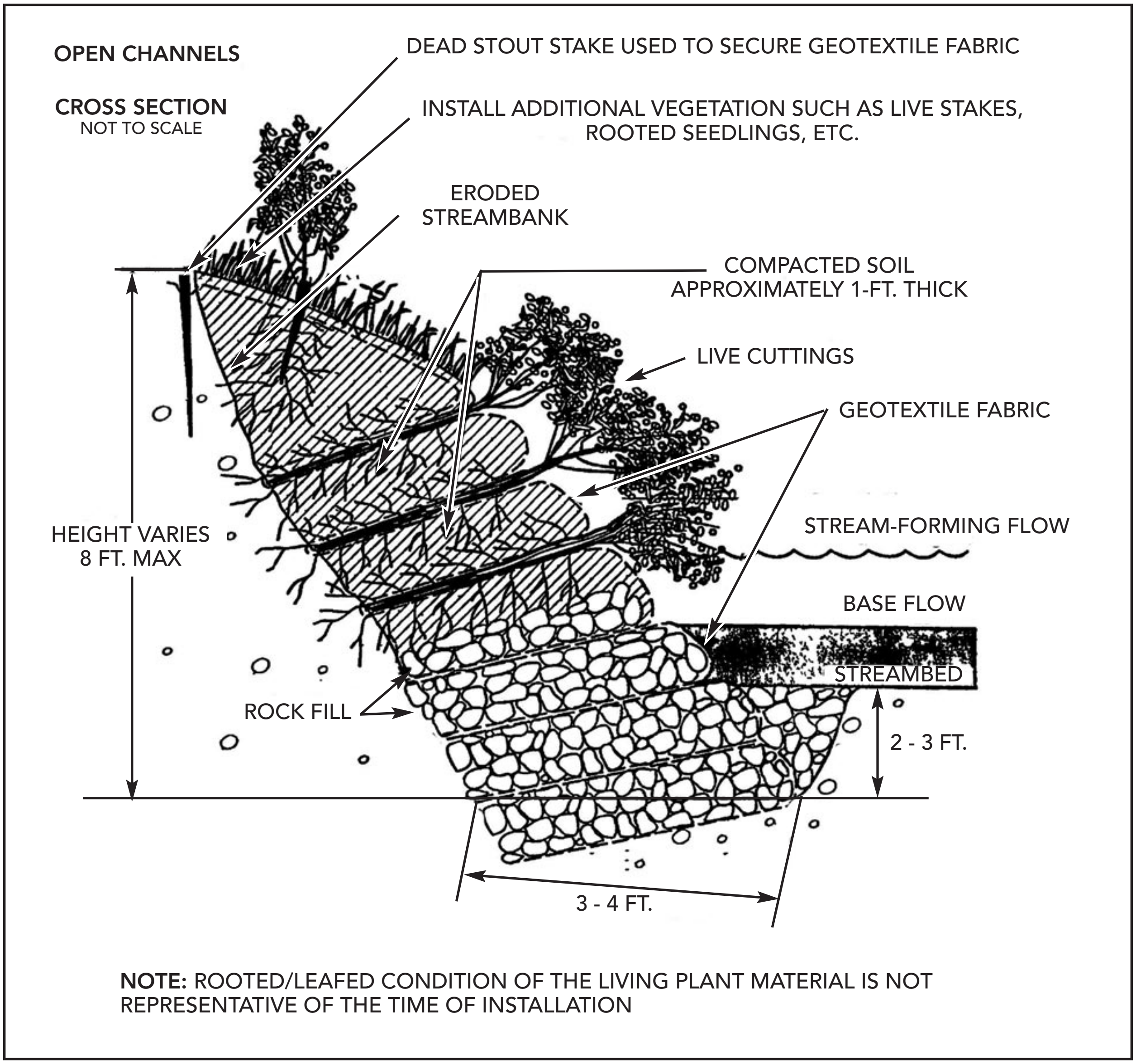


Figure 5-17 Vegetated Geogrid Details

Source: NRCS, 1996

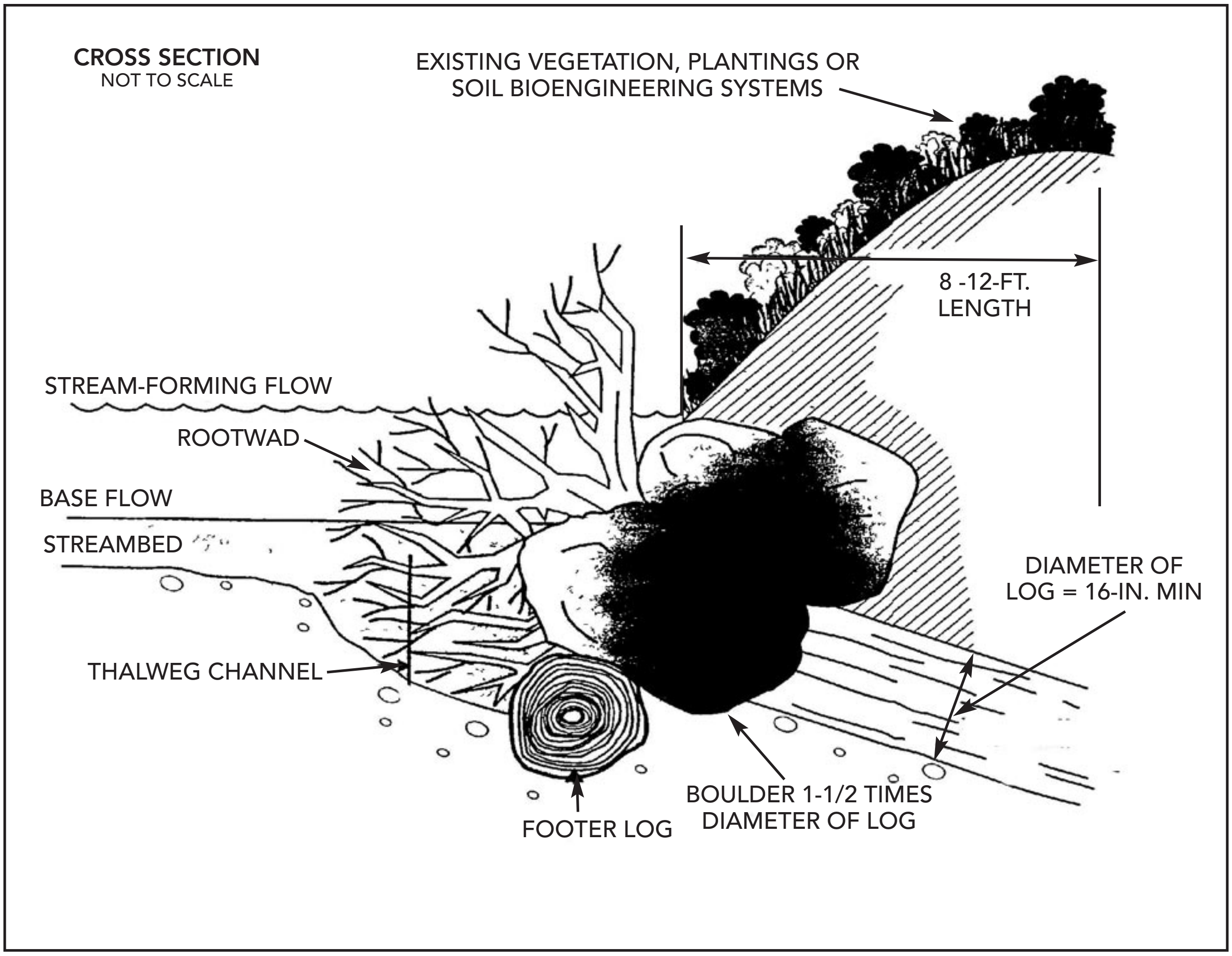


Figure 5-18 Log, Rootwad, and Boulder Revetment Details Source: NRCS, 1996

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Appendix 5-A

References

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References

American Society of Civil Engineers, Manuals and Reports of Engineering Practice No. 77. Design and Construction of Urban Stormwater Management Systems. 1992.

Chow, V. T., ed. Open Channel Hydraulics. McGraw Hill Book Co. New York. 1959

City of Lincoln, Nebraska Drainage Criteria Manual. February 2000, Revision – May 2004.

City of Tulsa, Oklahoma. Stormwater Management Criteria Manual. 1993.

French, R. H. Open Channel Hydraulics. McGraw Hill Book Co. New York. 1985.

Federal Highway Administration. Bridge Waterways Analysis Model (WSPRO), Users Manual, FHWA IP-89-027. 1989.

Harza Engineering Company. Storm Drainage Design Manual. Prepared for the Erie and Niagara Counties Regional Planning Board. Harza Engineering Company, Grand Island, N. Y. 1972.

King County, Washington. Guidelines for Bank Stabilization Projects In the Riverine Environments of King County. King County Department of Public Works Surface Water Management Division. 1993.

Lower Platte South Natural Resources District. Manual of Erosion and Sediment Control and Stormwater Management Standards. 1994

Maynord, S. T. Stable Riprap Size for Open Channel Flows. Ph.D. Dissertation. Colorado State University, Fort Collins, Colorado. 1987.

Morris, J. R. A Method of Estimating Floodway Setback Limits in Areas of Approximate Study. In Proceedings of 1984 International Symposium on Urban Hydrology, Hydraulics and Sediment Control. Lexington, Kentucky: University of Kentucky. 1984.

Peterska, A. J. Hydraulic Design of Stilling Basins and Energy Dissipators. Engineering Monograph No. 25. U. S. Department of Interior, Bureau of Reclamation. Washington, D. C. 1978.

Reese, A. J. Riprap Sizing, Four Methods. In Proceedings of ASCE Conference on Water for Resource Development, Hydraulics Division, ASCE. David L. Schreiber, ed. 1984.

Reese, A. J. Nomographic Riprap Design. Miscellaneous Paper HL 88-2. Vicksburg, Mississippi: U. S. Army Engineers, Waterways Experiment Station. 1988.

Urban Drainage and Flood Control District (UDFCD), Denver, Colorado, Urban Storm Drainage Criteria Manual, Vol. 2, Denver, 1969 (updated 2001).

U. S. Corps of Engineers: Design of Coastal Revetments, Seawalls, and Bulkheads. Engineering Manual EM-1110-2-1614. April 1985.

U. S. Department of Agriculture, Natural Resources Conservation Service. Part 650, Engineering Field Handbook. Chapter 16 Streambank and Shoreline Protection. Manual 210-vi-EFH. Washington, D.C. December 1996.

U. S. Department of Agriculture, Natural Resources Conservation Service. Stream Corridor Restoration: Principles, Processes, and Practices. Washington, D.C. 1998.

U. S. Department of Transportation, Federal Highway Administration. Design Charts For Open Channel Flow. Hydraulic Design Series No. 3. Washington, D.C. 1973.

U. S. Department of Transportation, Federal Highway Administration. Hydraulic Design of Energy Dissipators for Culverts and Channels. Hydraulic Engineering Circular No. 14. Washington, D. C. 1983

U. S. Department of Transportation, Federal Highway Administration. Guide for Selecting Manning's Roughness Coefficients For Natural Channels and Flood Plains. FHWA-TS-84-204. Washington, D. C. 1984.

U. S. Department of Transportation, Federal Highway Administration. Design of Stable Channels with Flexible Linings. Hydraulic Engineering Circular No. 15. Washington, D. C. 1986.

U. S. Department of Transportation, Federal Highway Admin. Design of Riprap Revetment. Hydraulic Engineering Circular No. 1. 1989.