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CHAPTER 8. OPEN CHANNELS

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1.0 OVERVIEW

1.1 Introduction

Natural and engineered open drainage channels are generally the primary component of the major conveyance system. The use of open systems and their integration into the existing topography is strongly preferred to the use of closed or lined systems, and early planning is necessary to accomplish this objective. When present, natural channels are the preferred system for managing storm water. In areas of new development and infrastructure improvements, a channel is regarded as natural if it has the capacity to adjust either its bed or banks in response to changes in flow or sediment load. In areas being redeveloped, streams that have been previously disturbed are considered natural if they possess a free boundary capable of adjusting to changes in flow, unless otherwise determined by the Department of Public Works.

This chapter provides an overview of the open channel planning and design process, including the initial submittal and permitting steps, types of open channel design options, design principles, design criteria for both natural and engineered channels, and design steps for different hydraulic structures. Small grade control structures are addressed in a separate section at the end of the chapter. Design illustrations are presented at the end of the chapter along with examples to demonstrate the design process. The SF-Channels Spreadsheet is provided on the CD accompanying this manual to aid in design of open channels and is used in the examples in this chapter. See Appendix A for a list of the worksheets provided in this spreadsheet.

1.2 Open Systems Requirements

One of the principles of sound urban storm water management is the practice of preserving floodplains and natural channels associated with major waterways. In situations where it is not feasible to utilize the natural system of channels and floodplains, it is preferable for engineered systems to be open and vegetated where possible, rather than enclosed or concrete lined. The community benefits of this policy include:

- Improved downstream flood protection due to preservation of naturally occurring floodplain storage, soil and plant absorption, and reduced velocities
- Protection of upstream reaches from accelerated erosion caused by actions in adjacent reaches.
- Enhanced water quality
- Improved public safety
- Generally lower construction cost than hard improvements

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- More aesthetic value to neighborhood and community
- More open space
- Recreational opportunities for neighborhood and community
- Improved habitat and biodiversity
- Lower long-term maintenance costs
- Generally enhanced flood control that exceeds design storm requirements due to wide and shallow geometry

1.3 Planning for Open Channels

When planning for open channels to serve a development, many important factors must be considered, such as:

- Public safety
- Permitting
- Cost, including capital expenses, operations, maintenance, and replacement
- Right of way, access and existing utilities
- Protection of existing natural channels and their riparian corridors
- The engineered channel and drainage easement for the design storm under full watershed development conditions and maximum potential peak flow
- Sediment budgets, including conditions with upstream construction activity and providing for sediment transport competency[1]
- Watershed or development master plans
- Existing or anticipated stream instabilities or meandering, particularly at the interface between natural and engineered channels
- Appearance

[1] Sediment transport competency – the ability of the channel to carry the sediment delivered to it without degrading or aggrading the channel bed.

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- Integration into community, including impact on property values

See Chapter 3, Section 2, Drainage Planning Principles, for additional information. Photograph OC-1 shows a well-planned waterway within a development.

Photograph OC-1. A well-planned major drainageway provides biological diversity, recreational opportunities, and aesthetic benefits in addition to flood conveyance.

1.4 Submittal Requirements

Detailed open channel plan submittal requirements and design submittal checklists are provided in Chapter 4, Plan Submittal. In summary, submittals must include detailed drawings, background calculations, and support information, including:

- Detailed plan and profile at the appropriate scale (profile shall include flow line and the top of each bank or channel wall)
- Water surface profiles (25- and 100-year)
- All design flow rates
- All design velocities
- Channel lining details, including seed and plant selection for vegetated channels
- Buffer delineation
- For natural channels, the completed geomorphic exhibit and channel stability matrix
- Evidence that relevant federal and state permits have been obtained and associated requirements have been met

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Water surface profiles shall be calculated using open channel methods discussed in this chapter and backwater calculation methods found in Chapter 7, Bridges and Culverts.

1.5 Permits

Construction involving major drainageways typically requires several federal, state, and local permits. See Chapter 3, Section 2.6, Required Permits, for more information. Early up-front planning for federal permits from the Federal Emergency Management Agency (FEMA) and the U.S. Army Corps of Engineers (USACE) is particularly relevant for open channels.

All documentation of correspondence with USACE must be provided to the City prior to approval of construction plans, regardless of whether the project is within USACE jurisdiction. All necessary federal permits to begin construction must be obtained and provided to the City prior to approval by the City to begin construction. It is the applicants' responsibility to obtain and comply with all relevant permits.

The USACE Section 404 permitting process typically requires mitigation for impacted wetlands and may require the preservation of certain aspects of existing natural channels. In cases where existing wetlands are eliminated or otherwise damaged, wetland mitigation may be required. In addition to any federal requirements, the City requires that all mitigation be completed on site.

1.6 Maintenance

All major drainageways and open channels shall be designed to allow regular maintenance. The designer shall consider access requirements for equipment necessary to maintain or replace walls, boulders, concrete mats, gabions, turf reinforcement mats (TRMs), etc. The responsible party must be financially and technically capable of providing long-term maintenance of facilities, including those that utilize concrete, grass or other bioengineered configuration. Additional information regarding maintenance can be found in Chapter 12, Easements and Maintenance.

1.7 Safety

Public safety shall be the paramount consideration when designing open channel systems. Representative issues that must be considered include channel configurations that limit the risk of a fall into the channel and channel hydraulic designs that minimize the risk of hazardous conditions, such as "reverse rollers" that can entrap a person downstream from a low head dam. All vertical walls greater than 3 feet in height shall have a safety fence or handrail if the wall is located where the public may be in close proximity. Warning signs may be necessary in areas with high risk. Channels that do not have vertical walls shall be designed with side slopes no greater than 3H:1V to allow for safe exit from the channel. All slopes that are to be maintained by motorized mowers shall be graded at a minimum of 3H:1V. Slopes of 4H:1V are preferred for safety and aesthetic reasons.

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2.0 TYPES OF OPEN CHANNELS

This manual addresses two basic channel types: natural and engineered. Natural channels are drainageways initially formed by nature and are capable of adjusting their bed and banks in response to changes in flows or sediment delivery. Engineered channels, in contrast, do not adjust to changing conditions in the same manner as natural channels. Types of engineered channels include, in order of preference: naturalized, vegetated, channels with manufactured linings, riprap-lined, and concrete-lined. Engineered channels can take various forms such as single-stage, two-stage, and channels with composite materials. The most commonly used types of engineered channels are addressed in Section 2.2, and different channel forms are discussed in Section 2.3. Standard design details can be found in the *City of Springfield, Missouri, Design Standards for Public Improvements* (Design Standards). Prior to choosing channel types in new developments, the designer shall consult with the City regarding master plans, regulations, and other constraints to assist in a sound and acceptable design. This is imperative so that preliminary layouts and space allocations will be adequate for drainage.

2.1 Natural Channels

Natural channels, as implied, are drainageways formed by nature. These channels exist in a state of dynamic equilibrium and have the inherent ability to adjust their bed or banks in response to changes in flow or sediment load. Natural channels also exist in constant interaction with their bordering vegetation. It is the ability of natural channels to self-manage that distinguishes natural channels from engineered channels and requires distinctly different management criteria. The ability to self-form and self-manage renders natural channels as the most efficient type of drainageway. It is difficult, if not impossible, to replicate all natural channel attributes in an artificial channel. For this reason, the City chooses to leave natural channels and adjacent riparian vegetation intact whenever feasible. Specific design criteria and guidelines for natural channels are provided in Section 4.0.

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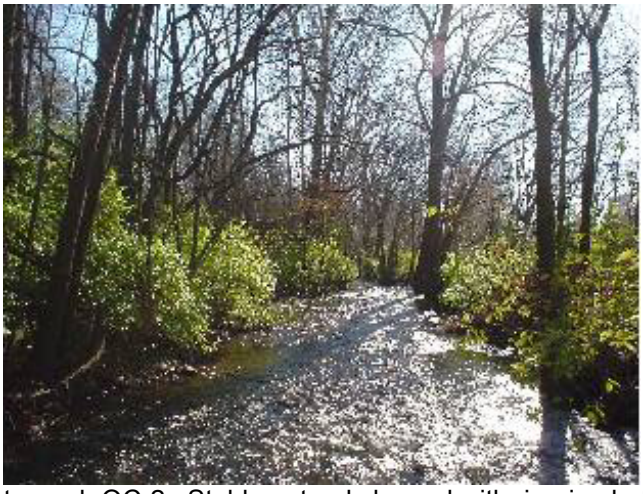

Photograph OC-2. Stable natural channel with riparian buffer.

2.2 Engineered Channels

Where an engineered channel is the preferred option, the choice of channel type and alignment must consider a variety of multi-disciplinary factors, including:

- The influence of channel alterations on the stability and ecological integrity of the adjacent unaltered reaches.
- Hydraulic considerations such as existing and future design flows and velocities, channel slope, available right-of-way, site topography, upstream and downstream conditions, and basin sediment yield.
- Structural considerations such as seepage and uplift forces, anticipated shear stresses, and adjacent loads, such as buildings.
- Environmental considerations such as municipal, county, state, or federal requirements, riparian zones, adjacent environmental hazards, existing perennial streams and wetlands, existing habitat, and wildlife and watershed objectives.
- Sociological considerations such as neighborhood character, street and traffic patterns, neighborhood social issues, public safety, pedestrian and bicycle traffic, recreational needs, and right-of-way corridor needs.
- Practical considerations such as cost, availability of material, and areas for wasting fill.
- Maintenance considerations such as life expectancy, repair and reconstruction needs, regular maintenance needs, proven performance, accessibility, and regulatory constraints to maintenance.

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The primary engineered channel types are described below in Sections 2.2.1 through 2.2.6. Specific design criteria and guidelines for engineered channels are provided in Section 5.0.

2.2.1 Naturalized Channels

Naturalized channels are previously manipulated channels that are restored to some degree of natural form, process, and function. Naturalized channels are not completely natural. Stream restoration, reclamation, and rehabilitation are all terms commonly used to describe the process of naturalizing a channel. In disturbed urban systems, complete restoration is not achievable; however, many of the physical processes associated with natural flows of water and sediment can be approximated and the ecological functions improved compared to purely artificial channels.

Photograph OC-3. Naturalized waterways using grade control structures provide long-term structural integrity and diverse ecology.

Naturalized channels provide channel storage, protect and restore the surface-groundwater connection, slow velocities, and provide various multiple-use benefits, including wildlife habitat and aesthetic values. Continuity of sediment transport, control of applied shear stress through channel geometry and hydraulic roughness, and use of natural materials are characteristics of naturalized channels. In naturalized channels, high shear stresses are commonly managed by energy dissipation features, such as riffles and pools, rather than using artificial channel linings. Proper selection of plant materials is critical for channel performance. The design of naturalized channels is a multidisciplinary exercise requiring expertise in fluvial geomorphology, aquatic biology, ecology and other life sciences, as well as civil engineering. The national consensus on design criteria for naturalizing channels (as of early 2007) is still evolving and criteria will not be included in this edition of the manual. Nevertheless, design teams with the necessary training and experience are encouraged to develop naturalized channels in situations where natural channels do not exist or cannot be preserved.

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2.2.2 Vegetated Channels

Vegetated channels lined with turf grass or native plants are traditional engineered channels with a vegetative lining. These channels are distinct from naturalized channels although both incorporate vegetated linings. Geomorphic principles of river process and function, as well as most life sciences, play a much smaller role in the design of vegetated channels than in naturalized channels. Vegetated channels can provide channel storage, reduced velocities and shear stresses, aesthetically pleasing open spaces, and various multiple use benefits. Vegetated channels in urbanizing watersheds may require grade control structures to reduce velocities and prevent degradation of the vegetative liner. Low-flow areas may need to be armored or otherwise stabilized to prevent erosion.

More stable and attractive facilities are typically achieved when sod or plant plugs are used rather than seed and mulch, particularly in the lower part of the channel that is inundated more often. The choice of vegetation is dependent on the frequency, depth and duration of inundation as well as water quality, habitat, and aesthetic considerations. Some settings require a highly groomed, manicured look where turf grass is desirable. However, traditional turf is energy intensive and requires frequent mowing, irrigation and fertilizing, which may adversely affect water quality. Alternative turf types such as low-maintenance fescue or buffalo grass provide the benefits of conventional turf with less maintenance. When the channel bed is likely to be inundated for more than 12 to 24 hours during frequent rain events, the designer should consider inundation-tolerant sedges and rushes for the bed and grasses for the slopes.

Where a manicured appearance is less of a requirement, the channel vegetation can include a more diverse selection of forbs, native grasses, and small shrubs. In all cases, the hydraulic roughness of the lining is an important part of the design. Although certain types of vegetation, such as shrubs, increase roughness and reduce channel capacity more than other types, designers are encouraged to account for the higher roughness and use it as a design element. For example, increased hydraulic roughness can be designed to direct scouring flows away from the toe of a slope and toward the channel centerline to reduce the risk of erosion. The roughness of the vegetation throughout its life cycle must be considered as well as the influence of roughness on channel capacity. In addition to stabilizing the channel, a diverse plant palette of native vegetation provides water quality benefits, desirable habitat and aesthetic benefits. Photograph OC-4 shows an attractive grass-lined channel.

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Photograph OC-4. Engineered grass-lined drainageway with rock lined low-flow channel, natural components and community recreation uses.

2.2.3 Channels with Manufactured Liners

Conditions may exist where a vegetated channel is desirable, but flows and velocities exceed the allowable conditions for a vegetated channel without reinforcement. The designer should consider reducing the applied stress by increasing hydraulic roughness in the channel, including energy dissipation structures, or adjusting channel geometry, as well as lining materials. Often, by applying these measures, the applied stress can be reduced to a degree that significantly reduces or eliminates the need for channel lining.

When flow conditions still exceed allowable conditions for vegetated channels, a manufactured liner may be appropriate. It may only be necessary to use these liners in the channel bed and lower banks. Liners can provide some of the benefits of vegetated channels, while remaining stable under high velocity conditions. Representative liner types include gabions, interlocked concrete blocks, concrete revetment, mats, modular blocks, reinforced sod, and various types of permanent TRMs. These liners are often proprietary, and new products are continually being introduced. Each type of channel lining must be scrutinized for its merits, applicability, ability to meet other community needs, long-term integrity, maintenance needs, and costs. Specific design criteria for manufactured liners are provided in Section 5.7.

When considering gabions, it is especially important to evaluate the right-of-way constraints and costs of replacement. If there is a possibility that the bed could degrade, gabions shall not be used to line channel banks because of the high risk of gabion collapse, rupture or toppling.

Photograph OC-5 shows a small, steep grass channel lined with a TRM to maintain stability. Photograph OC-6 shows a large drainageway lined with reinforced sod.

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Photograph OC-5. A steep, small grass-lined channel in a residential area reinforced by a TRM to maintain stability.

Photograph OC-6. A large drainageway with a reinforced sod channel lining to maintain stability and enhance water quality flowing into a downstream sinkhole.

2.2.4 Riprap-lined Channels

Riprap-lined channels can offer a compromise between vegetated channels and concrete-lined channels in terms of capacity, design velocities, cost of construction, and environmental impact. However, riprap-lined channels shall be used only when it can be shown that a naturalized or vegetated channel is not feasible. Photograph OC-7 shows a riprap-lined open channel.

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Photograph OC-7. A small channel stabilized with riprap and vegetation.

Riprap may be appropriate in short channel sections with a very steep slope, or as an energy dissipater or spreader at outfalls. Riprap may also be useful along sections of channels susceptible to erosion, such as outer banks of bends where applied stresses preclude the use of other materials. Other applications for riprap may be at transitions in geometry where turbulence may occur.

Riprap must be carefully designed to ensure it will not fail or induce a failure in an adjacent unarmored section. As with all engineered channels, the interface between reaches of differing hardness and hydraulic roughness must be accounted for in channel design.

Injecting grout into the voids of large riprap or filling the voids with soil and plantings to create a composite matrix is often desirable. Unless the riprap is more than 2.5 feet thick, it is practical and inexpensive to vegetate the toe of the bank with live stakes[2] of willow, some dogwood species, and buttonbush. The vegetation helps stabilize the riprap and improves the aesthetics, habitat, and water quality of the channel.

Many factors govern the size of rock necessary to resist the forces tending to move the riprap. For the riprap itself, this includes the size and weight of the individual rocks, shape of the stones, gradation of the particles, blanket thickness, type of bedding under the riprap, and slope of the riprap layer. Hydraulic factors affecting riprap include the water velocity, current direction, eddy action, waves, and hydraulic uplift forces. Refer to Section 5.7.4 for more information regarding riprap design details.

Riprap failures result from a wide variety of factors including, but not limited to: undersized individual rocks in the maximum size range; improper gradation of the rock, which reduces interlocking of individual particles; lack of rock angularity; toe scour that undermines the riprap; non-uniform placement of riprap,

[2] Live stake – a woody cutting of a plant capable of developing roots and shoots directly from the cutting. Live stakes are typically 3 to 4 feet long and ½ to 1 ½ inches in diameter. Stakes are driven into the soil or soil/rock matrix at least ¾ of their length and must be installed while dormant.

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with windows of undersized or gap-grade rock; flat and elongated rocks that do not interlock; settlement of sub-grade; geotechnical failures; ice and debris impacts; failure of filter fabric resulting from poor installation; failure to consider stress concentrators, such as curvature and contraction of the channel; and improper bedding for the riprap, which allows leaching of channel particles through the riprap blanket. Suggested reading regarding riprap design is provided in Section 6.0, Hydraulic Structures.

2.2.5 Grouted Boulder Channels

If properly designed and constructed, a grouted boulder channel can provide the appearance of a natural channel with rock outcroppings and can be an aesthetically pleasing option to concrete and riprap channels. Grouted boulder channels are particularly useful for lining low-flow channels and steep banks. A grouted boulder channel is shown in Photograph OC-8.

Photograph OC-8. Grouted boulder channel and drop structures.

Grouted boulders provide a relatively impervious channel lining which is less subject to vandalism than ordinary riprap and which requires less routine maintenance because of reduced silt and trash accumulation. The appearance of grouted boulders is enhanced by exposing the tops of individual stones and by cleaning the projecting rocks with a wet broom immediately after the grouting operation. It is also recommended that grouted boulders on channel banks and outside of frequent flow areas be at least partly buried with topsoil and revegetated. Boulders used for riprap shall meet all the properties of rock for ordinary riprap, and rock of uniform size shall be used. Rock properties are discussed in Section 5.7.4.1, Rock Sizing.

2.2.6 Concrete-lined Channels

Concrete-lined channels are generally discouraged due to safety, aesthetic and long-term maintenance issues, as well as negative impacts on habitat and water quality. In new developments, concrete channels will not be permitted unless it is shown that channel options utilizing more natural materials are not feasible. In general, proper planning will avoid the need for concrete-lined channels, though in certain

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circumstances they may be necessary Examples of concrete-lined channels are shown in Photograph OC-9 and Photograph OC-10.

Photograph OC-9. Trapezoidal concrete channel.

Photograph OC-10. Rectangular channel constructed of concrete and modular blocks. This type of configuration can present a public safety concern during storm events.

Conditions that may justify the use of concrete channels include hydraulic, topographic, or right-of-way constraints. A common hydraulic constraint requiring a concrete-lined channel is the need to convey high velocity flows within a restricted area. When a concrete lining is necessary, it must be designed to withstand the various forces and actions that can cause damage to the lining. If supercritical flow will exist, the channel must be lined with continuously reinforced concrete. More aesthetic alternatives to plain concrete should also be considered, such as modular block walls, stamped concrete, or a natural stone facing over a reinforced concrete wall. In addition to these considerations, the designer is also responsible for managing the interface with the upstream and downstream channels to prevent erosion and channel degradation.

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2.3 Channel Forms

In contrast to the discussions of specific channel types in Sections 2.2.1 through 2.2.6, this section addresses the broader issues of different channel cross-section forms and the application of different channel linings within the cross-section.

2.3.1 Two-stage Channels

Many natural channels maintain a two-stage cross-section, particularly at meanders. A two-stage cross-section is an efficient way to manage energy and prevent rapid or excessive channel adjustment. Typically, the lower stage conveys the base flow up to a discharge rate referred to as the channel forming or bank-full discharge flow. The channel forming flow is that which, over time, has the greatest influence on channel size and shape. In undisturbed settings, this flow generally corresponds to the 1.5- to 2-year recurrence interval. At this stage, natural channels often form an internal floodplain to reduce stress associated with higher flows (see Figure OC-1). Internal floodplains are depositional features in a natural channel.

In disturbed urban systems with poor hydrologic control, the channel forming discharge may occur many times in a year. The drastically increased frequency of the channel forming flow is a major reason for the poor condition of many urban channels.

Designers of engineered channels may use the two-stage approach as well. The lower channel shall be sized to accommodate the channel forming flow, while the larger channel may be sized to accommodate the desired design flow. Increasing the dimensions of the low-flow channel in an attempt to increase channel capacity is counterproductive for flood control and destructive of the water resource. When the channel is over-widened, the hydraulic slope effectively increases and the shear stress applied to the channel increases commensurately. Incision, or downcutting of the bed, then advances upstream, liberating sediment which deposits in the over-widened reach. When the over-widening is associated with a culvert or bridge, the sediment commonly deposits and consolidates in or immediately upstream of the culvert or bridge bay and reduces the capacity. Attempts to “maintain” the capacity by periodic sediment removal simply induce a new wave of incision and deposition.

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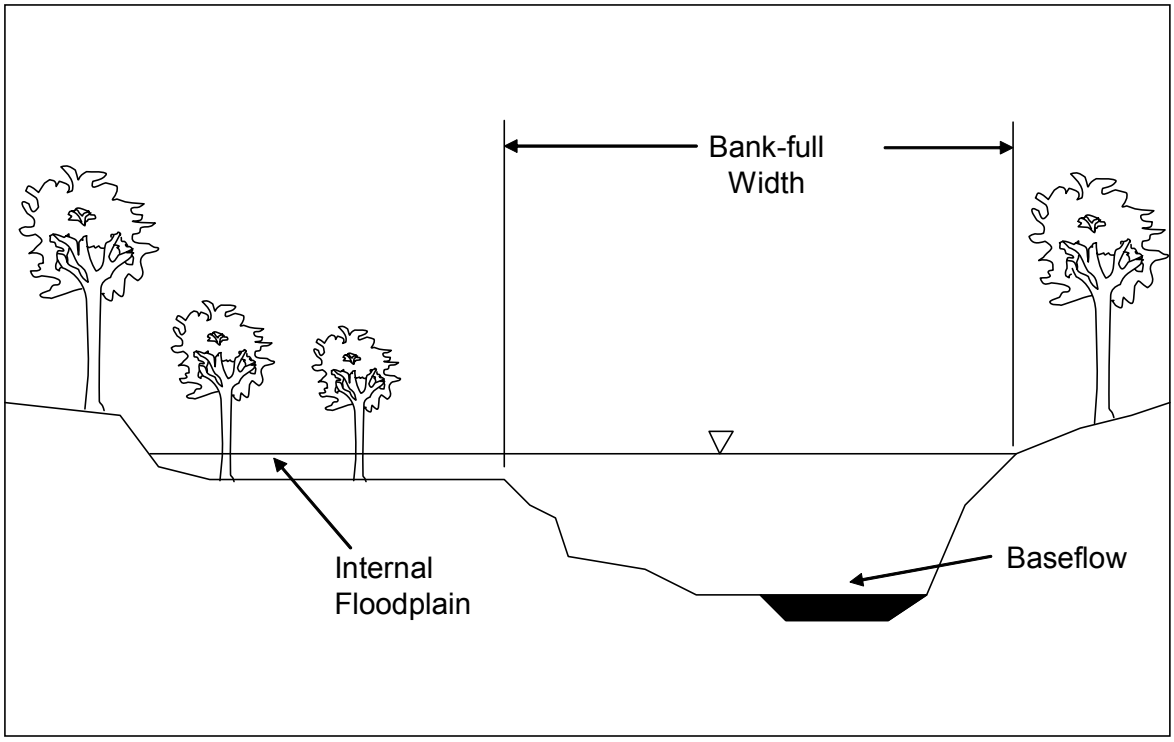

Figure OC-1
Cross-section of a Two-stage Channel with a Floodplain Internal to the Main Channel

Where the engineered channel will interface with a natural channel, it is extremely important to avoid over-widening the low-flow channel. By setting a channel width greater than the natural low-flow width, the designer may induce a draw-down curve upstream and induce incision or bank scour in the upstream channel. In addition to damaging the upstream reach, the liberated sediment will be deposited in the over-widened area downstream and may decrease needed flood capacity. Guidance on sizing a low-flow channel is provided in Section 5.9.

It is important to note that many two-stage channels do not maintain a two-stage cross-section throughout their length. Typically, the internal floodplain occurs at the inside of a meander and may decrease or disappear altogether in straight runs or transition points. Internal floodplains rarely occur on the outside of meanders.

Some geologically young channels, highly disturbed urban channels, or those dominated by gravel or bedrock may not form two-stage channels. If interfacing with a natural single-stage channel, it is reasonable to design a single-stage engineered channel, provided that the base width does not exceed that of the natural channel.

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2.3.2 Composite Channels

Channel linings and cross-sections can, and often should, vary throughout a channel. The designer has the flexibility to use different materials and cross-sections as appropriate. For example, unless a vegetated channel experiences only brief inundation, the bed vegetation should be different from that on the bank. The designer is encouraged to optimize the benefits of vegetation in concert with other structural armor. By using vegetation as a structural material, dissipating energy at controlled points, and designing cross-sections to reduce stresses on the bed and banks, the designer can reduce, though rarely eliminate, the need for hard armor in the channel.

A composite channel under construction using articulated concrete blocks, TRM, sod, and seed/mulch is shown in Photograph OC-11. The same channel after being completed is shown in Photograph OC-12.

Photograph OC-11. A large, retrofitted urban composite channel using articulated concrete blocks, TRM, sod, and seed/mulch during construction.

Photograph OC-12. Urban composite channel from Photograph OC-11, shortly after construction.

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3.0 OPEN CHANNEL DESIGN PRINCIPLES

Standard open channel analysis and design is based on fundamental assumptions of flow types and flow regimes. A brief discussion of these assumptions is provided to assist the designer in determining whether actual site conditions conform to these fundamental assumptions. Determining this requires knowledge of open channel hydraulic principles and requires background and references beyond the scope of this manual. The City assumes that designers have appropriate background in open channel hydraulics and design and are registered professional engineers.

3.1 Types of Flow

Open channel flow commonly characterized according to variability with respect to time and space using the following terms:

- Steady flow—conditions at any point in a stream remain constant with respect to time (Daugherty and Franzini 1977).
- Unsteady flow—flow conditions (e.g., depth) vary with time.
- Uniform flow—the magnitude and direction of velocity in a stream are the same at all points in the stream at a given time (Daugherty and Franzini 1977). If a channel is uniform and resistance and gravity forces are in exact balance, the water surface will be parallel to the bottom of the channel for uniform flow.
- Varied flow—discharge, depth, or other characteristics of the flow change along the course of the stream. For a steady flow condition, flow is termed *rapidly varied* if these characteristics change over a short distance. If characteristics change over a longer stretch of the channel for steady flow conditions, flow is termed *gradually varied*.

For the purposes of open channel design, flow is usually considered steady and uniform. For a channel with a given roughness, discharge, and slope, there is only one possible depth for maintaining a uniform flow. This depth is the *normal depth*. When roughness, depth, and slope are known at a channel section, there can only be one discharge for maintaining a uniform flow through the section. This discharge is the *normal discharge*.

3.2 Manning's Equation

Manning's equation describes the relationship between channel geometry, slope, roughness, and discharge for uniform flow:

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$$Q = \frac{1.49}{n} AR^{2/3} S^{1/2}$$ (Equation OC-1)

In which:

Q = discharge (cubic feet per second [cfs])

n = Manning's roughness coefficient

A = area of channel cross-section (ft^2)

R = hydraulic radius (ft) = Area/Wetted Perimeter

S = channel bottom slope (ft/ft)

Manning's equation can also be expressed in terms of velocity by employing the continuity equation, $Q = VA$, as a substitution in Equation OC-1, where V is velocity (feet per second [ft/s]).

At channel bends, velocity will increase on the outside of the bend, increasing the risk for erosion. Higher design velocities at these locations may require an increase in the level of protection. The following equation shall be used to estimate velocity on the outside of bends when the channel centerline radius, r_c, divided by the water top width, T, is less than 8.0. When $r_c/T \geq 8.0$, no adjustment is needed.

$$V_a = (-0.147 \frac{r_c}{T} + 2.176)V$$ (Equation OC-2)

In which:

V_a = adjusted channel velocity along the outside of channel bends (ft/s)

V = mean channel velocity (ft/s)

r_c = channel centerline radius (feet)

T = Top width of water (feet)

Commercial software is commonly available to aid in the solution of Manning's equation to find flow capacity, velocity, and normal depth. For studies and designs submitted to the City, the designer can utilize the Normal and Critical Flow Analysis Worksheet in the SF-Channels Spreadsheet to perform normal flow calculations. Example OC-1, provided at the end of this chapter, illustrates application of the Normal and Critical Flow Analysis Worksheet for calculation of normal depth for a trapezoidal channel.

It is imperative that the designer understand the limitations of Manning's equation and the assumption of uniform flow. When flow conditions in a channel are not characterized by uniform flow, Manning's equation is not appropriate for approximating flow conditions. Depending on the conditions, a culvert

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analysis or backwater calculation routine (using a program such as HEC-RAS or other method) may be necessary to accurately estimate flow conditions.

3.3 Manning's Roughness Coefficients

When applying Manning's equation, the choice of the Manning's roughness coefficient, *n*, is the most subjective parameter. Table OC-1 provides allowable maximum and minimum Manning's roughness coefficients to use for channel design.

Both minimum and maximum roughness coefficients shall be used for channel design to check for sufficient channel lining stability (velocity check) and hydraulic capacity (flow rate check), respectively. The maximum roughness coefficient value is also used to check the minimum velocity to prevent the occurrence of standing water. Average roughness coefficient values shall be used for broader applications, such as watershed modeling.

Table OC-1
Typical Manning's Roughness Coefficient (n) Values for Open Channels

Channel Lining	Minimum	Average	Maximum
Earthen	0.020	0.025	0.030
Mowed grass	0.025	0.030	0.035
Grass-not mowed	0.030	0.035	0.040
Grass with brush/trees	0.040	0.050	0.060
Cobble bottom, grass/root side	0.030	0.040	0.050
Concrete-smooth	0.012	0.013	0.015
Concrete-rough	0.015	0.017	0.020
Riprap d_{50} 6 inches	0.032	0.035	0.038
Riprap d_{50} 9 inches	0.035	0.038	0.040
Riprap d_{50} 12 inches	0.038	0.040	0.042
Riprap d_{50} 18 inches	0.040	0.042	0.044
Riprap d_{50} 24 inches	0.042	0.044	0.047
Grouted boulders	0.025	0.032	0.040

Notes:
Values for average riprap roughness are based on Strickler Formula (USACE 1994).
Reference website: http://www.usace.army.mil/usace-docs/eng-manuals/em1110-2-1601/c-5.pdf
Strickler formula does not apply to grouted boulders.
Roughness coefficient values listed above do not apply to very shallow flow (where hydraulic radius will be less than or equal to 2 times the maximum rock size) where the roughness coefficient will be greater than indicated above.
Roughness coefficient values for natural channels are from Mays (2001).

For natural channels with floodplains and composite channels with multiple linings, Manning's roughness coefficient, *n*, is best estimated by the following equation:

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$$n_c = \frac{n_L A_L^{5/3} / P_L^{2/3} + n_R A_R^{5/3} / P_R^{2/3} + n_M A_M^{5/3} / P_M^{2/3}}{A_L^{5/3} / P_L^{2/3} + A_R^{5/3} / P_R^{2/3} + A_M^{5/3} / P_M^{2/3}}$$ (Equation OC-3)

In which:

n_c = Manning's n for the composite channel

n_L = Manning's n for the left overbank

n_R = Manning's n for the right overbank

n_M = Manning's n for the middle area (low flow)

A_L = Area of the left overbank

A_R = Area of the right overbank

A_M = Area of the middle area

P_L = Wetted perimeter of the left overbank

P_R = Wetted perimeter of the right overbank

P_M = Wetted perimeter of the middle area

This method of computing a composite roughness factor may be applied to all natural and engineered channels, including two-stage channels and channels with varying cross-sections and materials. For studies and designs submitted to the City, the designer can use the Analysis of Composite Channel Worksheet from the SF-Channels Spreadsheet to calculate minimum and maximum values of Manning's n for a composite channel. Example OC-2, provided at the end of this chapter, illustrates application of the Analysis of Composite Channel Worksheet.

3.4 Froude Number and Flow Regime

Another important characteristic of open channel flow is the state of the flow, often referred to as the flow regime. Flow regime is determined by the balance of the effects of viscosity and gravity relative to the inertia of the flow. The Froude number, F_r, is a dimensionless number that is the ratio of inertial forces to gravitational forces that defines the flow regime, calculated as follows:

$$F_r = \frac{V}{\sqrt{gd}}$$ (Equation OC-4)

In which:

V = mean velocity (ft/s)

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

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d = hydraulic depth (ft) = A/T, cross-sectional area of water/ top width of free surface

Flow regimes are characterized as critical, subcritical, or supercritical, based on Froude number.

3.4.1 Critical Flow

Critical flow is defined as flow with F_r = 1.0. Flows with F_r near 1.0 are considered unstable and are likely to tend toward phenomena such as hydraulic jumps and standing waves, which are both highly turbulent and lead to a higher risk of erosion or structural failure. Designs that result in F_r near 1.0 (> 0.8 and < 1.2) shall be avoided by adjusting the design of the cross-section, roughness and slope.

Critical velocity, V_c, can be calculated from the critical hydraulic depth, d_c. For a rectangular channel, the critical flow depth is equal to the critical hydraulic depth ($y_c = d_c$), and the critical flow velocity is:

$$V_c = \sqrt{gy_c} \qquad \text{(Equation OC-5)}$$

In which:

V_c = critical velocity (ft/s)

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

y_c = critical flow depth

In addition, the Normal and Critical Flow Analysis Worksheet from the SF-Channels Spreadsheet can be used to perform critical depth calculations.

3.4.2 Subcritical Flow

Subcritical flow is defined as flow with F_r < 1.0. These flows have the following characteristics relative to critical flows:

- Flow velocity is lower.
- Flow depth is greater.
- Hydraulic losses are lower.
- Erosive power is less.
- Behavior is easily described by relatively simple mathematical equations.
- Surface waves can propagate upstream.

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Most stable natural channels have subcritical flow regimes. Consistent with the philosophy that the most successful artificial channels utilize characteristics of stable natural channels, major drainage design shall seek to create channels with subcritical flow regimes.

3.4.3 Supercritical Flow

Supercritical flow is defined as flow with $F_r > 1.0$. Supercritical flows shall be avoided wherever possible and have the following characteristics relative to critical flows:

- Flow velocity is higher.
- Flow depth is less.
- Hydraulic losses are higher.
- Erosive power is greater.
- Surface waves propagate downstream only.

In cases where supercritical flow cannot be avoided, concrete linings shall be utilized (refer to Section 2.2.6). The channel must be designed to safely dissipate energy so that the discharge to the downstream reach is in a non-erosive, sub-critical condition. The design of channels with supercritical flow conditions is addressed in the Analysis of Steep (Supercritical Flow) Channel Worksheet in the SF-Channels Spreadsheet.

4.0 NATURAL CHANNEL DESIGN CRITERIA

This section sets forth requirements for the protection of natural channels as a conveyance for storm water, an ecological asset, and an amenity for the community. General design guidelines for utility crossings, bridges and culverts, and discharge outfalls, as they relate to natural channels, are also included in this section. Design criteria for these structures are addressed in Section 6.0, Hydraulic Structures.

The benefits of natural stream protection and the rationale for these requirements are presented in Chapter 1, Storm Water Drainage Principles and Chapter 3, Storm Water Planning. Unless otherwise provided for by local, state, or federal ordinance, regulation, or standards, the City's policy is that existing natural streams shall be preserved and protected in accordance with this section. This applies to both newly developing and existing urban areas, including channels that have noncontiguous physical or structural modifications. The City may, at its discretion, waive this requirement for natural stream preservation for intensely urbanized stream reaches that are experiencing significant erosion, locations where existing structures are being compromised by channel degradation, or for other compelling

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circumstances. Where natural streams are not preserved, reference should also be made to Chapter 6, Streets, Inlets and Storm Drains; Chapter 7, Culverts and Bridges; and Section 5.0 of this chapter, Engineered Channel Design Criteria.

4.1 Natural Channel Preservation and Buffer Zones

Natural channels shall be preserved as continuous systems and not segmented on a project-by-project basis because the frequent intermixing of natural and man-made systems tends to degrade the function of both. The following buffer requirements shall apply to natural channels:

1. Natural channels shall be preserved to the maximum extent practicable. If a channel is to be disturbed, the provisions of Section 4.2, Channel Assessment, shall be followed to determine what actions may be necessary. In cases where channel intervention is necessary, the use of natural materials and vegetation should be used to the maximum extent practicable. A channel intervention is any action that alters the shape, strength or roughness of bed, bank or riparian vegetation. Installation of culverts, bridges, outfalls, and below-grade crossings that involve surface cuts constitute interventions. Necessary federal and state permits must be obtained when a channel intervention is planned (refer to Section 1.5).

2. Buffer zones shall be maintained along natural channels. The limit of buffer zones shall be within an area maintained by an association and shall be formally designated on a plat, deed, easement, or restrictive covenant, as directed by the City. Buffer widths, as measured from the ordinary high water mark (OHM)[3] outward in each direction, shall meet or exceed the distances specified in Table OC-2.

Table OC-2
Buffer Width Requirements Along Natural Channels

Contributing Drainage Basin Size (Acres)	Buffer Width (From OHM Outward, Measured Separately in Each Direction)
Less than 40 acres	20 feet (recommended)
40 to 160 acres	30 feet
160 to 640 acres (1 square mile)	50 feet
1 to 4 square miles	75 feet
Greater than 4 square miles	100 feet

[3] "Ordinary High Water Mark" is the line on the bank established by the fluctuation of water indicated by a physical characteristic such as a clear natural line impressed on the bank, shelving, changes in the character of the soil, absence of terrestrial vegetation, presence of litter or debris, or other appropriate means.

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3. The City may require additional buffer width for less stable channels or special conditions to address water quality and ecological needs. The widths specified in Table OC-2 provide only moderate allowance for widening or migration in channels of average stability. Geotechnical studies may be required if there is a risk of slope failure due to the condition of underlying soil or rock materials. If necessary, the buffer width shall be expanded to contain the potential zone of failure as recommended by a geotechnical engineer. Smaller buffers in isolated locations may be allowed where provision of the full width is impractical and bank stability concerns have been addressed. Additional quality buffer areas may be considered as compensation for smaller buffers through part of the reach.

4. No construction or disturbance of any type, including clearing, grubbing, stripping, fill, excavation, linear grading, paving, or building is allowed in the buffer zone except by permission of the City. Dense stands of native vegetation shall be encouraged, particularly in the 25 feet closest to the top of bank. Exceptions to this policy will be allowed for trails, green space, recreation, and education purposes, provided that removing vegetation does not pose a threat to the stability or proper function of the waterway.

5. Unless otherwise accepted by the City, any maintenance of riparian buffers shall be the responsibility of the property owner. Healthy vegetation in the buffer zone and the capacity to convey floodwater without excessive backwater effects shall be maintained. Maintenance may include removal of vines and exotic or diseased vegetation. Trees may not be “topped” but may be trimmed to prevent damage to overhead utilities. If the property owner fails to maintain the buffer, the City may, at its discretion, hold the property owner financially responsible for maintenance conducted by the City.

6. For work on existing facilities already located closer to the channel than allowed, the new construction shall not encroach closer to the channel. Unstable banks shall be stabilized using methods described in this chapter. Formal designation of the full buffer zone may not be required; however, the part of the buffer zone not encroached upon shall be formally designated.

7. The City may approve deviations of the buffer requirement, provided that they are consistent with the public interest, and where, due to special conditions, a literal enforcement of the provisions would result in unnecessary hardship. Criteria for variance from the buffer requirement are:

    a. Granting of the deviation does not adversely affect the rights of adjacent land owners;

    b. Granting of the deviation will not create a public nuisance, induce a public expense, cause fraud or victimization of the public, or conflict with existing local, federal, or state laws;

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c. The spirit of the requirement is observed; and

d. Granting the requested deviation will not adversely affect public safety, convenience, order, or general welfare.

8. Edge-of-buffer outfalls, located in the outer half of the riparian buffer, shall be designed to disperse the discharge to promote overland flow, infiltration, and associated water quality benefits. Overland flow shall be directed to run in the outer portion of the buffer parallel to the channel direction. This will increase the length of flow and prevent short-circuiting directly into the stream. Low weirs and berms may be graded to direct flow and encourage short-term ponding. The buffer zone utilized for infiltration shall be maintained in dense, erosion-resistant grasses or grasses with TRMs designed to withstand the shear stresses of a 10-year storm. Edge-of-buffer outfalls shall only be used if each individual outfall can be designed to operate without scour or the formation of gullies.

The City may also require mitigation for any deviation from the buffer requirement. The mitigation may include:

a. A significant improvement of riparian corridor quality, as determined by density, forest structure, species, and diversity;

b. Inclusion of Best Management Practices such as bioswales, micro-detention features, and vegetated roofs that mimic the thermal, hydrologic, and ecological benefits of the riparian corridor; and

c. Restoration of physical and ecological stability of the channel system. Measures for local streambank stabilization such as retaining walls, gabions, and riprap banks do not constitute restoration and shall not be construed as mitigation.

4.2 Channel Assessment

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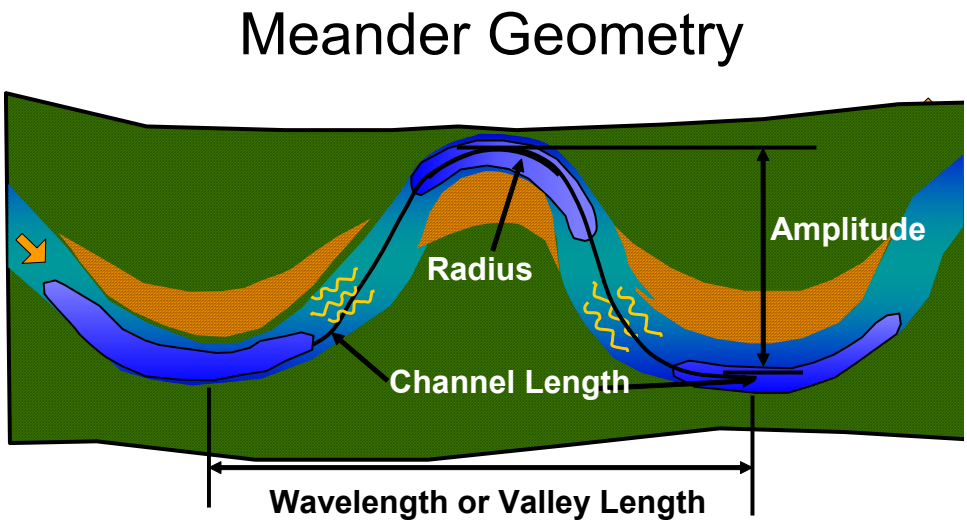
Prior to any intervention in or utilization of a natural channel, the designer shall conduct a channel assessment according to the protocol described below. The assessment is intended to protect the natural channel resources and demonstrate that the responsible engineer has taken measures to assess and protect the channel. The assessment protocol described here was specifically developed for designers who may not have training in river mechanics, fluvial geomorphology or related disciplines.



The purpose of the assessment is to enable the designer to identify and evaluate significant channel stability problems at the beginning of the project so that measures can be taken to ensure the channel remains stable. In the absence of major system-wide instability, the design proceeds according to the criteria presented in this section. For reference, common features of stream geometry are presented in Figure OC-2, below.

Figure OC-2
Common Features of Stream Geometry

The natural channel assessment includes completing a plan and profile exhibit of basic channel geomorphology (Section 4.2.1) and completion of the Channel Condition Scoring Matrix (Section 4.2.2). The channel assessment shall, at a minimum, address the channel for a length equivalent to twelve channel widths or one wavelength up- and down-channel of the area to be impacted by construction.

4.2.1 Plan and Profile Exhibit

The plan and profile exhibit shall include the components listed below, except as modified by the City to better fit project needs. Refer to Figure OC-2 for illustration of terms defined below:

- Ordinary high water mark.

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- Top of bank.
- Topographic contours (maximum interval of 2 feet).
- "Bank-full" and 1 percent Annual Exceedance Probability (AEP) ultimate-conditions floodplain (see Items 2 and 3 below).
- Thalweg, locations of riffles and pools, and spacing between riffles (see Item 3 below).
- Exposed bedrock, areas of differing bed and bank soil or rock materials, and the d_{50} and shear stress ratio at each riffle (see Item 4 below).
- Springs, sinkholes, gaining, or losing reaches.
- Active scour and depositional areas, point bars, and islands.
- Vegetation within the buffer zone, called out as mowed grass, mowed with trees, unmowed grass and plants, wooded, and bare. Trees greater than 6 inches in diameter within 25 feet of the top of bank shall be located individually or by group. The species of dominant trees shall be noted.
- Meander length, wavelength, meander amplitude, bank-full width, and radius of curvature for each bend.
- Total meander, valley length, and sinuosity for the reach.
- Photographs of main channel, streamside vegetation, and each riffle, appropriately referenced to plan-view location.

Additional information related to the plan and profile exhibit for the channel assessment is outlined below:

1. Planform Analyses and Inventory: The plan-view of the natural channel using aerial photographs or planning-level aerial survey shall be plotted at a scale of 1 inch equals 20 feet. A field survey of the entire reach study area is not required if topographic contours are used with intervals of no more than 2 feet.

2. Bank-full Width, Depth and Discharge: The geomorphic bank-full (or stream forming) width, depth, and discharge shall be estimated using field indicators as detailed in Chapter 7 of USDA (1996). Briefly, field indicators of bank-full depth include internal floodplains or shelves, the lower limit of woody vegetation, the lowest persistent scour line, and in some cases, the flat tops of gravel bars. All of the indicators shall be plotted on the profile sheet, and if the best-fit line of the indicators is parallel to the bed elevation, this elevation is a usable approximation of the bank-full

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elevation. Note: disturbed urban channels often do not have a consistent bank-full, or stream forming, elevation. If field indicators are not used, bank-full flow shall be estimated as the 50 percent AEP flow under predevelopment conditions. The bank-full width and depth are estimated based on the dimensions of that flow through the existing channel. This assumption is intended to provide a rough upper estimate of the bank-full flow.

3. Longitudinal Profile and Sections: The elevations of the profile along the thalweg shall be field surveyed to the nearest 0.1 foot. The following features shall be noted: riffles, pools, exposed bedrock, sinkholes, springs, and advancing headcuts (areas of bed elevation change that appear to be actively migrating upstream). The top of left and right bank and any field indicators of bank-full flow, such as limits of woody vegetation or top of point bars, shall be plotted at the correct elevation along the profile. The bank-full flow and 1 percent AEP ultimate flow profiles shall be plotted. One field cross-section shall be surveyed through each pool and riffle, and the depth and width of bank-full flow and 1 percent AEP ultimate conditions floodplain shall be shown on each section.

4. Bed and Bank Materials Analyses: The type of rock exposed in the bed and banks shall be identified. Bank soils shall be reported by Uniform Soil Classification using the visual-manual procedures (ASTM D 2488-00). The median (d_{50}) particle size shall be determined using visual observation, grain size analysis of the surface layer, or the Wolman Pebble Count Method described in Chapter 11 of USDA (1996). A shear stress ratio shall be calculated for each riffle based on the applied shear at bank-full flow divided by the critical shear of the material in the riffle, using methods and tables described below. For coarse grain material, the d_{50} particle size shall be used.

5. Critical Shear Stress Analysis: The shear stress ratio must be less than 1.0 at the farthest point of the drawdown curve of any channel intervention, in accordance with the guidelines below:

   a. Shear Stress Ratio

      The shear stress ratio is defined as:

      $$\tau_o / \tau_c \qquad \text{(Equation OC-6)}$$

      In which:

      τ_o= average boundary shear stress (lbs/ft^2) (see Equation OC-7)

      τ_c = critical shear stress (lbs/ft^2) (see Equation OC-8)

      If bed and bank materials are distinct, then the shear stress ratio shall be calculated for each. If the shear stress ratio of either streambed or bank is greater than 1.0, the channel is prone

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to near-term adjustment, and any interventions shall be designed to prevent accelerated erosion. If the bed consists of rock that is prone to fracturing, slaking, or break-up, the median particle size shall be used for calculation of the ratio.

b. Average Boundary Shear Stress

The average applied shear stress, τ_o, may be calculated from the hydraulic data as follows:

$$\tau_o = \gamma R S_e \qquad \text{(Equation OC-7)}$$

In which:

τ_o = average boundary shear stress (lbs/ft^2)

γ = specific weight of water (62.4 lb/ft^3)

R = hydraulic radius at bank-full or stream forming flow (flow area/wetted perimeter)

S_e = slope of energy grade line (averaged over several bends in the area of intervention)

The stream-forming flow may be assumed to be equivalent to the 2-year discharge under pre-disturbance conditions.

c. Critical Shear Stress

At the critical shear stress, τ_C, particles in the bed or bank are entrained and scour ensues. Shield's method is used for calculating the critical shear stress of spherical, non-cohesive particles, as follows:

$$\tau_c = \theta(\gamma_s - \gamma) d_{50} \qquad \text{(Equation OC-8)}$$

In which:

τ_c = critical shear stress (lb/ft^2)

θ = Shield's parameter (0.06 for gravel to cobble, 0.044 for sand) (dimensionless)

γ_s = specific weight of sediment (160 lb/ft^3)

γ = specific weight of water (62.4 lb/ft^3)

d_{50} = median particle size in the surface layer of bed or banks (ft)

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There are limited methods for calculating τ_C for fine-grained material. Field or laboratory testing generally determines the critical shear stress for these materials. The most widely available source is Chow (1988). More recently, the USDA Agricultural Research Service National Sedimentation Laboratory has developed computer software for calculating toe scour (ARS Bank-Toe Erosion Model, Prototype Version 3.4, 2004). The combination of these two sources is presented in. Critical shear stress may also be determined from American Society of Civil Engineers (ASCE) and the Water Environment Federation (WEF) (1992), Figure 9.6, p. 335.

In lieu of calculated values, the τ_C from Table OC-3 may be used. Table OC-3 presents critical shear for sediment-laden water and where noted, clear water. The user must exercise judgment as to future conditions. Clear water values may be used below a heavily piped area, for concrete channels designed to contain the future flows, or immediately below a managed detention pond.

5. Planform Ratios: Natural channels have generally predictable patterns in plan and profile. A channel with a planform substantially different than the norm may be exhibiting system-scale instability. The ratios listed in Table OC-4 shall be calculated, and those outside the typical range shall be noted. Natural channels are highly variable, and ratios outside these ranges do not necessarily indicate problems. Planform data must be considered as part of the larger evaluation.

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Table OC-3
Critical Shear Stresses for Channel Materials
(solely for use in channel assessments)

Granular Material	Critical Shear Stress (τ_C) (pounds per square foot)
Boulders (100 cm) (39 in)	20.295
Boulders (75 cm) (30 in)	15.222
Boulders (50 cm) (20 in)	10.148
Boulders (25.6 cm) (11 in)	5.196
Riprap (6-8 in)	3.132
Cobbles (6.4 cm) (2.5 in)	1.299
Cobbles and shingles	1.100
Cobbles and shingles, clear water	0.910
Coarse sand (1 mm) (0.4 in)	0.015
Coarse gravel, noncolloidal (GW), clear water	0.300
Coarse gravel, noncolloidal (GW)	0.670
Gravel (2 cm) (0.78 in)	0.406
Fine gravel	0.320
Fine gravel, clear water	0.075
Fine sand (0.125 mm) (0.005 in)	0.002
Fine sand (0.125 mm) (SP) (0.005 in)	0.002
Fine sand (SW), (SP), colloidal	0.075
Fine sand, colloidal, (SW), (SP), clear water	0.027
Graded loam to cobbles, noncolloidal (GM)	0.660
Graded loam to cobbles, noncolloidal (GM), clear water	0.380
Graded silts to cobbles, colloidal (GC)	0.800
Graded silts to cobbles, colloidal (GC), clear water	0.430
Fine-Grained Material	**Critical Shear Stress (τ_c) (pounds per square foot)**
Resistant cohesive (CL), (CH)	1.044
Stiff clay, very colloidal (CL)	0.460
Stiff clay, very colloidal (CL), clear water	0.260
Moderate cohesive (ML-CL)	0.104
Ordinary firm loam (CL-ML)	0.150
Ordinary firm loam (CL-ML), clear water	0.075
Alluvial silts, colloidal (CL-ML)	0.460
Alluvial silts, colloidal (CL-ML), clear water	0.260
Alluvial silts, noncolloidal (ML)	0.150
Alluvial silts, noncolloidal (ML), clear water	0.048
Sandy loam, noncolloidal (ML)	0.075
Sandy loam, noncolloidal (ML), clear water	0.037
Silt loam, noncolloidal (ML)	0.110
Silt loam, noncolloidal (ML), clear water	0.048
Shales and hardpans	0.670
Other Materials	**Critical Shear Stress (τ_c) (pounds per square foot)**
Jute net	0.46
Plant cuttings	2.09
Well established dense vegetation to the normal low water	2.16
Geotextile (synthetic)	3.01
Large Woody Debris	3.13

Notes:
For non-cohesive soils, the table values are based on spherical particles and Shield's equation (see Equation OC-8).
For cohesive soils, the values are based on limited testing as reported in Chow (1988) and U.S. Department of Agriculture Agricultural Research Service (USDA ARS) (2004).
Material type abbreviations:

GW – Gravel, well graded	GC – Clayey gravel
SP – Sand, poorly graded	CL – Clay
SW – Sand, well graded	CH – Clay, high plasticity
GM – Silty gravel	ML – Silt

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Table OC-4
Planform Ratios

Ratio	Typical Range
Meander Length/Wavelength (sinuosity)	1.1 to 1.5
Meander Length/Bank-full Width	10 to 14
Radius of Curvature/Bank-full Width	2 to 5
Riffle Spacing /Bank-full Width	5 to 7

A typical reach with the required plan and profile information is shown on Figure OC-3 and Figure OC-4.

4.2.2 Channel Condition Scoring Matrix

Using information summarized in Section 4.2.1 above, a channel condition scoring matrix shall be completed. The channel scoring matrix is provided in Table OC-5.

Results of the channel scoring matrix are used to assess the condition of a natural channel, as follows:

1. A total rating of 12 or lower indicates a channel of at least moderate stability and suggests the design guidance provided will typically be sufficient.

2. A rating between 12 and 18 indicates some channel instability will be present that will require special measures to address those issues rated as poor in the assessment. Depending on the type and severity of instability noted, this may include adding energy dissipation or other structural measures.

3. A rating greater than 18 typically indicates the channel will exhibit significant system-wide instability. In such cases, the designer must meet with the City to discuss how to proceed; it may be necessary for a qualified professional in fluvial geomorphology to conduct a detailed study of the causes of instability and make recommendations for structural measures to correct the stability problem.

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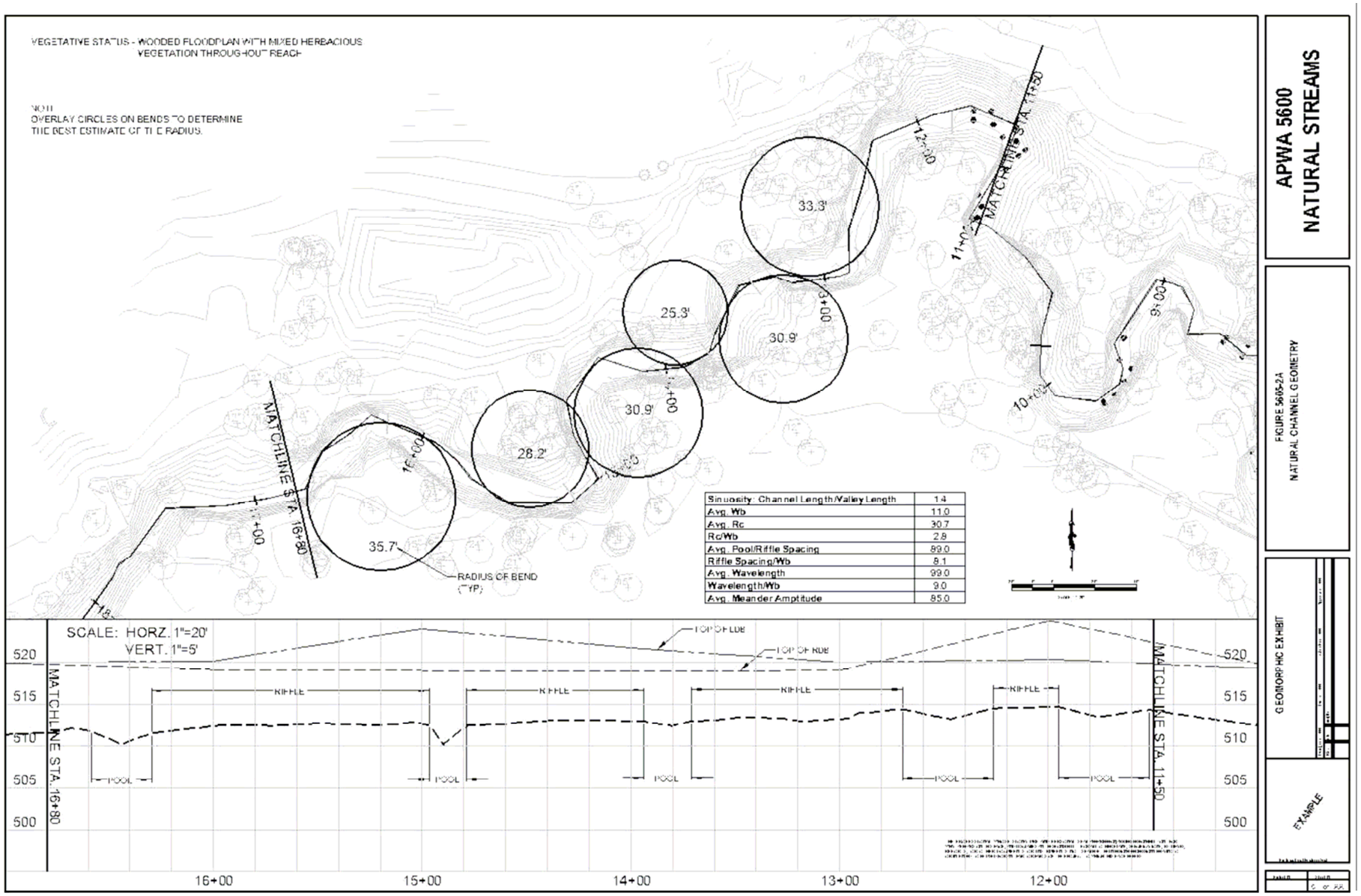

Figure OC-3
Natural Channel Assessment (Part 1)

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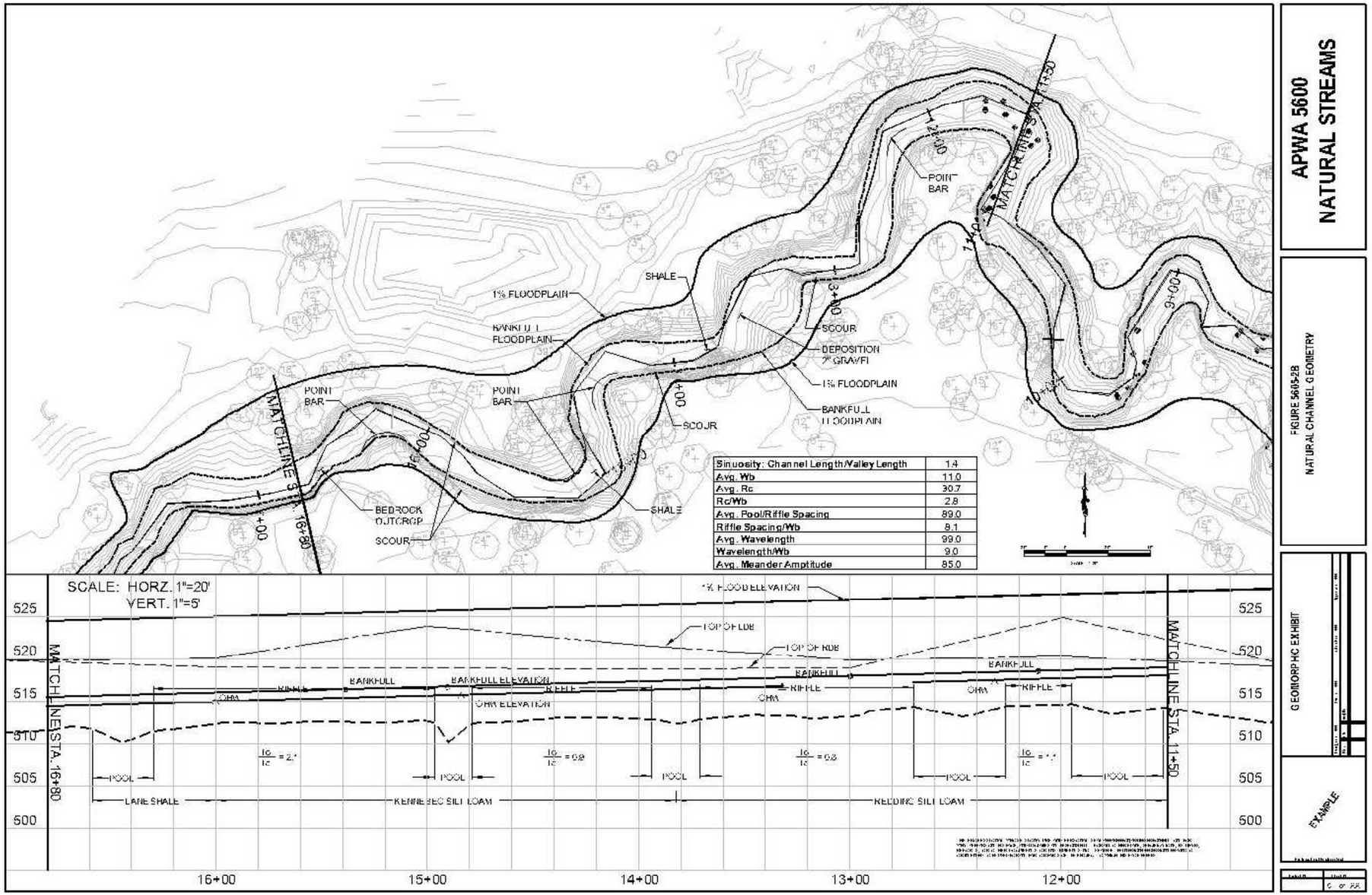

Figure OC-4
Natural Channel Assessment (Part 2)

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Table OC-5
Channel Condition Scoring Matrix
(adapted from Johnson et al. 1999)

Project: _____

Channel Name and Location: _____

Evaluated by: _____ Firm: _____ Date: _____

Stability Indicator	Good (1)	Fair (2)	Poor (3)	Score (S)	Weight (W)	Rating (S*W= R)
Bank soil texture and coherence	Cohesive materials, clay (CL), silty clay (CL-ML), massive limestone, continuous concrete, clay loam (ML-CL), silty clay loam (ML-CL), thinly bed limestone	Sandy clay (SC), sandy loam (SM), fractured thinly bedded limestone	Non-cohesive materials, shale in bank, (SM), (SP), (SW), (GC), (GM), (GP), (GW)		0.6	
Average bank slope angle	Slopes ≤2:1 on one or occasionally both banks	Slopes up to 1.7:1 (60˚) common on one or both banks	Bank slopes over 60˚ on one or both banks		0.6	
Average bank height	Less than 6 feet	Greater than 6 and less than 15 feet	Greater than 15 feet		0.8	
Vegetative bank protection	Wide to medium band of woody vegetation with 70 - 90 percent plant density and cover. Majority are hardwood, deciduous trees with well-developed understory layer, minimal root exposure.	Narrow bank of woody vegetation, poor species diversity, 50-70 percent plant density, most vegetation on top of bank and not extending onto bank slope, some trees leaning over bank, root exposure common.	Thin or no band of woody vegetation, poor health, monoculture, many trees leaning over bank, extensive root exposure, turf grass to edge of bank.		0.8	
Bank cutting	Little to some evident along channel bends and at prominent constrictions, some raw banks up to 4 feet.	Significant and frequent. Cut banks 4 feet high. Root mat overhangs common.	Almost continuous cut banks, some over 4 feet high. Undercut trees with sod-root mat overhangs common. Bank failures frequent.		0.4	
Mass wasting	Little to some evidence of slight or infrequent mass wasting, past events healed over with vegetation. Channel width relatively uniform with only slight scalloping.	Evidence of frequent and significant mass wasting events. Indications that higher flows aggravated undercutting and bank wasting. Channel width irregular with bank scalloping.	Frequent and extensive mass wasting evident. Tension cracks, massive undercutting and bank slumping are considerable. Highly irregular channel width.		0.8	
Bar development	Narrow relative to channel width at low flow, well consolidated, vegetated, and composed of coarse bed material to slight recent growth of bar as indicated by absence of vegetation on part of bar.	Bar widths wide relative to channel width with freshly deposited sand to small cobbles with sparse vegetation.	Bar widths greater than ½ the channel width at low flow. Bars are composed of extensive deposits of finer bed material with little vegetation.		0.6	

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Table OC-5 (continued)

Stability Indicator	Good (1)	Fair (2)	Poor (3)	Score (S)	Weight (W)	Rating (S*W= R)
Debris jam potential	Slight—small amounts of debris in channel. Small jams could form.	Moderate—noticeable debris of all sizes present.	Significant—moderate to heavy accumulations of debris apparent.		0.2	
Obstructions, flow deflectors (walls, bluffs) and sediment traps	Negligible to few or small obstructions present causing secondary currents and minor bank and bottom erosion but no major influence on meander bend.	Moderately frequent and occasionally unstable obstructions, noticeable erosion of channel. Considerable sediment accumulation behind obstructions.	Frequent and unstable causing continual shift of sediment and flow.		0.2	
Channel bed material, condition, consolidation, and armoring	Massive competent to thinly bed limestone, continuous concrete, hard clay, moderately consolidated with some overlapping. Assorted sizes of particles, tightly packed and overlapped, possibly imbricated[1]. Small percentage of particles < 4mm.	Shale in bed, soft silty clay, little consolidation of particles, no apparent overlap, moderate percentage of particles < 4 mm, knickpoints < 200 mm.	Silt, weathered, thinly bedded, fractured shale, high slaking potential, very poorly consolidated, high percentage of material < 4 mm, knickpoints > 200 mm.		0.8	
Sinuosity[2]	1.2 ≤ Sinuosity ≤ 1.4	1.1 < Sinuosity < 1.2	Sinuosity < 1.1		0.8	
Ratio of radius of curvature (R_c) to channel width (W_b)	$3 \le R_c/W_b \le 5$	$2 < R_c/W_b < 3$, $5 < R_c/W_b < 7$	$2 < R_c/W_b$, $R_c/W_b > 7$		0.8	
Ratio of pool - riffle spacing to channel width at elevation of 2-year flow	$4 \le \text{Length}/W_b < 8$	$3 \le \text{Length}/W_b < 4$, $8 < \text{Length}/W_b \le 9$	$3 < \text{Length}/W_b$, $\text{Length}/W_b > 9$, unless long pool or run because of geologic influence		0.8	
Percentage of channel constriction	< 25%	26-50%	> 50%		0.8	
Sediment movement	Little to no loose sediment	Scour and/or deposition, some loose sediment	Near continuous scour and/or deposition and/or loose sediment		0.8	
					TOTAL	

[1] Imbrication-a deposition feature in which bed load is laid down in an overlapping pattern like fish-scales or shingles; the shingling is in the downstream direction. Natural channels imbricate to self-armor.

[2] Sinuosity-the degree of curvature of a channel. Strictly, sinuosity it the ratio of channel length to valley length and is usually measured over considerable distance. For the current purposes, sinuosity can be approximated as channel length/wavelength.

4.3 In-channel Construction Requirements

Construction in natural channels or their buffer zones shall conform to the general requirements of this section and to the appropriate specific requirements of the subsections that follow (Sections 4.3.1 through 4.3.7). In-channel construction shall generally be limited to infrastructure crossings and outfalls. All channel interventions shall be designed so that the function and stability of the adjacent reaches are preserved. The side slopes of banks where construction occurs shall be restored with vegetation.

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4.3.1 Energy Management

An important consideration for the design engineer working on a natural channel is to evaluate and manage the energy throughout the reach of the project. The pre-project and post-project hydraulic and energy grade lines for the 1-, 10-, and 100-year storms shall be plotted. The region of a channel where in-stream construction causes a change in these grade lines is considered the zone of influence. Downstream from the construction region, the extent of the zone of influence shall be generally limited by energy dissipation and use of naturally occurring or Newbury-style grade control. Grade control structures shall be designed to dissipate energy sufficiently to match the energy grade line of the project reach with that of the upstream and downstream adjacent reaches. Design criteria for energy dissipation and grade control structures are addressed in Section 6.0, Hydraulic Structures and Section 7.0, Small Grade Control Structures.

There should not be an increase in depth or velocity sufficient to threaten the channel bed or bank. Within the zone of influence, the energy of the flow on the channel shall be evaluated for the potential of excessive scour, deposition, initiation of headcuts, or other instability (i.e., consider the shear stress and energy grade line, and evaluate whether the applied shear is greater than the critical shear along the channel bed or bank). Upstream from the construction region, the limit of the zone of influence may extend a distance beyond the construction as a drawdown or backwater curve.

By deliberately designing hydraulic roughness, engineers can dissipate scouring energy and guide it towards the channel thalweg. Thoughtful use of energy management structures can substantially reduce the need for channel armor. Spot usage of hard armor is not an acceptable design approach because it transfers the energy and damage elsewhere in the reach. Instead, the channel shall be designed to dissipate the energy and alleviate the need for armor.

Boulder drop structures and shaped grade controls are especially useful for focusing flow to the channel thalweg and away from the banks. When using riprap in in-stream structures, it should be left rough. Where possible, the riprap should be staked with live vegetation such as shrub willow stakes at the toe of the slope and up the banks to lock the riprap in place and provide additional stage-dependent energy dissipation. When installing live stakes into riprap, the stakes must extend at least 12 inches into soil below the rock and extend roughly 12 inches above it. Since it is difficult to acquire live stakes longer than 48 inches, and it is also difficult to drive the stakes through more than 24 inches of rock, this is the practical limit of their use.

Streamside vegetation also provides energy management benefits and should be protected. The designer shall set the construction limits to not disturb riparian vegetation, except by permission from the City. Use of vegetation is recommended to increase bank resistance and minimize increases or abrupt

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changes in velocities. Vegetative bank or bed stabilization may be required in areas where increases in depth or velocity are necessary.

4.3.2 Sediment Transport Continuity

To maintain the ability of the channel to transport sediment, the minimum applied shear to the bed of the channel for the post-project condition shall not be less than 90 percent of the minimum applied shear for the pre-project condition. This requirement applies to the zone of influence for the 1-, 10-, and 100-year flows for current and ultimate development conditions. For maximum allowable applied shear, the post-project condition shall not exceed the critical shear strength of either bed or bank.

4.3.3 Transitions

In-channel structures shall be designed to gradually blend into the natural channel and provide a smooth transition of both geometry and roughness. Abrupt changes in cross-section, strength of material or hydraulic roughness tend to concentrate erosive forces and the designer must take particular care to avoid them. In-channel structures shall be designed to gradually blend into the natural channel and provide a smooth transition of both geometry and roughness. Robust vegetation such as live stakes is useful in managing a gradual transition from riprap to native bank material.

4.3.4 Discharge Outfalls

Discharge outfalls into natural open channels from enclosed conduits or constructed channels shall be designed depending on the type of outfall, as described below. Calculations to evaluate energy management and sediment continuity, as discussed in Sections 4.3.1 and 4.3.2, are not required for these outfalls; however, energy dissipation shall be provided at these locations to reduce increased shear stress caused by development in the watershed. For further discussion on calculations to evaluate energy management, refer to Chapter 6, Streets, Inlets, and Storm Drains.

4.3.4.1 Primary Outfalls

Primary outfalls are those where the entire main channel upstream is replaced by an enclosed system or constructed channel that discharges flow in line with the direction of the existing downstream segment. Energy dissipation shall be provided at the outlet to reduce velocities. Grade control downstream of the outlet and energy dissipation device shall be provided to prevent undermining of the outfall by future headcuts. The alignment and location of the outfall and associated energy dissipation and grade control structures shall make a smooth transition into the downstream channel. Primary outfalls shall be used whenever the contributing drainage area of the outfalls is greater than 80 percent of the downstream channel.

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4.3.4.2 Tributary Outfalls

Tributary outfalls are those which discharge to a downstream segment that has a drainage area separate from the tributary that is larger than the drainage area of the tributary itself. Energy dissipation and transition to natural stream flow shall take place in the tributary, upstream of the confluence with the larger channel by a distance of at least one channel width. Newbury-style grade control structure(s) in the tributary upstream of the confluence shall be provided if the tributary flow line is higher than the adjoining channel or if future incision of the adjoining channel is anticipated. Tributary outfalls may be used in all situations of tributary flow.

4.3.4.3 Lateral Outfalls

Lateral outfalls are small outfalls that discharge into a natural stream at its embankment. Outfalls shall be located to enter on a riffle or from the outside of a bend; they should generally not enter from the inside of a bend. Outfall pipes shall be oriented perpendicular to the flow of the stream, with the invert at or slightly below the top of the next downstream riffle. Outfalls shall be flush with or setback from the bank. The bank shall be shaped to provide a smooth transition and protected with reinforced vegetation (preferred) or riprap.

If the lateral outfall is in a bend, it shall be set back from the existing bank a sufficient distance to account for future meander migration, and the transition shall be graded and reinforced with vegetation. Riprap or hard armor protection should not be used in a bend. Perpendicular outfalls may only be used when the contributing drainage area of the outfall is less than 40 percent of that in the downstream channel.

4.3.4.4 Edge-of-Buffer Outfalls

Edge of buffer outfalls are addressed in the Section 4.1 text regarding natural channel buffer zones.

4.3.5 Culverts, Bridges, and Above-grade Crossings

4.3.5.1 Crossing Location

Crossings should generally be located on a riffle. If the width of the crossing is large relative to the length of the riffle, then Newbury-style grade control structures shall be provided at the riffles upstream and downstream to isolate the impact of the crossings.

4.3.5.2 Realignment of Channels

Realignment of channels to accommodate crossings and their approach should be avoided and minimized as much as possible. Designers proposing to realign a natural channel must thoroughly document the influence of this action on the upstream and downstream reaches. (Refer to Section 4.2 for natural channel assessment process). Any areas relocated shall have the banks stabilized with natural

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vegetation, and the designer shall reinforce the adjacent upstream and downstream riffles with Newbury-style grade control structures.

4.3.5.3 Bridges

For bridges, the multi-stage channel shape shall be maintained. Additional cross-sectional channel area to convey the design flow shall be located above the elevation of the bank-full discharge.

4.3.5.4 Multi-Cell Pipe and Culvert Crossings

Multi-cell pipe and culvert crossings shall be designed to minimize impacts on streams and minimize maintenance requirements. For crossings that have a cumulative width larger than the bank-full width, certain guidelines apply to prevent build up of sediment and loss of channel capacity. Those cells wider than the bank-full width shall have a flow line located at the lowest estimated bank-full depth. Alternatively, a weir wall or other structure, located upstream of the culvert opening, shall be installed with sufficient height to prevent access to the cell during flows less than bank-full flow. The weir wall shall be designed so that the hydraulic efficiency during the 100-year event conditions is not reduced.

4.3.5.5 Culverts

Culverts shall be designed so there is minimal backwater effect at all flows up to the 100-year discharge. Energy management and sediment transport continuity shall be checked (refer to Sections 4.3.1 and 4.3.2).

4.3.6 Below-grade Stream Crossings

4.3.6.1 Riffle Crossing

Below-grade stream crossings primarily involve utility pipelines. Crossings should generally be located at riffles or at Newbury-style grade control structures constructed at the riffle. Any necessary encasement of the utility line may be integrated with, or constructed in addition to, the grade control structure.

4.3.6.2 Pool Crossing

If riffle crossing is not feasible, the crossing should be in a pool that is protected by a downstream naturally occurring or Newbury-style grade control structure. The top of crossing elevation shall be at least 2 feet below the top of grade control. Crossings under pools shall not be armored directly, but shall be protected by downstream grade control at the next downstream riffle.

4.3.6.3 Orientation to Channel

Below-grade crossings shall be perpendicular to the stream whenever possible. If a perpendicular crossing is not feasible, the Newbury-style grade control structure protecting the crossing shall be perpendicular.

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4.3.6.4 Channel Alteration

Constriction or alteration of the pre-existing channel shape shall be avoided. If alteration occurs, sediment transport continuity and energy management shall be verified (refer to Sections 4.3.1 and 4.3.2). Streambanks shall be repaired using vegetative methods whenever possible. The hydraulic roughness of the repaired streambank should match that of the undisturbed streambanks.

4.3.7 Professional Judgment

Natural channels are complex, variable systems whose forms are shaped by local geology and climate. The standards discussed in this manual are based on generally accepted design principles. However, these guidelines may not be optimal or sufficient in all cases. Designs shall be completed by qualified professionals. Although the 100-year floodplain of a natural channel may, in many cases, be larger than the 100-year floodplain for an engineered channel, it is of the utmost importance to preserve or enhance the natural corridor because the first Fundamental Canon in ASCE's Code of Ethics states: "Engineers shall hold paramount the safety, health, and welfare of the public and shall strive to *comply with the principles of sustainable development* in the performance of their professional duties."

5.0 ENGINEERED CHANNEL DESIGN CRITERIA

This section provides design criteria for engineered open channels. Subjects addressed include: flow rate, flow regime, flow velocity, channel slope, channel curvature and superelevation, freeboard, channel linings, channel cross-section, low-flow channels, and outfalls into channels. Each subject is explained in terms of its application to different channel types. Detailed construction drawings are provided in the Design Standards.

5.1 Flow Rate

The primary purpose of engineered open channels is to convey water safely and efficiently and to control flooding on adjacent properties. Where engineered channels are used, open channels shall be designed to convey the 25-year flow. In addition, for all open channels it must be shown that the 100-year flow will be contained within the drainage easement.

Design flows shall be calculated for fully developed watershed conditions based on current or anticipated zoning and land uses. Upstream detention storage may be accounted for in design flow if the storage is currently being maintained and ownership and future maintenance responsibilities for the detention facility are clearly defined. Flow rate reduction due to storage will be accepted only if detailed modeling and detention basin routing have been completed. All design flows shall be determined using methods described in Chapter 5, Calculation of Runoff.

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Low-flow channels should generally be designed to convey the 1-year flow, although site conditions may justify a varied design that requires City approval. Any existing perennial or intermittent base flows shall also be taken into account when designing low-flow channels.

5.2 Flow Regime

To protect channel stability and hydraulic performance, critical flow conditions shall be avoided. The Froude number, F_r, must be calculated for all unique sections of open channels for the 25-year flow. Calculating F_r for other frequency flows may be necessary to ensure channel stability. F_r must first be calculated using the *minimum* value of the Manning's roughness coefficient, *n*, found in Table OC-1 (Section 3.2).

In general, the maximum allowable value of F_r is 0.8. However, if values greater than 0.8 are necessary due to site constraints, the channel shall be designed so that the flow is supercritical, with a F_r greater than 1.2. In such cases, the calculation should use the maximum value for Manning's roughness, found in Table OC-1 (Section 3.2). For supercritical flows, calculation of the conjugate depth is necessary and a well-accepted open channel hydraulics reference should be used. Designs with supercritical flows require use of a concrete channel lining. In addition, such designs must avoid all obstructions, transitions, and curvature. It must be shown how adjacent properties will be protected from flooding should a hydraulic jump occur.

Under certain conditions, values of F_r between 0.8 and 1.2 may be allowed, and the requirement to calculate conjugate depths may be waived. This exception applies to channels with a 25-year design flow of 20 cfs or less when no potential hazards exist.

5.3 Velocity

For an engineered open channel to function properly, the channel must be designed to fall within a range of acceptable minimum and maximum values. Generally, maximum design velocity should be controlled through the use of grade controls, design slope, channel geometry, and channel roughness. Through proper planning of new developments and use of these design parameters, subcritical flows should be maintained, and in nearly all cases, concrete channels should not be necessary.

Maximum velocities must be considered to minimize the potential for channel erosion and to protect channel stability. Maximum velocities shall be checked using the 25-year design flow and minimum roughness coefficient values. Maximum allowable velocities for channels with various types of linings are listed in Table OC-6.

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Minimum velocity must be considered to ensure channels will have a reasonable capacity to transport sediment and avoid sedimentation. Minimum velocities shall be checked using the 2-year design flow and maximum roughness coefficient values. Minimum allowable velocities are listed in Table OC-6.

Table OC-6
Design Velocity Limitations for Open Channels with Different Linings

Channel Type	Minimum Velocity (2-year check)	Maximum Velocity (25-year check)
Grass, seed and mulch	2 ft/s	4 ft/s
Grass, sod	2 ft/s	6 ft/s
Grass, TRM	2 ft/s	8 ft/s
Grass, pre-vegetated TRM	2 ft/s	10 ft/s
Manufactured hard lining	5 ft/s	12 ft/s
Riprap	5 ft/s	12 ft/s
Concrete	5 ft/s	18 ft/s

Velocity in simple, uniform channels can be estimated using Manning's equation. In complex channels with varied linings, geometry, and curvature, the HEC-2 or HEC-RAS models shall be used to estimate velocities. When it is necessary to calculate flows under distinctly non-uniform flow, varied or unsteady conditions, HEC-2 or HEC-RAS are not acceptable, and other appropriate methods must be used.

Open channel design should account for high localized velocities at drops, expansions, contractions, and other structural controls (see Section 6.0, Hydraulic Structures). The effect of velocity and the selection of channel lining types are addressed in Section 5.7, Channel Linings.

5.4 Slope

5.4.1 Longitudinal Slope

The criteria for flow regime and flow velocity will generally determine acceptable longitudinal slope. Minimum slope criteria are specified to provide positive drainage with minimal ponding. Minimum slopes of channels with natural linings shall be 0.4 percent. For channels with concrete linings, minimum slopes shall be 0.2 percent.

Maximum slope criteria are defined to keep velocities within acceptable ranges. Maximum slopes are constrained by the allowable Froude number, F_r. As discussed in Section 3.4, designs that result in F_r near 1.0 (> 0.8 and < 1.2) shall be avoided by adjusting the design of the cross-section, roughness, and slope. In general, in cases where drainageways have F_r greater than 0.8, drop structures must be integrated into the design to control slopes and keep F_r within the acceptable range.

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An important consideration when designing channel slope within natural channels or topography is sinuosity. Straightening of a natural channel inevitably results in an increase in slope. Conversely, for a constructed channel, a design incorporating meanders can be used to satisfy slope criteria and potentially reduce the number of grade control structures required.

5.4.2 Side Slopes

Channels with natural linings requiring mowing or regular maintenance shall have a side slope no steeper than 4H:1V, unless it can be shown that site conditions prohibit construction of a channel with these dimensions. In such cases, side slopes as steep as 3H:1V may be considered.

For concrete channels, non-vertical side slopes shall not have a slope steeper than 1H:1V, to allow for safe exit from the channel. An exception is allowed for short transitions between vertical and 1H:1V concrete channels.

For channels lined with materials other than concrete and when side slopes steeper than 3H:1V are necessary, slopes armored with riprap, geoweb, or other material may be considered on a case-by-case basis. The maximum allowable side slope using these types of materials shall be 2H:1V.

Factors to consider when determining side slopes include ease of maintenance, safety, and public acceptance, particularly in neighborhoods. A fence with a minimum height of 4 feet shall be installed at the top of any slope steeper than 1H:1V for channels with a depth of 3 feet or more, where homes, streets, parking lots, buildings or other facilities cause people to be in close proximity.

5.5 Curvature and Superelevation

As discussed in Section 5.4.1, sinuosity may be used to control velocity in conjunction with drops. Every design is site specific. The use of curvature in a channel design to flatten slope should be done only with careful consideration given to channel erosion and instability. Layout of small engineered channels should minimize the number of curves and the degree of curvature of any necessary curves. Curves shall only be used where it is shown they are necessary due to layout of the development or to create sinuosity and reduce longitudinal slope. Where curves are used, the centerline of curvature of the channel shall have a minimum radius of twice the top width of the design flow (25-year event), but not less than 100 feet.

Supercritical flow in an engineered open channel in an urban area may create hazardous conditions. Curvature shall not be used in a channel under these conditions. If curvature is proposed, it may be considered with an analysis of conjugate depths and potential hazards as outlined in Section 5.2, Flow Regime.

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Velocities and depths are higher on the outside of open channel curves. This rise in water surface on the outside of a curve is referred to as superelevation. Superelevation must be calculated for all curves in open channels and accounted for in the design of the channel and freeboard. For subcritical flows, superelevation can be estimated by:

$$\Delta y = \frac{V^2 T}{2 g r_c} \qquad \text{(Equation OC-9)}$$

In which:

Δy = difference in water surface elevation between the inner and outer banks of the channel in the bend (resulting from superelevation) (ft)

V = mean flow velocity (ft/s)

T = top width of the channel under design flow conditions (ft)

g = gravitational constant = 32.2 ft/s^2

r_c = radius of curvature (ft)

Velocity shall be calculated utilizing minimum roughness coefficient values found in Table OC-1 (Section 3.3). When the ratio of the radius of curvature of the channel centerline to the top width of the channel is less than 8, the velocity of the flow along the outside of the bend shall be calculated using Equation OC-2. Because of this increase in velocity, it is often necessary to provide increased erosion protection along the outside of bends. Riprap shall be used when the velocity of the upstream reach for the 25-year storm is greater than 8 ft/s. (Riprap design information is provided in Section 2.2.4).

Increased erosion protection based on higher bend velocities shall apply to the outside half of the channel bottom and on the channel side slope for the entire length on the outside of the bend, plus a distance of two times the top width downstream of the bend. In cases where an outside bend in a grass-lined channel needs protection, riprap shall be covered, if possible, with soil and vegetation to provide a grassed-lined channel appearance. Buried riprap may lose vegetated cover in a major flood and require re-burial and revegetation.

5.6 Freeboard

The required freeboard for engineered open channels is dependent on the type of channel:

- For concrete channels, the required freeboard is 6 inches above the 25-year water surface.
- For other types of channel linings, the required freeboard is 1 foot above the water surface, except for channels where the 25-year flow depth is 12 inches or less; in such cases the channel shall have a freeboard of 6 inches above the 25-year water surface.

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For all channel types, the 100-year water surface, including the freeboard, shall remain within the drainage easement.

It must be shown that the lowest enclosed space of all buildings is at least 1 foot above the 100-year water surface elevation at the upstream side of the building. Particular care in setting floor elevations shall be taken along channels existing within backwater conditions of existing or proposed culverts. In these cases, the water surface must be determined using the appropriate hydraulic analysis found in Chapter 7, Bridges and Culverts.

In cases where curves exist, freeboard must be above the water surface calculated by adding the superelevation, from Equation OC-7, to the normal water surface elevation.

5.7 Linings

Typical lining options for engineered open channels are listed and summarized in Section 2.2. As discussed previously, channel linings using natural materials are preferred. Proper planning to provide enough space and to install structural controls is necessary to enable the use of open, vegetated drainage systems to the maximum extent practicable.

Allowable velocities associated with various types of channel linings are summarized in Table OC-6 (Section 5.3). Velocities can be controlled using a variety of design options, including grade control structures, wide or flat channel cross-sections, and increased channel roughness.

Design criteria for different types of engineered channel linings are provided in Sections 5.7.1 through 5.7.6.

5.7.1 Soil Bioengineered Lining

Soil bioengineering integrates native vegetation as a structural element of streambank stabilization. Whether used alone or in combination with inert natural or manmade materials, plants provide mechanical, hydrologic, and hydraulic benefits. Advantages of soil bioengineering may include:

- Effective protection of streambanks from scouring and overland flows
- Effective energy dissipation in the stream channel
- Protection of aquatic habitat and provision of mosquito control benefits through stream shading and supply of organic materials
- High terrestrial habitat values
- Substantial capacity for self-repair and simple predictable maintenance

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- High aesthetic values

Despite the significant reinforcement provided by soil bioengineering, these treatments should only be used in relatively stable channels or subsequent to systemic stabilization. Soil bioengineering is particularly useful for repairing disturbed banks after construction access or repairing local scour or erosion. Before attempting to reinforce a streambank using soil bioengineering, the designer shall determine whether the instability is caused by fluvial erosion processes or is the result of underlying geotechnical instability. If there is a weaker plane below the root zone, soil bioengineering will not reduce the risk of slope failure. Soil bioengineering alone is not appropriate in areas where rapid drawdown can occur, such as in a spillway or dam embankment. In accordance with the principles of NRCS (1996) and Gray and Sotir (1996), bioengineering projects shall:

- Be self-sustaining or reduce requirements for future human support
- Use native, living materials for restoration
- Restore the physical, biological, and chemical functions and values of streams or shorelines
- Improve water quality through reduction of temperature and chronic sedimentation problems
- Provide opportunities to connect fragmented riparian areas
- Retain or enhance the stream corridor or shoreline system

Guidelines for plants used in soil bioengineering in open channels include:

- Selection of plants and specifications for planting methods and soil amendments shall be prepared by a professional competent in the biological and stabilization properties of plants.
- Plants selected shall be appropriate to local conditions and be native varieties to the greatest extent practical. Evaluation of local conditions includes assessment of site microclimate, bank slope, soil composition, soil strength and fertility, type and condition of existing vegetation, proximity to existing infrastructure, soil moisture conditions, and likelihood of wildlife predation. Engineering factors influencing plant selection include frequency, height, and duration of channel inundation, near-bank shear stress, size and volume of bed load, as well as depth and frequency of scour.
- Plants may be either locally harvested or purchased from commercial nurseries. When harvesting, no more than 10 percent of a given stand may be removed, and no plant on the state rare or endangered species list may be harvested or damaged in harvesting operations. Plant

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material grown near the metropolitan area is adapted to local climatic conditions and is preferred over more remote sources. Some species such as red maple are particularly sensitive to locale and may only be used if locally available. Seed, plant plugs, rhizomes, whips, live stakes, bare root, and container stock may be used. Turf grasses, noxious, or invasive species shall not be used. A wide variety of plant species shall be used to provide greater reliability to a design. For critical functions such as protection from toe scour, a minimum of three species should generally be employed.

5.7.2 Grass Lining

When it is not feasible to preserve a natural drainageway or construct a naturalized channel, the preferred method of conveyance is a grass-lined open channel. The design velocity in the channel will determine the type of grass lining to use (see Table OC-6 [Section 5.3] for allowable velocities for different types of grass linings). Design velocity should be controlled using grade control structures (see Section 6.0, Hydraulic Structures). Channels with relatively low design velocities may be seeded and mulched. If design velocities exceed the allowable for seed and mulch, the channel shall be sod, approved TRM, or approved reinforced sod installed up to the level of the 25-year water surface. Detailed installation specifications that meet or exceed the manufacturer's requirements must be provided to the City for approval. Maintenance specifications must also be provided for approval to ensure grass growth and repair and replacement of any failed TRM or sod for a warranty period of one year.

A typical detail of an improved natural channel or composite channel is shown in Figure OC-5.

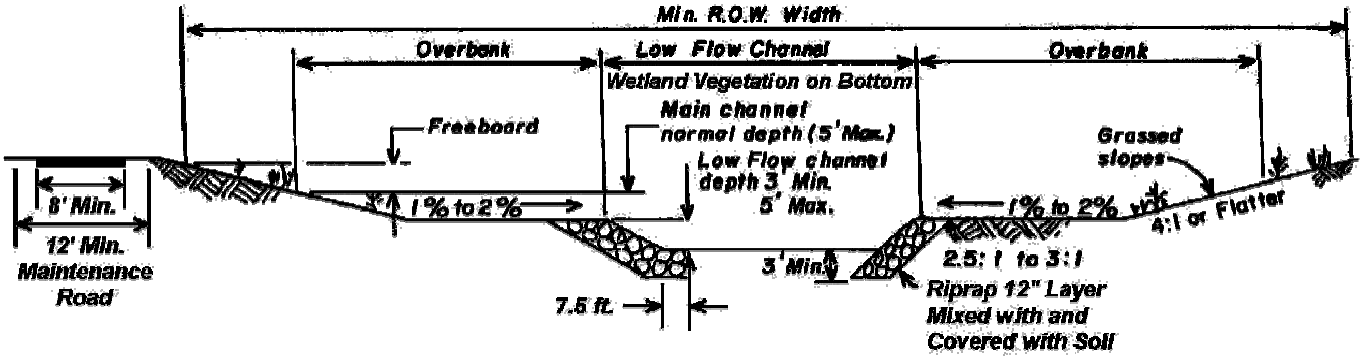

Figure OC-5
Typical Cross-section of an Improved Natural Channel or Composite Channel

Under bridges, vegetation can be difficult to grow and/or maintain. Therefore, beneath bridges, an erosion-resistant hard lining shall be used, with special care given to erosion protection at each end where the hard lining transitions to the vegetated channel.

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Calculations for sizing a grass-lined channel using hydraulic equations from Section 3.0, Open Channel Design Principles and criteria from Section 5.0, Engineered Channel Design Criteria can be performed using the Design of Trapezoidal Grass-lined Channel Worksheet of the SF-Channels Spreadsheet. For the design of a grass-lined channel with a low-flow channel, the Design of Composite Channel Worksheet of the SF-Channels Spreadsheet can be used. An example of this tool is provided in Example OC-2 at the end of this chapter.

5.7.3 Manufactured Hard Lining

Higher flow velocities may require a manufactured hard lining, such as articulated blocks, cabled concrete blocks or other materials. Manufactured hard linings that allow for plant growth and infiltration are preferred to impervious concrete channels. Allowable design velocities for manufactured hard linings are specified in Table OC-6 (Section 5.3). In cases where a manufactured hard lining is required, the channel must be lined with an approved material up to the level of the 25-year water surface. Detailed installation specifications that meet or exceed the manufacturer's requirements must be provided to the City for approval. Maintenance specifications must be provided for approval to ensure plant growth, repair and replacement of any failed blocks, mats or other materials for a warranty period of one year.

5.7.4 Riprap Lining

Riprap lining should be used only when design constraints prevent the channel design velocity from falling within the allowable range for vegetated channels. Rock used for riprap shall be hard, durable, angular in shape, and free from cracks, overburden, shale, and organic matter. Neither breadth nor thickness of a single stone should be less than one-third its length, and rounded stone should be avoided. Criteria for rock sizing, thickness of riprap layer, and thickness of riprap bedding material are provided in the following subsections.

5.7.4.1 Rock Sizing

Equation OC-8 relates flow velocity, channel longitudinal slope, mean rock diameter, and the specific gravity of the stone being used for riprap.

$$\frac{VS^{0.17}}{d_{50}^{0.5}(G_s - 1)^{0.66}} = 4.5 \qquad \text{(Equation OC-8)}$$

In which:

d_{50} = mean rock diameter (feet)

V = mean channel velocity (ft/s)

S = longitudinal channel slope (ft/ft)

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G_s = specific gravity of stone (minimum = 2.6 for Springfield area)

Equation OC-9, derived from Equation OC-8, has the variable for mean rock diameter removed. Solving Equation OC-9 provides a value, *K*, which is referenced in Table OC-7 to determine the specific size of riprap to use for lining an open channel.

$$K = \frac{VS^{0.17}}{(G_s - 1)^{0.66}} \qquad \text{(Equation OC-9)}$$

Equation OC-8 and Equation OC-9 (and hence Table OC-7) are applicable only for cases where:

- $F_r < 0.8$
- Channel side slope is no steeper than 2H:1V

Equation OC-8, Equation OC-9, and Table OC-7 are not intended for use in sizing riprap for rundowns or culvert outlet protection. Information on rundowns and protection of culvert outlets is provided in Section 6.0, Hydraulic Structures.

To size riprap for an open channel, solve Equation OC-9 for *K* to identify the appropriate type of riprap from Table OC-7. A check must be conducted to confirm that F_r is less than 0.8 (see Equation OC-5 in Section 3.4 to calculate F_r). This check is performed automatically when using the Design of Riprap Channel Worksheet in the SF-Channels Spreadsheet. Riprap types specified in Table OC-7 are based on a specific gravity of 2.6. Classification and gradation of ordinary riprap types are outlined in Table OC-8. Riprap types VL, L, and M, which are relatively small and light, should be buried with on-site topsoil and vegetated. For boulders, classification and size criteria are provided in Table OC-9.

Table OC-7
Riprap Requirements for Channel Linings

K Value $K = \frac{VS^{0.17}}{(G_s - 1)^{0.66}}$	**Rock Type**
< 3.3	VL**(d_{50} = 6 inches)
≥ 3.3 to < 4.0	L**(d_{50} = 9 inches)
≥ 4.0 to 4.6	M**(d_{50} = 12 inches)
≥ 4.6 to 5.6	H**(d_{50} = 18 inches)
≥ 5.6 to 6.4	VH**(d_{50} = 24 inches)

*Applicable only where F_r < 0.8 and side slopes are no steeper than 2H:1V.
** Use G_s = 2.6 unless the source of rock and its density are known at the time of design.

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Table OC-8
Classification and Gradation of Ordinary Riprap

Riprap Designation	Percent (%) Smaller Than Given by Weight	Intermediate Rock Dimension (inches)	d_{50} (inches)*
Type VL	70-100 50-70 35-50 2 -10	12 9 6 2	6**
Type L	70-100 50-70 35-50 2-10	15 12 9 3	9**
Type M	70-100 50-70 35-50 2-10	21 18 12 4	12**
Type H	70-100 50-70 35-50 2-10	30 24 18 6	18
Type VH	70-100 50-70 35-50 2-10	42 33 24 9	24

* d_{50} = mean particle size (intermediate dimension)
**Mix VL, L, and M riprap with 30 percent (by volume) topsoil and bury it with 6 or more inches of topsoil, all vibration compacted.

Table OC-9
Classification of Boulders

Boulder Classification	Nominal Size and [Range in Smallest Dimension of Individual Rock Boulders (inches)]	Maximum Ratio of Largest to Smallest Rock Dimension of Individual Boulders
B18	18 [17-20]	2.5
B24	24 [22-26]	2.0
B30	30 [28-32]	2.0
B36	36 [34-38]	1.75
B42	42 [40-44]	1.65
B48	48 [45-51]	1.50

5.7.4.2 Riprap Thickness

The riprap blanket thickness shall be at least 1.75 times the d_{50} of the rock used. At the upstream and downstream termination of a riprap lining, the thickness shall be increased 50 percent for at least 3 feet to prevent undercutting.

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5.7.4.3 Riprap Bedding

The long-term stability of riprap erosion protection is strongly influenced by proper bedding conditions. Many riprap failures are directly attributable to bedding failures. Properly designed bedding provides a buffer of intermediate-sized material between the channel bed and the riprap to prevent channel particles from being transported through the voids in the riprap. Bedding is required both along the side slopes and the channel bottom for a stable lining. Two types of bedding commonly used are granular bedding filter and filter fabric.

5.7.4.3.1 Granular Bedding

Two types of granular bedding gradations include:

- Type I bedding, which is designed to be the lower layer in a two-layer filter for protecting fine-grained soils. Type I bedding has a gradation identical to concrete sand specification AASHTO M-6.

- Type II bedding, which is designed to be the upper layer in two-layer filter. Type II bedding specifications have a gradation somewhat similar to Missouri Department of Transportation (MDOT) Grade A filter material (MDOT Section 1005.2.2).

A bedding that uses Type I and Type II gradations in combination is adequate for most ordinary riprap and grouted riprap applications. Thickness requirements of bedding layers are specified in Table OC-10.

Table OC-10
Thickness Requirements for Granular Bedding

Riprap Designation	Minimum Bedding Thickness (inches)		
	Fine-Grained Soils[1]		Coarse-Grained Soils[2]
	Type I (lower layer)	Type II (upper layer)	Type II (one layer only)
VL (d_{50} = 6 in), L (d_{50} = 9 in)	4	4	6
M (d_{50} = 12 in)	4	4	6
H (d_{50} = 18 in)	4	6	8
VH (d_{50} = 24 in)	4	6	8

[1] May substitute one 12-inch layer of Type II bedding. The substitution of one layer of Type II bedding shall not be permitted at drop structures. Use of a combination of filter fabric and Type II bedding at drop structures is acceptable.
[2] Fifty percent or more retained on the #40 sieve.

A second method for establishing gradation requirements for granular bedding utilizes a procedure referred to as the Terzaghi-Vicksburg (T-V) design (Posey 1960, USACE 1970). The T-V filter criteria

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establish an optimum bedding gradation for a specific channel soil. Specifications for the T-V filter relate the gradation of the protective upper layer (filter) to that of the lower bed material (base) by the following equations:

$$d_{15(filter)} \leq 5d_{85(base)} \quad \text{(Equation OC-10)}$$

$$4d_{15(base)} \leq d_{15(filter)} < 20d_{15(base)} \quad \text{(Equation OC-11)}$$

$$d_{50} < 25d_{50(base)} \quad \text{(Equation OC-12)}$$

In which:

$d_{(filter)}$ = filter grain size

$d_{(base)}$ = base grain size

Application of channel side slope bedding is shown in Figure OC-6.

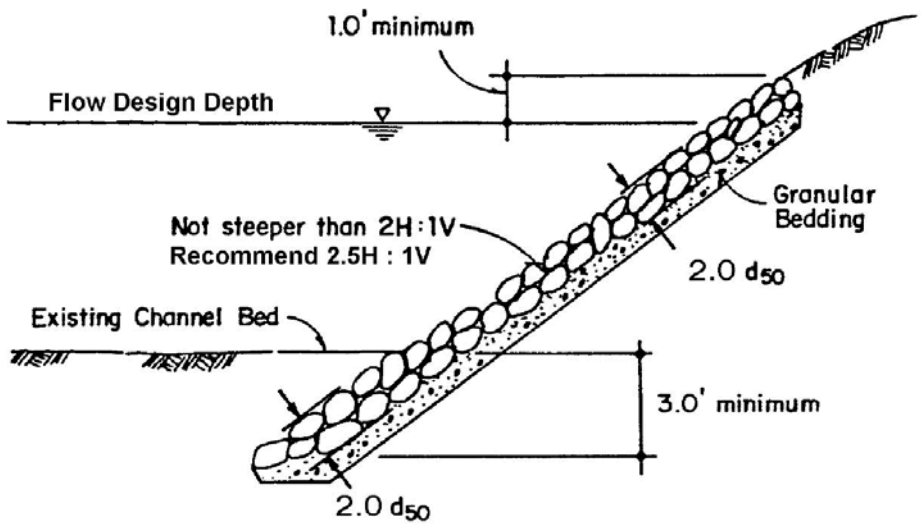

Figure OC-6
Riprap Channel Side Lining with Toe Protection

5.7.4.3.2 Filter Fabric

Filter fabric may be used in some cases as an alternate to bedding material. Filter fabric may be used if the riprap d_{50} is less than 12 inches, longitudinal slope is less than 2 percent, and side slopes are no steeper than 3H:1V.

Filter fabric provides filtering action only perpendicular to the fabric and is not a substitute for granular bedding. Filter fabric has a relatively smooth surface, which provides less resistance to stone movement. The maximum side-slope criterion of 3H:1V is to reduce the potential for stone movement. Since tears in

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filter fabric greatly reduce its effectiveness, placing riprap directly on the fabric is not allowed, and care must be exercised during construction.

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

Filter fabric has only a single equivalent pore opening between the channel bed and the riprap. Fine silt and clay can clog the openings and prevent free drainage, increasing failure potential due to uplift. For this reason, a double granular filter is often more appropriate bedding for fine silt and clay channel beds.

Calculations for sizing a riprap-lined channel using hydraulic equations from Section 3.0, Open Channel Design Principles and criteria from Section 5.0, Engineered Channel Design Criteria are shown in Example OC-3 using the Design of Riprap Channel Worksheet of the SF-Channels Spreadsheet. Example OC-3 is located at the end of this chapter.

5.7.5 Grouted Boulders

Grouted boulders provide a useful lining option for low-flow channels and steep banks; however, boulders larger than 18 inches may be difficult to obtain in the Springfield area. Grouted boulders shall be placed directly on subgrade. Full penetration of grout around the lower two-thirds of the rock is essential for successful grouted boulder performance. Grout shall be injected in a manner that minimizes air voids between the grout, subgrade, and boulders. Grout shall be injected with a grout pump and placed by lowering the grouting nozzle to the bottom of the boulder layer and building up the grout from the bottom up, while using a vibrator or aggressive manual rodding. Inject the grout to a depth equal to two-thirds of the boulders' heights, while keeping the upper one-third ungrouted and clean. Remove all grout splatters off the exposed boulder portion immediately after grout injection using wet brooms and brushes.

Technical specifications for grout mix and grout placement are provided with Figure OC-9 in Section 7.1.4.3.

5.7.6 Concrete Lining

Concrete lining shall be used only when design constraints prevent the channel design velocity from falling within the allowable range for vegetated channels. Generally, concrete channels should only be used for retrofitting in existing urban areas where space is constrained. Well-planned, new developments should not require the use of concrete-lined channels.

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All concrete lining shall be designed to withstand the anticipated hydrodynamic and hydrostatic forces. Trapezoidal channels shall have side slopes no steeper than 1H:1V. Concrete floors and sidewalls for trapezoidal channels shall have a minimum thickness of 6 inches and be reinforced with woven wire or fiber mesh concrete. Rectangular channels shall be structurally designed for all foreseeable loads. All walls shall have a minimum thickness of 6 inches with designed steel reinforcement. In addition, a fence or handrail is required along the top of all channel walls if the channel depth is 3 feet or more, and it is anticipated people will be in close proximity.

Concrete joints shall meet the following criteria:

- Channels shall be constructed of continuously reinforced concrete without transverse joints
- Expansion/contraction joints shall be installed where new concrete lining is connected to a rigid structure or to an existing concrete lining that is not continuously reinforced.
- Longitudinal joints, where required, shall be constructed on the sidewalls at least 1 foot vertically above the channel invert.
- All joints shall be designed to prevent differential movement.
- Construction joints are required for all cold joints and where the lining thickness changes. Reinforcement shall be continuous through the joint.

Calculations for sizing of a concrete-lined channel using hydraulic equations from Section 3.0 and criteria from this section are shown in Example OC-4 using the Normal and Critical Flow Analysis Worksheet in the SF-Channels Spreadsheet.

5.8 Cross-section

In addition properly designing channel linings, as described in Sections 5.7.1 through 5.7.6, the channel cross-section must be designed to achieve the desired velocities, as well as other objectives such as satisfying needs for wildlife habitat and open space. The most desirable cross-section is one that is relatively wide and primarily vegetated to provide benefits related to recreation, maintenance, safety, water quality, downstream impacts, and habitat.

The channel bottom width shall be designed to satisfy the hydraulic capacity of the cross-section, recognizing the allowable range of velocity, depth, and Froude number. For a given discharge, the bottom width can be calculated using the depth, velocity, and Froude number constraints given in this chapter.

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For grass-lined channels, as discussed in Section 5.4.2, the channel shall have a maximum side slope of 4H:1V for safety and aesthetics. A minimum side slope of 1 percent shall be provided for positive drainage. When base flow is present or is anticipated as the drainage area develops, a trickle or low-flow channel shall be provided. See Section 5.9 for low-flow channel design.

For riprap-lined channels, as discussed in Section 5.5.2, the channel and other armored materials should have a preferred side slope of 3H:1V with a maximum side slope of 2H:1V. Where only the channel sides are to be lined, the riprap blanket shall extend at least 3 feet below the channel flow line, and the thickness of the blanket below the existing channel bed shall be increased to at least 3 times d_{50} to accommodate possible channel erosion.

Concrete-lined channels that are not rectangular shall have a maximum side slope of 1H:1V.

5.9 Low-flow Channels

Low-flow channels are necessary depending on the type of channel lining and the conditions that exist. A low-flow channel is necessary under these conditions:

- Vegetated channels where:
    - Baseflow exists
    - High peak runoff from developed areas may cause erosion of vegetated areas
    - 2-year flow exceeds 5 cfs (for unreinforced grass only).
- All types of channel linings in locations where erosion could potentially occur, such as downstream of point discharges.

If conditions warrant a low-flow channel, the low-flow channel shall be designed to convey the 1-year flow under fully developed watershed conditions. Variations from this design must be justified by the hydrologic characteristics of the site.

Low-flow channel requirements vary by channel type, as listed below:

- In naturalized channels, low-flow channels typically are unlined. Depending on the projected stresses, riffle areas may require some reinforcement.
- In engineered grass-lined channels, riprap, boulders, or a soil-riprap mix for the low-flow channel lining can provide a stable, vegetated low-flow channel. Soil and riprap should be mixed prior to placement for these low-flow channels. Vegetated portions of the channel can remain dry and

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easy to mow and maintain. Typical details of a grass-lined channel with a low-flow channel are shown in Figure OC-5.

- In engineered channels that are not grass-lined, low-flow channels typically consist of riprap or boulders. If concrete low-flow channels are considered, a specific approach for addressing disease vectors associated with standing water, such as mosquitoes, should be identified.

5.10 Outfalls

Outfalls into channels must be designed with consideration given to the nature and condition of the receiving channel. Such outfalls shall be perpendicular to flow or directed downstream. Any protrusions of pipes or other structures into the channel must be trimmed flush with the main channel wall or bank.

Discharges into natural, vegetated or reinforced vegetated channels shall be at the flow line, in a manner consistent with the channel outfalls for natural channels described in Section 4.3.4. Vegetated or reinforced vegetated channels are generally not capable of withstanding point discharges. Energy dissipation, such as a headwall or riprap protection, shall be designed around the outfall to minimize bank, channel or wall erosion. Energy dissipation in the main channel shall be designed to withstand the flows that occur there.

Discharges into channels lined with concrete or riprap generally require no special protection against erosion. Discharges into hard-lined channels shall be a minimum of 1 foot above the flow line.

6.0 HYDRAULIC STRUCTURES

This manual does not provide detailed information related to the design of large hydraulic structures. In most cases where large or complex hydraulic structures are proposed, a preliminary meeting shall be held with City staff. If it is determined that the structure is necessary, a qualified professional in the design of hydraulic structures must be retained for the design.

Specific types of hydraulic structures and suggested references for the designer are listed in Table OC-11 While Table OC-11 is not intended to provide a complete list of hydraulic structure types or reference information, it does provide a good general summary of suggested resources for a design engineer working on hydraulic structures. Full citations are provided in Section 9.0, References. For smaller, less complex drop structures, design information is provided in Section 7.0.

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Table OC-11
Suggested Further References for Hydraulic Structures

Type of Hydraulic Structure	Suggested Reference Information
Channel Grade Control	General hydraulic analysis Chow (1959), Rouse (1949), USACE (1994), Henderson (1966), Barnes (1967), Bathurst, Li, and Simons (1979), Sabol (1982), Aisenbrey et al. (1978)
	Hydraulic jump Chow (1959), Little and Daniel (1981), Little and Murphey (1982), USACE (1994), Peterka (1984), Sandover et al. (1962)
	Seepage analysis Cedergren (1967), USBR (1987), Taylor (1967)
Conduit Outlet	Aisenbrey et al. (1974), Biechley (1971), Peterka (1984)
Transitions and Constrictions	Chow (1959), Rouse (1949), FHWA (2000)
Bends and Confluences	Chow (1959), Rouse (1949)
Rundowns	Chow (1959)
Energy Dissipators	Corry et al. (1975), Peterka (1984), Rhone (1977)
Riprap (Different Applications)	Riprap (multiple applications) Abt et al. (1977), Anderson (1968), Anderson et al. (1973), Hughes (1976), Li Simons Assoc. (1989), Maynord (1978), Maynord and Ruff (1987), Reese (1986), USACE (1994), Reese (1984), Stevens et al. (1976), Stevens (1981), U.S. Bureau of Public Roads (1967), US SCS (1976), Wittler and Abt (1988), NCHRP (2006)

7.0 SMALL GRADE CONTROL STRUCTURES

This section provides design criteria for relatively small grade control structures. Structures of this type are typically used to maintain acceptable velocities and flow characteristics in order to protect channel stability.

7.1 Small Grade Control Structures

Designs for small grade control structures are presented in this section for a maximum drop height of 2 feet for stable, non-boatable grass channels that meet the design conditions listed in Table OC-12.

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Table OC-12
Design Criteria for Small Grade Control Structures

Design Parameter	Criteria
Peak flow rate	200 cfs
Typical channel longitudinal slope	0.3 to 0.8 percent
Normal flow depth (maximum)	3 feet
Flow velocity (maximum)	6 ft/s
Froude number (maximum)	0.8
Geotechnical condition (assumed)	Moderate strength clay with chert

Design criteria presented in this section are for grade control structures in relatively small channels and are based on the assumptions that effects are minimal from channel curvature, unstable beds, other hydraulic structures, or other special conditions that require detailed analysis. It is the responsibility of the design professional to determine if these assumptions are met. In addition, grade control structure dimensions may require modifications to adjust the design to field conditions. Deviations from maximum height and flow criteria, or altering designs to have dimensions less than the minimum specified, require project-specific design and analysis. In all cases, the design professional is responsible for the structural integrity of the grade control structure.

The following five types of small grade control structures are described in this section:

1. Grouted sloping boulder structure (Section 7.1.2)
2. Sloping concrete structure (Section 7.1.3)
3. Vertical hard basin structure (Section 7.1.4)
4. Newbury-style structure (Section 7.1.5)
5. Sculpted sloping structure (Section 7.1.6)

The process for selecting the most suitable type of small grade control structure for a specific application is described in Section 7.1.1.

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7.1.1 Small Grade Control Structure Selection Process

7.1.1.1 Initial Evaluation Steps

Prior to selecting the most suitable type of grade control structure for the project, these initial evaluation steps must be completed:

1. Define the representative channel design flows for the 25-year storm event. If the 25-year design storm flow rate is greater than 200 cfs, the small grade control structure design process described in this section is not appropriate. In such cases, designs for larger grade control structures (see Section 6.0, Hydraulic Structures) shall be developed. If the 25-year design storm flow rate is less than 200 cfs, then the 25-year design flow rate should be used as the basis for peak flow for the small grade control structure design. The channel dimensions and longitudinal slope necessary to convey the 25-year design flow can then be approximated.

2. Determine whether the channel has perennial or intermittent flow. If the channel has intermittent flow, then the Newbury-style structure is not suitable, and an alternative type of grade control structure should be selected.

3. Evaluate preliminary grading requirements for the channel and grade control structures, taking into consideration the 2-foot limit on grade control structure heights when using the design criteria outlined in this section.

After completing the initial evaluation steps, the designer should refer to the evaluation criteria described in Section 7.1.1.2 to select the most suitable type of grade control structure for the site application.

7.1.1.2 Grade Control Structure Evaluation Criteria

Several factors should be taken into consideration to select the appropriate type of small grade control structure for a specific location. Primary considerations include:

- Public safety—Can the grade control structure convey the 25-year design flow without causing undue safety hazards (e.g., creation of reverse roller hydraulic condition that can potentially entrap a person)?

- Functional hydraulic performance of the structure—Can the grade control structure convey the design flow without damaging the structure or the downstream channel?

Secondary considerations include:

- Land use—Is the grade control structure compatible with its surroundings?

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- Cost—Does the grade control structure represent the most economical option for channel grade control while simultaneously achieving other design objectives?

- Ecological impact—Is the amount of disturbed area caused by the grade control structure acceptable with respect to the habitat where the structure will be located? Will the completed structure provide habitat benefits and allow aquatic species to move longitudinally upstream and downstream through the structure?

- Aesthetics—Is the grade control structure aesthetically pleasing with respect to its surroundings? (Aesthetics are subjective and are best evaluated by a landscape architect with experience in drainage design.)

- Maintenance—Does the grade control structure have excessive maintenance requirements or costs, relative to other grade control structures?

- Environmental permitting—Are there wetlands, habitat disturbance, or other concerns that require permitting for the grade control structure? (Soliciting expertise in environmental permitting is suggested in cases where such matters are a concern).

Using the primary and secondary considerations listed above, the five types of small grade control structures described in Section 7.1 were evaluated. A summary of the evaluation is presented in Table OC-13 and a summary of the relative advantages and disadvantages of each structure type, based on the evaluation criteria, is provided in Table OC-14. Based on the information presented in Table OC-13 and Table OC-14, the designer can select the type of small grade control structure that is most suitable for the unique conditions at a specific project site.

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Table OC-13
Summary of Considerations for Selecting Small Grade Control Structure Type

Considerations for Grade Control Structure Design	Grade Control Structure Type				
	Grouted Sloping Boulder	Concrete Sloping	Vertical Hard Basin	Newbury-style	Sculpted Concrete
Primary Considerations					
Public Safety	More preferred for areas with high public usage	Less preferred for areas with high public usage	Less preferred for areas with high public usage, (though the potential for reverse rollers and backflow eddies is reduced with drop of 2 feet or less)	More preferred for areas with high public usage	More preferred for areas with high public usage
Functional Hydraulic Performance	Good flexibility of layout options. Roughness effective for dissipating kinetic energy	Maximum vertical drop limited by public safety concern	Maximum vertical drop limited by public safety concern (see above)	Good flexibility of layout options. Roughness effective for dissipating kinetic energy	Good flexibility of layout options
Secondary Considerations					
Land Use (Contextual Design)	Provides natural channel appearance	Best suited for urban setting	Best suited for urban setting	Provides natural channel appearance	Provides natural channel appearance
Cost	Costs comparable for all options	Costs comparable for all options	Costs comparable for all options	Costs comparable for all options	Costs comparable for all options
Ecological Impacts	Creates larger footprint than vertical drop	Creates larger footprint than vertical drop. Has no habitat or water quality benefits and may be detrimental.	Creates smallest footprint of any option. Has no habitat or water quality benefits and may be detrimental.	Provides refuge for macroinvertebrates and small fish, fish passage, simulates naturally occurring riffle. Provides refuge during flow event.	Creates larger footprint than vertical drop. Has no habitat or water quality benefits and may be detrimental.
Aesthetics	Natural-appearing, aesthetic option	Less aesthetic relative to other options	Less aesthetic relative to other options	Natural-appearing, aesthetic option	Natural-appearing, aesthetic option
Maintenance	Potential for scour erosion at downstream end	Potential for scour erosion at downstream end	Sediment deposition in impact basin, scour erosion at downstream end of basin	Little potential for scour erosion at downstream end	Potential for scour erosion at downstream end
Environmental Permitting	More disturbed area than other options	More disturbed area than other options	Less disturbed area than other options	More disturbed area than other options. Simulates naturally occurring riffle. No concrete in stream. When vegetated, supports both terrestrial and aquatic species.	More disturbed area than other options

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Table OC-14

Summary of Relative Advantages and Disadvantages for Different Types of Small Grade Control Structures

	Grade Control Structure Type				
	Grouted Sloping Boulder	**Concrete Sloping**	**Vertical Hard Basin**	**Newbury-style**	**Sculpted Concrete**
Advantages	• Preferred in areas with high public usage • More aesthetic than vertical hard basin drop • Less maintenance	• Allows for sloped drop if boulders unavailable • Relatively straightforward to construct	• Can use if boulders unavailable • Smaller disturbance area than other structures	• Interstitial rock spaces provide refuge for macroinvertebrates and small fish • More aesthetic than vertical hard basin • Simulates natural riffle • Energy dissipation • Roller and eddies on ramp • No concrete /grout near stream • Not affected by freeze/ thaw like grouted structures • Preferred in areas with high public usage • Less maintenance • Allows for sloped drop if boulders unavailable • Relatively easy to construct • Naturalizes over time	• Preferred in areas with high public usage • Allows for sloped drop if boulders unavailable • More aesthetic than vertical hard basin drop
Disadvantages	• Larger disturbance area	• Larger disturbance area • Less aesthetic • Smooth concrete does not dissipate energy as effectively as rough surfaces, resulting in greater potential for scour at toe of structure.	• Less preferred in areas with high public usage • Less visually aesthetic • Higher maintenance caused by scour at bottom of drop	• Shallow slope of rack ramp results in large footprint from structure • Live stake must be planted during dormant period • More difficult to achieve shape in very small streams.	• Requires contractor labor force with specialized skill and/or more field oversight by designer • Less energy dissipation than grouted boulders

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7.1.2 Grouted Sloping Boulder Grade Control Structure

A grouted sloping boulder grade control structure is shown in Photograph OC-13. Grouted sloping boulder structures provide flexibility in terms of applicability for a range of channel types, from broad floodplains to narrow, incised channels. This type of structure has gained acceptance in areas where quality rock sources are located within reasonably close proximity. In the Springfield area, boulders are generally available in sizes up to a maximum diameter of 18 inches. Larger boulders may be difficult to obtain; however, 18-inch diameter boulders should be sufficiently large, in most cases, for the small grade control structures described in this section.

Photograph OC-13. Grouted sloping boulder grade control structure with low-flow channel.

The design criteria outlined in Section 7.1.2.1 are for grouted sloping boulder structures with a drop of 2 feet or less. For grouted sloping boulder drops of more than 2 feet, a detailed hydraulic analysis shall be conducted, and the design process described in this section is not applicable. (Refer to Section 6.0, Hydraulic Structures).

7.1.2.1 Grouted Sloping Boulder Design Criteria

For channels where the design flow is within the acceptable limits for depth and velocity described in Section 7.1.1.1, design criteria for a grouted sloping boulder grade control structure with a drop height of 2 feet or less are summarized in Table OC-15.

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Table OC-15
Design Criteria for Grouted Sloping Boulder Grade Control Structure (with Drop Height 2 Feet or Less)

General Feature	Design Parameter	Parameter Value
Approach	Approach length (L_a)	8 feet (armored with grouted rock- see below for boulder sizing)
Boulders	Boulder sizing—nominal size	18 inches (acceptable range: 17 to 20 inches)
	Boulder placement—crest and cutoff	Grouted boulders must cover the crest and cutoff and extend downstream through the energy dissipating basin
	Boulder placement—through drop	Boulders must be carefully placed to create a stepped appearance, which helps to increase roughness.
	Boulder placement—basin end	Boulders must be placed at basin end to create a sill transition to downstream channel invert elevation.
Grout	Grout thickness (D_g)	½ mean diameter of boulders (D_r)
Crest	Crest width (minimum)	Minimum width same as upstream channel bottom width
Longitudinal slope of drop	Maximum slope	4H:1V (slopes flatter than 4:1 promote increased safety, enhanced structure stability, and improved appearance)
Basin Geometry	Basin length (L_b)	20 feet
	Basin width (B)	Same as crest width
	Basin depression	1 foot
Low-flow Zone (if necessary)	Upstream configuration	Trickle or low-flow channel should extend through the drop crest section
	Downstream configuration	Trickle or low-flow channel protection should extend downstream from the main channel protection
	Trickle zone protection width below drop	Smaller of: i) 3 times trickle zone channel width, or ii) trickle zone channel width, squared
	Energy dissipation	Install large boulders in center basin zone to dissipate energy of high flow stream
Downstream channel	Downstream channel armoring	Buried riprap zone shall be installed for a minimum of 10 feet downstream of the drop basin sill

Note: Design guidelines contained in this table are for channels that meet the threshold criteria for maximum allowable flow depth and velocity.

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7.1.2.2 Grouted Sloping Boulder Construction Concerns

The grouted sloping boulder grade control structures require significant construction control efforts. To achieve acceptable structural integrity, the quality of rock used and proper grouting procedure are key concerns.

Problems with rock density, durability, and hardness can vary widely for different locations. The rock shall be inspected at regular intervals to ensure it meets minimum physical dimensions, strengths, and weights as defined in the specifications.

Individual boulders shall be used that are all larger in diameter than the grout layer so that the contractor and the inspector can verify the grout depth and have grout placed directly to the subgrade. Individual boulders should be machine-placed one at a time in their final position. The best balance is to use boulders with twice the diameter of the grout thickness and with overall mass sufficient to offset uplift (taking into consideration a safety factor). This procedure also improves the overall appearance of the structure.

The condition of the subgrade and adequate seepage control are critical. The subgrade is frequently disturbed during rock placement, leaving a potential route for water piping. This condition should be controlled by good subgrade preparation, careful rock placement, and removal of loose materials. Absolutely no granular bedding or subgrade fill using granular materials shall be used because of the potential for piping.

With respect to grouting, the greatest potential inadequacy lies with a “sugar-coated” grout job, where the grout does not penetrate the voids fully between the rock and the subgrade, resulting in voids below the grout that act as a preferential pathway for water. Specifications regarding grout material and grout placement are provided in Figure OC-7 (Section 5.7.5).

7.1.2.3 Grouted Sloping Boulder Design Drawings

Design drawings for a grouted sloping boulder grade control structure are shown in Figure OC-7.

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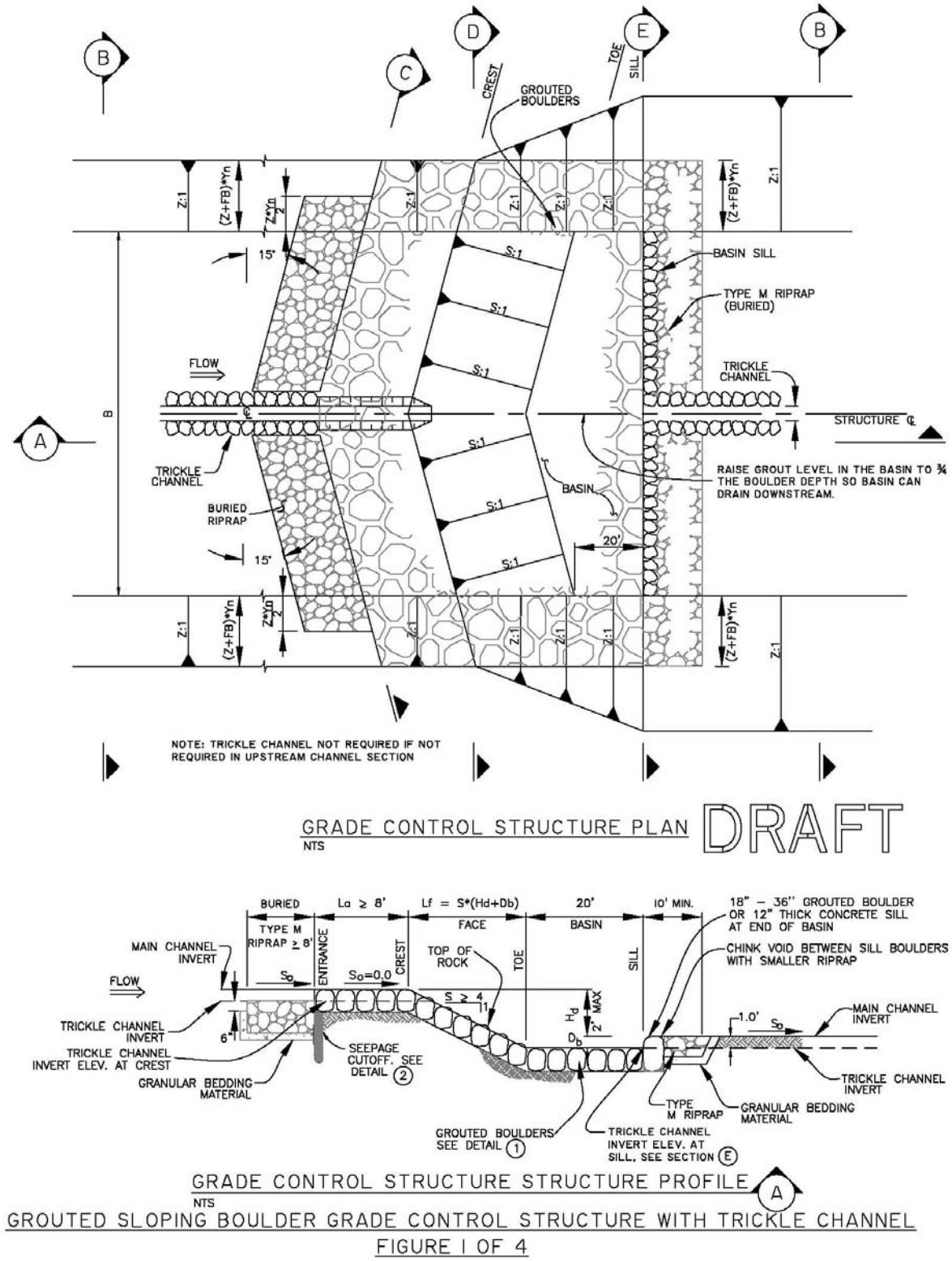

Figure OC-7a
Grouted Sloping Boulder Grade Control Structure

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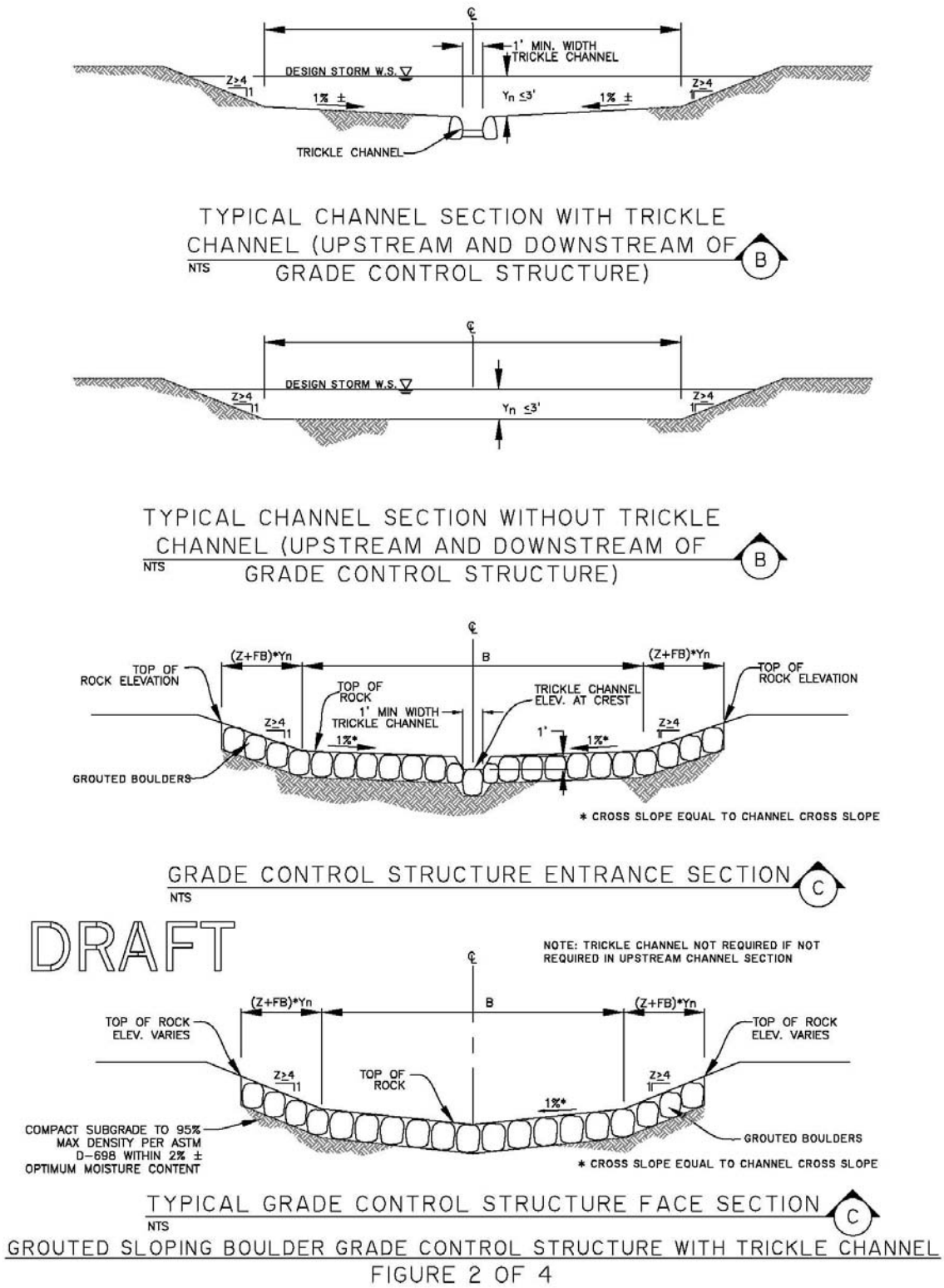

Figure OC-7b
Grouted Sloping Boulder Grade Control Structure

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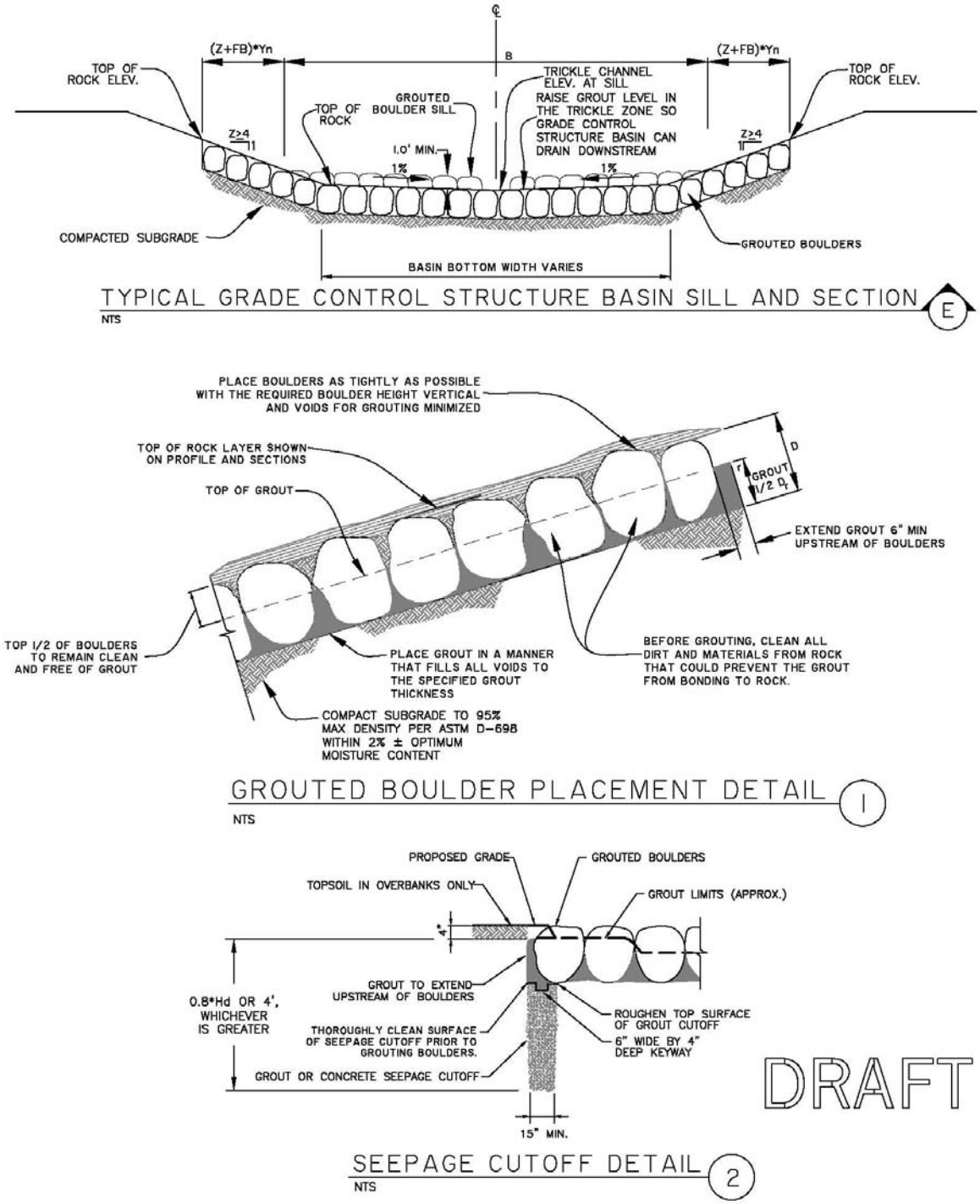

Figure OC-7c
Grouted Sloping Boulder Grade Control Structure

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GROUT NOTES

Material Specifications

1. All grout shall have a minimum 28-day compressive strength equal to 4000 psi.
2. One cubic yard of grout shall have a minimum of six (6) sacks of Type II Portland cement.
3. A maximum of 25% Type F Fly Ash may be substituted for the Portland cement.
4. For Type A grout, the aggregate shall be comprised of 70% natural sand (fines) and 30% ⅜ -inch rock (coarse).
5. For Type B grout, the aggregate shall be comprised of ¾ -inch maximum gravel, structural concrete aggregate.
6. Type B grout shall be used in streams with significant perennial flows.
7. The grout slump shall be 4-inches to 6-inches.
8. Air entrainment shall be 5.5%–7.5%.
9. To control shrinkage and cracking, 1.5 pounds of Fibermesh, or equivalent, shall be used per cubic yard of grout.
10. Color additive in required amounts shall be used when so specified by contract.

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Placement Specifications

1. All Type A grout shall be delivered by means of a low pressure (less than 10 psi) grout pump using a 2-inch diameter nozzle.
2. All Type B grout shall be delivered by means of a low pressure (less than 10 psi) concrete pump using a 3-inch diameter nozzle
3. Full depth penetration of the grout into the boulder voids shall be achieved by injecting grout starting with the nozzle near the bottom and raising it as grout fills, while vibrating grout into place using a pencil vibrator.
4. After grout placement, exposed boulder faces shall be cleaned with a wet broom.
5. All grout between boulders shall be treated with a broom finish.
6. All finished grout surfaces shall be sprayed with a clear liquid membrane curing compound as specified in ASTM C-309.
7. Special procedures shall be required for grout placement when the air temperatures are less than 40°F or greater than 90°F. Contractor shall obtain prior approval from the design engineer of the procedures to be used for protecting the grout.
8. Clean Boulders by brushing and washing before grouting.

GROUTED SLOPING BOULDER GRADE CONTROL STRUCTURE WITH TRICKLE CHANNEL
FIGURE 4 OF 4

Figure OC-7d
Grouted Sloping Boulder Grade Control Structure

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7.1.3 Vertical Hard Basin Grade Control Structure

A vertical hard basin grade control structure is shown in Photograph OC-14. The vertical hard basin grade control structure provides design flexibility through the use of different components for the crest wall, hard basin, and low-flow or trickle channel. However, despite the flexibility of designs, vertical drops should be avoided where practical due the potential for turbulent hydraulic conditions and related maintenance, depending on the flow regime (ASCE and WEF 1992).

Photograph OC-14. Vertical hard basin grade control structure.

A vertical grade control structure creates a jet of water that overflows the crest wall into the basin below. The jet hits the basin and is redirected horizontally in a supercritical mode until the specific force of the tailwater is sufficient to force the hydraulic jump. The turbulence of the hydraulic jump dissipates energy. Therefore, the basin shall be sized large enough to contain the supercritical flow and the associated turbulent zone of the hydraulic jump that can cause channel erosion. A rough basin is generally advantageous since increased roughness will result in a shorter, more economical basin. An example of a rough basin is shown in Photograph OC-14, with boulders placed in the basin to dissipate energy.

The design criteria outlined in Section 7.1.3.1 are for vertical hard basin drops of 2 feet or less. Vertical drops greater than 2 feet raise safety concerns related to the potential for creating a hydraulic condition, known as a “reverse roller,” that can form during certain flow conditions and entrap a person. Therefore, for vertical drops larger than 2 feet, a detailed hydraulic analysis shall be conducted and the design process described in this section is not applicable. (See Section 6.0, Hydraulic Structures).

7.1.3.1 Vertical Hard Basin Design Criteria

For channels where the design flow is within the acceptable limits for depth and velocity described in Section 7.1.1.1, design criteria for a vertical hard basin grade control structure, with a drop height of 2 feet or less, are summarized in Table OC-16.

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Table OC-16
Design Criteria for Vertical Hard Basin Grade Control Structure (with Drop Height of 2 Feet or Less)

General Feature	Design Parameter	Parameter Value
Approach	Approach length (L_a)	10 feet (armored with buried riprap)
Crest	Crest width (minimum)	Minimum width same as upstream channel bottom width
Basin geometry	Basin length (L_b)	25 feet
	Basin width (B)	Same as crest width
	Basin depression	1 foot
Basin sill (concrete)	Sill thickness	6 to 8 inches
Basin sill (grouted boulders)	Boulder sizing—nominal dimension	18 inches
	Grout thickness (D_g)	9 to 12 inches (Apply thicker grout at edges to direct flow to center. Cover grouted boulders on side slopes by filling to top of boulder with lightly compacted in-situ soil and capping with a minimum of 4 inches of topsoil. Vegetate buried surfaces with native grasses).
Trickle flow zone (if necessary)	Energy dissipater placement	Install large boulder or baffles in center zone to break up high flow stream-locate downstream from point where nappe hits basin and at least 10 feet from the basin end.
	Energy dissipater placement	Boulders used to dissipate energy shall be sized to project into the flow 0.6 to 0.8 times the critical depth.
Downstream channel	Downstream channel armoring	Buried riprap zone shall be installed for a minimum of 10 feet downstream of the drop basin sill.

Note: Design guidelines contained in this table are for channels that meet the threshold criteria for maximum allowable depth and velocity.

7.1.3.2 Vertical Hard Basin Construction Concerns

Construction of an end sill in the hard basin is necessary to dissipate kinetic energy and reduce erosion effects at the transition between the basin and the downstream channel. However, even with an end sill, the transition area between the end of the basin and the downstream channel is susceptible to erosion. Armoring of the channel at the downstream end of the basin is necessary to minimize erosion effects. Buried riprap shall be placed for a minimum of 10 feet downstream of the drop basin sill.

7.1.3.3 Vertical Hard Basin Design Drawings

Design drawings for a vertical hard basin grade control structure are shown in Figure OC-8.

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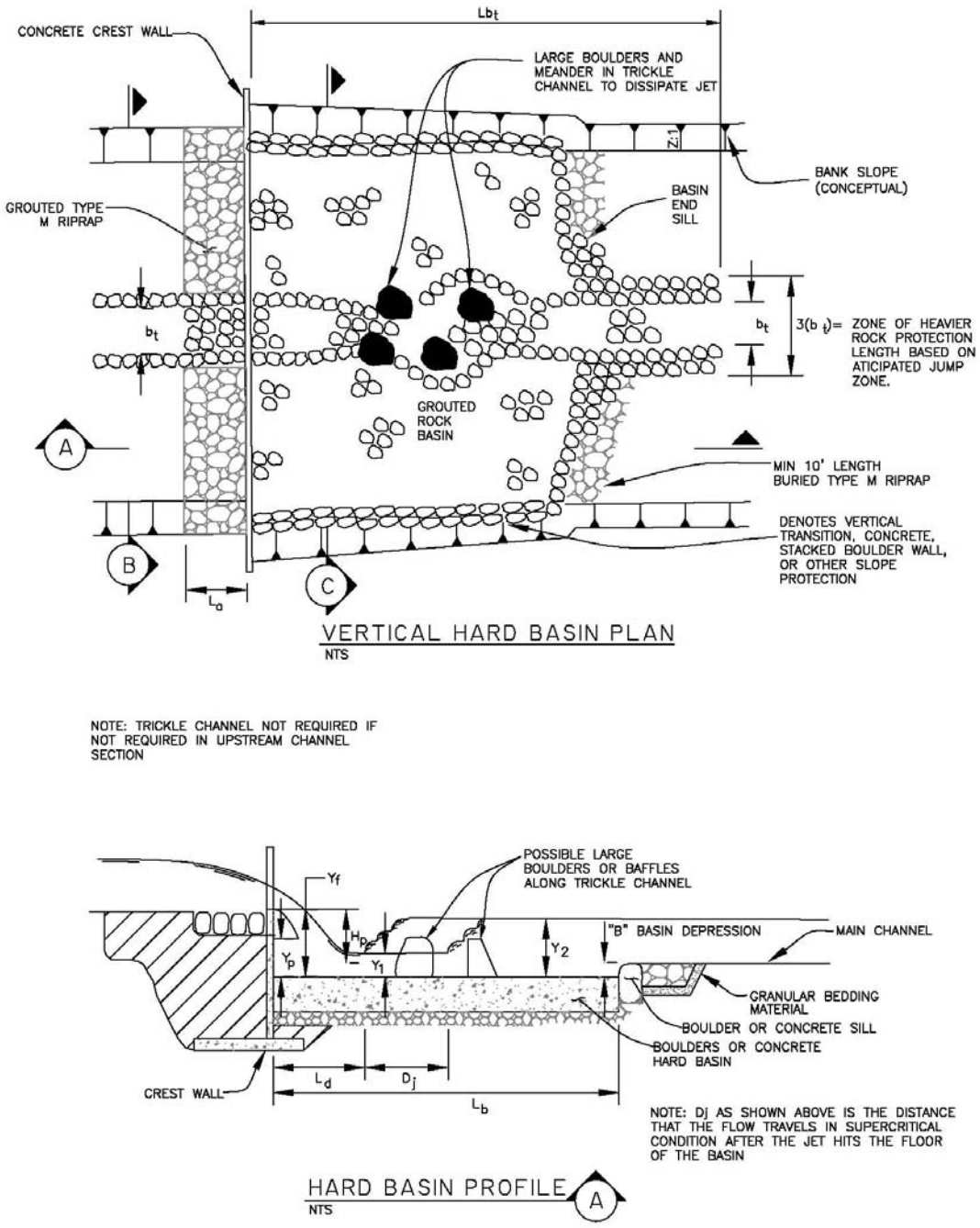

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VERTICAL HARD BASIN GRADE CONTROL STRUCTURE
FIGURE 1 OF 2

Figure OC-8a
Vertical Hard Basin Grade Control Structure

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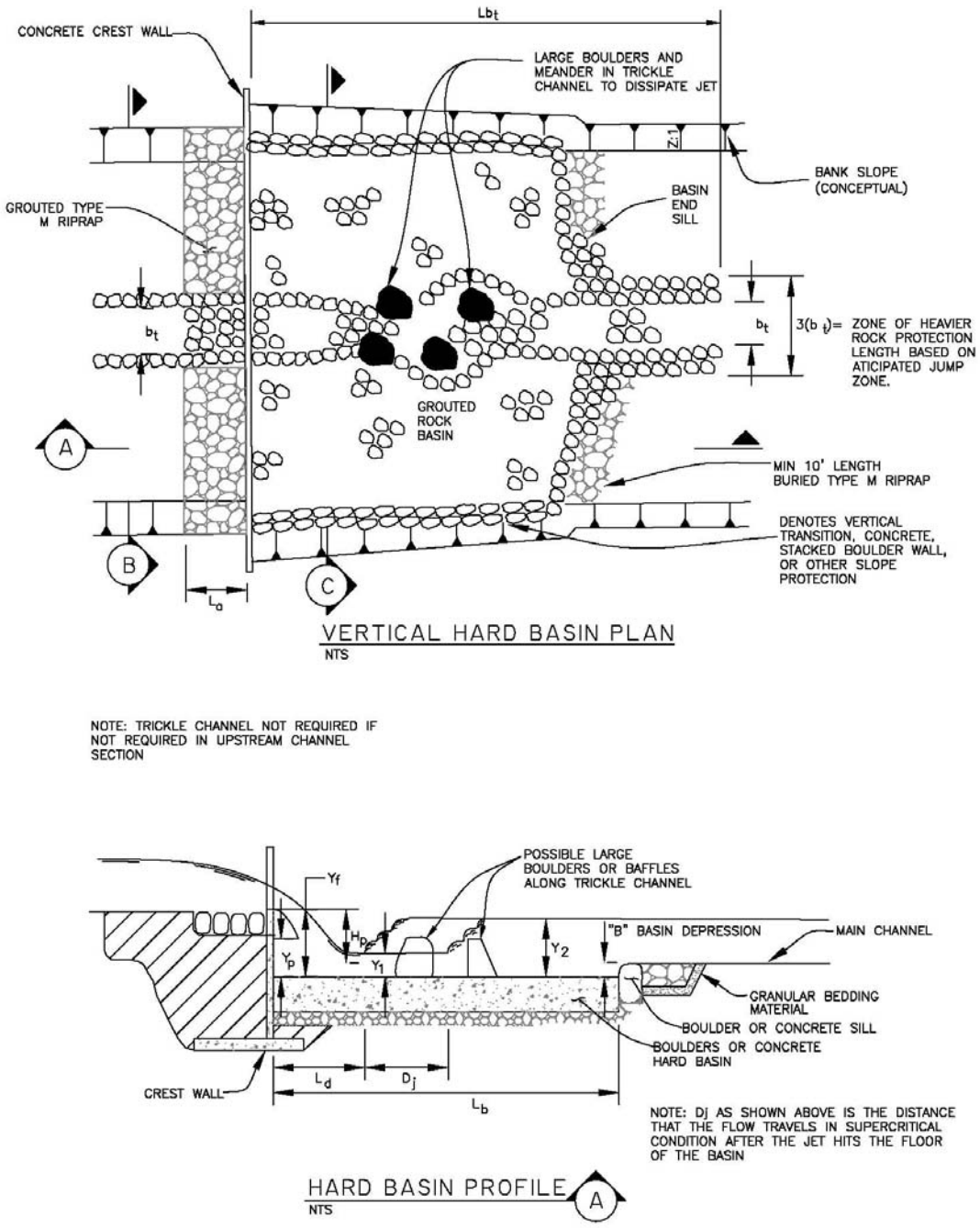

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VERTICAL HARD BASIN GRADE CONTROL STRUCTURE
FIGURE 1 OF 2

Figure OC-8b
Vertical Hard Basin Grade Control Structure

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7.1.4 Sloping Concrete Grade Control Structure

A sloping concrete grade control structure is shown in Photograph OC-15. In areas where adequately-sized boulders are not available, a sloping concrete grade control structure provides an alternative to the grouted sloping boulder structure described in Section 7.1.2, although the smooth sloping concrete structure does not dissipate energy as effectively as the grouted boulders.

Photograph OC-15. Sloping concrete grade control structure.

7.1.4.1 Sloping Concrete Grade Control Structure Design Criteria

For channels where the design flow is within the acceptable limits for depth and velocity described in Section 7.1.1.1, design criteria for a sloping concrete grade control structure, with a drop height of 2 feet or less, are summarized in Table OC-17.

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Table OC-17
Design Criteria for Sloping Concrete Grade Control Structure (with Drop Height of 2 Feet or Less)

General Feature	Design Parameter	Parameter Value
Approach	Approach length (L_a)	10 feet (armored with buried riprap)
Crest	Crest width (minimum)	Minimum width same as upstream channel bottom width
Longitudinal slope of drop	Maximum slope	4H:1V
Basin Geometry	Basin length (L_b)	20 feet
	Basin width (B)	Same as crest width
	Basin depression	1 foot
Low-flow zone (if necessary)	Upstream configuration	Trickle or low-flow channel should extend through the drop crest section
	Downstream configuration	Trickle or low-flow channel protection should extend downstream from the main channel protection
	Trickle zone protection width below drop	whichever is smaller of: i) 3 times trickle zone channel width, or ii) trickle zone channel width, squared
	Energy dissipation	Install concrete baffles or large boulders in center basin zone to dissipate energy of high flow stream
Downstream channel	Downstream channel armoring	Buried riprap zone shall be installed for a minimum of 10 feet downstream of the drop basin

Note: Design guidelines in this table are for channels that meet the threshold criteria for maximum allowable depth and velocity.

7.1.4.2 Sloping Concrete Grade Control Structure Construction Concerns

The transition between the basin and the downstream channel is susceptible to scour and erosion. Armoring of this transition area is critical for reducing channel maintenance.

7.1.4.3 Sloping Concrete Grade Control Structure Design Drawings

Design drawings for a sloping concrete grade control structure are shown in Figure OC-9.

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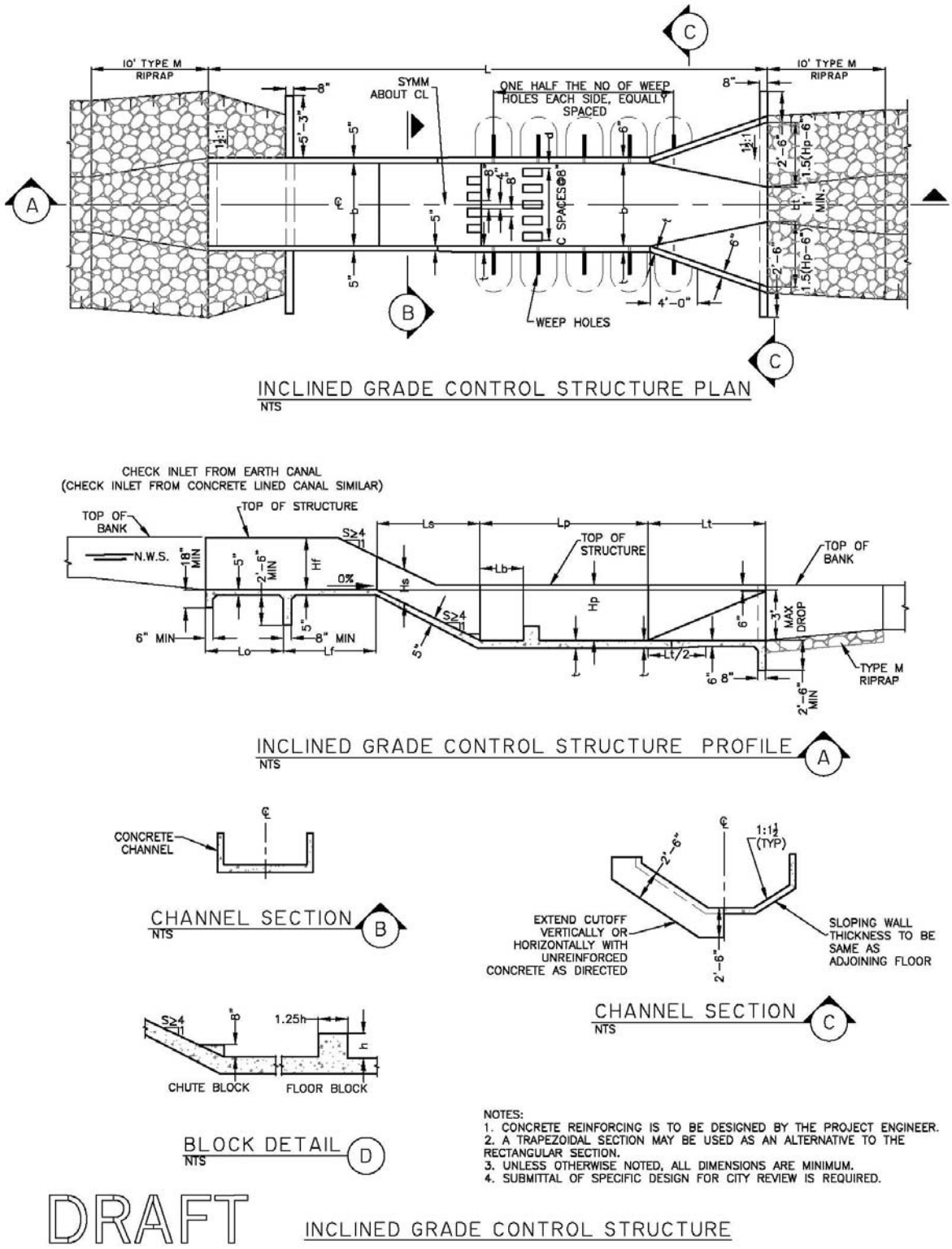

Figure OC-9
Sloping Concrete Grade Control Structure

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7.1.5 Newbury-style Grade Control Structure

A Newbury-style grade control structure, during construction, is shown in Photograph OC-16. A Newbury-style grade control structure, following construction and with water in the channel, is shown in Photograph 16.

Photograph OC-16. Newbury-style grade control structure under construction.

Photograph OC-17. Newbury-style grade control structure following construction.

A Newbury-style grade control is similar to a naturally occurring riffle in a cobble or gravel stream and is useful for both grade stabilization and energy dissipation. While the Newbury-style grade control structure was originally designed to promote fish passage, an added benefit of the structure is the space between rocks that provides refuge for macroinvertebrates and small fish. Similar to the riffle it simulates, the crest height of a Newbury-style grade control structure is close to the height of bank-full flow.

In plan view, the crest of a Newbury-style grade control structure forms an arch, with the open end facing downstream (see Figure OC-10). In section-view, the crest slopes from the banks to the thalweg. The crest shall be sufficiently keyed into the bed and banks of the channel to prevent flows from scouring

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under or around the ends of the grade control (see Table OC-18 for key depth specifications). Existing vegetation is preserved during construction to the extent possible.

Although the typical longitudinal channel slope for the small grade control structures described in this section ranges from 0.3 to 0.8 percent, Newbury structures can be used for channels with longitudinal slopes as steep as 2 percent.

The shape of a Newbury-style grade control structure directs the main flow path away from the banks and onto the downstream rock ramp (Photograph OC-17). A Newbury-style structure does not have to be symmetrical in either plan or section. By varying the shape, flow can be turned slightly to match the thalweg transitions through meanders. To facilitate proper flow patterns, the constructed upstream face shall not be flat. In general, since Newbury-style grade controls have a crest height of 2 feet or less, and a shallow slope on the downstream rock ramp (20H:1V), the hydraulic jump normally occurs on the tail ramp.

The upstream and downstream limits and sides of the Newbury structure above the bank-full elevation are live-staked to interlock the rock structure into the banks. Plant species and staking specifications are described in Table OC-18. In addition to interlocking with the rocks, the live stakes provide an effective transition between the natural bank and the rock structure. Further, the hydraulic roughness of the live stakes helps direct flow away from the banks, which minimizes scour at the rock-soil interface.

7.1.5.1 Newbury Style Grade Control Structure Design Criteria

For channels where the design flow is within the acceptable limits for depth and velocity described in Section 7.1.1.1, design guidelines for a Newbury-style grade control structure, with a drop height of 2 feet or less, are summarized in Table OC-18.

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Table OC-18
Design Criteria for Newbury Grade Control Structure
(with Drop Height 2 Feet or Less)

General Feature	Design Parameter	Parameter Value
Rock	Size	For channels with longitudinal slope of 0.5 percent, rock d_{50} = 10 inches For channels with longitudinal slope of 0.8 percent, rock d_{50} = 12 inches Rock shall be well-graded and contain sufficient fines (approximately 30 percent) to fill voids
Crest	Side slopes	5H:1V to 10H:1V
	Streambank angle (normal soils)	80 degrees (see Figure OC-10) (angle can be decreased for less erosive soils, though designer should check potential for bank erosion)
	Key depth	1.5 D_{90} below the thickness of rock ramp (see rock sizing procedure following this table to calculate D_{90})
Downstream Rock Ramp	Slope	20H:1V
	Tail angle	80 degrees (see Figure OC-10) (angle can be decreased for less erosive soils, though designer should check potential for bank erosion)
Live stake plantings	Suitable plant types	Shrub willow, swamp or redosier dogwood, buttonbrush (Taller species, such as black willow, shall not be used)
	Stake length below grade	1 foot (minimum)
	Stake length above rock surface	1 foot (maximum)
	Stake angle	Approximately 15 to 20 degrees downstream (to prevent debris trapping)

Note: Design guidelines contained in this table apply to Newbury grade control structures in natural channels.

7.1.5.2 Newbury-style Grade Control Structure Rock Sizing Procedure

Structures shall be constructed from durable rock, sized using the USACE methodology for steep channels (USACE EM 1110-2-1601, page 3-8, Equation 3-5). Rock shall generally comply with the requirements of riprap. Well-graded shotrock with sufficient fines to fill voids may be used. The use of filter fabric and uniform gradations of rock are discouraged in streambeds.

7.1.5.3 Newbury style Grade Control Structure Construction Concerns

Grade control structure designs discussed in this chapter are for longitudinal slopes ranging from 0.3 to 0.8 percent. For steeper bed slopes, particularly if greater than 2 percent, Newbury style structures shall

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not be used because of the necessity for near-continuous and unnecessary bed armoring. Other structures are more appropriate for steeper slopes (see Section 6.0, Hydraulic Structures).

Where possible, Newbury grade controls should be reinforced with live stakes at the downstream crest and edges of each structure. Live stakes shall be installed while dormant. Species selection criteria should include tolerance to inundation, scour, and bed load impact. Stoloniferous species (those capable of sending up shoots from shallow stems) are strongly preferred. Taller species, such as black willow, shall not be used as live stakes. Taller species do not provide sufficient hydraulic roughness at the bank toe to effectively dissipate energy.

7.1.5.4 Newbury style Grade Control Structure Design Drawings

Design drawings for a Newbury-style grade control structure are shown in Figure OC-10.

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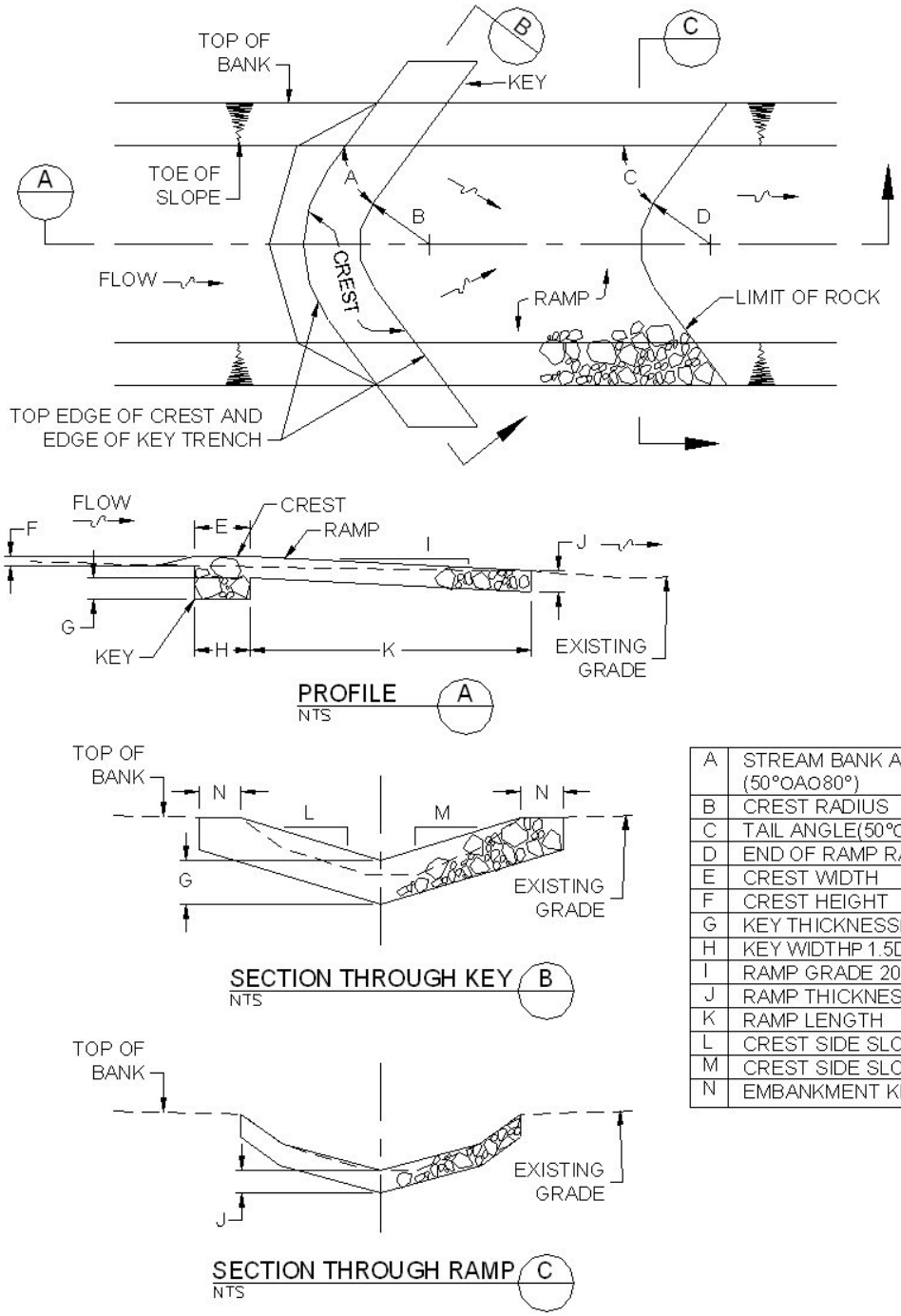

A	STREAM BANK ANGLE (50°OAO80°)
B	CREST RADIUS
C	TAIL ANGLE(50°OAO80°)
D	END OF RAMP RADIUS
E	CREST WIDTH
F	CREST HEIGHT
G	KEY THICKNESSP 1.5D90
H	KEY WIDTHP 1.5D90
I	RAMP GRADE 20H:1V
J	RAMP THICKNESSP 1.5D100
K	RAMP LENGTH
L	CREST SIDE SLOPE
M	CREST SIDE SLOPE
N	EMBANKMENT KEY

Figure OC-10
Newbury Grade Control Structure

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7.1.6 Sculpted Sloping Grade Control Structure

A sculpted sloping grade control structure is shown in Photograph OC-18. Sculpted sloping grade control structures provide an aesthetically appealing option for channel grade control and can be used in situations where certain options for grade control, such as grouted sloping boulders, may not be feasible because of an inadequate supply of available materials.

Photograph OC-18. Sculpted sloping grade control structure designed to blend into landscape.

7.1.6.1 Sculpted Sloping Grade Control Structure Design Criteria

For channels where the design flow is within the acceptable limits for depth and velocity described in Section 7.1.1.1, design guidelines for a sculpted sloping grade control structure, with a drop height of 2 feet or less, are summarized in Table OC-19.

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Table OC-19
Design Guidelines for Sculpted Sloping Grade Control Structure (with Drop Height 2 Feet or Less)

General Feature	Design Parameter	Parameter Value
Approach	Approach length (L_a)	10 feet (armored with buried riprap)
Crest	Crest width (minimum)	Minimum width same as upstream channel bottom width
Longitudinal slope of drop	Maximum slope	4H:1V
Basin Geometry	Basin length (L_b)	20 feet
	Basin width (B)	Same as crest width
	Basin depression	1 foot
Low-flow Zone	Configuration	No trickle or low-flow channel in sculpted sloping structure
Downstream channel	Downstream channel armoring	Buried riprap zone shall be installed for a minimum of 10 feet downstream of the drop basin

Note: Design guidelines contained in this table are for channels that meet the threshold criteria for maximum allowable depth and velocity.

7.1.6.2 Sculpted Sloping Grade Control Structure Construction Concerns

Design of sculpted sloping grade control structures requires an understanding of local rock outcroppings. Consultation with a geologist or landscape architect, as necessary, is recommended. Construction of sculpted sloping grade control structures requires using a labor force with proper concrete forming and shaping skills to create a structure that is structurally sound and achieves the aesthetic objectives. Construction of a sculpted sloping grade control structure will require additional oversight by the designer to ensure the structure meets the design requirements.

7.1.6.3 Sculpted Sloping Grade Control Structure Design Drawings

Design drawings for a sculpted sloping grade control structure are shown in Figure OC-11.

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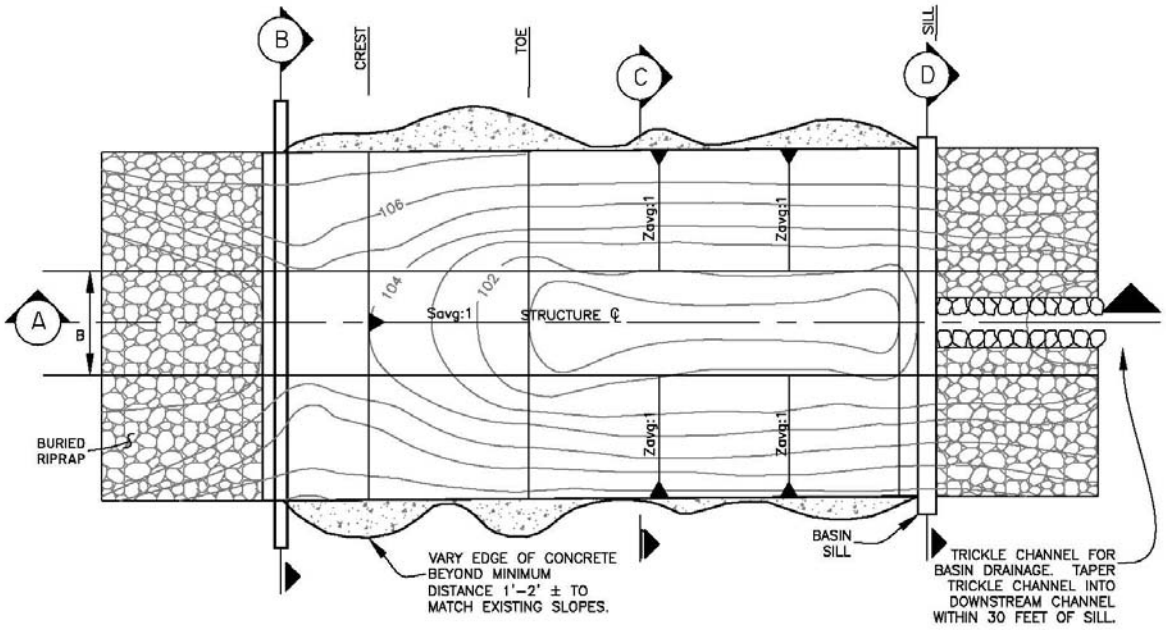
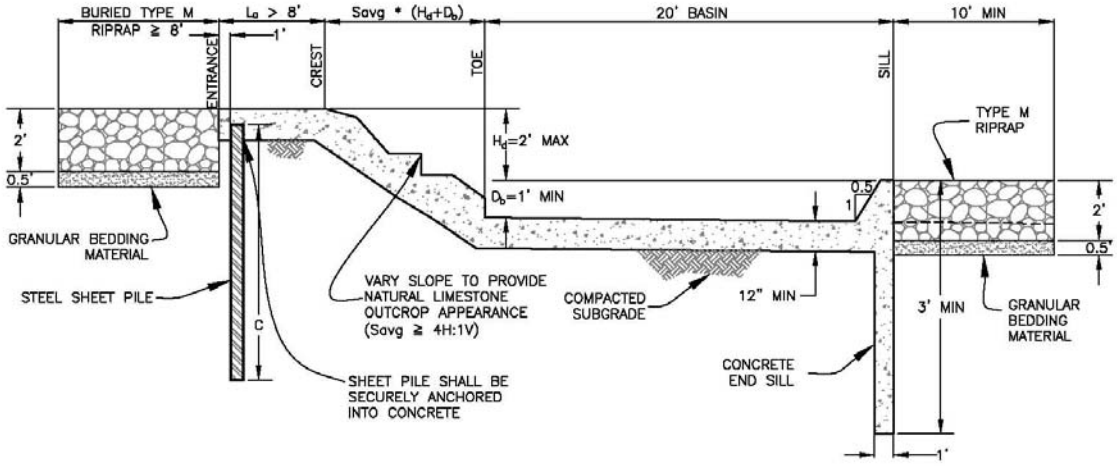


SCULPTED CONCRETE GRADE CONTROL STRUCTURE PLAN
NTS



SCULPTED CONCRETE GRADE CONTROL STRUCTURE PROFILE A
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SCULPTED CONCRETE GRADE CONTROL STRUCTURE
FIGURE 1 OF 2

Figure OC-11a
Sculpted Sloping Grade Control Structure

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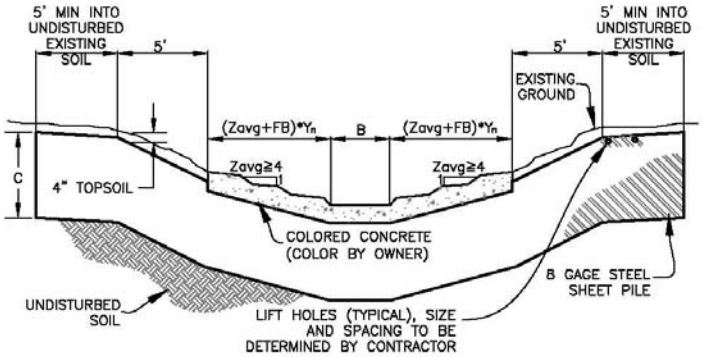
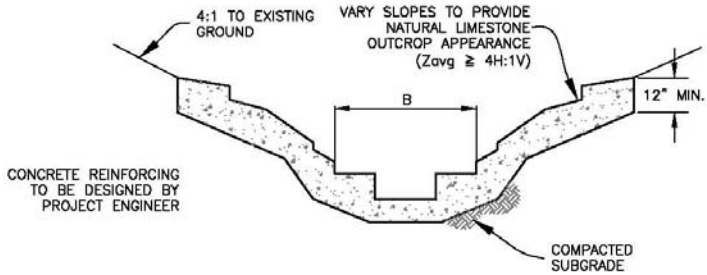
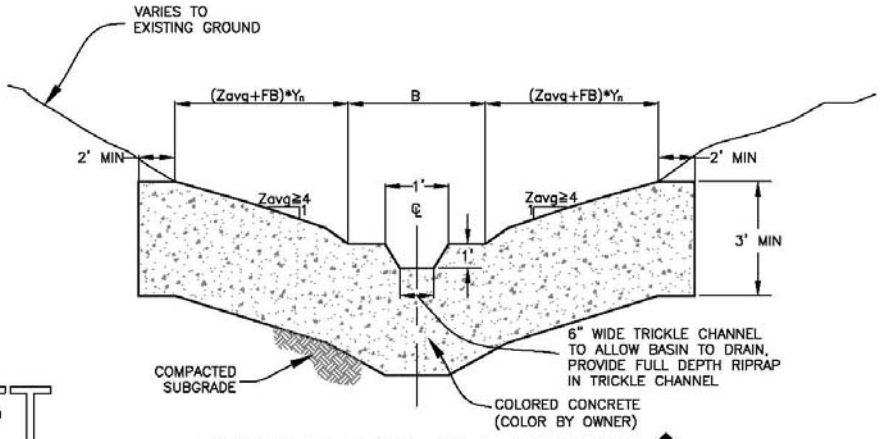


STEEL SHEET PILE SECTION (B)
NTS



BASIN SECTION (C)
NTS



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CONCRETE END SILL SECTION (D)
NTS

SCULPTED CONCRETE GRADE CONTROL STRUCTURE
FIGURE 2 OF 2

Figure OC-11b
Sculpted Sloping Grade Control Structure

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8.0 EXAMPLES

8.1 Example OC-1. Normal Depth Calculation Using the Normal and Critical Flow Analysis Worksheet

This example demonstrates use of the Normal and Critical Flow Analysis Worksheet in the SF-Channels Spreadsheet to determine the capacity and other relevant hydraulic parameters for a channel, given the channel's geometry and flow at normal depth.

Data Input

Channel characteristics and sizing constraints are entered into the "Design Information (Input)" section of the Normal and Critical Flow Analysis Worksheet. For this example, a grass-lined trapezoidal channel, channel characteristics and constraints are listed below:

Channel Characteristics:

S_o = channel invert slope (longitudinal slope) = 0.003 ft/ft (0.3%)

n = Manning's n (grass-lined channel, not mowed, average condition) = 0.035

(Note: Manning's n values are provided for different channel linings in the Design Info Worksheet of the SF- Channels Spreadsheet)

B = bottom width = 8 ft

Z = Z1 = Z2 = channel side slopes (left and right) = 4H:1V

Constraints:

F = freeboard height required = 2.0 ft

Y = design water depth (maximum allowable depth of flow in channel) = 5.0 ft

Results

Results of the analysis are displayed in the bottom half of the Normal and Critical Flow Analysis Worksheet (see sample worksheet on following page). The results indicate:

- Channel flow capacity — 655 cfs
- Total bank height necessary (hydraulic depth + required freeboard) — 4.9 ft
- Flow regime — Subcritical (F_r = 0.48)
- Flow velocity — 4.68 ft/s

Note: The estimated velocity (4.68 ft/s) is above the maximum allowable velocity (4 ft/s) for a 25-year event for a grass-lined channel using seed and mulch. The designer must consider changing the channel geometry or using a lining (such as sod, with a maximum allowable velocity of 6 ft/s) for which the

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maximum allowable lining will not be exceeded. In addition, the spreadsheet should be re-run using a lower Manning's n value (e.g., 0.030, the minimum Manning's n for an un-mowed grass-lined channel) to assess whether the maximum velocity criterion is exceeded for the channel lining selected.

Normal Flow Analysis - Trapezoidal Channel

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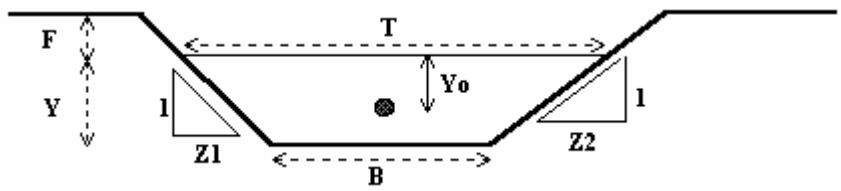
Project: Example OC-1

Channel ID: Sample



Design Information (Input)			
Channel Invert Slope	So =	0.0030	ft/ft
Manning's n	n =	0.035	
Bottom Width	B =	8.00	ft
Left Side Slope	Z1 =	4.00	ft/ft
Right Side Slope	Z2 =	4.00	ft/ft
Freeboard Height	F =	2.00	ft
Design Water Depth	Y =	5.00	ft

Clear all cells

Normal Flow Condtion (Calculated)			
Discharge	**Q =**	**655.24**	cfs
Froude Number	**Fr =**	**0.48**	
Flow Velocity	**V =**	**4.68**	fps
Flow Area	A =	140.00	sq ft
Top Width	T =	48.00	ft
Wetted Perimeter	P =	49.23	ft
Hydraulic Radius	R =	2.84	ft
Hydraulic Depth	D =	2.92	ft
Specific Energy	Es =	5.34	ft
Centroid of Flow Area	Yo =	1.89	ft
Specific Force	Fs =	22.49	kip

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8.2 Example OC-2. Composite Section Calculation Using Design of Composite Channel Worksheet

This example demonstrates use of the Design of Composite Channel Worksheet (in the SF-Channels Spreadsheet) to calculate channel cross-section geometry parameters for a composite channel consisting of:

- A low-flow channel with side slope protection for conveyance of frequent flows (up to 2-year).
- Vegetated overbanks to accommodate larger runoff events (up to the 25-year event).

Data Input

The grass-lined composite channel sizing is based on the following hydraulic design parameters entered into the "Design Information (Input)" section of the Design of Composite Channel Worksheet.

Q-2yr = 2-year discharge	300 cfs
Q-25yr = 25-year discharge (for fully-developed, un-detained condition)	600 cfs
Qlf = design discharge for low-flow channel	200 cfs
Z1 = low-flow channel left side slope	3H:1V
Z2 = low-flow channel right side slope	3H:1V
N-min-lf = low-flow channel Manning's n (minimum)	0.03
N-max-lf = low-flow channel Manning's n (maximum)	0.04
Low-flow channel lining type	grass (sod)
Ym = low-flow channel bank-full depth	2 ft
Bm = low-flow channel bottom width	4 ft
Longitudinal channel invert slope	0.005 ft/ft (0.5%)
ZL = left overbank side slope	4H:1V
N-left-min = left overbank Manning's n (minimum)	0.03
N-left-max = left overbank Manning's n (minimum)	0.04
Left overbank channel lining type	grass (seed and mulch)
ZR = right overbank side slope	4H:1V
N-right-min = right overbank Manning's n (minimum)	0.03
N-rightmax = right overbank Manning's n (minimum)	0.04
Right overbank channel lining type	grass (seed and mulch)
Yob = overbank flow depth	1.5 ft
Left overbank width as a percentage of total overbank width	50%

Results

Results of the analysis are displayed in the bottom half of the Design of Composite Channel Worksheet (see sample worksheet following this text). The results indicate:

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- The low-flow channel has the capacity to convey the 2-year flow at a depth not exceeding 2 feet.
- Flow is subcritical for all flow conditions evaluated. The $F_r < 0.8$, thereby satisfying Froude number criterion for non-erosive soils.
- Longitudinal channel invert slope ≥ 0.4 percent (the City criterion for recommended minimum slope to prevent ponding).
- Channel velocities are less than the allowable velocities for specified types of channel linings (low-flow channel and overbanks).
- 4H:1V side slopes permit maintenance of vegetated channel over banks.

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Design of Composite Channel

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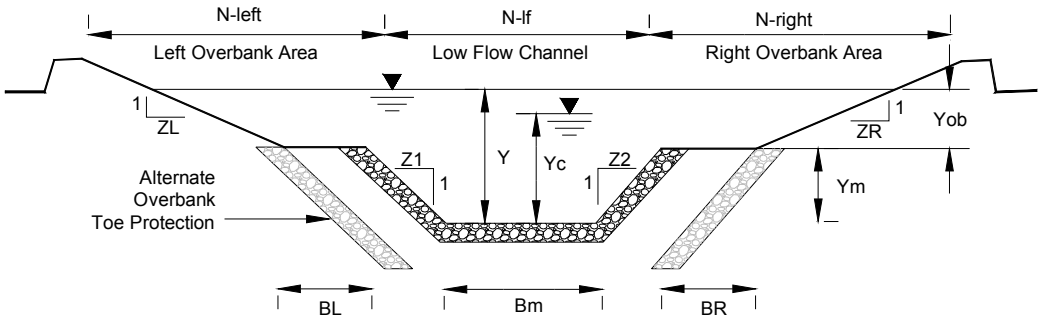
Project: Example OC-2 (DRAFT)

Channel ID: Sample Channel



Design Information (Input)

2-Year Discharge - Total	Q-2yr =	300	cfs	Left Overbank Side Slope	ZL =	4	ft/ft
25-Year Discharge - Total	Q-25yr =	600	cfs	Left Overbank Manning's n (min)	n-min-L =	0.03	
Design Discharge - Low Flow Channel	Qlf =	200	cfs	Left Overbank Manning's n (max)	n-max-L =	0.04	
Low Flow Channel Left Side Slope	Z1 =	3	ft/ft	Left Overbank Channel Lining Type		seed and mulch, Vmax = 4 fps	
Low Flow Channel Right Side Slope	Z2 =	3	ft/ft	Right Overbank Side Slope	ZR =	4	ft/ft
Low Flow Channel Manning's n (min)	n-min-lf =	0.03		Right Overbank Manning's n (min)	n-min-R =	0.03	
Low Flow Channel Manning's n (max)	n-max-lf =	0.04		Right Overbank Manning's n (max)	n-max-R =	0.04	
Low Flow Channel Lining Type		sod, Vmax = 6 fps		Right Overbank Channel Lining Type		seed and mulch, Vmax = 4 fps	
Low Flow Channel Bank-full depth	Ym =	1.92	ft	Overbank Flow Depth Yob = (Y - Ym)	Yob =	1.47	ft
Low Flow Channel Bottom Width	Bm =	4.00	ft				
Longitudinal Channel Invert Slope	So =	0.005	ft/ft	Left overbank width as a % of total overbank width		50	%

Flow Condition (Calculated)

Channel Invert Slope **So = 0.0041 ft/ft**

Low Flow Channel Condition for Qd				**Middle Section Bank-Full Flow Condition for Q25**			
Channel Bottom Width	Bm =	26.15	ft	Low Flow Channel Bottom Width	Bm =	26.15	ft
Channel Normal Flow Depth	Ym =	1.92	ft	Top width	Tm =	37.67	ft
Top width	Tlf =	37.67	ft	Flow area	Am =	116.64	sq ft
Flow area	Alf =	61.27	sq ft	Wetted perimeter	Pm =	38.29	ft
Wetted perimeter	Plf =	38.29	ft	**Discharge** (based on max n)	**Qm =**	**584.61**	**cfs**
Discharge (based on max n)	**Qlf =**	**199.90**	**cfs**	Max Velocity check (based on min n)	Vm =	5.99	fps
Min Velocity check (based on max n)	**Vlf =**	3.26	**fps**	**Froude #** (based on min n)	**Frm =**	**0.65**	
Froude number (based on min n)	Fr-lf =	0.59		25-Yr. Critical Velocity (min n)	Vmc =	7.98	fps
				25-Yr. Critical Depth (min n)	Ymc =	2.27	ft

Left Overbank Flow Condition for Q25				**Right Overbank Flow Condition for Q25**			
Overbank Bench Width	BL =	0.00	ft	Overbank Bench Width	BR =	0.00	ft
Normal Depth in Overbanks	YLob =	1.47	ft	Normal Depth in Overbanks	YRob =	1.47	ft
Top width	TL =	5.88	ft	Top width	TR =	5.88	ft
Flow area	AL =	4.32	sq ft	Flow area	AR =	4.32	sq ft
Wetted perimeter	PL =	6.06	ft	Wetted perimeter	PR =	6.06	ft
Discharge (based on max n)	**QL =**	**8.23**	**cfs**	**Discharge** (based on max n)	**QR =**	**8.23**	**cfs**
Max Velocity Check (based on min n)	**VL =**	**1.96**	**fps**	**Max Velocity check** (based on min n)	**VR =**	**1.96**	**fps**
Froude # (based on min n)	**FrL =**	**0.49**		**Froude #** (based on min n)	**FrR =**	**0.49**	
25-Yr. Critical Velocity (min n)	VLc =	3.49	fps	25-Yr. Critical Velocity (min n)	VRc =	3.49	fps
25-Yr. Critical Depth in Overbanks (min n)	YLc =	0.75	ft	25-Yr. Critical Depth in Overbanks (min n)	YRc =	0.75	ft

Composite Cross-Section Bank-Full Flow Condition for Q25

Top width	**T =**	**49.43**	**ft**	**Discharge** (based on max n)	**Q =**	**601.06**	**cfs**
Channel Depth Y	**Y =**	**3.39**	**ft**	**Max Velocity check** (based on min n)	**V =**	**5.83**	**fps**
Flow area	A =	125.29	sq ft	Froude number (based on min n)	Fr =	0.68	
Wetted perimeter	P =	50.42	ft	25-Yr. Critical Velocity (min n)	Vc =	7.80	fps
Composite Manning's n (Calculated)	n-min =	0.030		25-Yr. Critical Depth in Overbanks (min n)	Yc =	2.32	ft
Composite Manning's n (Calculated)	n-max =	0.040					

Clear all cells

Click here for important information regarding the use of this spreadsheet

Click here for explanation of minimum and maximum Manning's n values

Click here for instructions on adjusting overbank widths

Click here for information regarding Velocity check and Froude number

NOTE:

The sum of QL + QR + Qm will slightly overestimate the total composite channel discharge, and will not equal Q. These element values are used, however, to estimate critical velocity and critical depth for design purposes.

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8.3 Example OC-3. Riprap Channel Cross-Section Calculation Using Design of Riprap Channel Worksheet

This example demonstrates use of the Design of Riprap Channel Worksheet (in the SF-Channels Spreadsheet) to determine riprap sizing for a trapezoidal channel. The worksheet calculates riprap sizing, with adjustments for channel curvature, to determine the riprap type required for the channel lining. Calculations are based on channel characteristics provided by the user:

Data Input

The riprap sizing is based on the following hydraulic design parameters entered into the "Design Information (Input)" section of the Design of Riprap Channel Worksheet.

So = channel invert slope = 0.008 ft/ft (0.8%)
B = bottom width =20 ft
Z1 = left side slope = 2.5H:1V
Z2 = right side slope = 2.5H:1V
Ss = specific gravity of rock = 2.6
Ccr = radius of channel centerline = 200 ft
Q = design discharge = 2,000 cfs

Results

Results of the analysis are displayed in the bottom half of the Design of Composite Channel Worksheet (see sample worksheet following this text). The results indicate:

- Type M riprap is suitable for straight and curved sections of the channel and will meet minimum K factor requirements.
- Flow is subcritical and $F_r < 0.8$ as required for riprap channels ($F_r = 0.77$).
- Superelevation may occur because of channel curvature and was calculated. The riprap height needs to be increased approximately 0.3 ft on the outside of the channel bend.

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Design of Riprap Channel Cross Section

Project: Example OC-3 (Draft)
Channel ID: Sample

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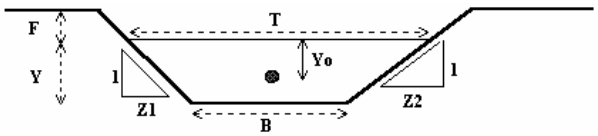

Design Information (Input)			
Channel Invert Slope	So =	0.0080	ft/ft
Bottom Width	B =	20.0	ft
Left Side Slope	Z1 =	2.5	ft/ft
Right Side Slope	Z2 =	2.5	ft/ft
Specific Gravity of Rock (minimum of 2.6)	Gs =	2.60	
Radius of Channel Centerline (enter 0 for straight channel)	r_c =	200.0	ft
Design Disharge	**Q =**	**2,000.0**	**cfs**

	Flow Condition (Calculated)			
	Riprap Type (Straight Channel)	**Type =**	**M**	
	Intermediate Rock Diameter (Straight Channel)	**D50 =**	**12**	**inches**
	Calculated Manning's n (Straight Channel)	**min-n =**	**0.038**	
*	**Riprap Type (Outside Bend of Curved Channel)**	**Type =**	**H**	
*	**Intermediate Rock Dia. (O.B. of Curved Channel)**	**D50 =**	**18**	**inches**
*	**Calculated Manning's n (O.B. of Curved Channel)**	**min-n =**	**0.040**	
	Water Depth	Y =	6.24	ft
	Top Width of Flow	T =	51.2	ft
	Flow Area	A =	222.1	sq ft
	Wetted Perimeter	P =	53.6	ft
	Hydraulic Radius (A/P)	R =	4.1	ft
	Average Flow Velocity (Q/A)	V =	9.0	fps
	Hydraulic Depth (A/T)	D =	4.3	ft
	Froude Number (max. = 0.8)	Fr =	0.766	
	Channel Radius / Top Width	r_c/T =	3.91	
**	Riprap Design Velocity Factor For Curved Channel	Kv =	1.60	
	Riprap Sizing Velocity For Curved Channel	V_{Kv} =	14.5	fps
	Minimum Riprap Sizing Paramenter for Straight Channel	**K =**	**2.92**	
	Minimum Riprap Sizing Paramenter for Outside Bend of Curve	**K_{curve} =**	**4.68**	
***	Superelevation (dh)	dh =	0.33	ft
	Required channel depth (based on max n value)	$Y_{required}$ =	6.56	ft
	Total channel depth including superelevation	Y_{total} =	6.89	ft
	Discharge (Check)	**Q =**	**2,010.1**	**cfs**

Clear all cells

Click here for important information regarding this spreadsheet

*** Riprap type for outside bend and adjacent 1/4 of channel bottom. As an alternative to riprap lining the channel bottom, carry the bank liner at the bank slope to 5-ft. below the channel bottom.**

**** Increases the average channel velocity by a factor Kv, equal to -0.147 * (rc/T) + 2.176, which is part of Equation OC-2. This is used to size riprap on the outside bank when the channel curve has a radius <= 8 times top flow width. Minimum radius to t**

***** Superelevation to be carried from the beginning of the channel bend to a distance of two times the top width (T) downstream of the channel bend.**

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