4. OPEN CHANNELS

4.1 Overview

Open channels are the cornerstone of most major drainage systems, providing conveyance of drainage and floodwaters through natural and manmade drainageways. This chapter discusses the fundamentals of open channel hydraulics and includes procedures for the design of open channels. The designer should consult the most recent editions of Hydraulic Design Series No. 4: Introduction to Highway Hydraulics (HDS 4) and Hydraulic Engineering Circular No. 15: Design of Roadside Channels with Flexible Linings for detailed explanations of specialized procedures and methods pertaining to open channel hydraulics.

Use of natural channels is encouraged whenever possible, particularly for the major drainage system, as there can be advantages in terms of cost, capacity, and multiple use (i.e., recreation, wildlife habitat, etc.). Where natural channels are not well defined, drainage paths can usually be determined by topography and inspection, and these paths can be used as the basis for location and construction of channels. For any open channel conveyance, channel stability must be evaluated to determine what measures may be needed to prevent bottom scour and bank cutting or incising. Channels shall be designed for long-term stability but be left in as near natural condition as possible. Even where streams retain a relatively natural state, streambanks may need to be stabilized while vegetation recovers. To preserve riparian characteristics of channels, channel improvement or stabilization projects should minimize the use of visible concrete, riprap, or other hard stabilization materials.

Hydraulic analysis software such as the US Army Corps of Engineers HEC-RAS or Federal Highway Administration's Hydraulic Toolbox may be useful for preliminary and final channel analysis and design. Channel alignment revisions will require a Corps of Engineers 404 permit if the work is on a jurisdictional channel.

4.2 Open Channel Flow

Several types of flow are possible in open channels, which can be classified as:

- Uniform or Non-uniform
- Steady or Unsteady
- Subcritical, Critical, or Supercritical

Uniform flow is defined as a flow with a constant depth, cross-section, and velocity as it travels the length of channel. ***Non-uniform flow*** is one where the flow depth, cross-section, and/or velocity changes as it travels a length of channel.

Steady flow is defined as a flow with a constant discharge over time. ***Unsteady flow*** is one where the amount of discharge changes over time.

Subcritical flow is defined as a flow with a Froude number less than one ($Fr < 1.0$) and the depth of the channel flow is greater than the critical depth for the channel. Water flowing in a subcritical state has a relatively low velocity and is often described as tranquil. Subcritical flows will allow downstream losses to be transferred upstream.

Supercritical flow is defined as a flow with a Froude number greater than one ($Fr > 1.0$) and the depth of the channel flow is less than the critical depth for the channel. Water flowing in a supercritical state has a high velocity and is often described as rapid or shooting. Supercritical flows do not transfer downstream losses upstream.

Critical flow is defined as a flow with a Froude number equal to one (Fr = 1).

Non-uniform, unsteady, subcritical flow is the most common type of flow in open channels. However, due to the complexity and difficulty involved in the analysis of this type of flow, most hydraulic computations are made with certain simplifying assumptions that allow the application of steady, uniform (or gradually varied) flow principles.

The use of **steady flow methods** assumes that the discharge at a point does not change with time, and the use of **uniform flow methods** assumes that there is no change in velocity, in magnitude, or in direction with distance along a streamline. **Steady, uniform flow** is thus characterized by constant velocity and flow rate from section to section along the channel.

Steady, uniform flow is an idealized concept of open channel flow, which seldom occurs in natural channels and is difficult to obtain even in model channels. However, for most practical applications, the flow is assumed to be steady, and changes in width, depth, or direction (resulting in non-uniform flow) are sufficiently small that flow can be considered uniform. For these reasons, use of uniform flow theory is usually within acceptable degrees of accuracy.

4.2.1 Critical Depth

Critical depth is the depth at which a given quantity of water flows with the minimum content of energy. In a given channel, critical depth occurs when the specific energy (depth + velocity head) is at a minimum. Critical depth is important as a hydraulic "control point," which is a location along the channel or culvert where depth of flow can be computed directly.

Critical depth is particularly helpful in the hydraulic analysis of culverts. Since flow must pass through critical depth when changing from subcritical flow to supercritical flow, critical depth typically occurs at the following locations:

- Abrupt changes in channel or culvert slope when a flat slope is sharply increased to a steep slope (as in broken-back culverts)
- A channel constriction such as a culvert entrance
- The unsubmerged outlet of a culvert on subcritical slope, discharging into a wide channel or free outfall (no tailwater present at the outlet)
- The crest of an overflow dam or weir

The following relationship is used to calculate critical depth:

$$A^3/_T = Q^2/_g$$

where:

$A = Cross - sectional\ Area\ of\ Channel, ft^2$
$T = Topwidth\ of\ Water\ Surface, ft$
$Q = Discharge, cfs$
$g = Acceleration\ of\ Gravity = 32.2\ ^{ft}/_{sec^2}$

As can be seen from this equation, critical depth is dependent on channel geometry (shape) and discharge **only**. It is independent of channel slope and roughness. This means that for a given flow rate and channel cross-section, critical depth remains constant throughout the channel or culvert length, even though the channel slope may change.

4.2.2 Froude Number

The Froude number is a dimensionless number that represents the ratio of inertial to gravitational forces. It is defined by the following equation:

$$Fr = {}^{V}\!/_{(gD)^{0.5}}$$

where:

$Fr = Froude\ Number$

$V = Velocity\ in\ Channel, {}^{ft}\!/_{sec}$

$g = Acceleration\ of\ Gravity = 32.2\ {}^{ft}\!/_{sec^2}$

$D = Hydraulic\ Depth, ft = {}^{Flow\ Area}\!/_{Top\ Width}$

- **Critical flow** exists when inertial forces and gravity are equal, (Fr = 1.0).
- **Supercritical flow** (Shallow, Rapid flow) exists when the inertial forces are greater than gravity forces (High Velocity), (Fr > 1.0).
- **Subcritical flow** (Deep, Tranquil flow) exists when inertial forces are less than gravity forces (Low Velocity), (Fr < 1.0).

4.2.3 Manning's Equation

An open channel must be designed to convey the peak runoff rate for the selected design storm frequency. The hydraulic capacity of an open channel can be determined from Manning's equation for evaluating uniform flow in open channels. See Section 4.3.7 for Manning's equation and further discussion on open channel flow criteria.

4.3 Open Channel Design Criteria

4.3.1 General Criteria

The following criteria should be used for open channel design:

- Trapezoidal cross sections are preferred; triangular shapes should be avoided.
- Channel side slopes shall be stable throughout the entire length and side slope shall depend on the channel material. A maximum of 4H:1V is recommended for vegetation and 2H:1V for riprap, unless otherwise justified by calculations.
- If relocation of a stream channel is unavoidable, the cross-sectional shape, meander, pattern, roughness, sediment transport, and slope should generally conform to the existing conditions, taking increased flows from urbanization into consideration. Energy dissipation or grade control may be necessary.
- Streambank stabilization should be provided, when appropriate and should include upstream and downstream banks, as well as the local project site.
- A low flow or trickle channel may be needed for grass-lined channels.

4.3.2 Channel Transitions

The following criteria should be considered at channel transitions:

- Transitions from one channel section to another should be smooth and gradual to avoid turbulence and eddies.
- Energy losses in transitions should be accounted for as part of the water surface profile calculations.
- Scour downstream from rigid-to-natural and steep-to-mild slope transition sections should be accounted for through velocity-slowing and energy-dissipating devices.

4.3.3 Return Period Design Criteria

Open channels, including floodplains, shall be sized to handle the 100-year storm. The 100-year storm event shall not encroach on buildable lots and shall be contained in out-lots or easements when not confined to the channel itself. When comprising the minor drainage system, open channels shall be sized to handle the 5-year storm in residential areas and the 10-year storm in downtown, commercial, and industrial areas. If a low flow channel is incorporated into the channel cross section, it shall be designed to convey 1 percent of the 100-year storm.

4.3.3.1 Approximate Flood Limits Determination

The approximate flood limits of the 100-year storm shall be determined for all open channels and all areas inundated shall be protected from development through out-lots or easements as directed by the City. Using the Manning's Equation may be an acceptable procedure to determine flood limits for small and intermediate open channels. The City may require a hydraulic model to determine flood limits for large and/or complex channels where steady, uniform flow assumptions may provide inaccurate results.

4.3.4 Velocity Limitations

Sediment transport requirements must be considered for conditions of flow below the design frequency. Minimum channel flow velocity for the 2-year storm shall be 2 feet per second. A low flow channel component within a larger channel can reduce maintenance by increasing the velocity of small storms to improve sediment transport in the channel.

4.3.5 Freeboard

A minimum freeboard of 1 foot should be provided between the water surface and top of bank or the elevation of the lowest opening of adjacent structures. Freeboard should be determined based on the 100-year storm water surface elevation under mature channel conditions.

4.3.6 Grade Control Structures

Grade control structures are used to prevent streambed degradation. This is accomplished in two ways. First, the structures provide a firm structural flowline elevation that prevents bed erosion and subsequent slope increases. Second, some structures provide controlled dissipation of energy between upstream and downstream sides of the structure. Structure choice depends on existing or anticipated erosion, cost, and environmental objectives. Design guidance for grade control structures can be found in the most recent editions of Hydraulic Engineering Circular No. 14: Hydraulic Design of Energy Dissipators for Culverts and Channels (HEC 14) and Hydraulic Engineering Circular No. 23: Bridge Scour and Stream Instability Countermeasures.

4.3.7 Manning's Equation

An open channel must be designed to convey the peak runoff rate for the selected design storm frequency. The hydraulic capacity of an open channel can be determined from Manning's equation for evaluating uniform flow in open channels.

$$Q = VA$$

Where:

$Q = Discharge, cfs$

$A = Cross - sectional\ Area\ of\ Channel, ft^2$

$V = Velocity\ in\ Channel, {}^{ft}/_{sec}$

$$V = \frac{1.486}{n} R^{2/3} S^{1/2}$$

Where:

$R = Hydraulic\ Radius, ft = {}^{A}/_{WP}$

$WP = Wetted\ Perimeter, ft$

$S = Slope\ of\ Hydraulic\ Grade\ Line, {}^{ft}/_{ft}$

$(Can\ be\ Approximated\ by\ Channel\ Slope)$

$n = Manning's\ Roughness\ Coefficient$

If a channel cross section is irregular in shape, such as a channel with a relatively narrow, deep main channel and wide, shallow overbank channels, the cross section should be subdivided, and the discharge computed separately for the main channel and the overbank channels. The same procedure is used when parts of the cross section have different roughness coefficients. In computing the hydraulic radius of the subsections, the water depth common to adjacent subsections is not counted as wetted perimeter.

Table 4-1. Open Channel Manning's Roughness Coefficients

Lined, Straight Alignment		Manning's n Range
Concrete with Surface as Indicated	Formed, No Finish	0.013 – 0.017
	Trowel Finish	0.012 – 0.014
	Float Finish	0.013 – 0.015
	Float Finish, Some Gravel on Bottom	0.015 – 0.017
	Gunite, Good Section	0.016 – 0.019
	Gunite, Wavy Section	0.018 – 0.022
Concrete, Bottom Float Finished, Sides as Indicated	Dressed Stone in Mortar	0.015 – 0.017
	Random Stone in Mortar	0.017 – 0.020
	Cement Rubble Masonry	0.020 – 0.025
	Cement Rubble Masonry, Plastered	0.016 – 0.020
	Dry Rubble (Riprap)	0.020 – 0.030
Gravel Bottom, Sides as Indicated	Formed Concrete	0.017 – 0.020
	Random Stone in Mortar	0.020 – 0.023
	Dry Rubble (Riprap)	0.023 – 0.033
Asphalt	Smooth	0.013
	Rough	0.016
Concrete Lined Excavated Rock	Good Section	0.017 – 0.020
	Irregular Section	0.022 – 0.027
Excavated, Straight Alignment, Natural Lining		**Manning's n Range**
Earth, Uniform Section	Clean, Recently Completed	0.016 – 0.018
	Clean, After Weathering	0.018 – 0.020
	With Short Grass, Few Weeds	0.022 – 0.027
	In Gravelly Soil, Uniform Section, Clean	0.022 – 0.025
Earth, Fairly Uniform Section	No Vegetation	0.022 – 0.025
	Grass, Some Weeds	0.025 – 0.030
	Dense Weeds or Aquatic Plants in Deep Channels	0.030 – 0.035
	Sides Clean, Gravel Bottom	0.025 – 0.030
	Sides Clean, Cobble Bottom	0.030 – 0.040
Dragline Excavated or Dredged	No Vegetation	0.028 – 0.033
	Light Brush on Banks	0.035 – 0.050
Rock	Based on Design Section	0.035
	Based on Actual Mean Section, Smooth and Uniform	0.035 – 0.040
	Based on Actual Mean Section, Jagged and Irregular	0.040 – 0.045
Channels not Maintained, Weeds and Brush Uncut	Dense Weeds, High as Flow Depth	0.080 – 0.120
	Clean Bottom, Brush on Sides	0.050 – 0.080
	Clean Bottom, Brush on Sides, Highest Stage of Flow	0.070 – 0.110
	Dense Brush, High Stage	0.100 – 0.140

Channels & Swales with Maintained Vegetation (2-6 ft/s)			Manning’s n Range
Depth of Flow up to 0.7 Foot	Bermudagrass, Kentucky Bluegrass, Buffalograss	Mowed to 2 Inches	0.045 – 0.070
		Length 4-6 Inches	0.050 – 0.090
	Good Stand, Any Grass	Length 12 Inches	0.090 – 0.180
		Length 24 Inches	0.150 – 0.300
	Fair Stand, Any Grass	Length 12 Inches	0.080 – 0.140
		Length 24 Inches	0.130 – 0.250
Depth of Flow 0.7 – 1.5 Feet	Bermudagrass, Kentucky Bluegrass, Buffalograss	Mowed to 2 Inches	0.030 – 0.050
		Length 4-6 Inches	0.040 – 0.060
	Good Stand, Any Grass	Length 12 Inches	0.070 – 0.120
		Length 24 Inches	0.100 – 0.200
	Fair Stand, Any Grass	Length 12 Inches	0.060 – 0.100
		Length 24 Inches	0.090 – 0.170
Natural Stream Channels			**Manning’s n Range**
Minor Streams, Surface Width at Flood Stage Less than 100 Feet	Fairly Regular Section	Some Grass & Weeds, Little or No Brush	0.030 – 0.035
		Dense Growth of Weeds, Depth of Flow Materially Greater than Weed Height	0.035 – 0.050
		Some Weeds, Light Brush on Banks	0.035 – 0.050
		Some Weeds, Heavy Brush on Banks	0.050 – 0.070
		Some Weeds, Dense Willows on Banks	0.060 – 0.080
		For Trees within Channel with Branches Submerged at High Stage, Increase all Above Values by:	0.010 – 0.020
	Irregular Sections w/ Pools & Channel Meander, Increase all Above Values by:		0.010 – 0.020

Natural Stream Channels			Manning’s n Range
Floodplains Adjacent to Natural Streams	Pasture, No Brush	Short Grass	0.030 – 0.035
		High Grass	0.035 – 0.050
	Cultivated Areas	No Crop	0.030 – 0.040
		Mature Row Crops	0.035 – 0.045
		Mature Field Crops	0.040 – 0.050
	Heavy Weeds, Scattered Brush		0.050 – 0.070
	Light Brush & Trees	Winter	0.050 – 0.060
		Summer	0.060 – 0.080
	Medium to Dense Brush	Winter	0.070 – 0.110
		Summer	0.100 – 0.160
	Dense Willows, Summer, Not Bent by Current		0.150 – 0.200
	Cleared Land w/ Tree Stumps	No Sprouts	0.040 – 0.050
		Heavy Growth of Sprouts	0.060 – 0.080
	Heavy Timber, Little Brush	Depth Below Branches	0.100 – 0.120
		Depth Reaches Branches	0.120 – 0.160
Major Streams, Surface Width at Flood Stage More than 100 Feet, No Boulders or Brush (1)			0.028 – 0.033

(1) Roughness coefficient is usually less than for minor streams of similar description on account of less effective resistance offered by irregular banks or vegetation on banks. Values of n may be somewhat reduced.

4.3.8 Flow in Bends

Flow around a bend in an open channel induces centrifugal forces because of the change in flow direction. This results in a super elevation of the water surface at the outside of bends and can cause the flow to splash over the side of the channel if adequate freeboard is not provided. This super elevation can be estimated by the following equation.

$$\Delta d = {}^{V^2T}\!/_{gR_c}$$

Where:

$\Delta d = Difference\ in\ Water\ Surface\ Elevation\ Between\ Inner\ \&\ Outer\ Banks$

$V = Average\ Velocity, {}^{ft}/_{sec}$

$T = Surface\ Width\ of\ Channel, ft$

$g = Acceleration\ of\ Gravity = 32.2\ {}^{ft}/_{sec^2}$

$R_c = Radius\ of\ Centerline\ of\ Channel, ft$

The elevation of the water surface at the outer channel bank will be Δd/2 higher than the centerline water surface elevation (the average water surface elevation immediately before the bend) and the elevation of the water surface at the inner channel bank will be Δd/2 lower than the centerline water surface elevation. Flow around a channel bend also imposes higher shear stress on the channel bottom and banks and may impact channel stability as described in the following sections.

4.3.9 Shear Stress

The hydrodynamic force created by water flowing in a channel causes a shear stress on the channel bottom. The bed material, in turn, resists this shear stress by developing a tractive force. Tractive force theory states that the flow-induced shear stress should not produce a force greater than the tractive resisting force of the bed material. This tractive resisting force of the bed material creates the permissible or critical shear stress of the bed material.

4.3.9.1 Shear Stress in Straight Channels

The maximum shear stress for a straight channel occurs on the channel bed and is less than or equal to the shear stress at maximum depth. The maximum shear stress is computed as:

$$\tau_d = \gamma d S_o$$

Where:

$\tau_d = Maximum\ Shear\ Stress, {}^{lb}/_{ft^2}$

$\gamma = Unit\ Weight\ of\ Water, 62.4\ {}^{lb}/_{ft^3}$

$d = Maximum\ depth\ of\ Flow, ft$

$S_o = Average\ Bed\ Slope\ or\ Engery\ Slope, {}^{ft}/_{ft}$

4.3.9.2 Shear Stress of Channel Sides

Shear stress is generally reduced on the channel sides compared with the channel bottom. The maximum shear on the side of a channel is given by the following equation for trapezoidal channels:

$$\tau_s = K_1 \tau_d$$

Where:

$\tau_s = Side\ Shear\ Stress,\ {}^{lb}/_{ft^2}$

$K_1 = Ratio\ of\ Channel\ Side\ to\ Bottom\ Shear\ Stress$

Table 4-2. Ratios of Channel Side to Bottom Shear Stress

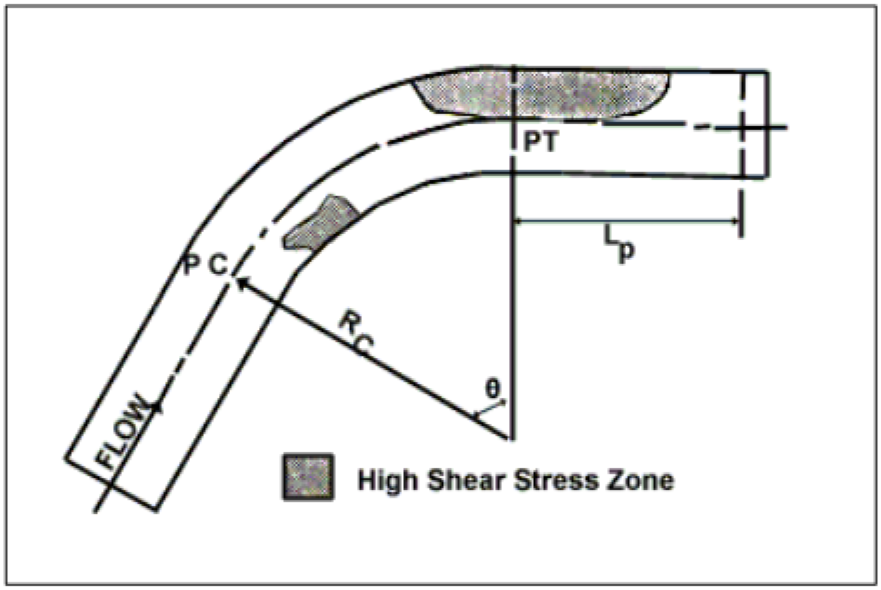
Value of K_1	Channel Side Slope
0.77	$Z \leq 1.5$
0.066Z + 0.67	$1.5 < Z < 5$
1.0	$5 \leq Z$

The Z value represents the horizontal dimension Z:1 (H:V). Use of side slopes steeper than 3:1 (H:V) is not encouraged for flexible linings other than riprap or gabions because of the potential for erosion of the side slopes.

4.3.9.3 Shear Stress in Bends

Flow around a bend creates secondary currents, which impose higher shear stresses on the channel sides and bottom compared to a straight reach as shown on Figure 4-1. At the beginning of the bend, the maximum shear stress is near the inside and moves toward the outside as the flow leaves the bend. The increased shear stress caused by a bend persists downstream of the bend.

Figure 4-1. High Shear Stress Zone in Bends



The maximum shear stress in a bend is computed as:

$$\tau_b = K_b \tau_d$$

Where:

$\tau_b = Shear\ Stress\ in\ a\ Bend, {}^{lb}/_{ft^2}$

$K_b = Ratio\ of\ Channel\ Bend\ to\ Bottom\ Shear\ Stress$

The maximum shear stress in a bend is a function of the ratio of channel curvature to the top (water surface) width, R_C/T. As R_C/T decreases, that is as the bend becomes sharper, the maximum shear stress in the bend tends to increase. K_b can be determined from Table 4-3.

Table 4-3. Ratios of Channel Bend to Bottom Shear Stress

Value of K_b	${}^{R_C}/_T$
2.00	${}^{R_C}/_T \le 2$
$2.38 - 0.206\left({}^{R_C}/_T\right) + 0.0073\left({}^{R_C}/_T\right)^2$	$2 < {}^{R_C}/_T < 10$
1.05	$10 \le {}^{R_C}/_T$

The added stress induced by bends does not fully attenuate until some distance downstream of the bend. If added lining protection is needed to resist the bend stresses, this protection should continue downstream a length given by:

$$L_p = \alpha\left(\frac{R^{7/6}}{n}\right)$$

Where:

$L_p = Length\ of\ Protection, ft$

$R = Hydraulic\ Radius, ft = {}^{A}/_{WP}$

$n = Manning's\ Roughness\ for\ Lining\ Material\ in\ Bed$

$\alpha = Unit\ Conversion\ Constant = 0.60$

4.3.9.4 Effective Shear Stress in Grass Lined Channels

Grass linings move shear stress away from the soil surface. The remaining shear at the soil surface is termed the effective shear stress. When the effective shear stress is less than the allowable shear for the soil surface, then erosion of the soil surface will be controlled. Grass linings provide shear reduction in two ways. First, the grass stems dissipate shear force within the canopy before it reaches the soil surface. Second, the grass plant (both the root and stem) stabilizes the soil surface against turbulent fluctuations. This process model for the effective shear at the soil surface is given by the following equation.

$$\tau_e = \tau_d K_e$$

Where: $\tau_e = Effective\ Shear\ Stress\ on\ the\ Soil\ Surface, {}^{lb}/_{ft^2}$

$K_e = Ratio\ of\ Effective\ to\ Bottom\ Shear\ Stress$

Table 4-4 provides typical examples of K_e for common grass linings. See the most recent edition of Hydraulic Engineering Circular No. 15: Design of Roadside Channels with Flexible Linings (HEC 15) for effective shear stress development for grasses not provided in Table 4-4.

Table 4-4. Typical Ratios of Effective to Bottom Shear Stress

Grass Type	Grass Length	Flow Depth	K_e
Bermudagrass, Kentucky Bluegrass, Buffalograss	Mowed to 2 Inches	4 Inches	0.013
		8 Inches	0.016
		12 Inches	0.021
		18 Inches	0.028
	Length 4-6 Inches	4 Inches	0.010
		8 Inches	0.012
		12 Inches	0.015
		18 Inches	0.016
Fair Stand, Any Grass (Includes Native Grasses)	Length 12 Inches	4 Inches	0.021
		8 Inches	0.026
		12 Inches	0.033
		18 Inches	0.038
	Length 24 Inches	4 Inches	0.008
		8 Inches	0.010
		12 Inches	0.014
		18 Inches	0.017
Good Stand, Any Grass	Length 12 Inches	4 Inches	0.008
		8 Inches	0.010
		12 Inches	0.012
		18 Inches	0.013
	Length 24 Inches	4 Inches	0.003
		8 Inches	0.004
		12 Inches	0.005
		18 Inches	0.006
Good Stand, Wetland Mixture (Cattails)	Uncut	4 Inches	0.001
		8 Inches	0.001
		12 Inches	0.001
		18 Inches	0.001

4.3.9.5 Permissible Shear Stress

Flexible linings (grass, riprap, etc.) act to reduce the shear stress on the underlying soil surface. For example, a long-term lining of vegetation in good condition can reduce the shear stress on the soil surface by over 90 percent. Transitional linings (erosion control blankets, transition mats, etc.) act in a similar manner as vegetative linings to reduce shear stress. Performance of these products depends on their properties: thickness, cover density, and stiffness.

The erodibility of the underlying soil, therefore, is a key factor in the performance of flexible linings. The erodibility of soils is a function of particle size, cohesive strength, and soil density. The erodibility of non-cohesive soils (defined as soils with a plasticity index of less than 10) is due mainly to particle size, while fine-grained cohesive soils are controlled mainly by cohesive strength and soil density. For most construction, the density of the embankment is controlled by compaction rather than the natural density of the undisturbed ground. However, when the ditch is lined with topsoil, the placed density of the topsoil should be used instead of the density of the compacted embankment soil.

For stone linings, the permissible shear stress, τ_p, indicates the force required to initiate movement of the stone particles. Prior to movement of stones, the underlying soil is relatively protected. Therefore, permissible shear stress is not significantly affected by the erodibility of the underlying soil. However, if the lining moves, the underlying soil will be exposed to the erosive force of the flow.

Table 4-5 provides typical examples of permissible shear stress for bare soil and selected linings. See HEC 15 for permissible shear stress development for linings not provided in Table 4-5.

Table 4-5. Typical Permissible Shear Stresses for Bare Soil and Stone Linings

Lining Category	Lining Type	Permissible Shear Stress, $^{lb}/_{ft^2}$
Bare Soil, Cohesive (PI = 10)	Clayey Sands	0.037-0.095
	Inorganic Silts	0.027-0.110
	Silty Sands	0.024-0.072
Bare Soil, Cohesive (PI ≥ 20)	Clayey Sands	0.094
	Inorganic Silts	0.083
	Silty Sands	0.072
	Inorganic Clays	0.140
Bare Soil, Non-cohesive (PI < 10)	Finer than Coarse Sand, D_{75} < 0.05 inch	0.02
	Fine Gravel, D_{75} = 0.3 inch	0.12
	Gravel, D_{75} = 0.6 inch	0.24
Gravel Mulch	Course Gravel, D_{50} = 1.0 inch	0.4
	Very Course Gravel, D_{50} = 2.0 inch	0.8
Rock Riprap	NDOT, Type A, D_{50} = 0.77 feet	3.1
	NDOT, Type B, D_{50} = 1.02 feet	4.1
	NDOT, Type C, D_{50} = 1.28 feet	5.1
Concrete Riprap	NDOT, D_{50} = 1.10 feet	4.4

4.4 Construction and Maintenance Considerations

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

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

4.5 References

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