Chapter 6 - Roadside and Median Channels

Roadside and median channels are free water surface conveyance channels designed and constructed to collect stormwater from paved and other surfaces within the right-of-way (ROW) and, in some situations, adjacent areas. These channels provide a flow path to where stormwater can enter the offsite surface drainage system. Before entering the offsite drainage system, these channels may route water to an outfall structure or to a detention or retention basin or other storage component.

Designers commonly specify roadside and median channels with triangular or trapezoidal cross-sections. Construction techniques or the need for ongoing maintenance activities over the life of a transportation project may influence the exact cross-section shape, resulting in more rounded cross-sections. The surface of the channel may be vegetated or covered with other protective linings.

Limited ROW width, existing roadside development, and established adjacent land uses often constrain urban roadways and the associated roadside and median channels. Private and public utilities potentially share the ROW with stormwater conveyance features. Such elements include sanitary sewer access holes, water distribution valves, utility poles and conduits, illumination poles, traffic signal poles, signs, pedestrian sidewalks, bicycle paths, on-street parking lanes, flexible traffic barriers, and accessibility features.

Some of these features present potential safety hazards to the traveling public. While safety concerns guide the placement of those potential fixed objects, the location of some of these ancillary features within the boundaries of roadside channels is often unavoidable. Median channels for the conveyance of stormwater frequently share the median of divided roadways with illumination standards, signal standards, and flexible traffic barriers. Accommodating all the features needed for a safe and functional roadway encourages cooperation among the engineering team during the design phase. Designers of drainage features will likely find other references such as the AASHTO Roadside Design Guide (AASHTO 2011) helpful.

Although designed to carry stormwater, roadside and median channels also carry sediment, pollutants, and debris. During certain seasons, channels adjacent to residential areas may also contain plant material including bloom from trees in the spring and nuts and leaves in the fall that accumulate in streets and are washed into the drainage facilities. Over time, the accumulation of sediment, debris, and plant materials can obstruct flow in channels and medians. By understanding the adjacent land use, and anticipating debris type and occurrence, the designer can facilitate movement of these unintended materials through the channel or provide access for removal, or both.

This chapter presents concepts and relationships for the design of roadside and median channels beginning with open channel flow and channel design parameters. Next, the chapter presents the concepts and design steps for stable channel design. Finally, the chapter provides an overall process for designing roadside and median channels.

6.1 Open Channel Flow Concepts

The analysis and design of roadside and median channels rely on the principles of open channel flow. The following sections present summaries of several open channel flow concepts. Chow (1959), FHWA (2008), and many other hydraulic references provide more complete and specific discussion of open channel flow concepts.

6.1.1 Energy

Conservation of energy is a basic principle in open channel flow. As shown in Figure 6.1, the total energy (or head) at a given location in an open channel is expressed as the sum of the potential energy (channel bottom elevation plus depth) and kinetic energy (velocity head). (Pressure head is zero in open channel flow and, therefore, excluded from consideration.) The total energy at any cross-section along the channel can be approximated as:

$$E_t = Z + y + \frac{V^2}{2g} \quad (6.1)$$

where:

E_t	=	Total energy, ft (m)
Z	=	Elevation of the channel bottom above a given datum, ft (m)
y	=	Flow depth, ft (m)
V	=	Mean velocity, ft/s (m/s)
g	=	Gravitational acceleration, 32.2 ft/s^2 (9.81 m/s^2)

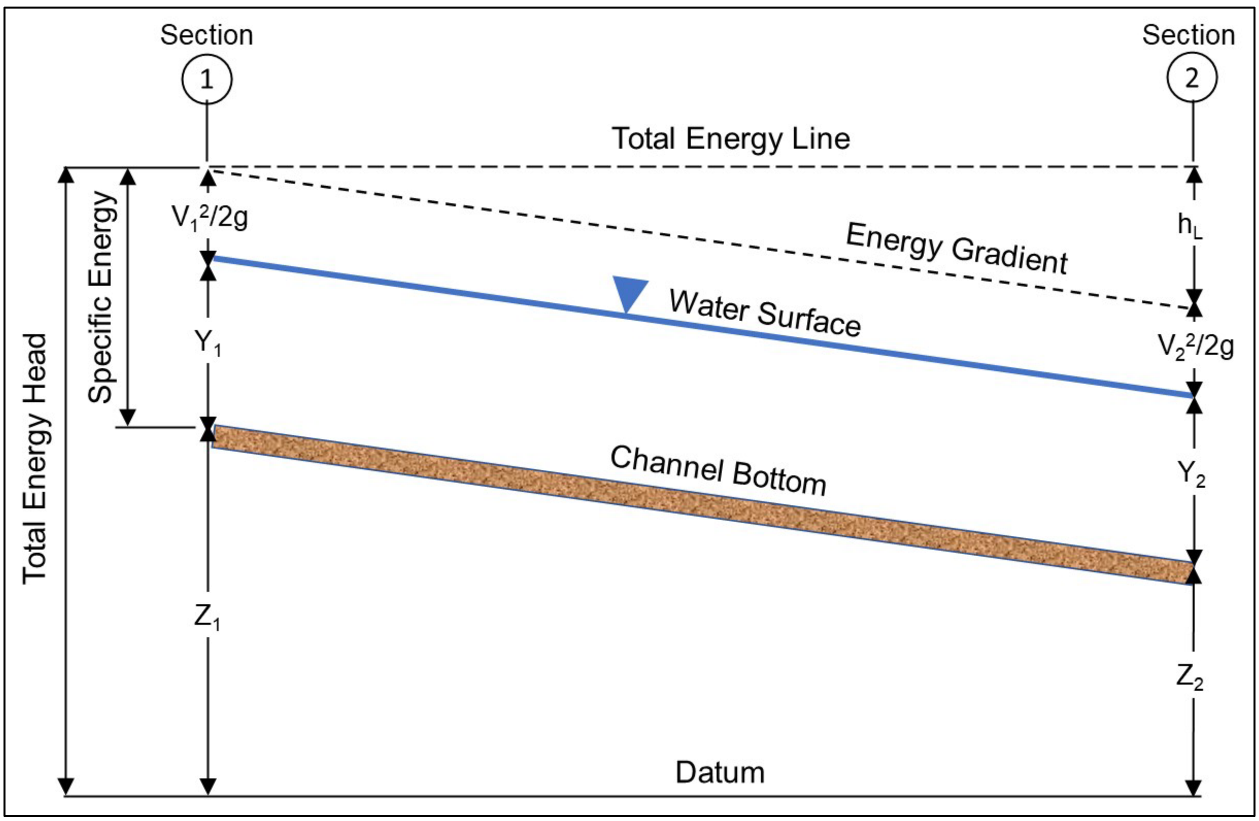

Figure 6.1. Total energy in open channels.

Figure 6.1 depicts a channel schematic highlighting two cross-section locations. Balancing energy between cross-section 1 and a downstream cross-section 2, the energy equation becomes:

$$Z_1 + y_1 + \frac{V_1^2}{2g} = Z_2 + y_2 + \frac{V_2^2}{2g} + h_L \quad (6.2)$$

where:

h_L = Energy (head) lost between section 1 and 2 to friction and turbulence, ft (m)

The energy equation states that the total energy head at an upstream cross-section is equal to the total energy head at a downstream cross-section plus the energy head loss between the two sections.

6.1.2 Critical, Subcritical, and Supercritical Flow

Hydraulic engineers classify open channel flow situations into critical, subcritical, and supercritical flow regimes using the **specific energy** of the flow and a dimensionless Froude number. The specific energy, E, is the energy head relative to the channel bottom. It is the sum of the flow depth and velocity head:

$$E = y + \frac{V^2}{2g} \tag{6.3}$$

For a given discharge and channel roughness, the specific energy changes with channel slope. At mild slopes, flow moves through a channel relatively slowly and with greater depths. As slope increases, velocity increases and depth decreases. Figure 6.2 illustrates the change in specific energy relative to the depth for three different flow rates, q_1, q_2, and q_3. The figure reveals that for each of the curves there is a depth at which the specific energy is a minimum.

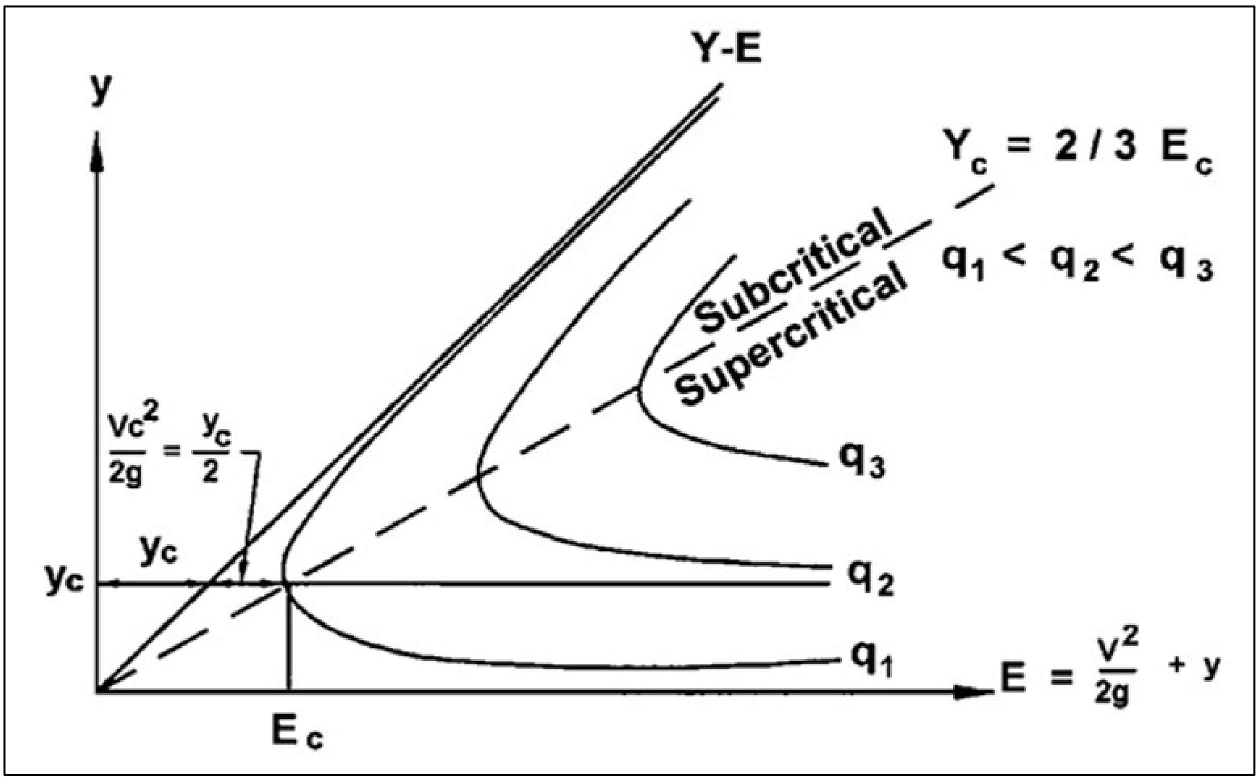

Figure 6.2. Specific energy diagram.

Critical flow occurs when the specific energy is at its minimum for a given flow and the corresponding depth is the **critical depth**. Figure 6.2 shows that at critical flow, the critical depth is two-thirds of the specific energy. The velocity head is the remaining one-third.

Subcritical flow occurs when the depth is greater than critical depth and supercritical flow occurs when the depth is less than critical depth. Hydraulic engineers use the Froude number to identify critical, subcritical, or supercritical flow conditions in a channel. The Froude number is calculated for rectangular channels using the following equation:

$$Fr = \frac{V}{\sqrt{gy}} \qquad (6.4)$$

where:

V	=	Mean velocity of flow, ft/s (m/s)
g	=	Gravitational acceleration, 32.2 ft/s^2 (9.81 m/s^2)
y	=	Flow depth, ft (m)

When the Froude number is less than one, the flow is classified as **subcritical**. Depth is greater than critical depth, the velocity is slower than critical velocity, and small water surface disturbances travel both upstream and downstream. Downstream conditions control the flow rate. The control may be a structure or obstruction in the channel, or the control may be the channel roughness. Subcritical flow generally occurs on mild slopes.

When the Froude number is greater than one, the flow is classified as **supercritical**. Depth is less than critical depth, the velocity is faster than critical velocity, and small water surface disturbances cannot move upstream and are swept downstream. Upstream conditions control the flow rate. Supercritical flow occurs only very rarely in natural channels but is common in constructed channels on relatively steep slopes.

When the Froude number is equal to one, the flow is critical. When the Froude number is close to one, small changes in the flow rate, channel geometry, or channel slope can initiate a change in flow regime. A change from subcritical flow to supercritical flow results in higher velocities than anticipated and a change from supercritical to subcritical flow results in higher depths than anticipated. Considering these changes and any resulting impacts on flow depth or channel stability will help engineers design roadside and median channels that serve their intended function.

When the Froude number is greater than one (flow is supercritical) and a change in channel condition, such as an obstacle or a reduction in channel slope, occurs, flow may transition abruptly from supercritical to subcritical in a **hydraulic jump**. A hydraulic jump results in a rapid increase in depth and reduction in velocity. In making this transition, the jump can dissipate a significant portion of the flow energy.

The turbulence of a hydraulic jump may threaten the stability of a roadside or median channel. Exposing an unprotected channel boundary material, e.g., soil, to the turbulence of a hydraulic jump may result in undesirable scour and erosion of the boundary, altering the channel shape and resulting in long-term or recurrent channel maintenance problems. In addition, as the flow varies over time (e.g., from the beginning of a runoff event to its peak and recession), the location of a jump along the channel can vary significantly as the Froude number varies with flow.

For these reasons, designers typically avoid hydraulic jump conditions in roadside and median channels. The designer may consider the potential for a hydraulic jump in cases where the Froude number is greater than one or where the slope of the channel bottom changes abruptly from steep to mild. If hydraulic jumps cannot be avoided, accounting for their likely presence allows the designer to apply measures, such as protective linings, that create a more sustainable design.

Lessons from Experience: Hydraulic Jumps

Jumps are common in the field, especially where there is concrete lining. The jumps are generally small and poorly developed, but they are often a source of channel problems. Because the slope in a roadside or median channel is driven by the ROW width and the grade of the edge of pavement, jump conditions occur but designers can recognize and mitigate these conditions.

6.1.3 Steady Uniform Flow

Typical roadside design practice assumes that flow conditions are both steady and uniform though there are situations where more complex situations occur. **Steady flow** does not change over time and **uniform flow** does not vary in depth over the length of a channel. Therefore, steady uniform flow neither varies with time nor depth within a given channel segment. Such conditions are unlikely to occur in natural channels but can be assumed in prismatic roadside and median channels. Prismatic channels are those with slope and cross-section geometry that do not change significantly over their length.

Unsteady flow varies with time. Channels experience unsteady flow in every runoff event as runoff increases over time, reaches a peak, and decreases. As a channel receives the runoff, flow and depth in the channel will increase, reach a peak, and decrease. State Department of Transportation (DOT) staff may use hydrographs in the design of a roadside channel to evaluate how it performs over a range of flows.

Nonuniform (varied) flow occurs when either flow rate or depth, or both, vary along the channel. **Gradually varied** flow is nonuniform flow in which the depth and velocity change gradually enough in the flow direction that vertical accelerations can be neglected in estimating the water surface profile in the channel. A typical example of gradually varied flow is the stream channel condition upstream of a culvert with ponded flow. **Rapidly varied** flow is nonuniform flow in which the depth and velocity change so that vertical accelerations cannot be neglected. An example of a rapidly varied flow is the flow profile through a constricted bridge opening.

6.1.4 Manning's Equation

Water flows in an open channel because of the force of gravity. Friction between the water and the channel boundary, and energy loss from turbulence near the boundary, resist the water flow and cause the loss of energy over distance. In the idealized model of steady uniform flow there are no significant accelerations, streamlines are straight and parallel, and the pressure distribution is hydrostatic. This is the simplest flow condition to analyze, but one that does not occur in the real world. However, for many applications, the flow is essentially steady and any changes in width, depth, or direction (resulting in nonuniform flow) are sufficiently small that the flow can be considered uniform.

The depth of flow in steady uniform flow is the **normal depth**. Designers commonly use Manning's equation to characterize steady uniform flow conditions and to determine normal depth in a channel. Manning's equation for discharge is:

$$Q = \frac{K_u}{n} A\, R^{2/3}\, S_o^{1/2} \tag{6.5}$$

where:

K_u	=	Unit conversion constant, 1.486 in CU (1.0 in SI)
Q	=	Discharge rate, ft/s^3 (m/s^3)
A	=	Cross-sectional flow area, ft^2 (m^2)
R	=	Hydraulic radius, ft (m)
S_o	=	Energy grade line slope, ft/ft (m/m)
n	=	Manning's roughness coefficient

Applied appropriately, Manning's equation is a useful and reliable representation of steady uniform flow in open channels. Whenever the steady uniform flow model is appropriate, or a reasonable approximation of that condition exists, calculating the discharge capacity of a given channel section using Manning's equation is straightforward. However, when working with a discharge from a hydrologic analysis, designers sizing a channel to convey that discharge will typically use an iterative trial and comparison process.

> **Manning's n**
>
> Manning's n is a way of representing energy loss in fluid flow. When using Manning's equation, the value of n accounts for energy losses attributable to all causes (boundary shear, form drag, turbulence, etc.).

Manning's roughness coefficient, n, is a critical input for evaluating Manning's equation. Designers usually select an appropriate Manning's n value based on tables or procedures in reference materials such as textbooks and hydraulic design manuals. For channels with rigid, manufactured boundaries such as concrete, designers can reasonably assume that the Manning's n value is constant with different applications and with time. For channels lined with vegetation or flexible materials, on the other hand, the Manning's n value can vary quite dramatically. Factors influencing this variance can include the type of vegetation, its height relative to flow depth, and its state of growth. Seasonal variations in vegetative vigor, mowing and vegetation management policies and procedures, as well as roadside maintenance procedures such as "blading" slopes and ditches, may involve a wide range of changes to the hydraulic texture of a channel boundary.

Over many decades, researchers have compiled typical Manning's n values for a wide range of channel conditions. Table 6.1 provides a tabulation of typical Manning's n values for various channel linings that can be used in roadside channel design including rigid linings, no linings, and rolled erosion control productions (RECPs). Designers will find more information on selecting Manning's n values for roadside and median channels in HEC-15 (FHWA 2005).

6.1.5 Superelevation in Bends

Flow around a bend in an open channel induces centrifugal forces because of the change in flow direction (Chow 1959). This results in **superelevation** (transverse slope) of the water surface at the outside of bends. Without adequate freeboard, superelevation can cause the flow to splash up or over the side of the channel. Superelevation may also expose channel linings to higher shear stresses. Designers can estimate superelevation using:

$$\Delta d = \frac{V^2\, T}{g\, R_c} \tag{6.6}$$

where:

Δd	=	Difference in water surface elevation between the inner and outer banks of the channel in the bend, ft (m)
V	=	Average velocity, ft/s (m/s)
T	=	Surface width of the channel, ft (m)
g	=	Gravitational acceleration, 32.2 ft/s^2 (9.81 m/s^2)
R_c	=	Radius to the centerline of the channel, ft (m)

Table 6.1. Typical channel lining Manning's roughness coefficients (FHWA 2005).

Lining Category	Lining Type	Manning's n Minimum	Manning's n Typical	Manning's n Maximum
Rigid	Concrete	0.015	0.013	0.011
	Grouted Riprap	0.040	0.030	0.028
	Stone Masonry	0.042	0.032	0.030
	Soil Element	0.025	0.022	0.020
	Asphalt	0.018	0.016	0.016
Unlined	Bare Soil	0.025	0.020	0.016
	Rock Cut	0.045	0.035	0.025
RECP	Open-weave textile	0.028	0.025	0.022
	Erosion control blanket	0.045	0.035	0.028
	Turf reinforcement mat	0.036	0.030	0.024

Equation 6.6 is valid for subcritical flow conditions. The elevation of the water surface at the outer channel bank will be $\Delta d/2$ higher than the centerline water surface elevation and the elevation of the water surface at the inner channel bank will be $\Delta d/2$ lower than the centerline water surface elevation.

Under supercritical flow conditions, the water surface is not influenced by conditions or geometry downstream, including bends in the channel. Bends intended to change the direction of supercritical flow may result in potentially undesirable hydraulic conditions such as standing waves oblique to the direction of flow, oblique hydraulic jumps, and directional jets. If supercritical flow conditions approaching a bend are unavoidable, the designer can consider introducing a controlled hydraulic jump to induce subcritical conditions prior to changing direction (Chow 1959).

6.2 Channel Design Parameters

For roadside and median channels, the designer uses information including discharge frequency, available space, elevation change, vegetation type, freeboard, and shear stress. This section provides information for selecting or computing these design elements.

6.2.1 Discharge Frequency

State DOTs typically design roadside and median drainage channels to convey the estimated 0.2 to 0.1 AEP design discharges (FHWA 2005). However, designers can consider and mitigate potential consequences of discharges exceeding the design discharge. For temporary channel linings, designers can use a lower design discharge, e.g., the 0.5 AEP discharge.

6.2.2 Channel Geometry

Engineers often design highway drainage channels to be trapezoidal or triangular. Figure 6.3 summarizes these channel geometries, but during construction and through years of maintenance activities, these shapes can vary. Channel geometry (e.g., depth, bottom width, top width, and side slopes) are frequently subject to the influence of the roadway profile grade at the edge of pavement, the available ROW width, and the adjacent land use and profile along the ROW line.

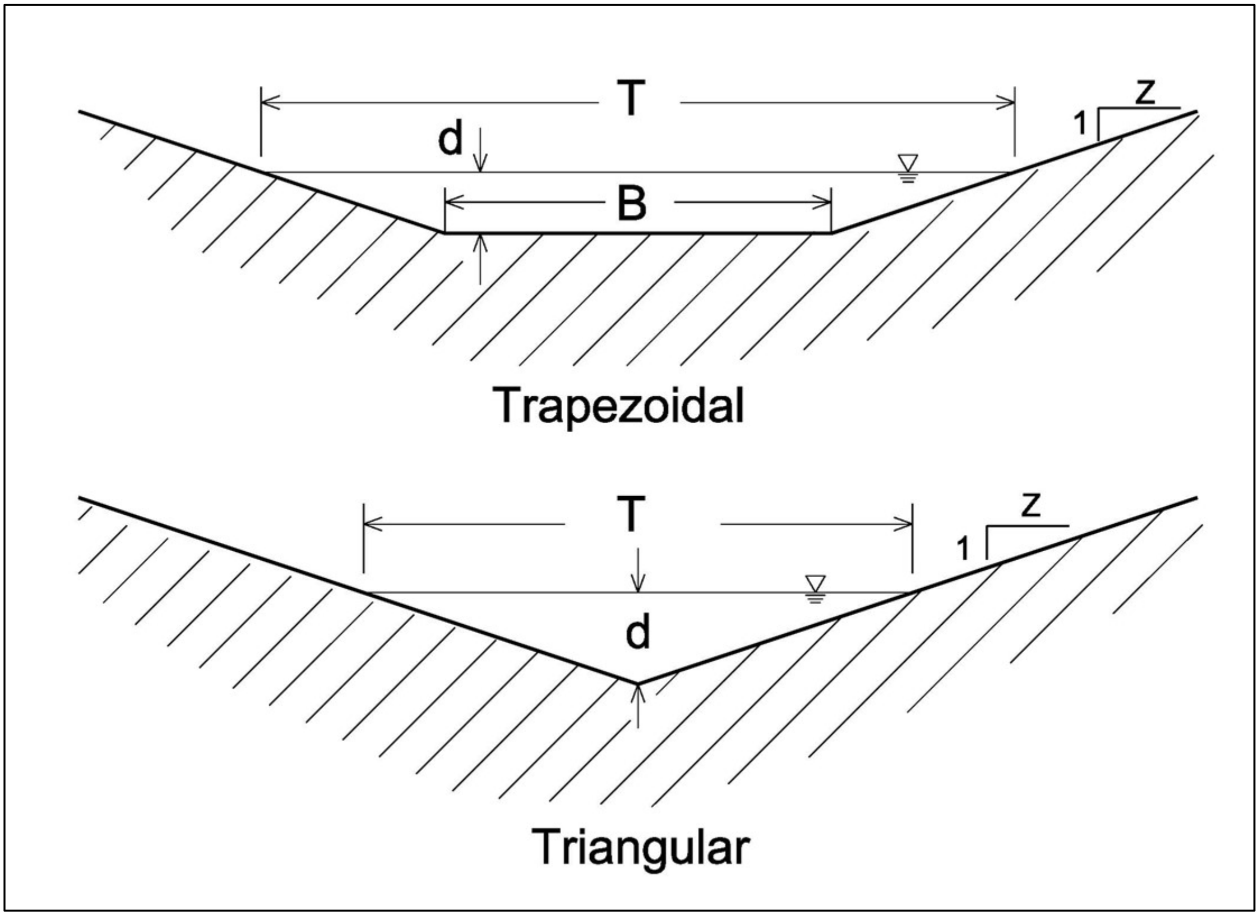

Figure 6.3. Channel geometries.

To avoid unstable side slopes, designers specify channel side slopes for roadside and median channels that do not exceed the angle of repose of either the soil or lining material, or both. Designers compute cross-section area, wetted perimeter, and flow top width for triangular (B = 0) and trapezoidal channels using:

$$A = Bd + zd^2 \quad (6.7)$$

$$P = B + 2d\,(z^2+1)^{0.5} \quad (6.8)$$

$$T = B + 2dz \quad (6.9)$$

where:

A	=	Cross-sectional area of the channel, ft^2 (m^2)
P	=	Wetted perimeter of the channel, ft (m)
T	=	Surface width of the channel, ft (m)

B	=	Bottom width, ft (m)
d	=	Maximum flow depth, ft (m)
z	=	Horizontal side slope dimension 1:z (V:H), dimensionless

Channels immediately adjacent to the roadway may be influenced by roadside safety needs or features such as traffic barriers. For example, geometric design criteria frequently specify channel side slopes that are **traversable** by errant vehicles (1V:3H or flatter with additional considerations) (FHWA 2005). In areas where roadside safety may be of concern, the Roadside Design Guide also allows for flatter channel side slopes, considering the functional classification of the roadway and traffic volume (AASHTO 2011). Design of roadside and median channels, the highway geometric and pavement design, and the design of appurtenances (e.g., signing, signals, illumination, and the accommodation of utilities) work together to ensure proper balancing of function, safety, utility, and drainage needs.

Lessons from Experience: Channel Shape and Construction

Engineers frequently design roadside and median channels in urban areas as triangles or trapezoids. However, at relatively small scale, they are often difficult to construct consistently. After completion of roadway construction, the actual shape of a channel cross-section is likely to be more rounded, possibly approximating a circle or parabola. This may be largely a factor of the equipment and methods used for construction.

If construction does not significantly alter the width and depth dimensions of the section, a consequential difference in performance among those shapes is unlikely.

Example 6.1:	Application of Manning's equation
Objective:	Estimate channel capacity and velocity for a channel lined with a turf reinforcement mat with an n value of 0.03.

Given: A trapezoidal channel (as shown in Figure 6.3) with the following characteristics:

S_o	=	0.01 ft/ft (m/m)
B	=	2.6 ft (0.8 m)
z	=	3
d	=	1.6 ft (0.5 m)

Step 1. Estimate the channel parameters.

Using equations 6.7, 6.8, and 6.9:

$$A = Bd + zd^2 = (2.6)(1.6) + (3)(1.6)^2 = 11.8 \text{ ft}^2$$

$$P = B + 2d(z^2+1)^{0.5} = (2.6) + (2)(1.6)(3^2+1)^{0.5} = 12.7 \text{ ft}$$

$$R = A/P = 11.8/12.7 = 0.93 \text{ ft}$$

Step 2. Compute the flow capacity using equation 6.5.

$$Q = (K_u/n)\, A\, R^{(2/3)}\, S_o^{(1/2)} = (1.486/0.030)(11.8)(0.93)^{(2/3)}(0.01)^{(1/2)} = 55.7 \text{ ft}^3/\text{s}$$

Step 3. Compute the flow velocity.

$$V = Q/A = 55.7/11.8 = 4.7 \text{ ft/s}$$

Solution:	The maximum flow for the channel is 55.7 ft^3/s (1.58 m^3/s) with an average velocity of 4.7 ft/s (1.4 m/s).

6.2.3 Channel Slope

The road profile and adjacent land use constraints often heavily influence channel slopes. However, if channel stability conditions warrant and geometry is feasible, the designer may choose to adjust the channel gradient slightly to achieve a more stable condition.

For steeper channel gradients, designers can use flexible or rigid linings to maintain stability. Knowledge of the material likely to constitute the channel bottom (usually the soil) informs the application of flexible linings. Soil erodibility is an important consideration. Linings, such as stone riprap, wire-enclosed riprap, and gabion mattress can be suitable for protecting very steep channels. See HEC-15 (FHWA 2005) for more information on slope limitations for different lining types. Section 6.3.2 discusses channel lining materials.

6.2.4 Freeboard

Freeboard is the vertical distance from the water surface at the design discharge to a pre-determined component of the roadway or channel. In a permanent roadside or median channel, a designer may use the bottom of the pavement structure base course as the relevant roadway component for defining freeboard. The need for freeboard depends on the consequences of overflows escaping the channel. At a minimum, appropriate freeboard prevents debris, waves, superelevation changes, or fluctuations in water surface from overflowing the sides. However, to accommodate the large variations in flow caused by shocks, standing waves, splashing, and surging in a steep channel, the designer can consider a freeboard height equal to the total energy depth. For temporary channels, freeboard is optional.

6.3 Stable Channel Design

Designers can use stable channel design concepts to specify channel geometry and lining types that result in long-term stability and low maintenance. A channel is stable when the material or the channel lining forming the channel boundary effectively resists the erosive forces of the flow. HEC-15 describes the principles of rigid boundary hydraulics and provides a detailed presentation of stable channel design concepts related to the design of roadside and median channels (FHWA 2005). This section provides a summary of significant concepts.

6.3.1 Shear Stress

The force of friction and the turbulence generated by flowing water (the same forces that cause head loss) result in **shear stress** or **tractive force** on the channel boundaries. The bed material resists this shear stress either by cohesion of the material itself, or by inertia and interlocking of cohesionless particles. To maintain stability, tractive force theory says that the flow-induced shear stress should not produce a force greater than the resisting force of the bed material. The force resisting the movement of the bed material is the **permissible** or **critical shear stress** of the bed material. In a uniform flow, the applied shear stress is equal to the effective component of the gravitational force acting on the body of water parallel to the channel bottom. The estimated average shear stress is:

$$\tau = \gamma \, R \, S \tag{6.10}$$

where:

τ	=	Average shear stress, lb/ft^2 (N/m^2)
γ	=	Unit weight of water, 62.4 lb/ft^3 at 60° F (9.81 kN/m^3 at 15° C)

R = Hydraulic radius, ft (m)
S = Average bed slope or energy slope, ft/ft (m/m)

The maximum shear stress for a straight channel occurs where flow is deepest (on the channel bed) (Chow 1959). It is computed using maximum depth instead of hydraulic radius:

$$\tau_d = \gamma \, d \, S \tag{6.11}$$

where:
τ_d = Maximum shear stress, lb/ft^2 (N/m^2)
d = Maximum depth of flow, ft (m)

Because shear stress is related to depth of flow and flow is shallower at the channel edges than in the middle of the channel, shear stress is not uniformly distributed along the wetted perimeter of a channel. The maximum shear on the side of a channel is estimated by the following (FHWA 2005):

$$\tau_s = K_1 \tau_d \tag{6.12}$$

where:
τ_s = Side shear stress on the channel, lb/ft^2 (N/m^2)
K_1 = Ratio of channel side to bottom shear stress
τ_d = Shear stress in the channel at maximum depth, lb/ft^2 (N/m^2)

The value K_1 depends on the size and shape of the channel. For triangular channels with rounded bottoms, there is no sharp discontinuity along the wetted perimeter. Therefore, computation of shear stress at any point on the side slope is related to the depth at that point using equation 6.11.

The work of Anderson et al. (1970) led to the development of estimates for K_1 in trapezoidal and triangular channels (FHWA 2005):

$$\begin{array}{ll} K_1 = 0.77 & z \leq 1.5 \\ K_1 = 0.066\,z + 0.67 & 1.5 < z < 5 \\ K_1 = 1.0 & 5 \leq z \end{array} \tag{6.13}$$

The z value is the horizontal dimension 1:z (V:H) of side slope. Side slopes steeper than 1:3 (V:H) are at greater risk for failure because of the potential for erosion of the side slopes.

For noncohesive linings such as gravel or riprap the resisting ability of the lining is reduced because the material has the potential to roll or slide out of place. While the reduced shear stress on the channel sides might suggest increased stability in that region of the channel, this may be diminished by the steepness of side slope. For example, when designing a trapezoidal channel lined with gravel or riprap having side slopes steeper than 1:3 the appropriate rock size for the side slopes is estimated as:

$$D_{50,\ sides} = \left(\frac{K_1}{K_2}\right) D_{50,\ bottom} \tag{6.14}$$

where:

D_{50} = Riprap or bed material median size, ft (m)
K_1 = Ratio of shear stresses on the sides and bottom of a trapezoidal channel
K_2 = Ratio of tractive force on the sides and bottom of a trapezoidal channel

K_2 is a function of the side slope angle and the stone angle of repose and is determined from equation 6.15. HEC-15 (FHWA 2005) provides the angle of repose for gravels and riprap of different types.

$$K_2 = \sqrt{1 - \left(\sin^2\Theta\right) / \left(\sin^2\Phi\right)} \tag{6.15}$$

where:

Θ = Angle of side slope
Φ = Angle of repose for the channel lining material

Flow around bends also creates secondary currents which impose higher shear stresses on the channel sides and bottom compared to straight reaches. Areas of high shear stress in bends are illustrated in Figure 6.4.

The maximum shear stress in a bend is a function of the ratio of channel curvature to the top (water surface) width. This ratio increases as the bend becomes sharper and the maximum shear stress in the bend increases. The bend shear stress can be computed using the following relationship:

$$\tau_b = K_b \, \tau_d \tag{6.16}$$

where:

τ_b = Bend shear stress, lb/ft^2 (N/m^2)
K_b = Ratio of channel bend to bottom shear stress
τ_d = Maximum channel shear stress, lb/ft^2 (N/m^2)

K_b can be determined from the following equation from Young et al. (1996) adapted from Lane (1955):

$$\begin{aligned} K_b &= 2.00 && R_c/T \leq 2 \\ K_b &= 2.38 - 0.206\left(R_c / T\right) + 0.0073\left(R_c / T\right)^2 && 2 < R_c/T < 10 \\ K_b &= 1.05 && 10 \leq R_c/T \end{aligned} \tag{6.17}$$

where:

K_b = Ratio of channel bend to bottom shear stress
R_c = Radius to the centerline of the channel, ft (m)
T = Top (water surface) width of channel, ft (m)

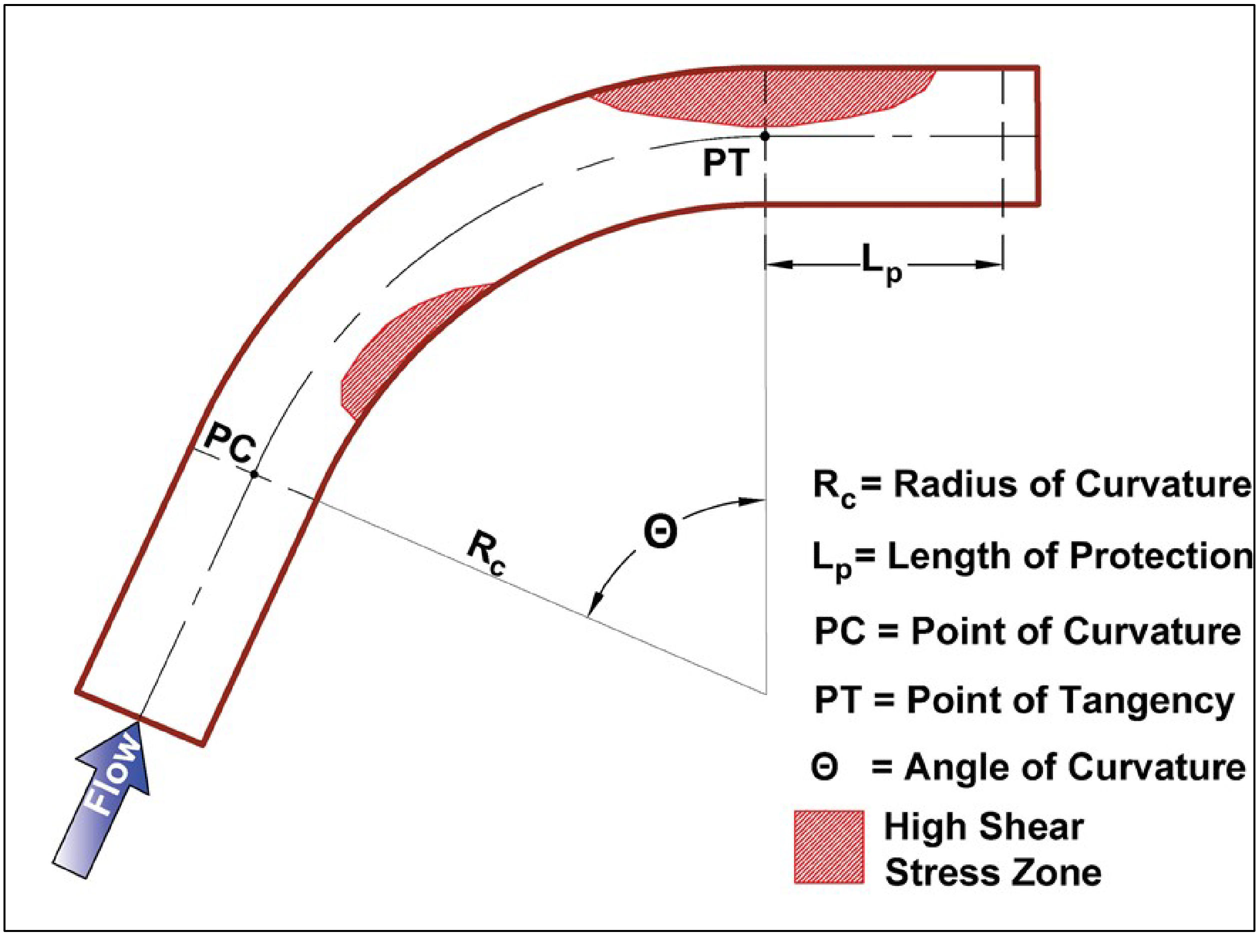

Figure 6.4. Shear stress distribution in channel bends. Source: HEC-15.

The increased shear stress produced by the bend persists downstream of the bend a distance L_p, as shown in Figure 6.4. This distance can be computed using the following relationship:

$$L_p = (K_u \, R^{7/6}) / n_b \tag{6.18}$$

where:

L_p	=	Length of protection (length of increased shear stress due to the bend) downstream of the curve point of tangency, ft (m)
n_b	=	Manning's n in the channel bend
R	=	Hydraulic radius, ft (m)
K_u	=	Unit conversion constant, 0.604 in CU (0.736 in SI)

6.3.2 Lining Materials

Lining materials may be classified as flexible or rigid. Flexible linings can conform to and sustain changes in channel shape while maintaining the overall integrity of the channel. Common flexible lining materials include vegetation and riprap. In contrast, rigid linings cannot change shape and tend to fail when a portion of the channel lining is damaged. Channel shape may change due to frost-heave, slumping, piping, and other causes. Concrete is a common rigid lining material. Flexible linings are generally less expensive, may have a more natural appearance, and are typically more environmentally acceptable. However, flexible linings are limited in the erosive forces they can sustain without damage to the channel and lining. A rigid lining can typically provide higher capacity and greater erosion resistance. In some cases, rigid linings may be the only feasible alternative.

Flexible linings can be either long-term, transitional, or temporary. Designers use long-term flexible linings where the channel needs protection against erosion for the life of the channel. Long-term lining materials include cobbles, rock riprap, wire-enclosed riprap, gabion mattresses, vegetation, and turf reinforcement. State DOTs often choose established vegetation as the primary long-term channel management strategy; vegetation may be planned or incidental but will frequently occur eventually.

Designers use transitional flexible linings to provide erosion protection until long-term protection, usually vegetation, can be established. They use temporary channel linings without vegetation to line channels that might be part of a construction site erosion and sediment management strategy, or some other short-term channel situation. State DOT staff can select turf reinforcement either as a transitional approach or as part of a long-term strategy of providing additional structure to the soil/vegetation matrix.

Vegetation and Channel Linings

Vegetation, such as native or locally popular grasses, will, by nature, establish themselves in drainage channels; seeds from ground cover are ever-present and naturally distributed by flowing water. Unlined channels or those with flexible liners are often ideal growing environments for grasses, weeds, woody shrubs, and even trees. While vegetative cover almost always enhances the stability of channels against erosive forces and will help lock flexible liner materials in place, they may also reduce channel capacity by increasing flow resistance.

Even rigid channel linings such as concrete slope pavement will invariably accumulate vegetative growth in cracks and construction joints. In this case, vegetation can be destructive. Growing vegetation serves to open cracks in concrete. In cases of woody brush or trees, root heave can destroy the lining.

Designers can reduce future maintenance costs by considering intended effects of vegetation on all types of lining materials.

Typical turf reinforcement materials include gravel/soil mixes and turf reinforcement mats (TRMs). A TRM is usually a non-degradable rolled erosion control product (RECP) processed into a three-dimensional matrix. A TRM is stiffer, thicker, and denser than an erosion control blanket, which is typically a degradable product composed of an engineered distribution of natural or polymer fibers bound together to form a continuous mat. Open-weave textiles (OWT) are a degradable RECP composed of natural or polymer yarns more loosely woven into a matrix. RECPs are laid in the channel and secured with staples or stakes.

Construction of rigid concrete linings involves considerable effort, costly materials, and specialized construction equipment. As a result, the cost of rigid linings is typically higher than flexible linings. Rigid lining such as concrete paving or grouted riprap is susceptible to failure from undermining, particularly when placed on constructed or disturbed material such as embankments. It can also be subject to structural instability from overtopping, freeze-thaw cycles, swelling, and excessive soil pore water pressure. Thermal stress causes ubiquitous cracking of concrete. Over time, water invasion and erosion of the supporting soil through cracks often results in concealed void spaces under the concrete. These concealed void spaces present the danger of sudden and unexpected collapse during runoff events or under the load of errant vehicles.

Prefabricated modular linings, such as interlocking concrete paving blocks, can be an alternative if shipping distances are not excessive, however these often involve labor-intensive placement. Modular linings are classified as flexible as they can withstand some movement and erosion underneath the lining before failing.

In general, when selecting a lining, the designer considers the cost of the lining that affords satisfactory protection as the baseline for comparison, but will also evaluate constructability, aesthetics, and long-term service. In some regions, State DOTs often use vegetation alone or in combination with other types of linings. Thus, a channel might be lined with vegetation on flatter slopes and with more erosion resistant material on steeper slopes. In cross-section, the channel might be lined with a resistant material within the depth necessary to carry frequent flows and lined with vegetation above that depth for protection from less frequent flows.

6.3.3 Stable Channel Design Procedure

The FHWA presented the permissible tractive force (shear stress) approach as the recommended design procedure for channels with flexible linings in HEC-15 (FHWA 2005). The tractive force approach necessitates that the shear stresses on the channel bed and banks do not exceed the allowable amounts for the given channel boundary. Tractive force procedures based on shear stress concepts originated largely through research by the Bureau of Reclamation in the 1950s. Based on the actual physical processes involved in maintaining a stable channel, specifically the stresses developed at the interface between flowing water and materials forming the channel boundary, the tractive force procedure is a realistic model of the processes that affect channel linings.

Designers also employ a permissible velocity approach where they assume the channel is stable if the mean velocity in the channel is lower than the maximum permissible velocity for the given channel boundary condition. This approach approximates the physical processes affecting channel linings. Researchers first introduced permissible velocity procedures around the 1920s and the Soil Conservation Service (now the Natural Resource Conservation Service) further developed and widely uses the approach.

For stable channel design, this manual uses the permissible tractive force approach building on the shear stress descriptions in Section 6.3.1. When the permissible shear stress is greater than or equal to the computed shear stress, the lining is considered acceptable. The safety factor in the following equation provides for a measure of uncertainty and failure tolerance, and typically ranges from 1.0 to 1.5.

$$\tau_p \geq SF\ \tau_d \tag{6.19}$$

where:

τ_p = Permissible shear stress for the channel lining, lb/ft^2 (N/m^2)
SF = Safety factor

Flexible linings reduce the shear stress acting directly on the underlying soil surface. Therefore, the erodibility of the underlying soil is a key factor in the performance of flexible linings. Erodibility of noncohesive (granular) soils (plasticity index less than 10) primarily relates to particle size and specific gravity, while in cohesive (clay or clay-bound) soils it largely corresponds with the cohesion and density of the soil. Vegetative and RECP lining performance relates to how well they protect the underlying soil from shear stress, therefore, the protection offered by these lining types depends on soil type. Figure 6.5 summarizes the basic procedure for designing a flexible lining.

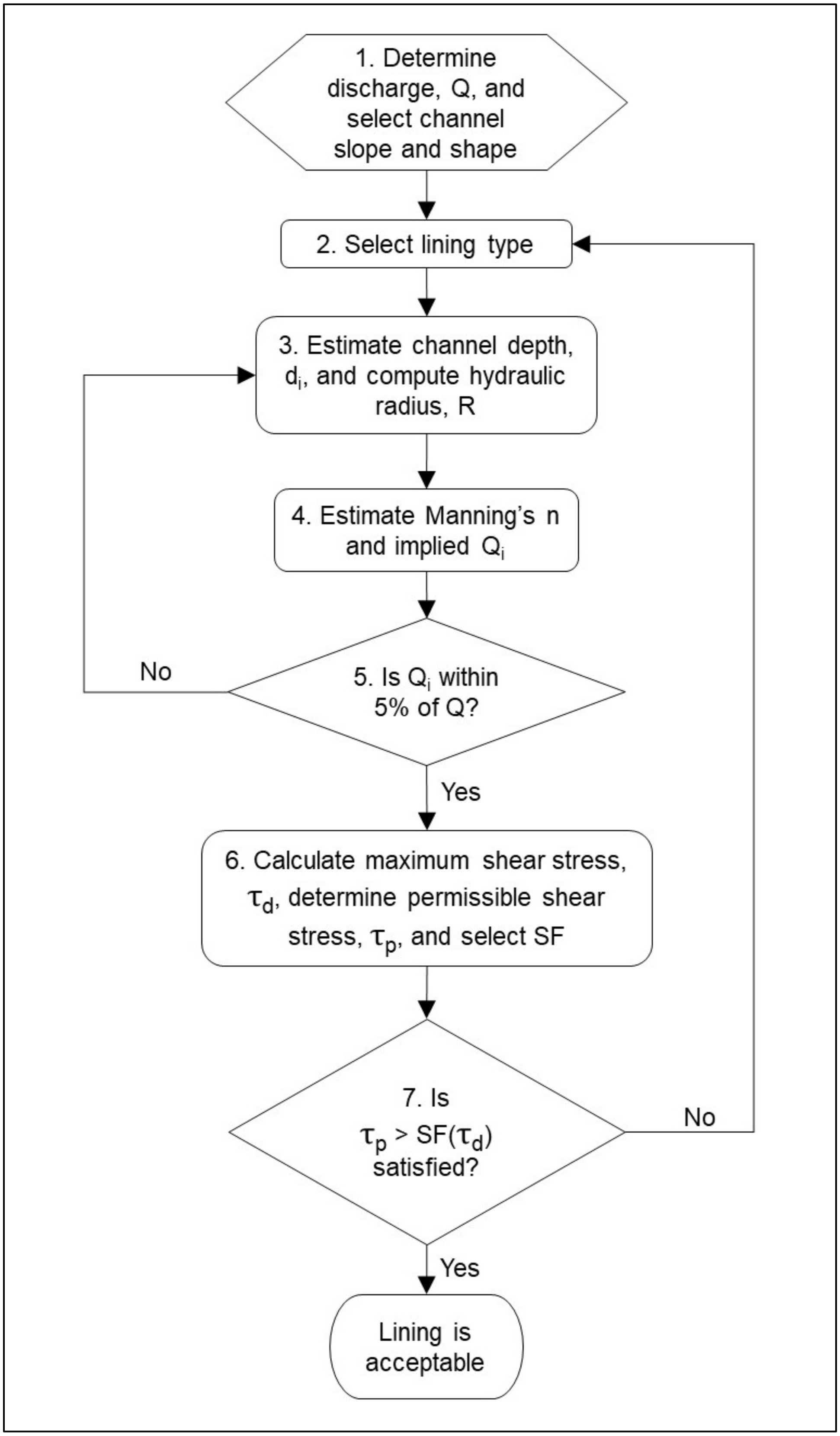

Figure 6.5. Flexible channel lining design process. Source: HEC-15.

Step 1. Select design hydrology and channel geometry.

Calculate a design discharge for the analysis. Select an initial channel cross-section shape and channel slope.

Step 2. Select a trial lining type.

Decide if a long-term lining is appropriate or whether a temporary or transitional lining is adequate. If the long-term lining is a constructed lining that provides full protection immediately, a transitional lining is not indicated. However, if the long-term lining is vegetation that will take time to provide full protection, a transitional lining is also indicated. For example, the designer could initially consider an established vegetated channel for the long-term and evaluate whether a bare soil (unlined) is adequate until vegetation is established. The designer evaluates both the long-term and temporary or transitional linings in separate analyses to determine their suitability for meeting design objectives.

Vegetated Channel Stability

Designers can improve the long-term performance of drainage features by planning for the establishment of temporary and permanent vegetation coverage. The first year or more following construction of a project, depending on the environment, presents the greatest challenge because the vegetation is not well established. Channels exhibiting erosion or sedimentation during that initial period may never stabilize and may present a recurring maintenance problem. In addition to maintenance issues, an eroding channel may present a safety hazard to vehicles that leave the roadway.

Step 3. Estimate the depth of flow.

The estimated depth may be based on physical limits of the channel and an initial estimate based on an assumed Manning's n value for the lining type and the design discharge. Depending on how close the initial estimate is to the final estimate, iterations of steps 3 through 5 may be necessary.

Step 4. Estimate implied discharge.

Estimate the implied discharge, Q_i, using the assumed Manning's n and estimated flow depth value from step 3.

Step 5. Compare implied and design discharges.

If Q_i is within 5 percent of the design discharge, Q, then proceed to step 6. The initial estimate of depth was appropriate. If not, return to step 3 and select a new estimated flow depth, d_{i+1}. This can be estimated from the following equation or any other appropriate method.

$$d_{i+1}=d_i\left(\frac{Q}{Q_i}\right)^{0.4} \tag{6.20}$$

where:

d_{i+1}	=	Next estimate of depth for computing the implied discharge, ft (m)
d_i	=	Previous estimate of depth for computing the implied discharge, ft (m)
Q	=	Design discharge, ft^3/s (m^3/s)
Q_i	=	Implied discharge based on the previous estimate of depth, d_i, ft^3/s (m^3/s)

Step 6. Calculate shear stresses and select safety factor.

Estimate the shear stress at maximum depth, τ_d, using equation 6.11. Determine the permissible shear stress, τ_p, according to the methods described in HEC-15 (FHWA 2005). Select an appropriate safety factor.

Step 7. Compare the permissible shear stress to the calculated shear stress.

Using equation 6.19, compare the permissible and calculated shear stresses from step 6. If the permissible shear stress is adequate, then the lining is acceptable. If the permissible shear is inadequate, then return to step 2 and select an alternative lining type with greater permissible shear stress. As an alternative, a different channel shape may be selected that results in a lower depth of flow.

When the selected lining is stable the design process is complete. If desired, other linings may be tested before specifying the preferred lining.

HEC-15 details the tractive force stable channel design procedure for vegetative linings, RECPs, riprap/cobble, and gabion linings. HEC-15 also includes information on special considerations for steep-slope riprap design and design of composite linings.

Example 6.2:	Channel shear stress and lining stability
Objective:	Estimate the maximum shear stress in a channel with straight and bend sections and determine if the channel lining is stable.

Given: A trapezoidal channel with the following characteristics:

S_o	=	0.01 ft/ft (m/m)
B	=	3.0 ft (0.90 m)
z	=	3

The channel reach consists of a straight section and a 90-degree bend with a centerline radius of 20.0 ft (6.1 m). The design discharge is 28 ft^3/s (0.79 m^3/s). Assume a vegetated lining with a Manning's n value of 0.030. Maximum depth in the channel is 1.3 ft based on the desired freeboard and channel dimensions.

Step 1. Select design hydrology and channel geometry.

The design hydrology (28 ft^3/s) and trapezoidal channel geometry were given above.

Step 2. Select trial lining type.

Assume a vegetative lining with a Manning's n value of 0.030 as given.

Step 3. Estimate the depth of flow.

Channel geometry and freeboard limit the maximum depth of flow to 1.3 ft. Assume an initial depth of 1 ft to estimate the implied discharge.

Step 4. Estimate implied discharge.

$A = Bd + zd^2 = (3.0)\ (1.0) + (3)\ (1.0)^2 = 6.0\ ft^2$

$P = B + 2d(z^2+1)^{0.5} = (3.0) + (2)\ (1.0)\ (3^2+1)^{0.5} = 9.3\ ft$

$R = A/P = 6.0/9.3 = 0.64\ ft$

$Q = (K_u/n)\ A\ R^{(2/3)}\ S_o^{(1/2)} = (1.486/0.030)\ (6.0)\ (0.64)^{(2/3)}\ (0.01)^{(1/2)} = 22.1\ ft^3/s$

Step 5. Compare implied and design discharges.

Implied discharge (22 ft^3/s) is less than the design discharge (28 ft^3/s) by more than 5 percent. Therefore, recompute with a higher estimate of design discharge and repeat step 4.

When using a 1.1 ft depth, the resulting implied discharge is 27 ft^3/s which is within the 5 percent tolerance of 28 ft^3/s. Continue with step 6 using 1.1 ft for the depth.

Step 6. Calculate shear stresses and select safety factor.

Permissible shear stress for vegetation depends on the type of vegetation and soils. Using the procedure in HEC-15 permissible shear stress is estimated for this channel as 2.7 lb/ft^2.

Safety factor selected for this channel is 1.2.

Maximum shear stress in the straight channel is computed as:

$\tau_d = \gamma dS = (62.4)\ (1.1)\ (0.01) = 0.69\ lb/ft^2$

Maximum shear stress in the bend is computed starting with computing the flow top width. Next, compute the ratio of bend to bottom shear stress and finally the bend shear stress:

$T = B + 2dz = 3.0 + 2(1.1)(3) = 9.6\ ft$

$K_b = 2.38 - 0.206(R_c/T) + 0.0073(R_c/T)^2 = 2.38 - 0.206\ (20/9.6) + 0.0073(20/9.6)^2 = 2.0\ lb/ft^2$

$\tau_b = K_b\ \tau_d = 2.0\ (0.69) = 1.4\ lb/ft^2$

Step 7. Compare the permissible shear stress to the calculated shear stress.

Use equation 6.19 to compare permissible to maximum shear stress in the bend of the channel:

$\tau_p \geq SF\ \tau_d = (1.2)\ (1.4) = 1.7\ lb/ft^2$

Since the maximum shear stress multiplied by the safety factor is less than the permissible shear stress, the channel is stable in the straight and bend portions of the channel.

Solution:	The maximum shear stress in the straight and bend sections are 0.69 lb/ft^2 (33.0 Pa) and 1.4 lb/ft^2 (67.0 Pa), respectively. Both are less than the permissible shear stress. Therefore, the vegetated channel lining is stable for the design flow.

6.4 General Design Procedure

This section presents a general procedure for designing roadside and median channels. Although each project is unique, the design steps outlined below will typically be applicable. State and local procedures may also be available and inform the design process.

Step 1. Establish a preliminary project drainage plan.

Chapter 3 discussed the development of a preliminary drainage concept plan. For proposed median or roadside channels, designers may take the following preliminary actions:

- Review municipal master drainage plan(s) and available outfall locations.
- Review available ROW, roadway schematic, and roadway profile; locate public utilities and traffic control/signage.
- Identify the locations of natural drainage divides and channel outlet points.

- Prepare existing and proposed plan and profile of the proposed channels. Include any constraints on design such as highway and road locations, culverts, and utilities.
- Collect any available site data such as soil types and topographic information.

Step 2. Obtain typical cross-section information.

Establish preliminary cross-section geometric parameters and controlling physical features considering the following:

- Roadway width, auxiliary lanes, shoulders, pedestrian facilities (e.g., sidewalks), and other roadway features when present.
- Adequate channel depth to drain the subbase and minimize freeze-thaw.
- Channel side slopes based on geometric design criteria including safety, economics, soil, aesthetics, and access.

Step 3. Select initial channel slope.

Plot initial slopes on the plan and profile. Note that highway grades often control slopes on roadside channels. Use the following guides when establishing initial channel slopes:

- Provide a channel slope with sufficient elevation drop to minimize ponding and sediment accumulation.
- Where possible, avoid features which may influence or restrict slope, such as utility (e.g., electricity and gas) structures.

Step 4. Check flow capacities and adjust sections.

Evaluate the hydraulic capacity of the channel and confirm that it meets the hydraulic design criteria using the techniques in Section 6.2. The following activities may be appropriate:

- Compute the design discharge at the downstream end of each channel segment (see Chapter 4).
- Set preliminary values for channel size, roughness, and slope as discussed in Section 6.2 based on long-term conditions and maintenance considerations.
- Determine the maximum allowable depth of channel including freeboard.
- Estimate the flow depth using the design discharge and channel characteristics.
- If the capacity is not adequate, consider possibilities for increasing capacity including:
    - Increasing bottom width.
    - Flattening channel side slopes.
    - Steepening channel slope.
    - Providing smoother channel lining.
    - Intercepting some flow before it reaches the channel.
    - Installing drop inlets and a parallel storm drainpipe beneath the channel to supplement channel capacity.

Step 5. Select channel protection.

Follow the procedure outlined in Section 6.3 to complete final design of channels that will involve a lining for stability.

Step 6. Check channel transitions and end of channel conditions.

At channel transitions, the designer may need to employ more detailed hydraulic evaluations because the assumption of uniform or gradually varied flow is not valid.

- Identify transition locations, e.g., significant changes in channel geometry (slope, roughness, or cross-section), channel bends, and channel inlets/outlets.
- Review hydraulic conditions upstream and downstream of the transition (flow area, depth, and velocity). If significant changes are observed, perform additional hydraulic evaluations to estimate flow conditions in the vicinity of the transition. Use the energy equation presented in equation 6.2 or other information in Chow (1959), FHWA (2005), FHWA (2006a), or other hydraulic references to evaluate transition flow conditions.
- Provide for gradual channel transitions to minimize the potential for sudden changes in hydraulic conditions at channel transitions.

Step 7. Analyze outlet points and downstream effects.

In this final step, the designer identifies possible adverse consequences for discharge of water downstream and considers appropriate mitigation. Table 6.2 summarizes possible adverse impacts to downstream and adjacent properties and potential mitigation approaches for each. To achieve a roadside channel system design that meets drainage requirements, protects roadside safety, and avoids adverse downstream consequences, the designer may make several trials of this design procedure before selecting a final design.

Table 6.2. Possible adverse channel outlet impacts and potential mitigation.

Adverse Impact	Potential Mitigation
Increase in discharge.	Enlarge outlet channel and/or install control structures to provide detention (see FHWA 2002).
Increase in flow velocity.	Install velocity control or energy dissipation structure (see FHWA 2006a).
Capture of sheet flow previously draining to a different outlet.	Increase channel capacity and/or improve lining of downstream channel.
Capture of concentrated or channel flow previously draining to a different outlet.	Avoid diversions of existing drainage patterns where possible. If not possible, see mitigations associated with increase in discharge and increase in velocity.
Decrease in outlet water quality.	Select lining types that may provide water quality improvements, e.g., vegetation, or provide other water quality mitigation approaches (see Chapter 11).

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