7

OPEN CHANNEL HYDRAULICS

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An open channel is a conveyance in which water flows with a free surface. This type of conveyance may be either natural or man-made. Natural channels usually consist of a main stream, or low flow, channel and the associated floodplains. For the purposes of this discussion, the term open channel will include the floodplains and the main stream channel.

The hydraulic design process for open channels consists of establishing criteria, developing and evaluating alternatives and selecting the alternative which best satisfies the established criteria. Elements that should be considered in the design process include capital investment and probable future costs, such as maintenance and flood damages to properties; traffic requirements; and impacts on the stream and floodplain environment.

Open channel hydraulics can be complex, requiring both specific education and extensive experience; however, when provided with specific procedures and criteria many urban applications can be successfully designed by engineers with substantially less experience. This section examines channel design for common urban applications including roadside channels, channels within developments, and existing channels in urban areas or growth areas that can be analyzed as "rigid". To assist the designer, checklists outlining the requirements and resources to be used for more complex channel designs are included in Section 7.1.

7.1 ARTIFICIAL CHANNELS

Artificial open channels are used in drainage of a wide variety of applications. The applications vary in scale from modest roadside ditches and onsite drainage to large conveyance structures that can be several hundred feet wide. This section will explore open channel design applications more commonly encountered by civil engineers.

Applications involving rivers and large washes or channels considered to be "non-rigid" require special design considerations. The design of these channels should not be attempted with the design techniques developed in this manual.

Rigid grade control is a requirement for using this section.

7.1.1 Route Considerations

Natural channels are in a constant state of change. Small changes resulting from periods of low flow and additional changes related to periods of relatively high flow are considered an equilibrium condition. The ideal artificial channel is one that approximates a natural channel in equilibrium. These channels do not have excessive velocities and are without closely-spaced, sharp and reverse curvatures.

Larger natural channels have low flow channels contained within the bottom width. To provide low cost maintenance, the artificial open channels should be stable for the range of flows expected. Consideration of a full range of flows may require the evaluation of low flow channels to prevent the accumulation of silt and the resultant reduction in channel capacity. The selected route should permit the use of uniform, stable channel side slopes; permit the maintenance of subcritical flow; and maintain constant channel properties such as width, side slopes, and depth.

7.1.2 Channel Selection

The selection of channel properties depends upon sound hydraulic practice, structural considerations, environmental concerns, basic project requirements, recognition of risk and maintenance. However, from a practical standpoint, the basic choice to be made initially is whether or not the channel lining is concrete, rock, grass or earth.

The actual choice must be made upon a variety of multi-disciplinary factors and complex considerations which include:

Hydraulic

- Slope of thalweg
- Right-of-way
- Stream bed controls - bed stability
- Capacity needed
- Basin sediment yield and channel transport capacity
- Ability to drain adjacent lands
- Geotechnical
- Groundwater levels and groundwater recharge

Structural

- Costs
- Availability of material
- Areas for excavation materials (spoil sites)

Environmental

- Neighborhood character
- Neighborhood aesthetic requirements
- Need for open space conservation
- Street and traffic patterns
- Municipal or Flood Control District policies/ordinances

7.1.3 Description of Channel Types

Artificial channel types can vary with the shape of the section and with the lining used for the channel bottom and banks. The type of linings listed above can be used alone or in combination with other linings. Typical linings and sections are shown in Figure 7.1 and are discussed in detail in Section 7.4.

Concrete lined channels: Concrete lined channels are used primarily where right-of-way is limited. The channels may be designed for either subcritical or supercritical flow and generally have steep side slopes because of right-of-way limitations.

Supercritical flows present greater problems during actual channel design and the design of appurtenances such as bridges and channel junctions. Channels with supercritical flow require special attention to channel freeboard, changes in channel alignment, transitions and at the interface with other hydraulic structures.

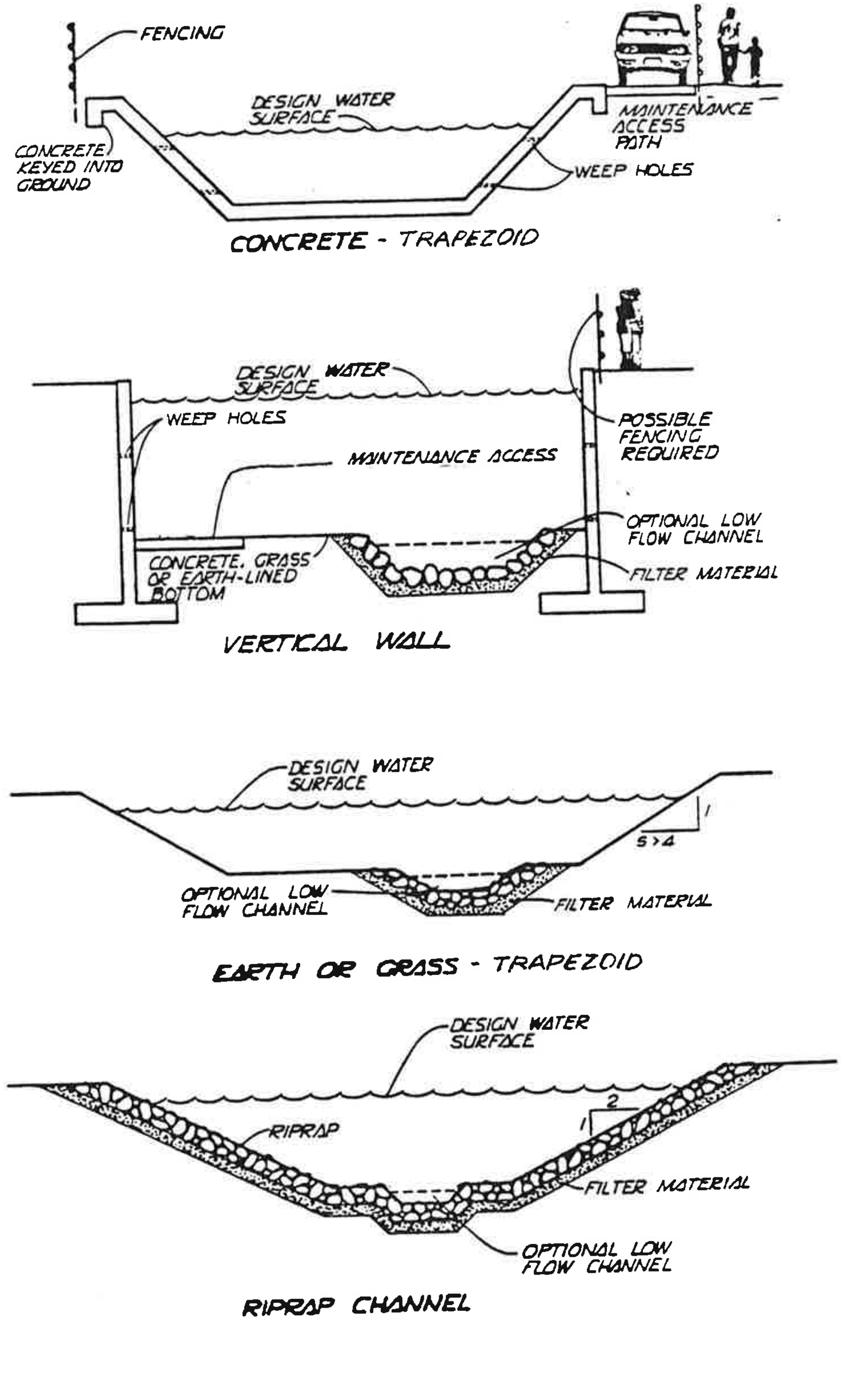
Use of concrete lined channels is discouraged in residential and recreation areas. If, because of right-of-way or other space limitations, concrete lined channels are needed in these areas, fencing will be required to prevent access.

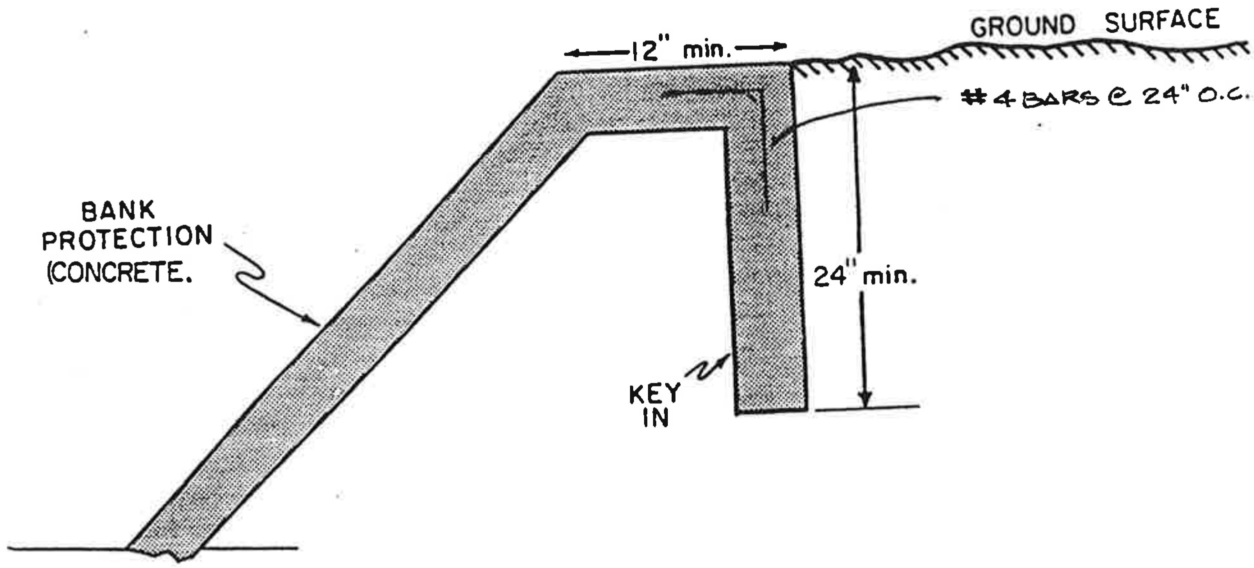
In come cases, concrete lined channels require reinforcing steel and minimum concrete thickness dictated by anticipated structural loads and clearance requirements for reinforcing steel. In addition, concrete lined channels require weep holes and/or subdrains to prevent uplift damages. Figure 7.2 illustrates two options available to "key" concrete lining into adjacent ground. The channel lining must be tied to the adjacent ground to prevent erosion caused by flows entering the channel laterally, eroding the soils behind the concrete causing damage to the channel lining.

Rock Lined Channels: The most common type of lining is this class is common riprap. In general, this type of lining requires placement of a gravel filter layer and/or filter fabric between the rock layer and the ground. Riprap lined channels are generally discouraged and shall be permitted only in areas of existing development where right-of-way is limited and such limitation excludes the use of other channel types.

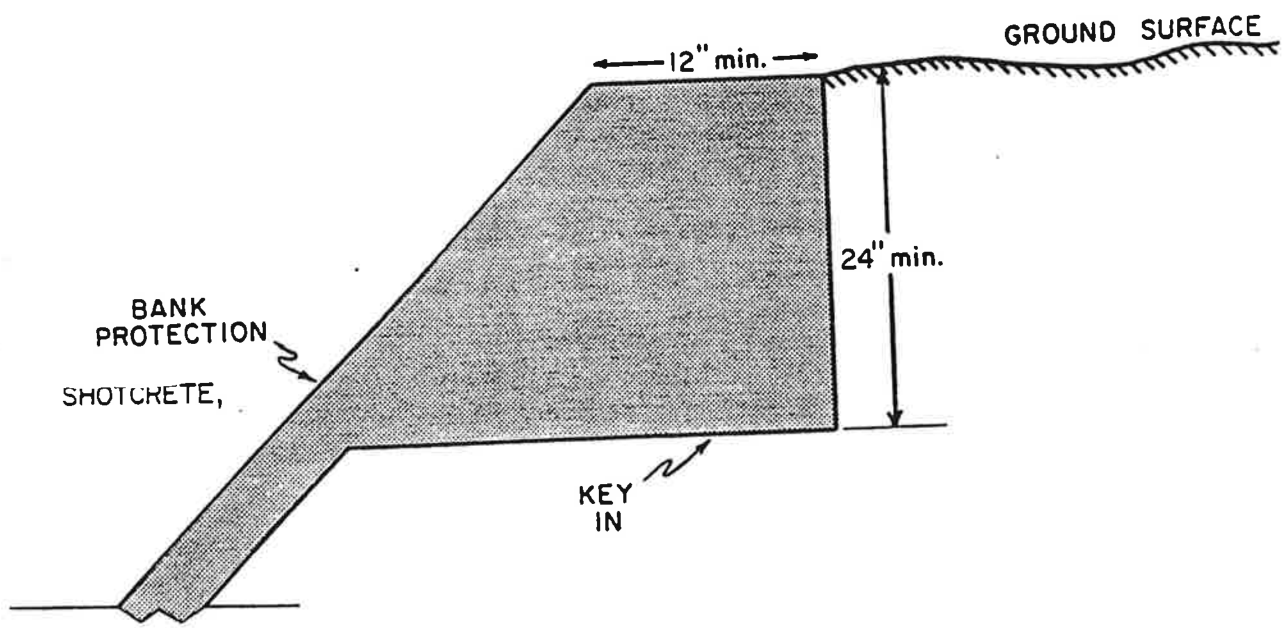
The advantage of rock lining is that a much steeper channel grade can be maintained due to the increase in roughness associated with the rock. In addition, the permissible side slopes (3 horizontal: 1 vertical) are steeper than those allowed for either grass lined or earthen channels. Where riprap is advantageous is in the design and construction of combination channel sections. Rock linings are permitted as a means of controlling erosion in natural channels and for use as slope and toe protection in a soft-bottom channel. The design of this type of channel should incorporate certain non-rigid design techniques. For instance, the riprap toe protection should be designed to protected against anticipated scour.

Grass Lined Channels: Grass lined channels are the most desirable channels when no right-of-way limitation or other restrictions exist in the area under


FENCING
DESIGN WATER SURFACE
CONCRETE KEYED INTO GROUND
MAINTENANCE ACCESS PATH
WEEP HOLES
CONCRETE - TRAPEZOID
DESIGN WATER SURFACE
WEEP HOLES
MAINTENANCE ACCESS
POSSIBLE FENCING REQUIRED
OPTIONAL LOW FLOW CHANNEL
CONCRETE, GRASS OR EARTH-LINED BOTTOM
FILTER MATERIAL
VERTICAL WALL
DESIGN WATER SURFACE
1
5>4
OPTIONAL LOW FLOW CHANNEL
FILTER MATERIAL
EARTH OR GRASS - TRAPEZOID
DESIGN WATER SURFACE
RIPRAP
2
1
FILTER MATERIAL
OPTIONAL LOW FLOW CHANNEL
RIPRAP CHANNEL



12" min.
GROUND SURFACE
#4 BARS @ 24" O.C.
BANK
PROTECTION
(CONCRETE.
24" min.
KEY
IN



12" min.
GROUND SURFACE
24" min.
BANK
PROTECTION
SHOTCRETE,
KEY
IN

consideration. The development of grass lined channels is encouraged where the design can be integrated into landscaped or open space areas or as part of local or regional parks where multi-use activities are included.

These channels have similar properties to earthen channels with permissible side slopes being no greater than 4 horizontal: 1 vertical. In addition, grass in channels creates turbulence which results in the loss of energy and increased flow retardance. Therefore, the designer should consider the potential for sediment deposition as well as the possibility of scour.

Because of the high probability that a non-irrigated, grass lined channel will revert to an earthen channel, all references to grass lined channels will be for irrigated grass. In addition, wherever possible reclaimed water should be used as the source of irrigation water.

Earth lined Channels: The category includes both bare earth channels and naturally vegetated channels. Earth lined channels should be designed for subcritical flow. The width to depth ratios are large, the side slopes are flatter than 4 horizontal:1 vertical, and grade control is a requirement for the design. The smaller size range of these types of channels does not require low flow channels; however, for larger sized channels and channels used for pedestrian corridors, an armored low flow channel may be used to achieve effective, low maintenance channels.

7.1.4 Low Flow Channels

The majority of storm events will be less than the design storm, resulting in frequent low flow conditions. Low flows in earth or grass lined channels will deposit sediment and develop their own pilot channel which will be meandering and could direct low flows into channel banks causing bank erosion. Design of low flow channels will prevent meandering and will direct low flows in a controlled manner.

Rounding the channel bottom to approximate a parabolic shape will cause the centerline of the channel to act as a low flow channel. Alternatively, the channel bottom could be graded into a shallow v-shape to lower the centerline.

7.2 DESIGN OF ARTIFICIAL CHANNELS

This manual provides the *Simplified Design Procedure* for normally encountered design problems in open channels that can be applied to discharges up to 2,500 cubic feet per second. When a condition is encountered that is beyond the scope of this simplified procedure, an increase in the detail of analysis is required. For common, controlled conditions there are simplified approaches to design that can be used; however, when a condition occurs that requires a higher level of technical analysis, the design procedures require engineers qualified in more complex open channel design procedures.

In Section 7.5.1 the designer will find a checklist outlining the simplified procedure for the design of artificial channels. The checklist is intended to identify the probable important factors the designer should address. The information contained in this section should be used as the designer proceeds through the checklist items. As often noted, the intent is to provide design approaches and support for the most commonly encountered conditions.

7.2.1 Open Channel Hydraulics

For relatively long, straight and uniform channels normal depth calculations can be used to determine the discharge capacity at varying depths for a constant cross-sectional area. Table 7.1 contains properties of channel cross sections to be used by designers of open channels using the *Simplified Design Procedure*. These properties should be used as guideline values when designing or analyzing uniform flow in drainage channels.

Table 7.1
Artificial Channel Properties
Simplified Design Procedure

Type of Channel Lin-ing	Maximum AllowableSide Slopes, H:V	Maximum Velocity
Concrete	Vertical	15
Rip-Rap	3:1	9.0
Grass	4:1	2.5 to 8.0 (1)
Earth	4:1	2.5 to 6.0
Grouted-Rock	3:1	9.0

(1) Dependent upon the type of grass proposed.

Uniform flow: 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. This is the condition of uniform flow; however, uniform flow is more often a theoretical abstraction than an actuality.

The depth associated with uniform flow is commonly known as normal depth. Normal depth in channels is computed so frequently that it is convenient to use design aids for various types of cross sections to eliminate the time-consuming process of trial and error solutions to various equations defining open channel flow. Equations 7.1 through 7.11 are presented to aid in the determination of the fundamental properties of open channel flow such as normal and critical depth, specific energy, minimum freeboard and radius of curvature.

Generally, it is necessary to apply Manning's Equation, Equation 7.1, to sections of the channel which have similar properties:

$$V=\left(\frac{1.486}{n}\right)R^{.67}S^{.5} \qquad \textbf{(7.1)}$$

Multiplying velocity by the cross sectional area of flow yields Equations 7.2, the continuity equation:

$$Q=VA \qquad \textbf{(7.2)}$$

Because of variable channel cross sections and channel properties, uniform flow computations are rarely used solely as the basis for open channel design. Normally these values will be used for conceptual level decisions. Decisions relative to preliminary and final design requirements should be made through backwater analyses.

Critical Flow: Critical flow in an open channel or closed conduit with a free water surface is characterized by several conditions, such as:

- The specific energy is a minimum for a given discharge.
- The discharge is a maximum for a given specific energy.
- The Froude number is equal to 1.0.

With the presence of a free surface in an open channel, the force of gravity has an effect on the state of flow. The effect of gravity on open channel flow is represented by the ratio of inertial forces to gravitational forces. This ratio is known as the Froude Number (F) and is computed by Equation 7.3:

$$F=\frac{V}{(gD)^{.5}} \qquad \textbf{(7.3)}$$

For subcritical and supercritical flows F<1 and F>1, respectively.

Due to erosion, scour and concerns with excessively high velocities, the recommended upper limit of F is 2.0

In the subcritical regime, as F increases toward 1.0, velocity of flow increases and the depth of flow decreases. As long as the velocity does not increase past the permissible velocity shown in Table 7.1, short-lived instability of near critical flow is acceptable. However, near critical flows in the supercritical regime may cause hydraulic jumps with minor changes in cross section, flow rate, channel roughness or slope. This type of flow is undesirable for any duration, therefore supercritical flow will be permitted only if the flow is established in the supercritical flow regime.

The limit of the Froude Number for rock, grouted rock, grass and earth lined channels is F<=0.86. For concrete, shotcrete or mortar lined channels, the additional limit 1.13<=F<=2.0 is allowed. The Froude Number should not fall between 0.86 and 1.13.

Since critical flow is to be avoided, it is important to be able to calculate critical depth. The general equation for the determination of critical depth is given as Equation 7.4:

$$\frac{Q^2}{g} = \frac{A^3}{T} \qquad \textbf{(7.4)}$$

Equation 7.4 is solved by successive approximation, and will only be satisfied for critical flow for the given discharge and cross section. When applying Equation 7.4 and solving for F in Equation 7.3, if the depth is found to be at or near critical, the shape of the cross section or the slope of the channel should be changed to achieve greater hydraulic stability.

Roughness Coefficient: Roughness coefficients (n) for use in Manning's equation vary considerably according to type of material, depth of flow and quality of workmanship. Table 7.11 lists various roughness coefficients for pipes, earthen and natural channels and for various artificial channels.

7.2.2 Design of Rigid Channels

The design parameters defined in the following sections should be used in situations where the design discharge is less than 2,500 cubic feet per second. In addition, the channel must be considered "rigid". To be considered rigid, both the banks and the channel bottom must be stable. Stability is generally the result of the channel layout and grade control.

Layout: In general, channel layout should follow existing washes, swales or depressions.

Unless special exception is made, all artificial channels shall begin and end where runoff has occurred historically.

This requirement applies both to the point where water becomes channelized and the point where runoff leaves the channel. Care should be taken not to choose routes which lengthen the channel sufficiently to reduce channel slopes below that which will cause sediment deposition during low flows.

Grade Control: Grade control must be established as a condition of the Simplified Design Procedure. In its basic form, grade control can be any natural or man-made section of channel that does not permit channel degradation or aggradation. Grade control is most often thought of as causing critical depth; however, this condition is not required to establish grade control.

Grade control and channel slope are interrelated. It does little good to establish grade control within a specific reach when the channel downstream is headcutting or undergoing rapid deposition. When designing artificial channels, the designer needs to assess the stability of the section(s) immediately downstream of the reach being considered. If there is evidence of ongoing downstream degradation, a grade control structure should be considered. The structure depth should be sufficient to preclude further headcutting in the channel.

For each alternative investigated, the selected channel slope should result in a stable channel, particularly for earth-lined channels. Within a reach of artificial channel, grade control structures should be used as necessary to meet the requirements listed in Table 7.1.

Controlling Water Surface Elevation: The following are generally considered control points for the calculation of the water surface profile:

- Where the channel slope changes from mild to steep or critical, the depth at the grade break is critical depth.
- Where the channel slope changes from critical to steep, the depth at the grade break is critical depth.
- Where a discharging or outletting channel or conduit is on a mild slope, the water surface is generally controlled by the outlet.

Additional criteria for the determination of the controlling water surface elevation can be found in the Los Angeles County Flood Control District's *Hydraulic Design Manual, Section C-2.2.*

Once the controlling water surface is determined, calculations shall proceed upstream when the depth of flow is greater than critical depth and shall proceed downstream when the depth of flow is less than critical depth.

Channel Curvature:

For channels with Froude Numbers less than 0.86, the ratio of the channel radius (at centerline) to the design width of the water surface shall be greater than 3.0.

Note for Froude Numbers greater than 0.85, the radius of curvature will computed from the equation:

$$r_c \geq \frac{4V^2T}{g}b \qquad \textbf{(7.5)}$$

Curves in a channel cause the maximum flow velocity to shift toward the outside of the bend. To minimize the effect due to channel bends, channel curvature should be used only where topographic or other conditions necessitate their use.

Along the outside of the curve, the depth of flow is at a maximum. *Superelevation* is the maximum rise in water surface at the outer wall above the mean depth of flow in an equivalent straight reach, caused by centrifugal force in a curving alignment.

- Rectangular Channels: For subcritical and supercritical velocity the superelevation (S) can be calculated from Equation 7.6:

$$S_c = \frac{V^2 b}{2gr} \qquad \textbf{(7.6)}$$

- Trapezoidal Channels: For subcritical velocity, the superelevation can be calculated from Equation 7.7, and includes a 15 percent factor of safety.

$$S_c = 1.15\frac{V^2(b+2ZD)}{2gr} \qquad \textbf{(7.7)}$$

  Where z = cotangent of the bank slope.

For supercritical velocity, the disturbance caused by a bend in the channel persists downstream. Therefore, a detailed hydraulic study utilizing special design criteria must be conducted to determine the effects of channel curvature.

Freeboard: Freeboard is the additional wall height applied to a calculated water surface.

The minimum freeboard value for rigid channels shall be 1 foot for subcritical and 2 feet for supercritical flows.

Additional requirements for freeboard may be called for in specific cases of curved alignments, high velocities and supercritical flow.

Rectangular Channels

- For curved alignments, add 2.0 feet or 1 foot above the superelevated water surface, whichever is greater.
- For average flow velocities greater than 35 f.p.s., add 3.0 feet. For curved alignments add 3.0 feet, or 2.0 feet above the superelevated water surface, whichever is greater.
- For supercritical flow where the depth falls between critical depth and 80% of critical depth, the wall height shall be equal to the sequent depth, but not less than the heights required above.

For a discussion of sequent depth, refer to *Handbook of Hydraulics* (King and Brater 1976).

Trapezoidal Channels

- For curved alignments, add 2.5 feet or 1.0 foot above the superelevated water surface, whichever is greater.
- For average flow velocities greater than 35 f.p.s., add 3.5 feet. For curved alignments, add 3.5 feet, or 2.0 feet above the superelevated water surface, whichever is greater.
- For supercritical flow where the specific energy is equal to or less than 105% of the minimum specific energy, the wall height shall be equal to the sequent depth, but not less than the heights required above.

Supercritical Flow: In a supercritical channel, there shall be no change of cross-sectional shape or area at bridges or culverts. Bridges or other structures crossing the channel must be anchored satisfactorily to withstand the full dynamic load which might be imposed upon the structure in the event of major debris plugging. Concrete linings must be protected from hydrostatic uplift forces which are often created by a high water table or momentary inflow behind the lining from localized flooding.

Full development of design procedures for supercritical flow in channels is beyond the scope of this manual; refer to *Handbook of Hydraulics* (King and Brater 1976) and *Open Channel Hydraulics* (Chow 1959).

7.2.3 Preliminary Design

It is important that major design issues be identified and decisions about them made before proceeding into final design. In addition to the master plan consideration of the initial alignment, downstream control and channel type, there are a number of technical items that must be evaluated prior to commencing final design. Some these issues are:

- Measures to control flow at the beginning and end of a channel reach to prevent damage to existing channels.

- Minimize the use of alignment deflection in supercritical channels.

- The degree to which local flows affect channel stability and maintenance should be reflected in the chosen channel cross section.

- Plan for possible secondary uses that can reduce urban costs by providing other benefits.

- Determine the need for freeboard requirements.

7.2.4 Final Design

Water surface profiles must be computed for all channels during final design and clearly shown on the final drawings. Computation of the water surface profile should use standard backwater methods, taking into consideration all losses due to changes in velocity, drops, bridge openings and other obstructions. It is necessary to show the energy gradient on all preliminary drawings to help insure against errors. Whether or not the energy gradient line is shown on the final drawings is optional.

7.3 Natural Channels

Natural channels tend to be in a steady state of change. Mountainous streams can be rigid, yet, in a geologic framework, are in a constant state of headcutting. In the more common alluvial cases, natural channels tend to deposit sediment and meander during low flow periods and to erode and straighten channel alignments during rare events. Generally if alluvial material exists then there is some potential for a stream to reoccupy the alluvial areas resulting from a period of high flows. Therefore, it is necessary to acknowledge the potential for a natural channel to be 'non-rigid'.

7.3.1 Analysis of Natural Channels

The investigations necessary to insure that a natural channel will be adequate are different for every waterway. Supercritical flow cannot always occur in natural channels and frequent checks should be made during the course of the backwater computations to insure that the computations do not reflect supercritical flow.

Where natural channels are used, the usual rules for freeboard depth, curvature and other design parameters applicable to artificial channels do not apply. Using natural channels requires that primary attention be given to erosive tendencies and carrying capacity. The floodplain of the waterway must be defined so that adequate zoning can take place to protect the waterway from encroachment to maintain its capacity and storage potential.

Section 7.5 contains a checklist of technical issues that need to be addressed when analyzing waterways in the vicinity of bridges and culverts. A general approach for analyzing the effectiveness of natural channels includes several tasks:

- Prepare cross-sections of the channel for the major design runoff.
- Investigate the bed and bank material as to the particle size classification.
- Study the stability of the channel under future conditions of flow.
- Examine channel and overbank capacity to determine adequacy for 100-year runoff.
- Define water surface limits so that the floodplain can be appropriately zoned.
- Use roughness factors which are representative of non-maintained channel conditions.
- Divide the channel cross sections into units of similar properties for determination of water surface profiles.
- Specify the use of drops or check dams to control water surface profile slope, particularly for more frequently occurring storm runoff.
- Prepare plans and profiles of the floodplain. Make appropriate allowances for future bridges which will raise the water surface profile and cause the floodplain to be extended.
- Evaluate the freeboard with reference to proposed non-drainage structures.

Filling the flood fringe reduces valuable storage capacity and tends to increase downstream runoff peaks. Filling should not be used in urban areas where hydrographs tend to rise and fall sharply.

7.3.2 Requirements for Natural Channels

Washes which traverse land designated for a proposed development may be left in their natural state provided that doing so would not be in conflict with an approved master drainage plan for the area - if one exists - and provided that the development is adequately protected from flooding and erosion.

During the course of the Master Planning process, the 100-year runoff will be used to delineate a floodplain for major channels with discharges of more than 1,000 cfs.

One method of developing in the vicinity of a natural wash is to keep all structures out of its 100-year floodplain, as well as its attendant erosion hazard areas. Another possible method is to use part of the floodplain for development, while leaving the channel in its natural state. However, this approach would involve demonstrating that: 1) the encroachment would not adversely effect adjacent properties; and 2) the development would be located outside any erosion hazard areas which border the natural wash.

Encroachments into the floodplain of a natural wash are to be analyzed according to the FEMA requirements.

The maximum rise in water surface shall not exceed those listed; generally 1.0 foot. As with all floodplain encroachments, the development must be adequately protected from flooding and erosion, and must not violate restrictions imposed by master drainage plans.

7.3.3 Applicable Methodologies

Normal Depth and Velocity: If the depth and direction of flow in an open channel are nearly constant, the flow regime is said to be "normal", and hydraulic characteristics of the channel can be evaluated by using Mannings Equation (Equation 7.1).

When delineating natural floodplains using Manning's equation, it is important to ensure that the energy grade line (EGL), slopes continuously in the downhill direction, The energy grade line is defined as a line connecting to points of known total head or total specific energy.

In those cases where the slope of the enegry grade line does not nearly equal the channel bed slope, then it is not reasonable to use a uniform flow approach, and backwater calculations must be made.

Backwater Procedure: The previous section contained a brief discussion on computing normal depth, which assumes that changes in discharge, bed slope, and cross-sectional area and form occur relatively gradually, however, sudden changes will produce additional turbulent energy losses which are not accounted for in the Manning's equation. This may be particularly true in cases of sudden contractions and expansions of the channel cross section.

In those instances where an upstream or downstream hydraulic control exists, the Standard Step Method should be used for evaluating water surface profiles. The procedure for making Standard Step calculations is given in several easily obtainable textbooks or references. Computer facilities are available, and the engineer should perform the Standard Step calculations by using the readily available and well-documented computer program HEC-2, written and distributed by the U S. Army Corp's of Engineers.

7.4 Channel Linings

The type of channel lining which may be best suited for a particular purpose will depend on a variety of factors, including hydraulic conditions, economic factors, soil conditions, material availability, aesthetics and compatibility with existing improvements. The following discussion provides information regarding the applicability and design parameters for acceptable lining types.

7.4.1 Concrete Lined Channels

Reinforced concrete and shotcrete are alternative lining materials for channels with limited right-of-way and/or high velocities. The most common problems of concrete lined channels are due to bedding and lining failures. Typical failures are: 1) cracking due to settlement of the subgrade; 2) cracking due to removal of bed and bank material by seepage force; and 3) cracking and floating due to hydrostatic back pressure from high ground water.

Flow Regime Considerations: Concrete lined channels are usually designed for flow conditions where the Froude number exceeds 1.13 and/or when velocities exceed five feet per second for earth lined channels. Froude numbers for supercritical flow shall be greater than 1.13 and less than 2.0.

Lining Criteria: Generally, if slopes steeper than 2:1 are used, then safety and structural requirements become a primary concern. The thickness of the lining should be a minimum 6-inches for concrete and 8-inches for shotcrete. This thickness is dependent on velocity and may increase as velocity increases. Additionally, design of the lining should account for any anticipated vehicular loads from maintenance or other equipment.

Tables 7.2 and 7.3 give required lining thicknesses for both concrete and shotcrete as a function of velocity.

Table 7.2
Required Concrete Lining Thickness

Velocities	Levee Thickness - T		Reinforcing
	Straight Reach	Curved Reach	
0 - 10 f.p.s.	6-inch	8-inch	#4 @ 18" Bothways
10 - 20 f.p.s.	8-inch	10-inch	#4 @ 18" Bothways

Gunite Levees (1-1/2:1 max. side slopes)

Table 7.3
Required Shotcrete Lining Thickness

Velocities	Levee Thickness - T		Reinforcing
	Straight Reach	Curved Reach	
0 - 10 f.p.s.	8-inch	10-inch	#4 @ 18" Bothways

Roughness Coefficient: The roughness coefficient for a concrete lining can vary from 0.013 for a troweled finish to 0.020 for a very rough or unfinished surface. For shotcrete, roughness coefficients can vary from 0.016 to 0.025.

Bedding: Long-term stability of concrete lined channels depends in part on proper bedding. Undisturbed soils often are satisfactory as a foundation for concrete lining without further treatment. Expansive clays are usually an extreme hazard to concrete lining and should be avoided.

Underdrainage: The probability of damaging the concrete lining due to hydrostatic back pressure and subgrade erosion can be greatly reduced by providing underdrains. There are two types of artificial drainage installations. One type consists of 4- or 6-inch diameter perforated pipelines placed in gravel-filled trenches along one or both toes of the inside slopes. These longitudinal drains are either connected to transverse cross drains which discharge the water at outlet boxes or at grade control structures. Where a lesser degree of seepage control is warranted, weep holes or cut-off walls spaced at appropriate intervals may be used.

Shotcrete: As a channel lining, shotcrete is an acceptable method of applying concrete with a general improvement in density, bonding, and decreased permeability. The design considerations discussed above apply in the design of shotcrete channels.

7.4.2 Riprap Lined Channels

Graded riprap can be an effective lining material if properly designed and constructed. Riprap design involves the evaluation of five performance areas. These areas include the evaluation of:

- riprap quality;
- riprap layer characteristics;
- hydraulic requirements;
- site conditions; and
- river conditions.

Specific criteria outlining the performance of these five considerations are provided in Appendix 1.

7.4.3 Grouted Rock

Grouted rock is a structural lining comprised of rock that is interlocked and bound together by means of concrete grout injected into the void spaces. Grouted rock provides a stable lining similar to concrete with the added advantage of a higher roughness factor due to the rock surfaces projecting above the rock layer.

Rock: Rock for grouting should conform to the property requirements described in Section 7.4.2.

Grout: The grout mix should be specified to provide the strength and durability required to meet the specific application. The minimum 28-day compressive strength shall be 2,000 psi, and the slump shall be within the range of 4 to 7 inches. The stone aggregate should conform to the No. 4 Concrete Aggregate Gradation Requirement and ASTM C-33. A maximum of 30 percent of the cementous material may be fly ash (ASTM C-618, Type C or F).

Design Considerations: Since grouted rock is a structural lining similar to reinforced concrete, it is subject to the same design considerations. Rock must be sized for the anticipated hydraulic design conditions. Foundation considerations must be evaluated and provisions made for underdrainage and seepage control.

If only bank protection is to be provided, the grouted rock protection must be extended below the channel invert to a depth below the estimated depth of scour.

7.4.4 Toe Protection

Scour at a poorly designed toe of a channel bank is one of the major causes of failure of riprap bank protection. Proper design of protection against toe scour involves two parameters. First, an estimate must be made of the maximum scour expected to occur over the design life of the structure. Second, a means of protection must be provided for the maximum depth of scour.

Design Guidelines: The two methods of providing toe protection in alluvial channels are:

1. To extend protection below the estimated depth of scour; and

2. To provide protection that adjusts to the scour as it occurs.

The first method is the preferred technique because the protection is initially placed to a known depth, and the designer does not have to depend on the uncertainties associated with the method that adjusts to the scour. Because of the uncertainties associated with self-adjusting toe protection, it is not recommended for use in the City of Hemet.

The First method of toe protection requires the extension of the bank protection into the excavated channel bed, see Figure 7.3. The maximum depth of extension is a function of the velocity of flow in the channel. The depth of extension should be established at the maximum depth of scour, or cut-off depth, associated with the maximum velocity in the channel. Care should be taken when estimating cut-off depths along curved channels reaches because of the velocity distribution caused by the super-elevated water surface.

Table 7.7 provides cut-off depths as a function of maximum channel velocity for both straight and curved channel reaches.

Table 7.7
Toe Protection Cut-Off Depths

Velocities	Straight Reaches	*Curved Reach
0 - 6 f.p.s.	6-foot	9-foot
6 - 10 f.p.s.	8-foot	12-foot
10 - 15 f.p.s.	10-foot	15-foot
18 - 20 f.p.s.	14-foot	21-foot

*Check the cut-off depth for curved reach on Table 7.10 in Section 7.6. Use that depth if greater than given hereon.

7.4.5 Grass lined Channels

Grass lined channels are considered a viable alternative under certain circumstances. Situations under which grass lined channels should be considered include applications where a flat, shallow channel is the best alternative, in large planned residential developments where open space areas will be integrated into the flood control system or when an open drainage structure will front a major thoroughfare in an urban area.

In any case where a grass lined channel is being considered, the alternatives should be thoroughly investigated and these findings presented to staff prior to preparation of the Phase I Drainage Report. Should staff agree that a grass lined channel is the best alternative, the Phase I Drainage Report will be required to be expanded to cover proposed design criteria, methods of irrigation and maintenance methods.

7.5 Design Procedures

This section provides the user of this manual with checklists (procedures) to be followed during design and examples of design computations that can be followed in order to clarify the procedures.

7.5.1 Artificial Channels

Table 7.8 is the checklist to be employed in the design of artificial channels. Most applications in the City of Hemet will be able to follow the Simplified Design Procedure. Should conditions fall outside of the Simplified Design Procedure, the more rigorous procedure, as shown in the remaining steps, must be completed.

Conditions for Using the Simplified Design Procedure: The steps required for the Simplified Design Procedure are marked with an asterisk in Table 7.8 and can be used to design open channels that meet the following conditions:

- Grade control established; and
- Design parameters within those listed in Table 7.1.

Table 7.8
Simplified Design Procedure Design Checklist for Artificial Channels

Item | **Section Reference**

Initial Data

- * ☐ Existing Structures
- * ☐ Existing Channel Characteristics
- * ☐ Existing Grade Control
- * ☐ Existing Flood Performance Characteristics
- * ☐ Scour Observations
- * ☐ Existing Stream Development
- * ☐ Land Use Changes
- ☐ Rainfall/Runoff Relationships

Possible Components and Strategies

- * ☐ Channels
- * ☐ Alignment
- * ☐ Grade Control
- * ☐ Bridge Components

Consideration for Right of Way

- ☐ Migration
- * ☐ Water Level

Economic and Alternative Analysis

- * ☐ Designation of Significantly Different Concepts
  - * ☐ Type of Lining
  - * ☐ Type of Cross Section
  - * ☐ Channel Alignment
  - * ☐ Location of Grade Control(s)
  - * ☐ Hydrologic and Hydraulic Detailing of Alternatives
  - * ☐ Least Total Expected Cost Evaluation
  - ☐ Environmental Considerations
  - * ☐ Safety Requirements

Hydraulic Analysis

- * ☐ Determination of Control
- ☐ Determination of Type of Flow Profile
- * ☐ Channel Lining
- * ☐ Normal Depth Calculations
- * ☐ Water Surface Profile Calculations
- * ☐ Bridge Hydraulics
- ☐ Supercritical Channel Hydraulics
- ☐ Superelevation
- * ☐ Drop Structure Hydraulics
- ☐ Physical Hydraulic Models
- * ☐ Low Flow Channel

Additional Considerations

- ☐ Permanent Record
- ☐ Post Construction Data
- ☐ Normal Inspection (References)

Table 7.9
Design Checklist for Natural Channels

Item	Section Reference
Initial Data	
☐ Existing Structures	
☐ Channel Characteristics	
☐ Existing Flood Performance Characteristics	
☐ Existing Grade Control	
☐ Scour Observations	
☐ Existing Stream Development	
— Dams, Diversions	
— Flood Control	
— Mining	
☐ Flood History	
☐ Rainfall/Runoff Relationships	
Possible Components and Strategies	
☐ Channels	
☐ Bridge Components	
☐ River Alignment Control Strategies or Mitigation	
☐ Alignment Control Structures	
☐ Grade Control Structures	
☐ Non-structural Measures (Easements, Acquisition, Litigation)	
Economic and Alternative Analysis	
☐ Designation of Significantly Different Concepts	
☐ Hydrological and Hydraulic Detailing of Alternatives	
☐ Least Total Expected Cost Evaluation	
☐ Extreme Flood Evaluation of Components and Alternatives	
☐ Environmental Considerations	
☐ Documentation and Comprehensive Evaluation	
Hydraulic Analysis	
☐ Determination of Control	
☐ Determination of Type of Flood Profile	
☐ Normal Depth Calculations	
☐ Water Surface Profile Calculations [Usually HEC-2]	
☐ Bridge Hydraulics	
☐ Sand Bed Formation Determination	
☐ Sand Bed Roughness	
☐ Cobble, boulder, or Riprap Roughness Determination	
☐ Vegetation or Combination Lining Roughness	
☐ Dune and Antidune Height	
☐ Supercritical Channel Hydraulics	
☐ Drop Hydraulics	
☐ Average Characteristics	
☐ Physical Hydraulic Models	
Sediment Transport Analysis	
Additional Considerations	
☐ Permanent Record	
☐ Post-construction data	
☐ Normal Inspections (References)	

7.5.2 Design Example

Example: Improve a small earth-lined channel with incised low flow, bank and edge erosion $S_o = 0.006$ ft/ft, partially vegetated sandy silt material to convey 100-year design flow, $Q_{100} = 650$ cfs.

Given:

>> Available channel width of 50 feet, with approximately 3 feet depth

>> Provide grass-lined main channel with concrete-lined low flow

>> Use 4:1 side slopes and provide minimum freeboard allowance.

Step 1: Check channel capacity.

A. Solve Manning Equation (Equation 7.1)

1. Find cross-sectional area of flow [Total area (A_T) = area of low flow channel (A_{lf}) + area of main channel (A_{mc})]

$$A_T = A_{lf} + A_{mc}$$

$$= (1.5)(5) + 3((18+42)/2)$$

$$= 7.5 + 90$$

$$A_T = 97.5 \text{ sf}$$

2. Find wetted perimeter and indicate a 4 inch thickness for low flow wall.

$$P_T = P_{lf} + P_{mc}$$

$$= (2(0.33)+2(1.5)+5)+((18-5.67)+2(3)(1^2+4+4^2)^{0.5})$$

$$= 8.67 + (12.33 + 24.7)$$

$$P_T = 45.7 \text{ ft}$$

3. Find hydraulic radius

$$R = \frac{A_T}{P_T} = \frac{97.5}{45.7} = 2.13 ft \qquad \textbf{(7.13)}$$

4. Determine Manning's "n" from Table 5.11.
Find composite "n" value:
Concrete-lined low flow: n = 0.015

$$n = [\sum_{1^i}^{i} P_i \, n_i^{1.5}) \; / \; P_T \,]^{0.67}$$

$$= [\frac{(P_{lf}) \; (N_{lf}^{1.5}) \; + \; 37.0(0.025)^{1.5}}{45.7}]^{0.67} \qquad \textbf{(7.14)}$$

$$= [\frac{(0.016 \; + \; 0.15)}{45.7}]^{0.67}$$

$$n = 0.023$$

Grass-lined main channel: n = 0.025

5. Substitute values to solve for slope
Multiply Equation 5.1 by A_T and rearrange:

$$Q = (1.49/n) \, A_T \, R^{\,0.67} \, S_o^{\,0.5}$$

$$S_o = \left[Qn/(1.49 \, A_T \, R^{\,0.67}) \right]^2$$

$$= \left[650 \, (0.023)/(1.49)(97.5)(2.13)^{\,0.67} \right]^2$$

$$S_o = 0.0038 \text{ ft/ft}$$

Since the channel bottom slope of 0.0038 ft/ft is sufficient to convey the design flow of 650 cfs, the steeper existing S_o of 0.006 ft/ft will convey the flow with a smaller cross sectional area. Equation 7.1 can be solved with $A_T R^{0.67}$ to determine the actual cross section of flow:

$A_T R^{0.67} = Qn/1.49S_{o\;0.5} = 650(0.023)1.49(0.006)^{0.5} = 129.5 \text{ ft}^{2.67}$

By trial and error,

$Y_n = 2.65$ ft,

$A_T = 7.5 + 2.65\ ((18{+}39.2)/2) = 83.3$ sf,

$P_T = 8.67 + ((18\text{-}5.67) + 2(2.65)\ (1^2 + 4^2)^{0.5}) = 42.9$ ft, and

$R\ = A_T/P_T = 83.3/42.9 = 1.94$ ft.

Flow along the channel at $S_o = 0.006$ ft/ft has reduced the water depth by 0.35 ft. Note that the composite "n" value has not changed with the new values of P_{lf}, P_{mc}, and P_T.

B. Check velocity and Froude Number

1. $V = Q/A$

$= 650 / 83.3$

$V = 7.8$ fps < 8 fps allowable for Bermuda grass-lined channels with erosion resistant soil only.

2. Check Froude

$$F\ =\ V/(gD)^{0.5} \quad \textbf{(7.15)}$$

$$= \frac{7.8}{((32.2)(\frac{83.3}{39.2}))^{0.5}} \quad \textbf{(7.16)}$$

$$F\ =\ 0.94>0.86 \quad \textbf{(7.17)}$$

The channel is under near critical flow conditions and will not be stable at a bottom channel slope of 0.006 ft/ft for the design flow. One solution is to provide grade control structures to main $S_o = 0.0038$ ft/ft, thereby having $V = QA = 650/97.5 = 6.7$ fps and $F = V/(gD)^{0.5} = 6.7/((32.2)(97.5/42))^{0.5} = 0.77$, which is within the acceptable range of subcritical flow. See Chapter 6 for grade control structures.

3. Check channel transitions (see Chapter 6).

C. Confirm freeboard requirement

$$FB = 0.25\left(Y + V^2/2_g\right)$$

$= 0.25(3.7)$

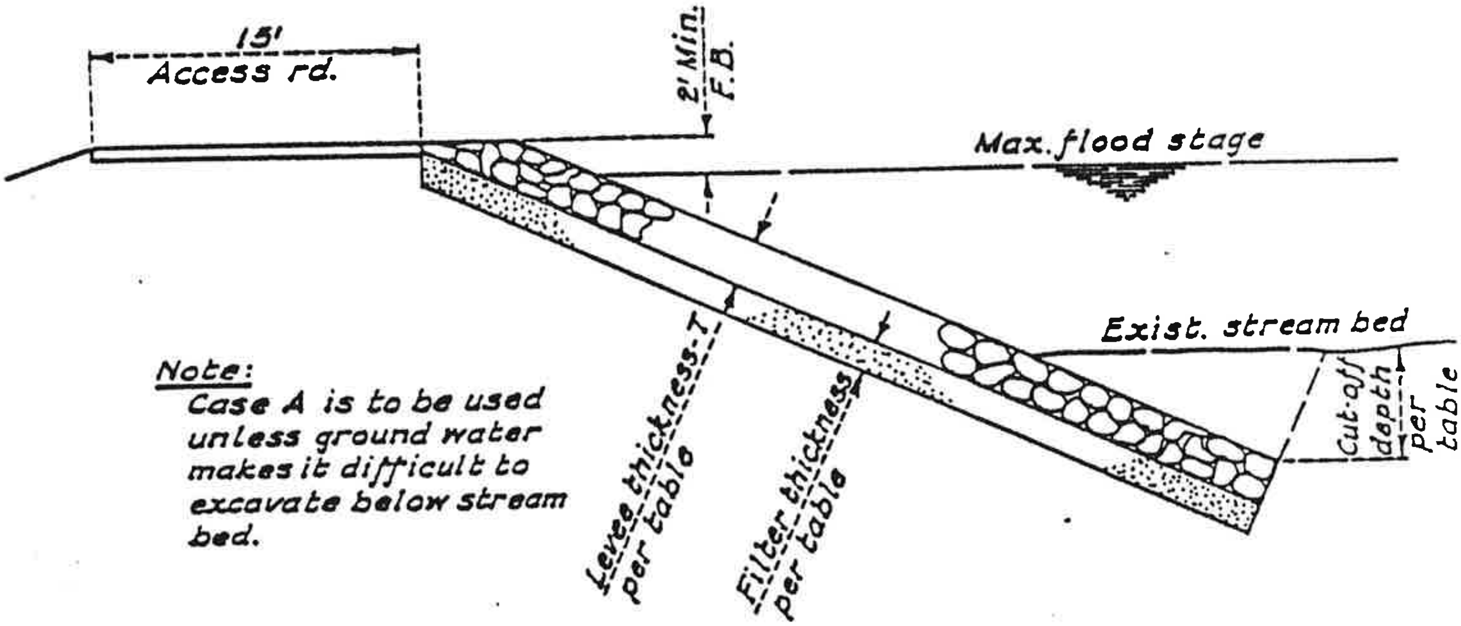
$FB = 0.92$ ft

$= 1$ ft minimum

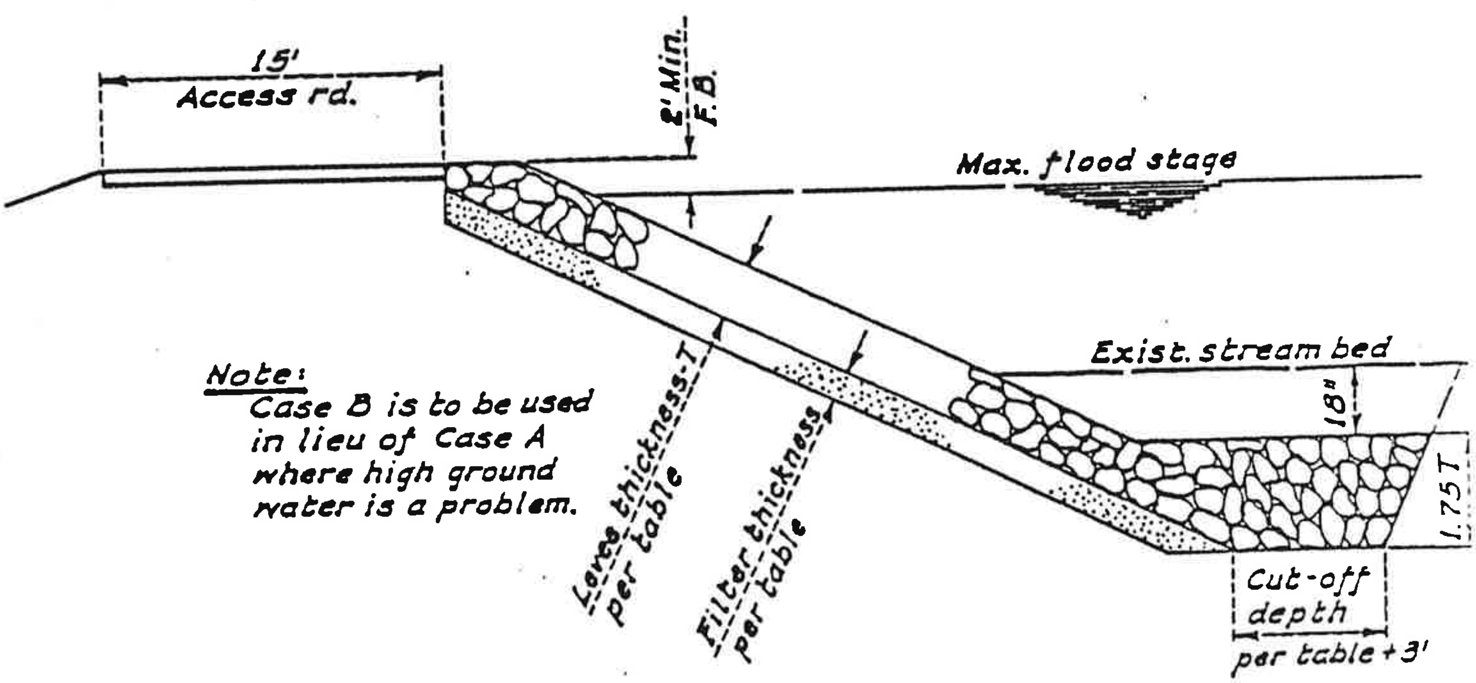
Summary:

- >> Grass-lined channel with 4:1 side slopes
- >> Velocity = 6.7 fps; F = 0.77, subcritical flow. See Table 5.2 for allowable grass and soil types.
- >> Channel slope = 0.0038 ft/ft < 0.006 ft/ft (existing)
- >> Provide grade control
- >> Provide 1 foot minimum freeboard allowance
- >> Check flow velocities and hydraulic proprties for other flows anticipated

TYPICAL ROCK RIP-RAP LEVEE SECTIONS



CASE A



CASE B

7.6 DESIGN AIDS

Tables 7.10 and 7.11 and Figures 7.4 and 7.5 are provided here to help in designing open channels.

Table 7-10
Scour Depths on Outer Curves

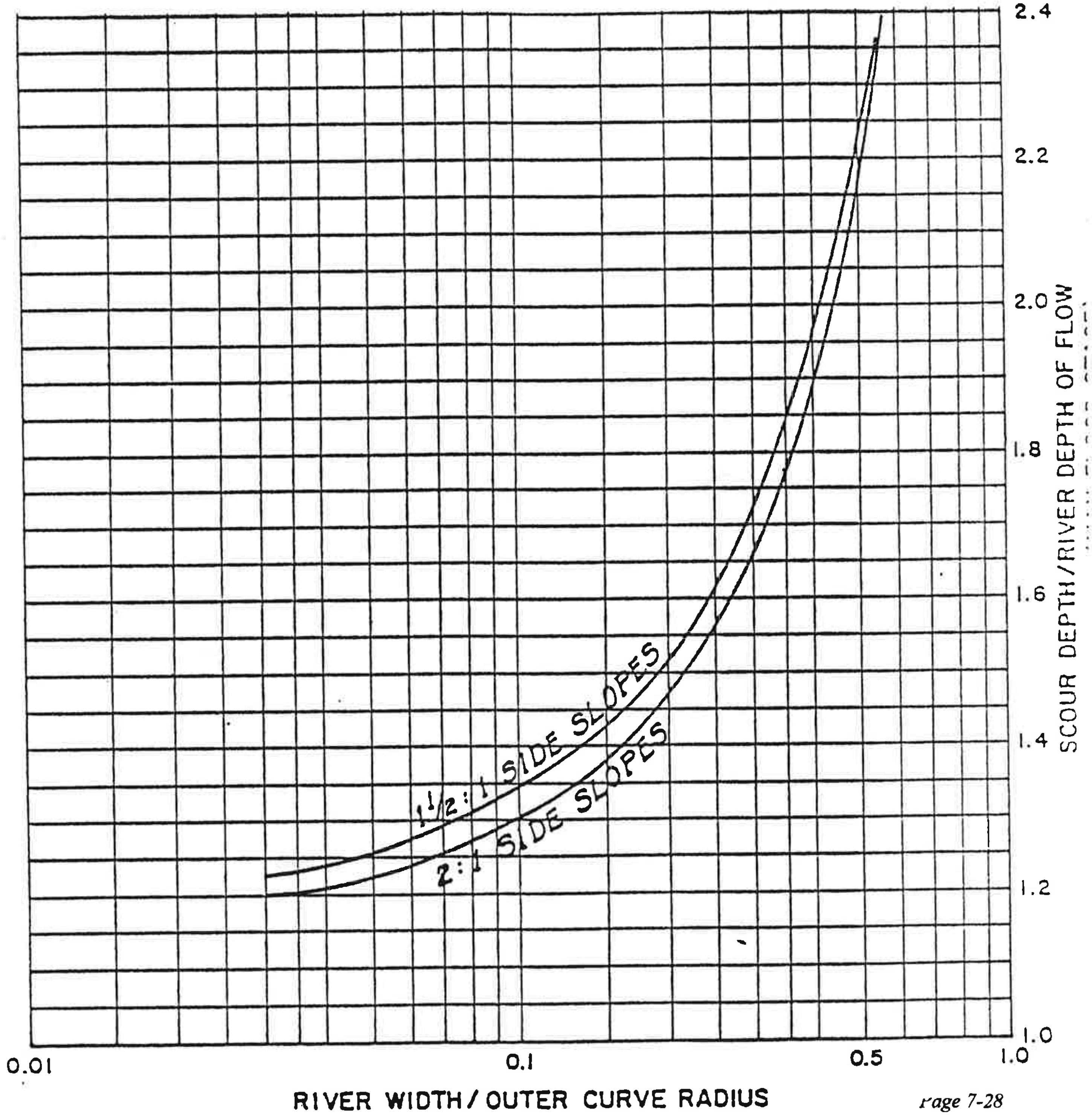


Table 7.11
Manning's Roughness Coefficients

Channel Material	Roughness Coefficient (n)		
	Minimum	Normal	Maximum
Corrugated metal	0.021	0.025	0.030
Concrete			
Trowel finish	0.011	0.013	0.015
Float finish	0.013	0.015	0.016
Unfinished	0.014	0.017	0.020
Shotcrete, good section	0.016	0.019	0.023
Shotcrete, wavy section	0.018	0.022	0.025
Asphalt (use maximum value when cars are present)	0.013	0.016	0.020
Constructed channels with earth or sand bottom and sides of:			
Clean earth; straight	0.018	0.022	0.025
Earth with grass and weeds	0.020	0.025	0.030
Earth with trees and shrubs	0.024	0.032	0.040
Shotcrete	0.018	0.022	0.025
Concrete	0.017	0.020	0.024
Dry rubble or rip-rap	0.023	0.032	0.036
Natural channels with sand bottom and sides of:			
Trees and shrubs	0.025	0.035	0.045
Rock	0.024	0.032	0.040
Natural channel with rock bottom	0.040	0.060	0.090
Overbank Floodplains			
Desert brush, normal density	0.040	0.060	0.080
Dense vegetation	0.070	0.100	0.160

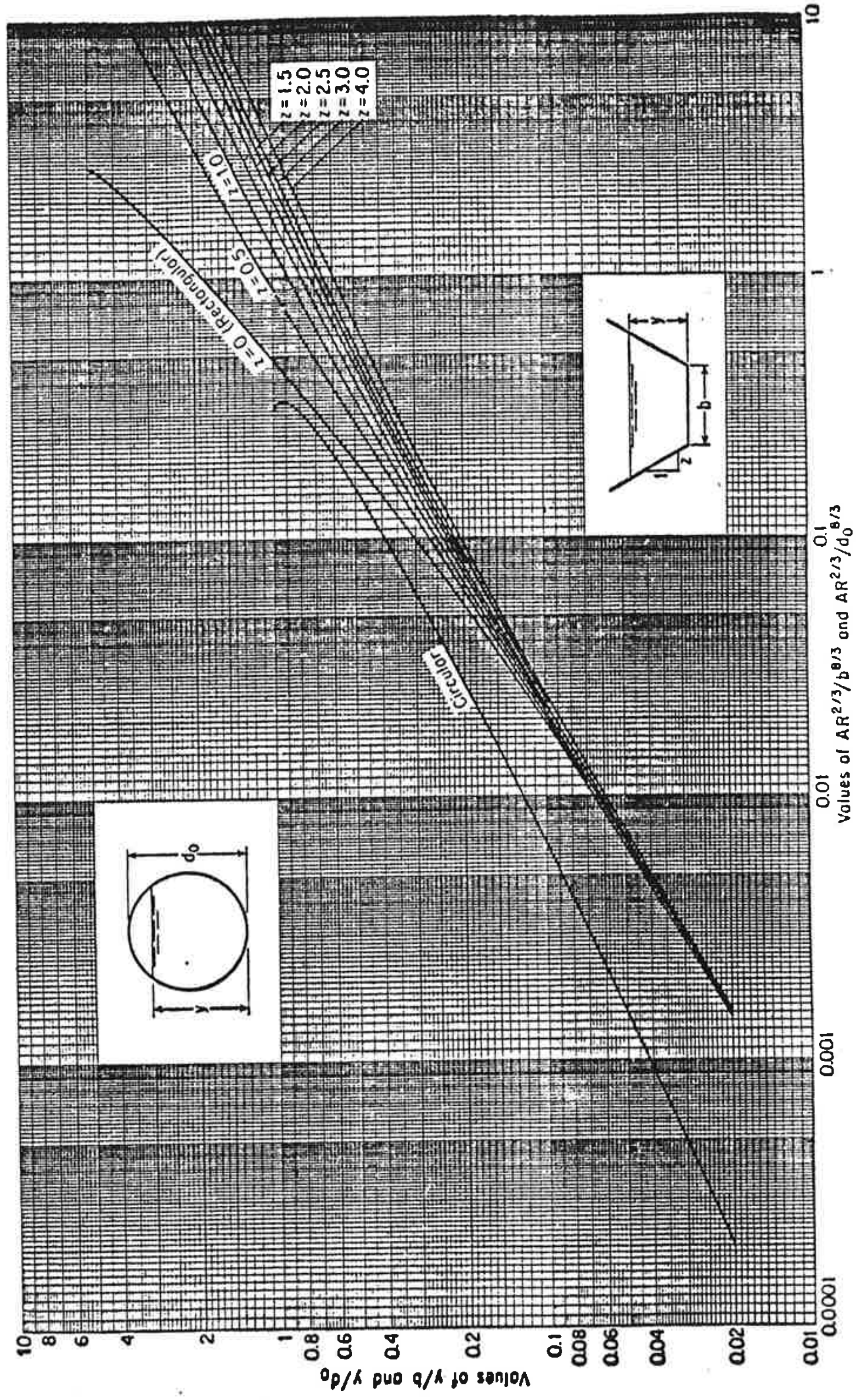


Figure 7.4
Curves for Determining the Normal Depth
for Uniform Flow in Open Channels

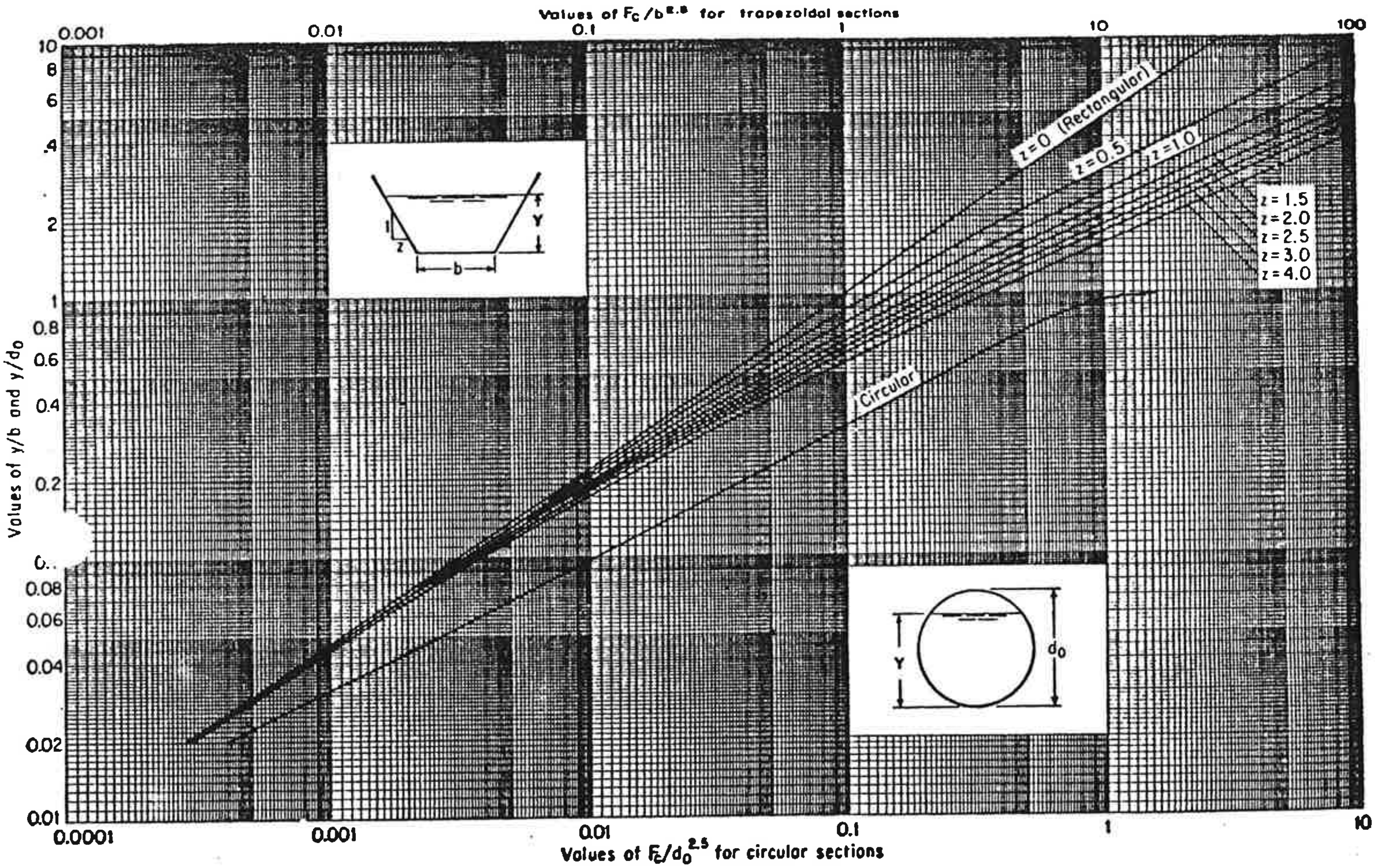


Figure 7.5

 Curves for Determining the Critical Depth in Open Channels

7.7 LIST OF VARIABLES

A	=	Cross sectional area
b	=	Basewidth
D	=	Depth of flow
F	=	Froude number
g	=	Acceleration of gravity, 32.2 FT/S^2
n	=	Manning's roughness coefficient
r	=	Radius at channel centerline
R	=	Hydraulic radius
Q	=	Flow rate in cubic feet per second
s	=	Longitudinal slope in feet per foot
S_c	=	Superelevation
T	=	Topwidth
V	=	Velocity in feet per second

7.8 REFERENCES

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