DESIGNING STABLE CHANNELS WITH ARMORFLEX ARTICULATED CONCRETE BLOCK REVETMENT SYSTEMS

DRAFT

Submitted to

Nicolon Corporation
3500 Parkway Lane
Suite 500
Norcross, Georgia 30092

Submitted by

Simons, Li & Associates, Inc.
3555 Stanford Road
P.O. Box 1816
Fort Collins, Colorado 80522

SLA Project Number GA-NCP-06
PROJD/R01A,WP

February 14, 1990

sla

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DESIGNING STABLE CHANNELS WITH ARMORFLEX ARTICULATED CONCRETE BLOCK REVETMENT SYSTEMS

I. INTRODUCTION

1.1 General

This manual addresses the design of stable open-channel conveyance systems using **Armorflex** articulated concrete block revetments. The primary difference between **Armorflex** systems and other materials commonly used to protect channel beds and banks from erosion scour and instability is the ability of **Armorflex** to accommodate minor changes in channel shape due to settlement, frost heave, slumping, and the like, while maintaining a nonerodible boundary between the channel subgrade and the potentially damaging flow of water.

Conventional rigid linings, such as cast-in-place concrete, asphaltic concrete, grouted riprap, stone masonry, and soil cement, can also be considered nonerodible. However, these treatments are usually expensive, and tend to fail when a portion of the lining is damaged. Once a rigid lining deteriorates, it is very susceptible to erosion damage because large, flat, broken slabs are easily moved by channel flow.[1] Deterioration and structural instability are usually caused by secondary (often nonhydraulic) forces which develop due to poor subgrade conditions, such as settlement, swelling soils, embankment slumping, frost heave, or hydrostatic uplift. Repair of rigid linings is often expensive and time-consuming.

Flexible linings such as meshes and blankets are generally inexpensive, permit infiltration and exfiltration, and provide better habitat opportunities for local flora and fauna. However, these treatments suffer from several disadvantages, noted as follows:

- Most meshes and blankets are designed to provide a reinforcing matrix for vegetation, and are therefore at risk during the establishment of the final cover. The vegetation itself, once fully established, forms the ultimate protection against erosion.
- Meshes and blankets are limited in the amount of hydraulic stresses which they can safely accommodate. To decrease the tractive forces on the lining material to safe limits, the designer must typically increase the geometric section of the conveyance channel, decrease the channel slope, or both. These measures result in an increased number of engineered drop structures and larger (wider) channels, thus increasing the overall project cost.

- Vegetative channel linings are not suited to long periods of submergence or sustained flow conditions.

The **Armorflex** family of revetment systems combines the favorable aspects of lightweight blankets and meshes, such as porosity, flexibility, vegetation encouragement and habitat enhancement, and facility of installation, with the nonerodibility, self-weight, and high tractive force resistance of rigid linings. **Armorflex** has proven to be a cost-effective, aesthetic, and functional alternative to dumped stone riprap, gabions, structural concrete, and other heavy-duty, durable channel protection systems.

The design relations presented in this manual are developed from physical principles of open-channel flow buttressed by extensive laboratory testing [2,3]. They represent a semi-empirical, dominant-process model which is internally consistent and well suited for use as a design tool. Because the relations represent a simplification of a complex process, the underlying assumptions of the methods, areas of applicability, and limits of the techniques are also described.

It is emphasized the selection criteria and design relations presented in this manual have been developed for one-dimensional, uniform channel flow. Both mild slope and steep slope conditions are considered. For flow conditions characterized by wave action, momentum changes (such as bends or drops), rapidly accelerating or decelerating flows (such as constrictions, expansions, and hydraulic jumps), and other local conditions which may produce abnormally high or oscillatory stresses, only general considerations are given for conceptual guidance. Where these flow conditions exist, the practitioner must utilize more sophisticated analysis and design techniques than this manual is intended to provide.

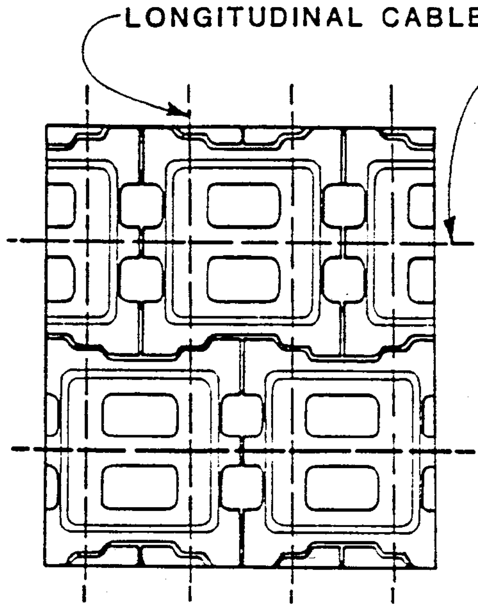
This manual updates and supercedes **Armorflex** Technical Bulletin BC-1, October, 1981, by Armortec, Incorporated.

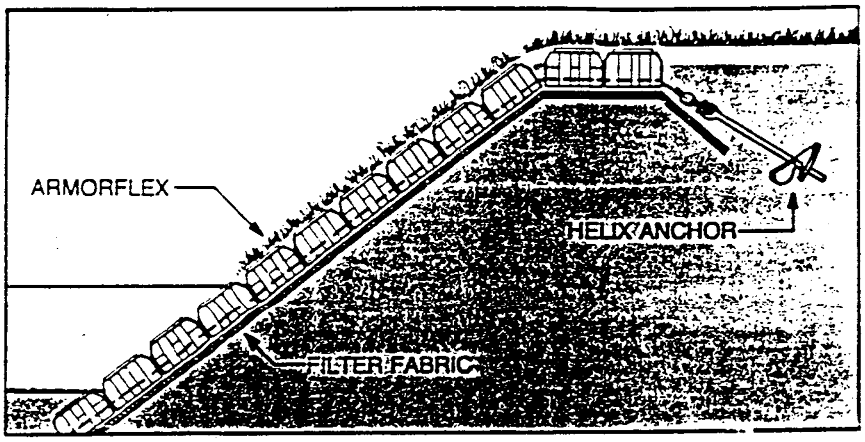
1.2 Background

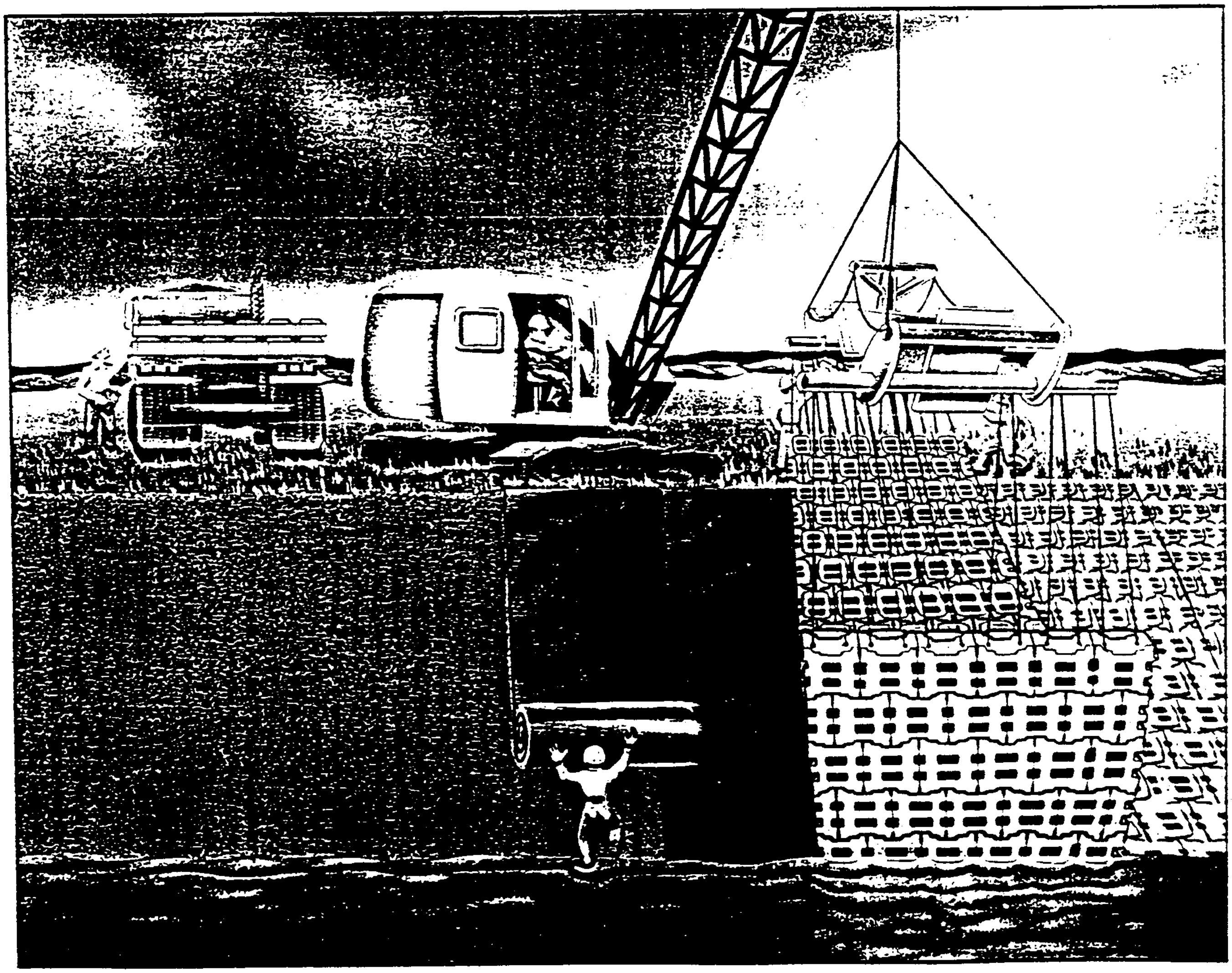
Armorflex is an interlocking matrix of precast concrete blocks of uniform size, shape, and weight, integrated by a series of cables which pass through preformed ducts in each block (**Figure 1.1**). At present, six classes of **Armorflex** are available to provide a range of size, unit weight, open area, and surface roughness. Three classes (Classes 30, 50, and 70) are of the open-cell configuration, while the remaining three classes (Classes 45, 55, and 85) are solid blocks. **Figure 1.2** illustrates the geometric properties and characteristic interlock of the different classes of **Armorflex**, with a listing of relevant physical data included.

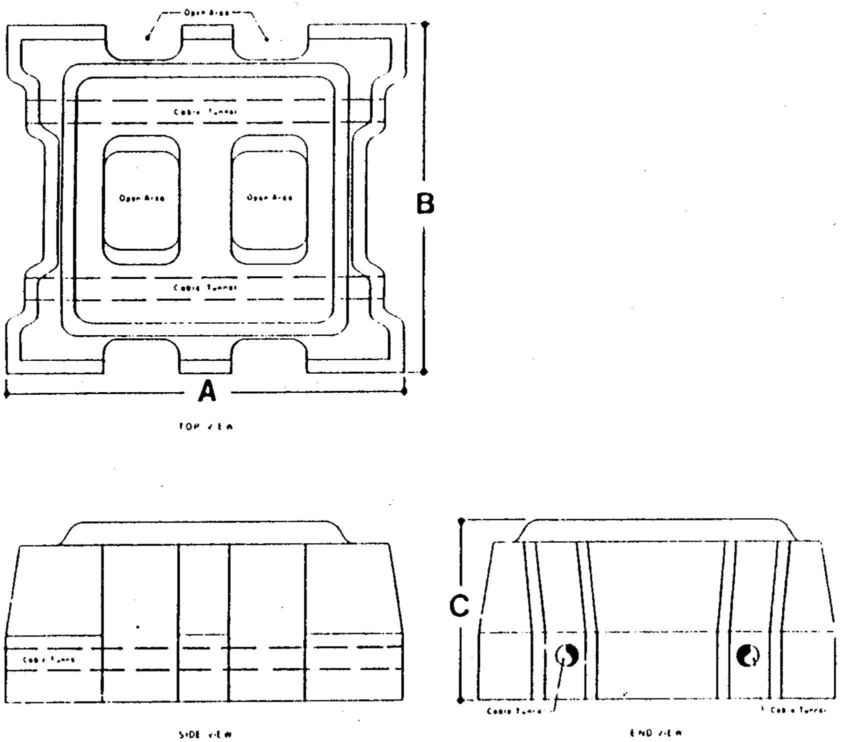
Beginning in 1983, a group of agencies of the federal government, led by the U.S. Federal Highway Administration, embarked on a multi-year research and testing program in an effort to determine, in a quantitative sense, the performance and reliability of commercially-available channel protection treatments.[4] This initial research focused on selected rigid and flexible systems, including vegetated treatments. The research was significantly expanded in 1985 with the entry of the U.S. Bureau of Reclamation into the group of sponsoring agencies. The Bureau's focus included the investigation of high-velocity, steep-slope flow conditions consistent with field occurrences of flood overtopping and chute spillway flows over earthen embankments.[2] This portion of the research was conducted under bare (unvegetated) conditions to replicate field installations in arid and semi-arid regions where the additional stability afforded by root anchorage cannot be relied upon. The research was concluded in July, 1989, with the final 2 years of testing concentrating specifically on the performance of articulated concrete block revetment systems.[3] During this research, the **Armorflex Class 30** system was tested under controlled, full-scale conditions in one of the nation's largest hydraulic testing facilities of this type. **Figure 1.3** illustrates the testing facility utilized in the evaluation of the **Armorflex Class 30** revetment system.

The tests conducted on the **Armorflex Class 30** system provided both quantitative data and qualitative insight into the hydraulic behavior of this revetment product under severe hydraulic loading. Velocities of up to 18 feet per second (ft/s) were generated during the course of the studies. The causative mechanisms contributing to the hydraulic instability of revetment linings were,

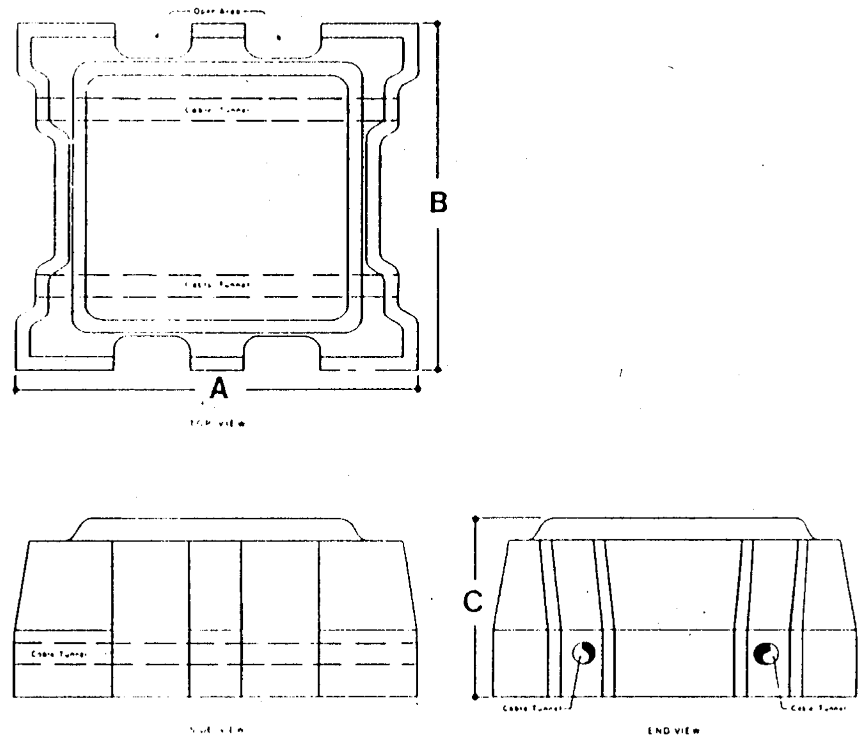

LONGITUDINAL CABLES
TRANSVERSE CABLES (Optional)


ARMORFLEX
HELIX ANCHOR
FILTER FABRIC





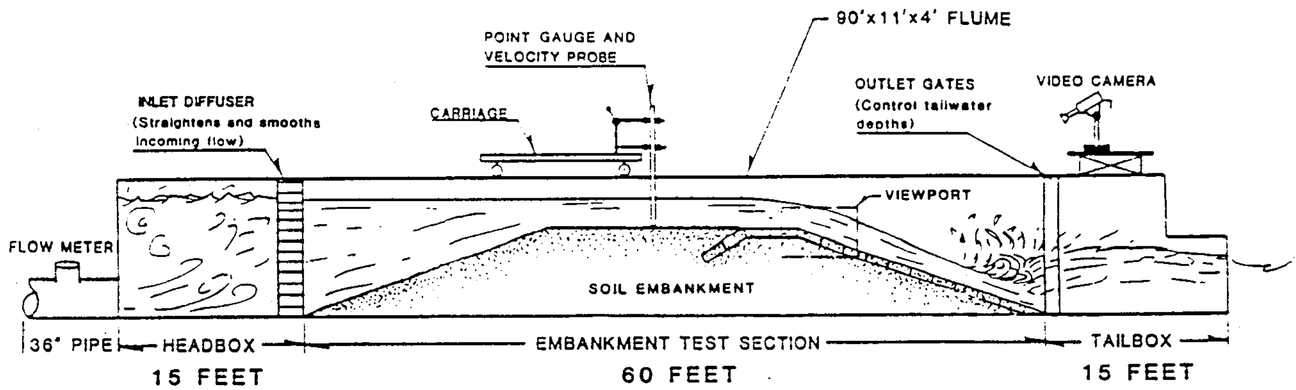
OPEN CELL GRID



CLOSED CELL GRID

ARMORFLEX GRID SPECIFICATIONS												
		TECHNICAL DATA			DIMENSIONS & WEIGHTS							
					NOMINAL DIMENSIONS IN.							
CLASS		SPECIFIC WEIGHT LBS./CU.FT.	COMPRESSIVE STRENGTH LBS./SQ IN	% MAXIMUM ABSORPTION	A	B	C	GROSS AREA/ GRID SQ FT	WEIGHT/ GRID LBS	WEIGHT/ AREA LBS /SQ FT	OPEN AREA %
OPEN CELL	30	130-150	4000-5000	5	13.0	11 6	4 75	0 98	31-36	32-37	25
	50	130-150	4000-5000	5	13 0	11 6	6 0	0 98	45 52	46 53	20
	70	130-150	4000-5000	5	17 4	15 5	9 0	1 77	120 138	68 78	20
CLOSED CELL	45	130-150	4000-5000	5	13 0	11 6	4 75	0 98	39-45	40 46	10
	55	130-150	4000-5000	5	13 0	11 6	6 0	0 98	53-61	54-62	10
	85	130-150	4000-5000	5	17 4	15 5	9 0	1 77	145-167	82-95	10

Figure 1.2. Standard sizes of Armorflex grids.



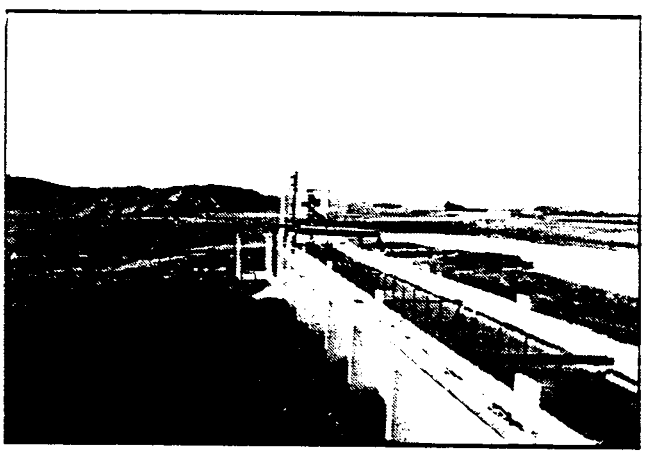
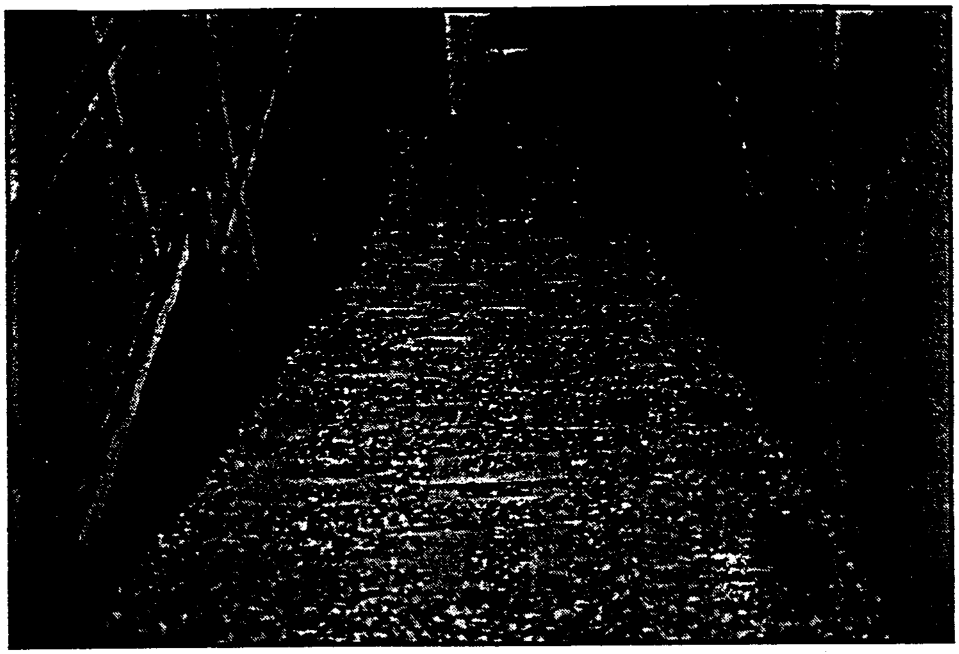


Figure 1.3. Testing facility utilized in the evaluation of the Armorflex system.

for the first time, identified and quantitatively described as a result of this research effort. Threshold hydraulic loadings were related to forces causing instability in order to better define selection, design, and installation criteria. Larger and heavier classes of **Armorflex** were not investigated in the federal studies, as evidence resulting from the Class 30 hydraulic tests indicated that hydraulic stresses significantly in excess of those which could be generated at the large-scale testing facility would be necessary to destabilize the larger systems. **Figures 1.4 and 1.5** provide "before" and "after" photographs of the **Armorflex** Class 30 tests.

Concurrently with the U.S. government tests, researchers in Great Britain were also evaluating erosion protection systems at full scale (**Figure 1.6**). Using well-vegetated installations, these investigators determined that velocities up to 26 ft/s can be safely accommodated by the **Armorflex** system.[5] The metric version of **Armorflex** used in the British tests was 17 percent smaller than the Class 30 blocks used in the previously described U.S. government tests. Both the U.S. and British research programs found that the stability of articulated concrete block revetment systems is dependent on hydraulic stress levels, but independent of the duration of the flow, thus confirming the concept of "threshold stress" as a viable criterion for stability analysis. Both sets of researchers agreed that an accurate, yet suitably conservative, definition of "failure" for articulated revetment systems can be described as the <u>local loss of intimate contact</u> between the system and the subgrade it protects. This loss of contact can result in the progressive growth of one or more of the following destabilizing processes:

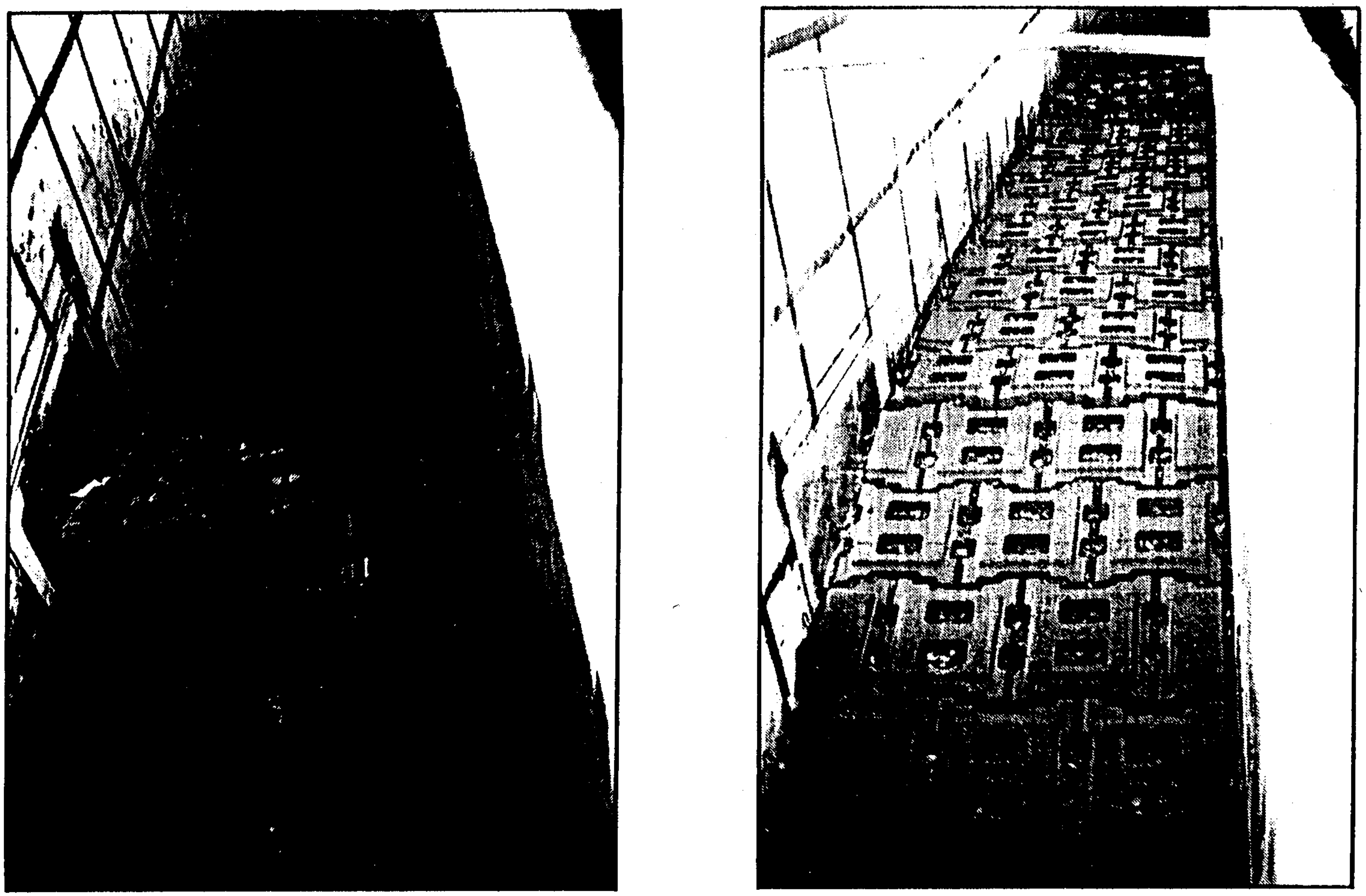
1. Ingress of flow beneath the armor layer, causing increased uplift pressure and separation of blocks from subgrade.
2. Loss of subgrade soil through gradual piping erosion and/or washout.
3. Enhanced potential for rapid saturation and liquefaction of sub-grade soils, causing shallow-slip geotechnical failure (silt-rich soils on steep slopes).
4. Loss of a block or group of blocks from the revetment matrix, directly exposing the subgrade to the flow. (This applies only to noncabled systems).



A. Looking downstream

B. Looking upstream

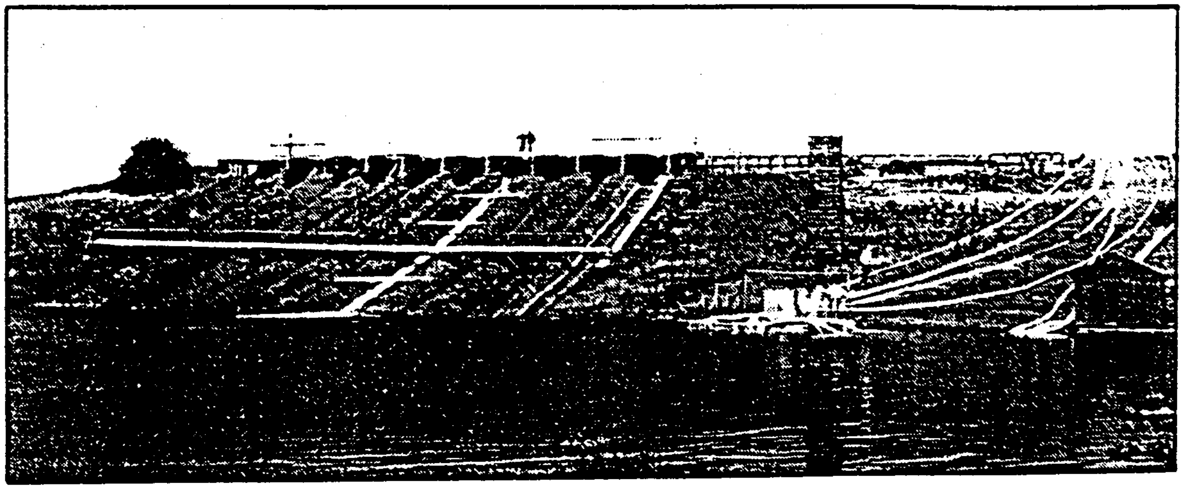
Figure 1.4. Armorflex Class 30 system prior to testing.



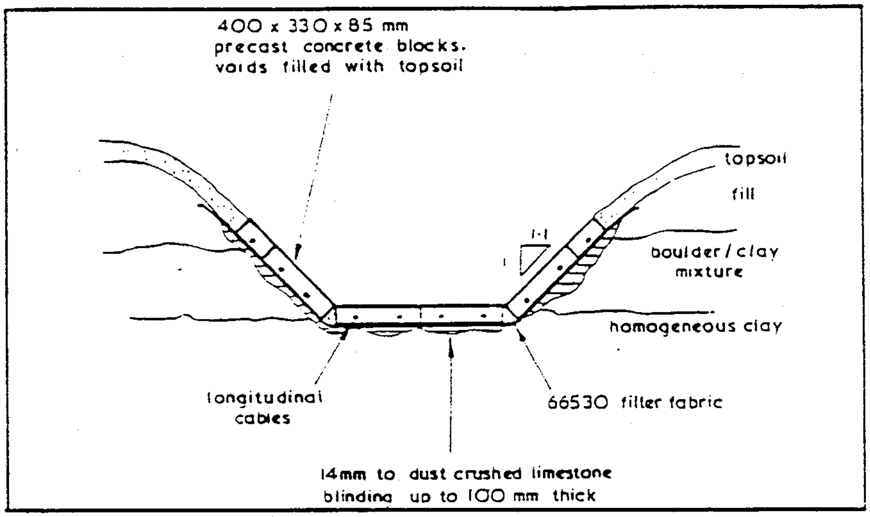
A. Looking downstream

B. Looking upstream

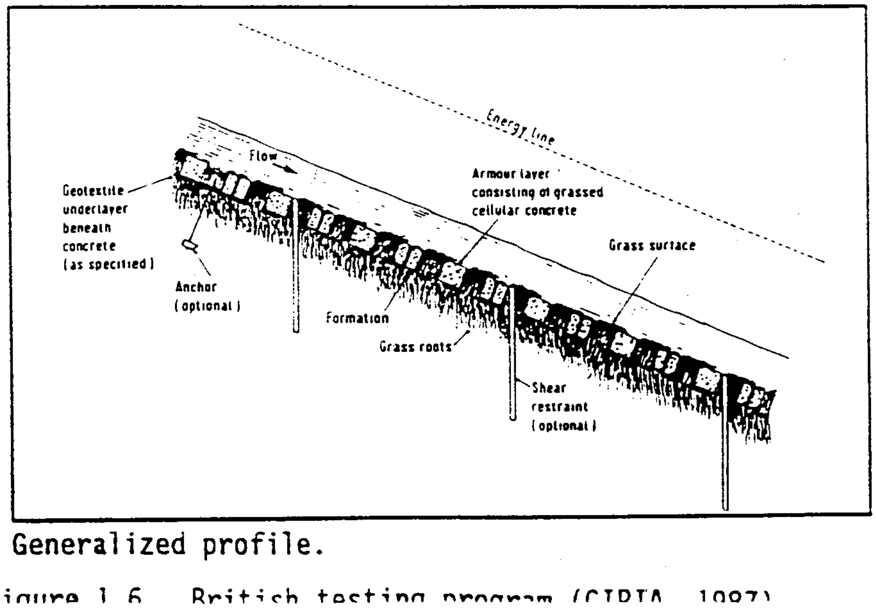
Figure 1.5. Armorflex Class 30 system after testing (note partial loss of gravel infill).



a. General view of Jackhouse field trials site.



b. Cross-sectional view through Armorflex test channel.



c. Generalized profile.

Figure 1.6 British testing program (CIRIA 1987)

Selection, design, and installation considerations must therefore be primarily concerned with maintaining intimate contact between system and subgrade for the stress levels associated with the hydraulic conditions of the design event, given the geometric properties of the channel section and its longitudinal slope.

This manual incorporates the results of the **Armorflex** Class 30 tests into a design procedure which is based on the fundamental principles of open-channel flow. The results of the Class 30 tests are extrapolated to the larger classes of **Armorflex** through the use of the ratio of resisting to overturning moments (the "force-balance" approach), as determined by the physical attributes of size and weight characteristics of each class of **Armorflex** system. This is then used to determine the Factor of Safety against the initiation of uplift about the most critical axis (the "Factor of Safety" method). Considerations are also incorporated into the design procedure which account for the additional forces generated on a block which protrudes above the surrounding matrix due to subgrade irregularities or nonprecise placement. The net result is a practical and easy-to-use design procedure for protecting trapezoidal channels from erosion damage under uniform flow conditions.

Due to the use of cabled installations during the controlled, full-scale laboratory tests, any added benefit of cables has been indirectly accounted for in the determination of stability. However, additional stability arising from the use of cables is not considered, since finite movement of an individual block within the overall matrix must occur prior to the development of tension in the cables to resist further displacement. As finite movement constitutes "failure", as defined in the foregoing discussion, the analysis methodology purposely contains no explicit attempt to account for resisting forces due to cables. Similarly, the additional stability which may arise from vegetative root anchorage or mechanical anchoring devices, while recognized as significant [5], is ignored in the analysis procedures for the sake of conservatism in selection and design.

1.3 Organization of the Manual

The fundamental principles of uniform flow in open channels are briefly developed in Chapter II. This chapter includes all necessary descriptions and equations used in standard engineering practice, and which are required for an understanding of the forces generated on a channel boundary by flowing water. The hydraulic properties of vegetated channels are also described.

Chapter III contains selection and design criteria for **Armorflex** linings in applications which utilize the Mild Gradient Design Procedure. Following the convention applied (somewhat arbitrarily) by the U.S. Federal Highway Administration, the mild channel gradient procedure is applied for those channels which exhibit a longitudinal bed slope of less than 10 percent. This condition will prevail in most all practical channel design situations, and includes both subcritical and supercritical hydraulic flow regimes. Charts and worked examples for commonly used trapezoidal channel geometries are provided. Corrections for computing local stress effects of bends, constrictions, and expansions are presented.

Chapter IV provides selection and design criteria for **Armorflex** linings in applications which utilize the Steep Gradient Design Procedure. This procedure applies for channel slopes ranging from 10 percent (10H:1V) to 50 percent (2H:1V), and takes into account the increased flow resistance in high-velocity, turbulent flow fields. Methods for accommodating hydraulic stresses at lining termination points are presented. Due to the potential for extremely high stress levels on steeply sloped installations, local irregularities in the flow pattern must be carefully avoided; therefore, no consideration for bends, constrictions, or expansions are provided for in the Steep Gradient Design Procedure.

Chapter V provides general installation procedures and recommendations, along with typical construction details which apply in the most commonly occurring channel lining situations. Subjects covered in this chapter include subgrade preparation and testing, geotextile considerations, anchoring methods, and the incorporation of vegetation.

Appendix A provides the detailed computations and assumptions used to derive the force balance and Factor of Safety methodologies used to define the stability envelopes for the various classes of the **Armorflex** family of products.

1.4 Disclaimer

This manual is intended for use as an analysis and design aid by engineering professionals having a background in hydrology and open-channel flow hydraulics. Although the design charts presented in this manual could be used in "cookbook" fashion, an understanding of free-surface flow behavior and boundary stresses by the practitioner is warranted. There is no substitute for experience and good engineering judgement; given these, designs based on the use of the charts and tables in this manual will, with very few exceptions, result in reasonably conservative installations. It is to be expressly understood that the responsibility for the success or failure of an engineering design rests with the engineer of record; use of the information contained in this manual in no way implies review or approval of a specific design by the Nicolon Corporation, its agents or consultants.

II. HYDRAULICS OF OPEN-CHANNEL FLOW

2.1 Basic Concepts

The hydraulic conditions of channel flow are a function of the channel geometry, discharge, roughness, and slope. The degree of erosion protection required can only be determined after the hydraulic conditions of flow are known. Typically, a design discharge is selected using appropriate hydrologic techniques; this discharge usually corresponds to a storm event of specified frequency, such as a 10-, 25-, or 100-year storm, as required by the local regulatory authority. The channel size and configuration is largely dictated by physical constraints of the site, although the designer usually has some latitude for refinement of cross-section, slope, and alignment during the design process. Several trials are usually required before arriving at a final design.

Open-channel flow can be classified according to three general conditions:

1. Uniform or nonuniform flow
2. Steady or unsteady flow
3. Subcritical or supercritical flow

In uniform flow, the depth and discharge along the reach of channel remain constant. Nonuniform flow is characterized by accelerations or decelerations caused by changes in slope or cross-sectional geometry of the channel. In steady flow, no change in discharge occurs over time; for natural flows, almost all flows are unsteady, as they are characterized by a runoff hydrograph which rises, peaks, and falls as dictated by the rainfall pattern. In most cases, the runoff hydrograph varies gradually, so that for practical purposes, the flow can be described as a series of intervals, with each interval assumed to exhibit steady flow characteristics. In practice, the peak flow rate of the runoff hydrograph is used as the design discharge, and, for purposes of hydraulic analysis and channel design, is usually treated as steady flow.

Subcritical flow is described as tranquil, and is characterized by relatively deep flow with slow velocity. Supercritical flow, on the other hand, is described as rapid or "shooting" flow, with shallow flow depths and high velocity. The dimensionless number known as the Froude number (F) is defined as the ratio of inertial forces to gravitational forces in the flow field, and is used to distinguish between subcritical and supercritical flow. The Froude Number is defined as:

$$F = \frac{V}{(gy)^{1/2}} \tag{2.1}$$

where V = average velocity of flow (ft/s)

g = acceleration due to gravity (32.2 ft/s^2)

y = hydraulic depth, defined as the flow area divided by the top width of the water surface (ft)

A Froude number less than 1.0 indicates that subcritical flow is occurring, whereas a Froude number greater than 1.0 indicates that the flow is supercritical. In the transition range $0.8 < F < 1.2$, the flow field is highly unstable and tends to oscillate rapidly and unpredictably between the subcritical and supercritical regimes. Channel designs which exhibit a Froude number in the transition range should be avoided.

2.2 Hydraulics of Steady Uniform Flow

For design purposes, uniform flow conditions are usually assumed, and therefore the slope of the energy line is equal to the slope of the channel bed. The Manning equation provides a reliable estimate of uniform flow conditions, and is expressed as:

$$Q = \frac{1.486}{n} A R^{2/3} S_f^{1/2} \tag{2.2}$$

where Q = design discharge, in cubic feet per second (cfs)

n = Manning's roughness coefficient

A = cross-sectional flow area (ft^2)

R = hydraulic radius, equal to the cross-sectional area A divided by the wetted perimeter P (ft)

S_f = energy slope (ft/ft) (approximated by the average bed slope)

Given the design discharge, cross-sectional geometry, roughness coefficient, and bed slope, numerically solving the Manning equation for flow depth y_0 typically requires an iterative procedure, because both the area A and the hydraulic radius R are functions of the unknown flow depth y_0. **Figure 2.1** provides a nomographic solution to the Manning equation for trapezoidal channels, and solves for the depth of flow y_0 under uniform flow conditions. This depth is termed normal depth, and is representative of flow conditions wherein the resistance to flow is exactly balanced by the gravitational force.

Once the depth of flow is known, the mean (cross-sectional average) velocity V of the flow can be calculated as:

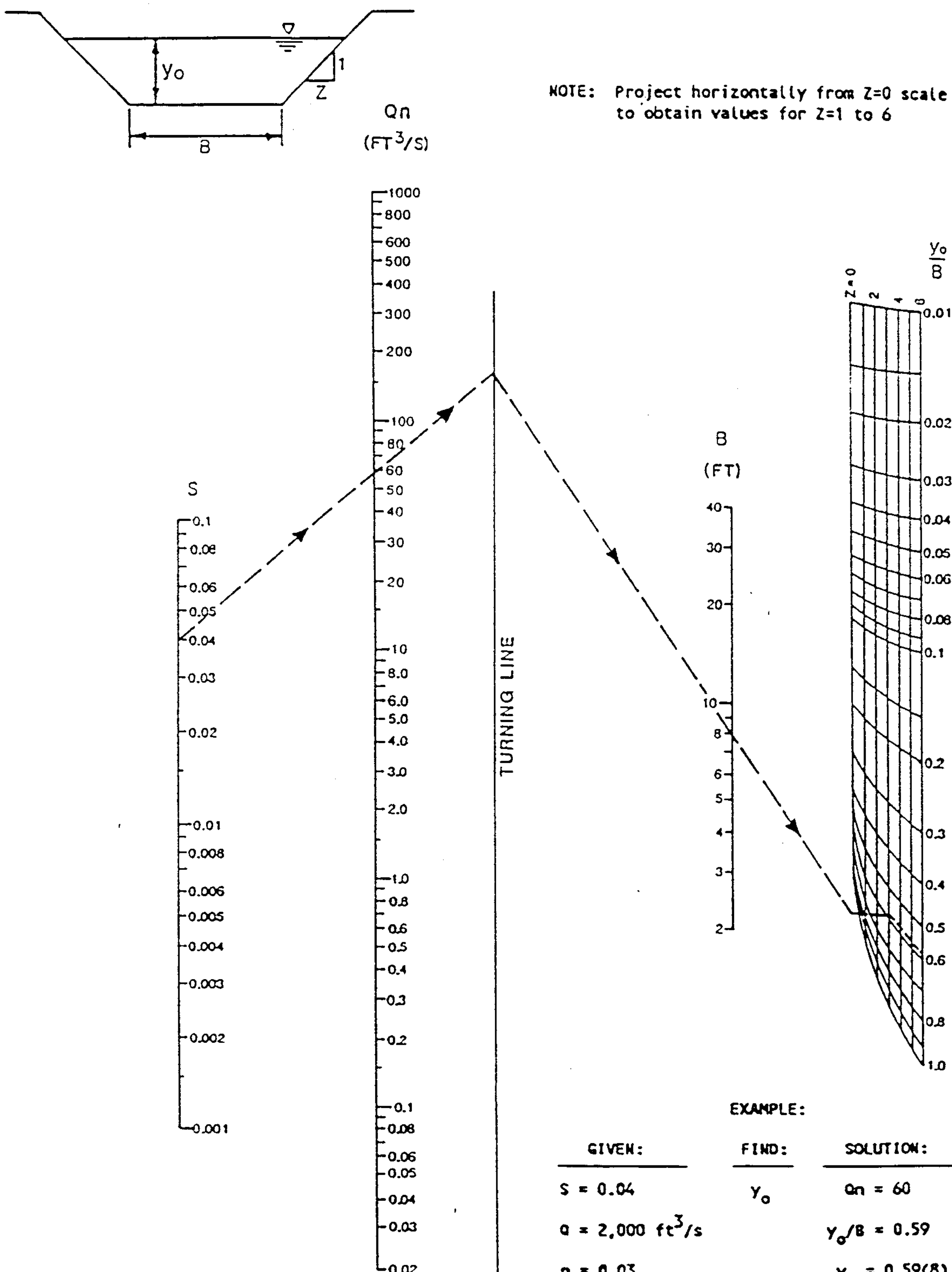
$$V = \frac{Q}{A} \qquad (2.3)$$

where $A = by_0 + zy_0^2$ for trapezoidal channels with sideslope ratio z horizontal to 1 vertical, and base width b.

The Manning's roughness coefficient n is approximately constant, for a given channel lining, over the range of slopes and discharges typically encountered in channel design situations. The roughness coefficient tends to increase for very shallow flows where the height of the roughness elements comprising the lining is a significant percentage of the total depth of flow.

For bare (unvegetated) **Armorflex** revetment systems on mild channel slopes under uniform or near-uniform flow conditions, the Manning coefficient n has been found to depend on the effective size of the individual blocks, and whether the blocks are of the open- or closed-cell configuration, as listed below:

Block Class	Range of n-values	Typical value
30 (open)	0.029 - 0.035	0.032
50 (open)	0.029 - 0.035	0.032
70 (open)	0.031 - 0.037	0.034
45 (closed)	0.024 - 0.029	0.026
55 (closed)	0.024 - 0.029	0.026
85 (closed)	0.025 - 0.030	0.028



NOTE: Project horizontally from Z=0 scale to obtain values for Z=1 to 6

EXAMPLE:

GIVEN:	FIND:	SOLUTION:
S = 0.04	Y_o	Qn = 60
Q = 2,000 ft^3/s		Y_o/B = 0.59
n = 0.03		Y_o = 0.59(8) = 4.7 ft
B = 8 ft		
Z = 3H:1V		

Figure 2.1. Nomographic solution of the Manning's equation for

When lined with a good, uniform stand of vegetation, a channel cannot be adequately described by a constant n value, since the resistance to flow is complicated by the fact that vegetation will bend in the flow, changing its height, and hence the amount of interference with the flow. The Soil Conservation Service has developed a method of predicting the amount of resistance which various types of vegetative linings exhibit under different flow conditions. **Table 2.1** describes the five categories of vegetation, referred to as conditions A (high resistance) through E (low resistance). The Manning's n value is found to be a function of the product of the flow velocity V and the hydraulic radius R, as shown in **Figure 2.2.** Solution of the uniform flow equation for a given discharge, channel geometry, slope, and vegetative condition is iterative, and depends on several trial-and-error estimates of n using Figure 2.2 to adjust the n value between successive iterations.

2.3 Stable Channel Design Concepts

2.3.1 Equilibrium Concepts

Stable channel design concepts focus on evaluating and defining a channel configuration which will perform within acceptable limits of stability. Methods for this evaluation and definition depend on whether the channel boundaries are viewed as (1) essentially rigid (static), or (2) moveable (dynamic). In the first case, stability is achieved when the material forming the channel boundary effectively resists the erosive forces of the design flow. Under such conditions, the channel bed and banks are in a state of static equilibrium, and remain unchanged during all stages of flow. Principles of rigid boundary hydraulics can be applied to evaluate this type of system.

In a dynamic system, some change in the channel bed or banks is to be expected if erosive forces of the flow are sufficient to detach and transport the materials comprising the boundary. Stability in a dynamic channel reach is generally achieved when the sediment supply rate from upstream equals the sediment-transport rate through the reach. This condition is referred to as dynamic equilibrium, and, although some detachment and transport of bed and bank materials may occur, this does not preclude attainment of a channel configuration that is basically stable. In this context, a dynamic system can be considered stable as long as the net change of the boundary does not exceed acceptable levels.

Table 2.1. Vegetative Retardance Categories.

Retardance	Cover	Condition
A Very high	Weeping love grass..........	Excellent stand, tall (av 30 in.)
	Yellow bluestem isehaemum...	Excellent stand, tall (av 36 in.)
B High	Kudzu......................	Very dense growth, uncut
	Bermuda grass...............	Good stand, tall (av 12 in.)
	Native grass mixture (little bluestem, blue gama, and other long and short Mid-west grasses)............	Good stand, unmowed
	Weeping love grass..........	Good stand, tall (av 24 in.)
	Lespedeza serices...........	Good stand, not woody, tall (av 19 in.)
	Alfalfa.....................	Good stand, uncut (av 11 in.)
	Weeping love grass..........	Good stand, mowed (av 13 in.)
	Kudzu......................	Dense growth, uncut
	Blue grama..................	Good stand, uncut (av 13 in.)
C Moderate	Crab grass..................	Fair stand, uncut (10 to 48 in.)
	Bermuda grass...............	Good stand, mowed (av 6 in.)
	Common lespedeza............	Good stand, uncut (av 11 in.)
	Grass-legume mixture-summer (orchard grass, redtop, Italian rye grass, and common lespedeza).........	Good stand, uncut (6 to 8 in.)
	Centipede grass.............	Very dense cover (av 6 in.)
	Kentucky bluegrass..........	Good stand, headed (6 to 12 in.)
D Low	Bermuda grass...............	Good stand, cut to 2.5 in. height
	Common lespedeza............	Excellent stand, uncut (av 4.5 in.)
	Buffalo grass...............	Good stand, uncut (3 to 6 in.)
	Grass-legume mixture-fall, spring (orchard grass, redtop, ItaLian rye grass, and common lespedeza).....	Good stand, uncut (4 to 5 in.)
	Lespedeza serices...........	After cutting to 2 in. height, very good stand before cutting
E Very low	Bermuda grass...............	Good stand, cut to 1.5 in. height
	Bermuda grass...............	Burned stubble

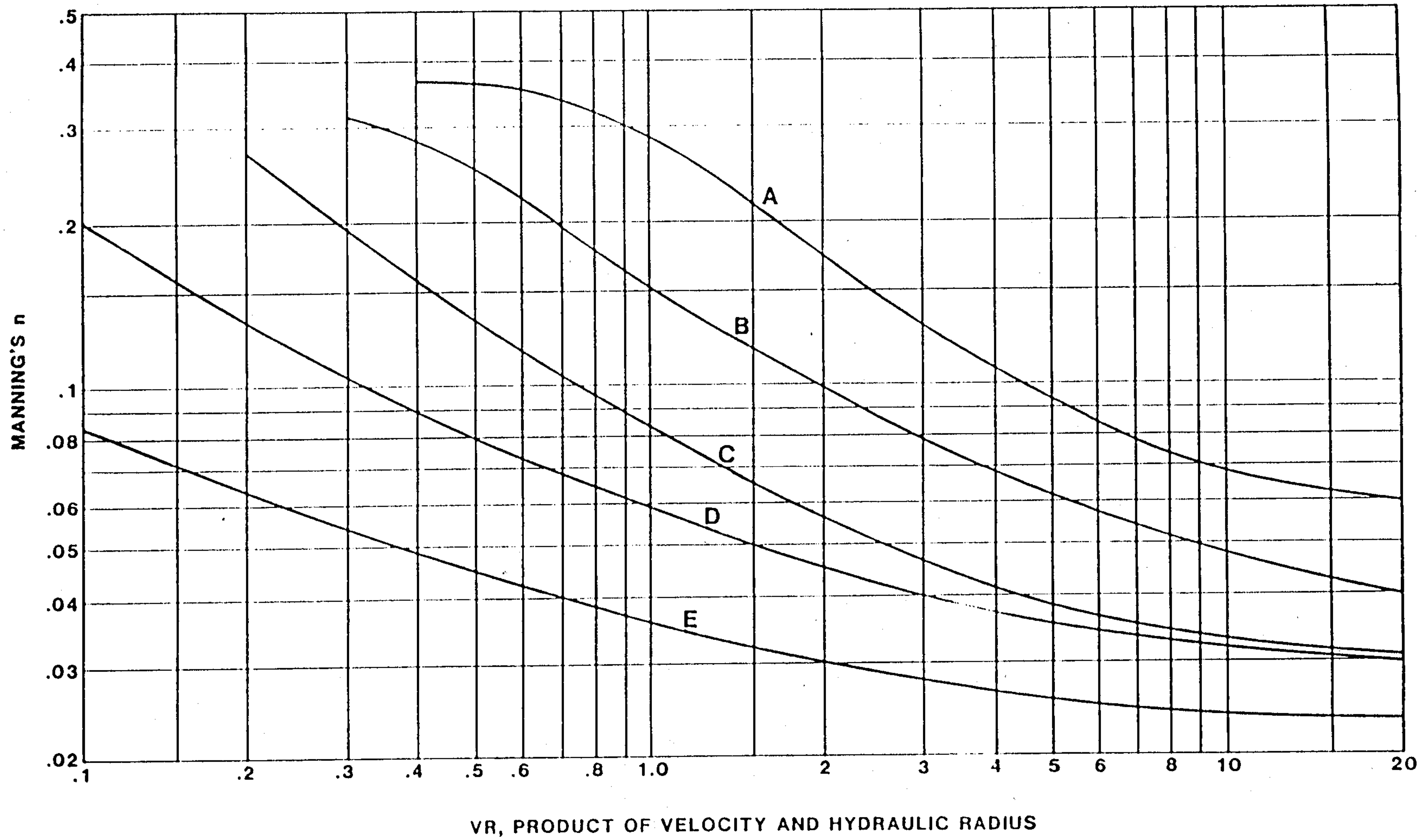


Figure 2.2. Vegetative resistance relationships.

Dynamic equilibrium evaluations and techniques are most often applied to natural streams and rivers in areas remote from urbanization or other man-made improvements. For most development projects, bridges, culverts, roadway drainage applications, and other designs where nearby structures are involved, bed and/or bank instability (with potential lateral migration) cannot be tolerated. In these situations, the development of static equilibrium through the utilization of erosion-resistant channel boundaries is preferred over dynamic equilibrium concepts.

2.3.2 Hydraulic Forces

Beginning in the 1920s, empirical design procedures began to center around the concept of maximum permissible velocity. This was defined as the highest velocity a channel boundary could withstand before movement of the boundary materials became imminent. The velocity limits were developed from observation and measurement of conditions in both natural and test channels, and considered a variety of channel lining materials and soil types. Procedures for design of vegetated channels using the permissible velocity approach were developed and standardized by the SCS, and have remained in common use. However, considering the actual physical processes occurring in open-channel flow, a more realistic model of boundary stability is based on the development of the tractive force theory, described below.

In the 1950s, research investigations by the U.S. Bureau of Reclamation led to the development of the permissible tractive force procedure. This methodology provided a more fundamental basis for relating the erosion resistance of boundary materials to the erosive force of the flow. Less empirical in nature than the permissible velocity approach, the tractive force procedure was more easily extended to various soil types and linings. The average tractive force (or shear stress) over the channel boundary is given by:

$$\tau = \gamma R S_f \tag{2.4}$$

where τ = average tractive force (<u>or shear stress</u>) (lbs/ft^2)

γ = unit weight of water, 62.4 lbs/ft^3 for clear water

R = hydraulic radius (ft)

S_f = slope of the energy line (approximated by the bed slope)

The maximum shear stress on the boundary of a straight channel occurs on the channel bed, and is determined by substituting the depth of flow y_0 for the hydraulic radius R in the above equation, yielding:

$$\tau_0 = \gamma y_0 S_f \tag{2.5}$$

where τ_0 = maximum shear stress
y_0 = maximum depth of flow; other terms as before

Shear stresses in channels are not uniformly distributed along the wetted perimeter. A typical distribution of shear stress in a straight reach of a trapezoidal channel is shown in **Figure 2.3**(a). Flow around a bend creates secondary currents, which impose higher than normal shear stresses on the channel sides and bottom in localized areas, as shown in Figure 2.3(b). At the entrance to the bend, the maximum shear stress is located near the inside of the curve. Near the exit of the bend, the zone of high shear stress is located near the outside of the curve, and persists a distance L_p downstream from the point of tangency. The amount of increase in the shear stress due to curvature of the channel is related to the ratio of channel curvature to the bottom width, R_c/b. The sharper the bend, the higher the amount of shear stress increase, as indicated by **Figure 2.4**. The bend shear stress, τ_b, is expressed by the dimensionless factor K_b from Figure 2.4 multiplied by the maximum shear stress for an equivalent straight reach:

$$\tau_b = K_b \tau_0 \tag{2.6}$$

It can be seen from Figure 2.4 and Equation 2.6 that for relatively sharp bends, the effective shear stress can nearly double in magnitude compared to straight reaches.

The distance L_p over which the high shear stresses persist downstream from the bend is a function of the roughness of the boundary in the bend, n_b, and the hydraulic radius R:

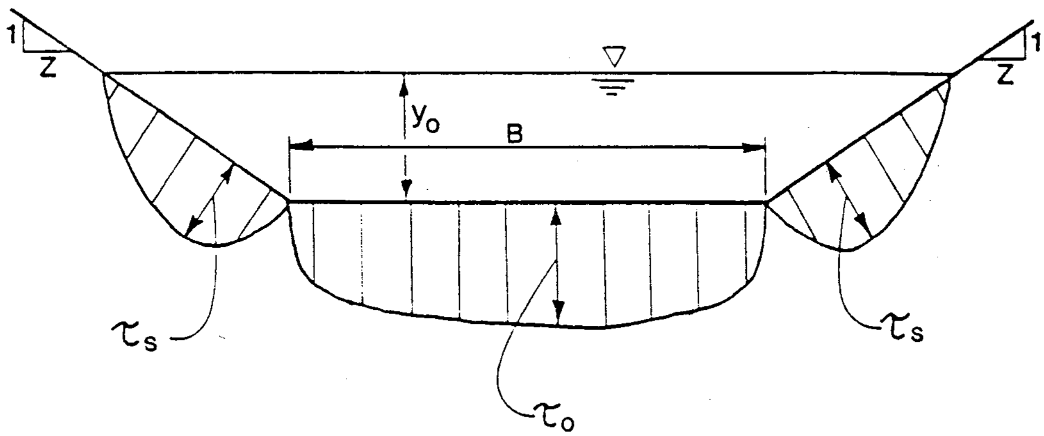


Figure 2.3a. Typical shear stress distribution on the boundary of a trapezoidal channel in a straight reach.

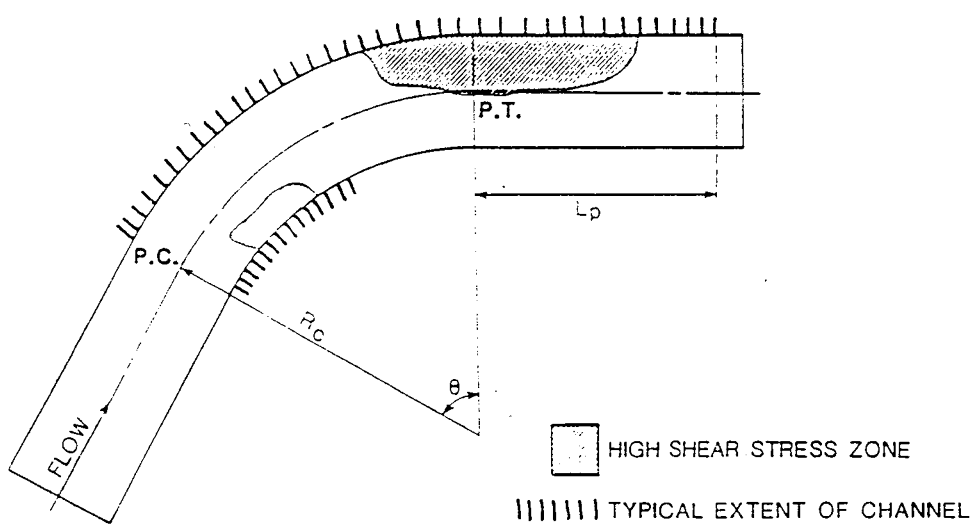


Figure 2.3b. Shear stress concentration areas in a channel bend.

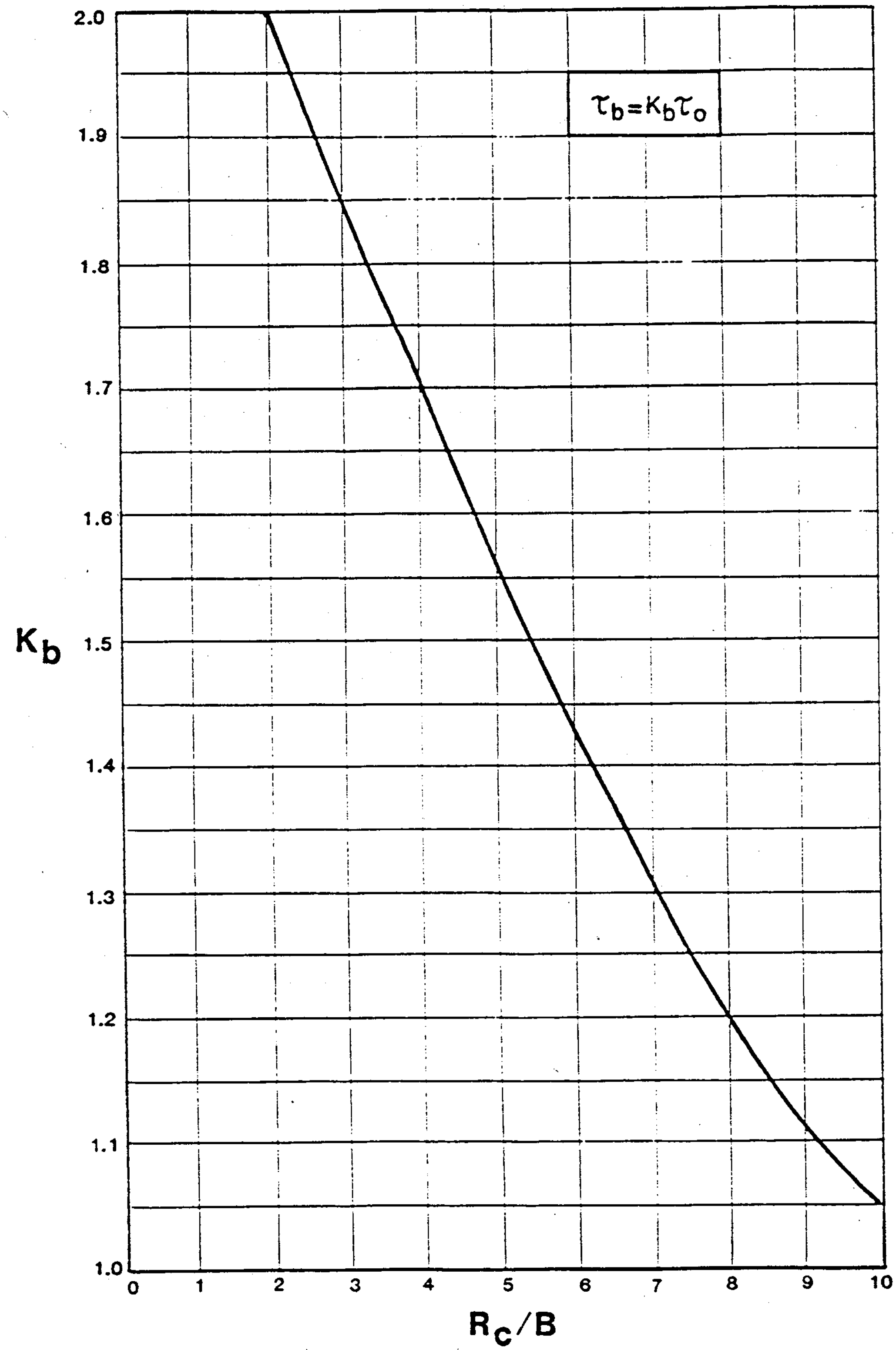


Figure 2.4. K_b factor for maximum shear stress on channel bends.

$$\frac{L_p}{R} = \frac{0.604\ R^{1/6}}{n_b} \qquad (2.7)$$

Figure 2.5 provides the relationship of L_p/R to n_b for typical ranges of the hydraulic radius R. From this chart, it is seen that the effect of increasing the bend roughness serves to decrease the downstream distance over which the shear stress is influenced. This is due to the ability of a rougher boundary to more rapidly dissipate the secondary currents created by the bend.

2.4 Hydraulic Stability of Armorflex Revetment Systems

2.4.1 Hydraulic Forces Affecting Stability

An individual block surrounded by a matrix of identical blocks is subjected to the forces of lift and drag under the action of flowing water. The lift force acts in a direction normal to the plane of the bed, and is typically comprised of the buoyant force and differential pressure across the block due to local accelerations. Lift forces can be substantially exacerbated due to excessive seepage pressures beneath the block, and by flow separation which causes a negative pressure to occur on the upper surface of the block. The latter commonly occurs, for example, at sharp transitions from a mild bed slope to a steeper one.

The drag force acts in the direction of flow, and is comprised of frictional drag and form drag. Form drag in particular can lead to the creation of forces large enough to initiate block movement (rotation) where the block in question presents a frontal profile which is subject to direct impact by the flow (Baker, 1989). This is possible in the instance where, due to irregular subgrade preparation or poor installation, an individual block protrudes vertically above its immediately adjacent neighbors.

The lift force and the drag force combine to produce an overturning moment, which is resisted by the submerged weight of the element (**Figure 2.6**) Additional anchorage or mechanical restraints can provide further resistance to overturning.

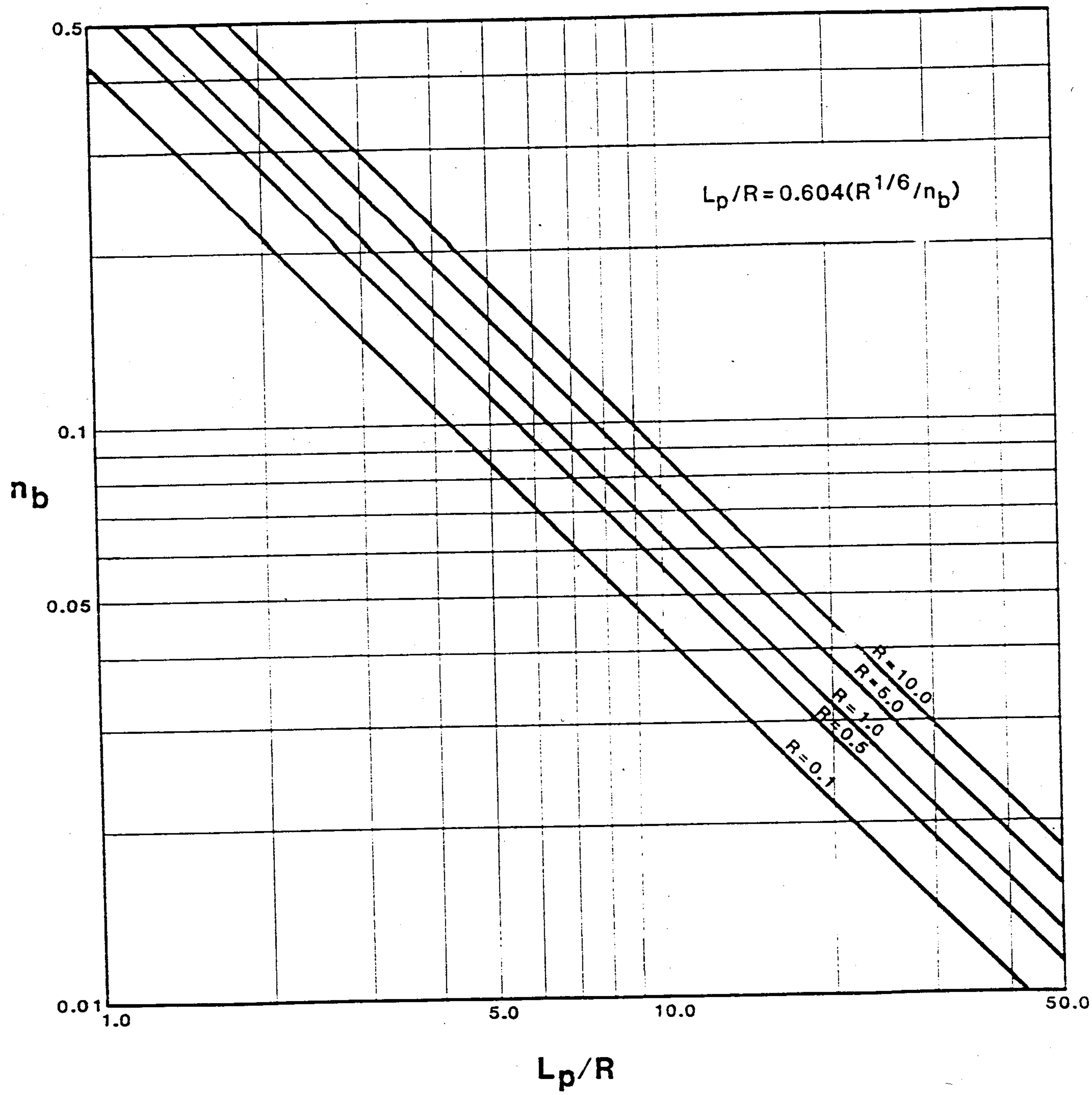


Figure 2.5. Protection length L_p downstream of channel bend.

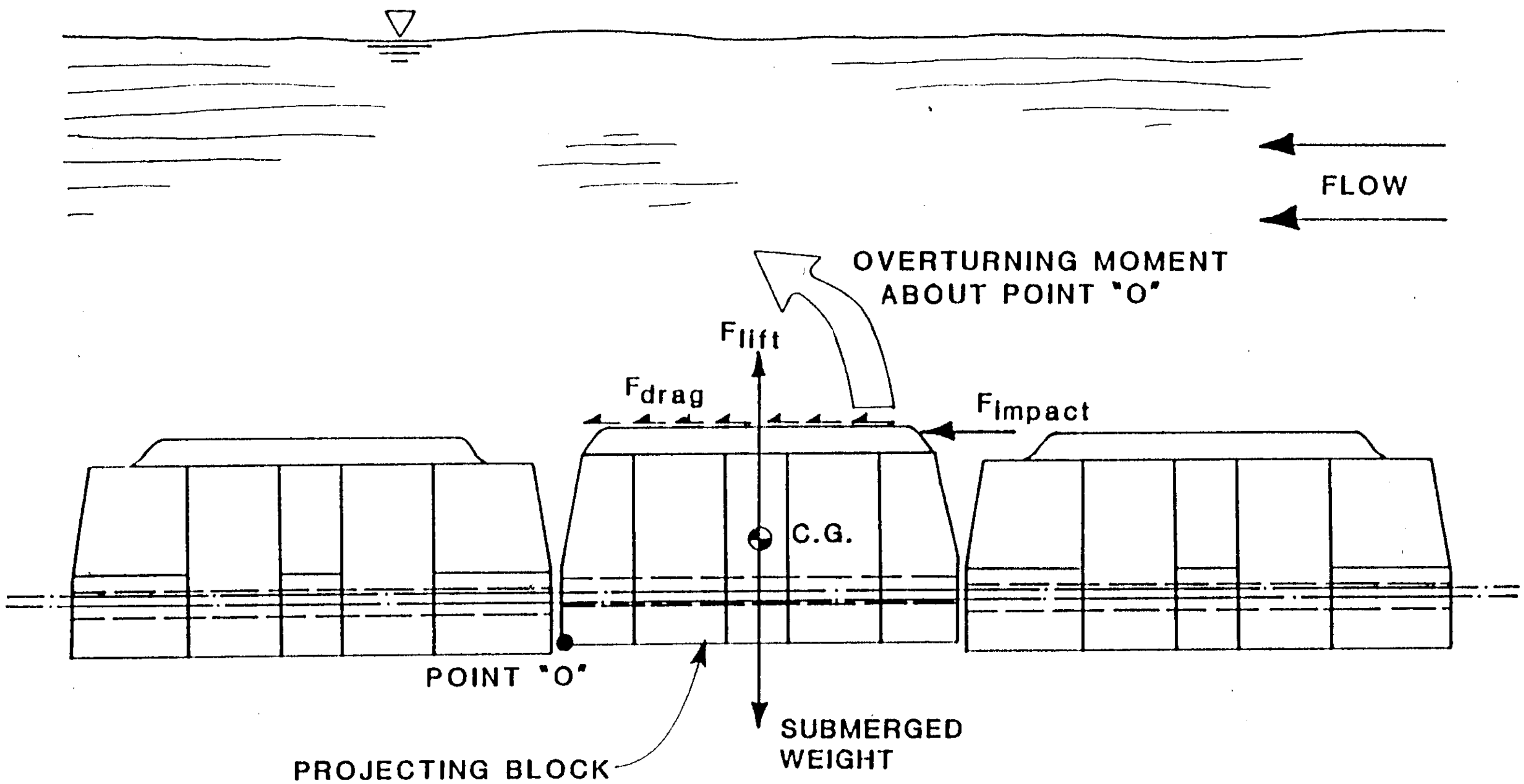


Figure 2.6. Hydrodynamic forces on a projecting block.

2.4.2 Definition of Failure

Loss of "intimate contact" between a block, or group of blocks, and the subgrade which they are to protect has been identified as the primary indicator of incipient failure (CIRIA, 1987; Clopper and Chen, 1988). Given the nature of revetment mattress installation in typical channel and spillway applications, failure due to slipping or sliding of the revetment matrix along the plane of the bed is remote and has never been observed under controlled test conditions, even in steeply sloped cases (2H:1V in the direction of flow) where no mechanical or vegetative shear restraint has been provided. This indicates that the frictional resistance to sliding which is developed between the blocks, geotextile and/or granular filter, and subgrade soil is sufficient to prevent this occurrence. The loss of intimate contact, therefore, is the result of overturning about the downstream edge, or about the downstream corner point when the block in question is located on the side slope of a steep channel. Physical dislodgement or even measurable movement does not need to occur in order for the onset of undesirable ingress of seepage flow into the sub-block environment to initiate and progress.

Acceptance of the foregoing developments leads to the definition of "failure" of an articulated block revetment system as the condition of <u>incipient overturning</u>; that is, when overturning moments equal resisting moments about the downstream edge (or corner point). Incipient overturning denotes the condition whereby the ingress of flow beneath the system is imminent, and continued intimate contact cannot be guaranteed. This definition of failure appears reasonably conservative in that the potential ability of a subsystem drainage medium (drainage net or granular filter) to conduct away limited sub-block flows is not depended upon by the designer; neither is any restraining force which can be attributed to cables considered, because the mobilization of tension forces in cables can only come into play once finite rotation has occurred, by which time the system has already been defined as having "failed."

2.4.3 Hydraulic Stability and the Factor of Safety Method

Both lift and drag on a block produce overturning moments proportional to their magnitude and to the length of the moment arms through which they act. The primary resistance to overturning is provided by the submerged weight of the block acting through the center of gravity, and its moment arm. The condition of incipient overturning is thus dependent on the hydraulic conditions of flow and the size, weight, and geometric characteristics of the revetment block within its matrix. This condition yields to analysis and quantification by way of the Factor of Safety method, developed originally by Simons and Senturk (1977) in their derivation of a methodology for evaluating the stability of rock riprap in open-channel flow. In their method, the critical shear stress at which particle motion is initiated was assumed to correspond to a Shields number of 0.047, as developed by Meyer-Peter (1948). In the case of articulated block revetment systems, the critical shear stress is determined through controlled hydraulic testing and measurement, allowing the development which parallels that of Simons and Senturk (see Appendix A).

The Factor of Safety procedure can be extended to blocks of different dimensions and weights, providing they are geometrically similar to the system for which the critical shear was previously determined through laboratory testing; that is, the blocks must be of the same "family" in terms of method of interlock, profile configuration, and characteristics of boundary roughness and interaction with the flow field. Given this basic similarity, the weight and dimensions of the block can be used with those of the tested block to determine the critical shear stress through a force balance approach:

$$\ell_2 W = F_L \ell_4 + F_D \ell_3 \tag{2.8}$$

Assuming that $F_L = F_D = F$, and designating subscripts t for the tested block and u for the untested block, then

$$\tau_{cu} = \tau_{ct} \frac{W_u \quad \ell_{2u} \, (\ell_{4t} + \ell_{3t})}{W_t \quad \ell_{2t} \, (\ell_{4u} + \ell_{3u})} \tag{2.9}$$

where W_u and W_t are the submerged weights of the untested block and the tested block, respectively. The complete set of terms for the Factor of Safety method have thus been defined for the untested block, and stability analyses may proceed.

Hydraulic stability can be enhanced through the use of mechanical soil anchors, subsystem drainage layers, and vegetative root anchorage. However, the concept of stability analysis, as presented, assumes a conservative approach which demands that each individual block within the matrix maintains stability independent of additional aids or amendments. A target safety factor is specified, typically 1.5 for open-channel bed and bank erosion protection projects, and the product selection and channel cross-section/profile configurations are chosen such that the resulting safety factor remains at or above the target value for all reaches under consideration. The design charts presented in the following chapters utilize the recommended Factor of Safety of 1.5 in their development.

III. MILD GRADIENT HYDRAULIC DESIGN PROCEDURE

3.1 General

This chapter presents Armorflex selection and design curves for straight channels of trapezoidal cross-section under conditions of uniform flow, with bed slopes up to 10 percent. The charts are based on standard bottom widths of 4, 8, 12, 20, 50, and 100 ft, and sideslope ratios of 2:1, 3:1, and 4:1. The range of bed slopes and discharges which the charts encompass will span most practical engineering applications. All curves have been prepared with a Factor of Safety of 1.5, using the developments presented in Chapter II and in Appendix A. The effect of additional lift and drag due to the potential for imprecise field placement of individual blocks has also been incorporated into the development of the selection and design charts. A vertical projection of [illegible] inches has been assumed, which is felt to be a value reasonably achieved under standard construction and installation practices, for purposes of design and specification for typical project conditions.

3.2 Use of the Selection and Design Charts and the Factor of Safety Method

This section presents two worked examples which illustrate the use of the Factor of Safety methodology for mild channel gradients ($S < 0.10$). The first example corresponds to the direct use of the charts for the assessment of hydraulic stability using the various classes of Armorflex revetment; the second example details the use of the Factor of Safety method, as presented in Appendix A, for situations which do not correspond to those for which the charts were prepared.

3.2.1 Example 1

Given:	Design discharge	Q = 1,300 cfs
	Average bed slope	S = 0.025 (2.5 percent)

A trapezoidal channel with 3H:1V sideslopes is proposed. Channel width is unconstrained; open-cell revetment is preferred for the encouragement of native grasses. Depth of flow is limited to 3.5 ft in order to meet required flowline elevation at downstream end of project.

Solution:

Step 1:

Assuming Armorflex Class 30 or Class 50 will be used for erosion protection, choose Manning's n of 0.032 and enter Figure 2.1 with standard bottom widths of 8, 12, and 20 ft to determine depth of flow for preliminary sizing of channel:

From Figure 2.1, with Qn = (1300)(0.032) = 41.6:

- Base width B = 8 ft, depth of flow = 4.4 ft
- Base width B = 12 ft, depth of flow = 4.0 ft
- Base width B = 20 ft, depth of flow = 3.3 ft

-> CHOOSE BASE WIDTH B = 20 FT FOR TRAPEZOIDAL CHANNEL

Step 2:

Determine stability of Armorflex Classes from Chart 3.10 (trapezoidal channel, B = 20, z = 3):

Entering Chart 3.10 with Q = 1,300 cfs and S = 0.025, the point falls above the stability line for Class 30 Armorflex, and below the stability line for Class 50 Armorflex. This indicates that the Class 50 Armorflex will provide stable erosion protection with a Factor of Safety greater than 1.5.

-> CHOOSE ARMORFLEX CLASS 50 REVETMENT

Step 3:

Check hydraulic conditions for vegetated revetment using Figures 2.1 and 2.2, assuming final vegetative condition will correspond to Class C retardance (Table 2.1):

First iteration: using depth of flow of 3.3 ft from Step 1, calculate

V = Q/A = 13.2 ft/s
R = A/P = 2.41 ft
VR = (13.2)(2.41) = 31.9

Extrapolating from Figure 2.2, the Manning's n value for fully vegetated conditions will be approximately 0.030, as the n versus VR relationship tends to asymptote to a constant n-value as the VR term increases beyond a value of about 20. Using this new value for Manning's n, hydraulic conditions are recomputed and the procedure repeated, yielding new values of the hydraulic conditions as follows:

Depth of flow = 3.2 ft
Velocity = 13.8 ft/s
Hydraulic radius = 2.34 ft
VR = (13.8)(2.34) = 32.3

Rechecking Figure 2.2, it is seen that the n-value will remain at approximately 0.030, indicating that the iterative procedure has converged to final values.

<u>Step 4</u>:

Summarize hydraulic conditions for Armorflex Class 50 channel with B = 20 ft, Q = 1,300 cfs, S = 0.025, and z = 3H:1V:

<u>Unvegetated</u>:	Depth	= 3.3 ft
	Velocity	= 13.2 ft/s
	Manning's n	= 0.032
<u>Vegetated</u>:	Depth	= 3.2 ft
	Velocity	= 13.8 ft/s
	Manning's n	= 0.030

3.2.2 Example 2

<u>Given</u>: Design discharge Q = 500 cfs
Average bed slope = 0.046 (4.6 percent)

A trapezoidal channel with sideslopes of 2.5H:1V is proposed. Due to right-of-way constraints, the bottom width B is limited to 15 ft. The designer is required to select an erosion-protection material which will result in a stable channel within reasonable economic limits.

Solution:

Neither the sideslope angle "z" nor the maximum allowable width "B" correspond to the standard applications provided by the selection and design charts of this manual. Guidance through the application of the methodology provided in Appendix A is therefore indicated.

Step 1:

As a conservative approach, the information content provided by the selection and design charts is consulted. Assuming a steeper sideslope angle of 2H:1V and a narrower channel bottom width of 12 ft, both of which will result in higher hydraulic stresses than the actual design conditions, Chart 3.3 is entered with Q = 500 cfs and S = 0.046. From this chart, either Armorflex Class 70 open-cell blocks or Class 85 closed-cell blocks could be specified with a Factor of Safety greater than the recommended minimum of 1.5. Considering that the actual hydraulic stresses will be somewhat less than provided for by Chart 3.3, the designer wishes to evaluate the potential for using either Class 50 open-cell revetment, or Class 55 closed-cell revetment, and still maintain a Factor of Safety of 1.5 or greater.

Step 2:

Compute hydraulic conditions. For Class 50, the recommended Manning's n Value is 0.032. For Class 55, the recommended Manning's n value is 0.026. These resistance coefficients yield the following hydraulic values, using the actual design parameters of B = 15 and z = 2.5 and the previously described procedures:

Class 50		Class 55	
Depth	= 1.93 ft	Depth	= 1.72 ft
Velocity	= 13.1 ft/s	Velocity	= 15.1 ft/s
Hyd. radius	= 1.51 ft	Hyd. radius	= 1.37 ft
Bed shear	= 5.53 psf	Bed shear	= 4.93 psf

Step 3:

Referring to Figure A.1 of Appendix A,

$\theta = \tan^{-1}(1/2.5) = 21.8°$

$\lambda = \tan^{-1}(0.046) = 2.63°$

From Equation A.28 and Table A.1,

Class 50 Armorflex blocks, $\eta = 5.53/20 = 0.277$

Class 55 Armorflex blocks, $\eta = 4.93/23 = 0.214$

From Equation A.22 and Table A.1, and conservatively assuming that $F_L = F_D$,

$$\frac{M}{N} = \frac{\ell_4}{\ell_3}\frac{F_L}{F_D} = \frac{0.54}{0.40} = 1.35 \text{ for both classes}$$

And from Equation A.27,

$$\beta = \tan^{-1}\left\{\frac{\cos(2.63°)}{\left(\frac{1.35 + 1}{\eta}\ \frac{0.25}{0.73}\right)\sin(21.8°) + \sin(2.63°)}\right\}$$

Therefore,

Class 50 Armorflex blocks, $\beta = 41.6°$

Class 55 Armorflex blocks, $\beta = 34.7°$

From Figure A.1,

$\delta = 90, - \beta - \lambda$

So Class 50 Armorflex blocks, $\delta = 45.8°$

Class 55 Armorflex blocks, $\delta = 52.7°$

From Equation A.21,

Class 50 Armorflex blocks, $\eta' = 0.241$

Class 55 Armorflex blocks, $\eta' = 0.178$

Now the effect of possible vertical projections in the flow must be considered. Consistent with the derivation of the design charts in this manual, it is assumed that an installation specification tolerance of 0.5 inches in the vertical dimension will be maintained. Therefore, from Equation A.38,

$$F_D' = (0.5)\left(\frac{0.5}{12}\right)(1.08)(1.94)(V^2) = 0.0437\ V^2$$

For Class 50 Armorflex, $V = 13.1$ so $F_D' = 7.5$
For Class 55 Armorflex, $V = 15.1$ so $F_D' = 10.0$

Now, assuming that the additional lift due to the vertical displacement is equal to the additional drag (that is, $F_L' = F_D'$), then from Equations A.33 and A.36,

$$SF = \frac{\frac{\ell_2}{\ell_1}\cos\theta}{\eta' \frac{\ell_2}{\ell_1} + \sin\theta\cos\beta + \frac{\ell_3 F_D' \cos\delta + \ell_4 F_L'}{\ell_1 W_A}}$$

For Class 50 Armorflex,

$$SF = \frac{\frac{0.73}{0.25}\cos(21.8^\circ)}{0.241\left(\frac{0.73}{0.25}\right) + \sin(21.8^\circ)\cos(41.6^\circ) + \frac{0.40(7.5)\cos(45.8^\circ) + 0.54(7.5)}{0.25(28.6)}}$$

$$= \frac{2.711}{0.7037 + 0.2777 + 0.8590}$$

$\underline{SF = 1.47}$ (Class 50)

For Class 55 Armorflex,

$$SF = \frac{\frac{0.73}{0.25}\cos(21.8^\circ)}{0.178\left(\frac{0.73}{0.25}\right) + \sin(21.8^\circ)\cos(34.7^\circ) + \frac{0.40(10.0)\cos(52.7^\circ) + 0.54(10)}{0.25(33.3)}}$$

$$= \frac{2.711}{0.5198 + 0.3053 + 0.9398}$$

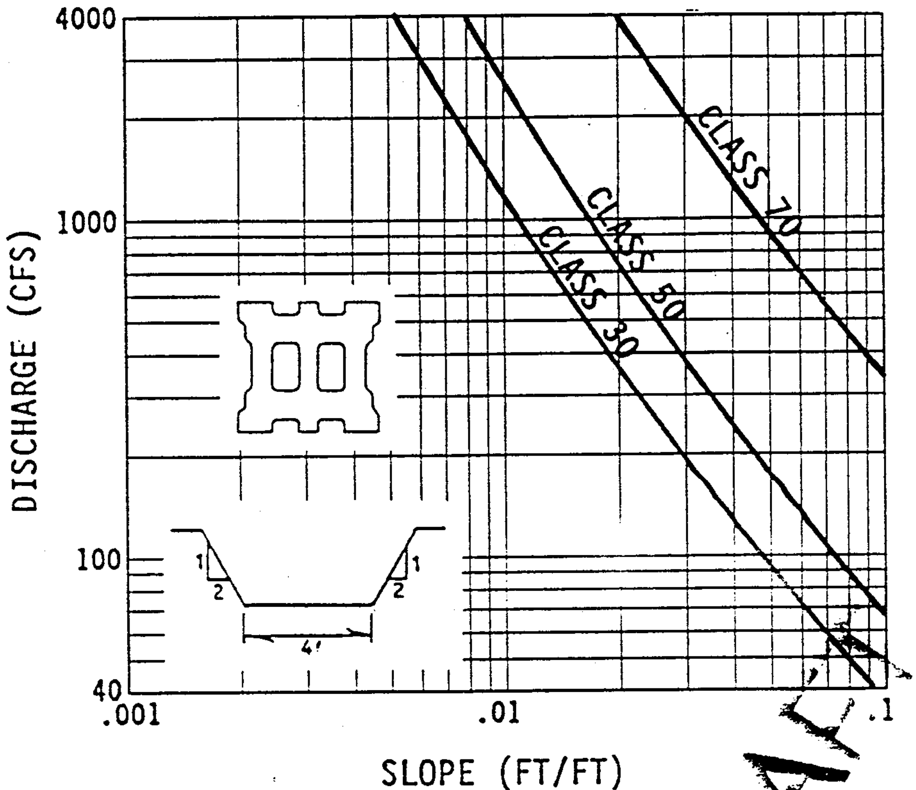
$\underline{SF = 1.54}$ (Class 55)

Step 4:

Conclude that Class 50 Armorflex blocks exhibit a Factor of Safety slightly less than the target value of 1.50; Class 55 Armorflex blocks exhibit a Factor of Safety slightly greater than 1.50.

--> RECOMMEND CLASS 55 ARMORFLEX

Note: This detailed example, though somewhat cumbersome, illustrates the use of the Factor of Safety method for the selection of appropriate revetment under "nonstandard" channel conditions. The practitioner will be able to utilize this procedure where local areas of increased shear stress, such as in channel bends, or higher velocities, such as at channel constrictions, exist and nonuniform flow conditions prevail.


4000
1000
100
40
DISCHARGE (CFS)
CLASS 70
CLASS 50
CLASS 30
1
2
1
2
4'
.001
.01
.1
SLOPE (FT/FT)

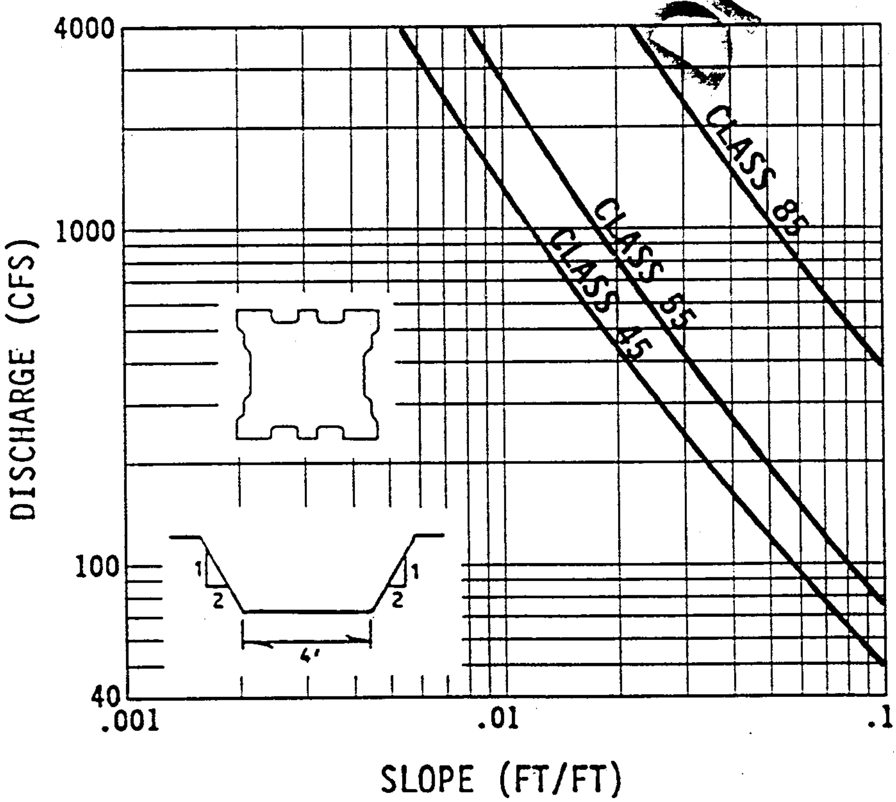
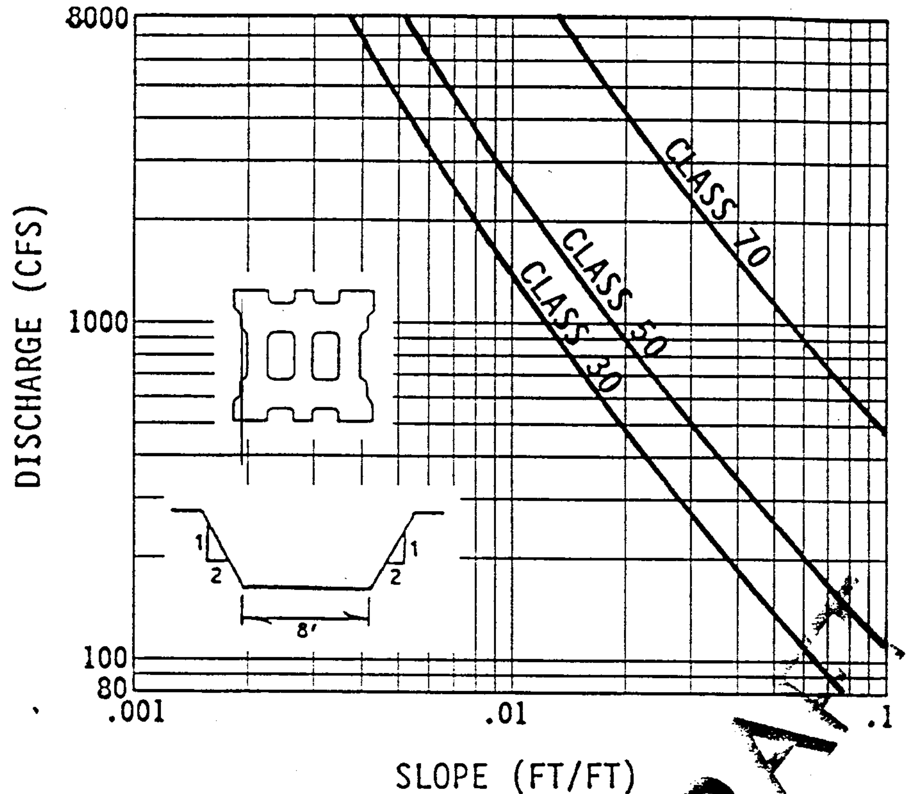

4000
1000
100
40
DISCHARGE (CFS)
CLASS 85
CLASS 55
CLASS 45
1
2
1
2
4'
.001
.01
.1
SLOPE (FT/FT)

CHART 3.1


8000
1000
100
80
.001
.01
.1
DISCHARGE (CFS)
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
2
8'

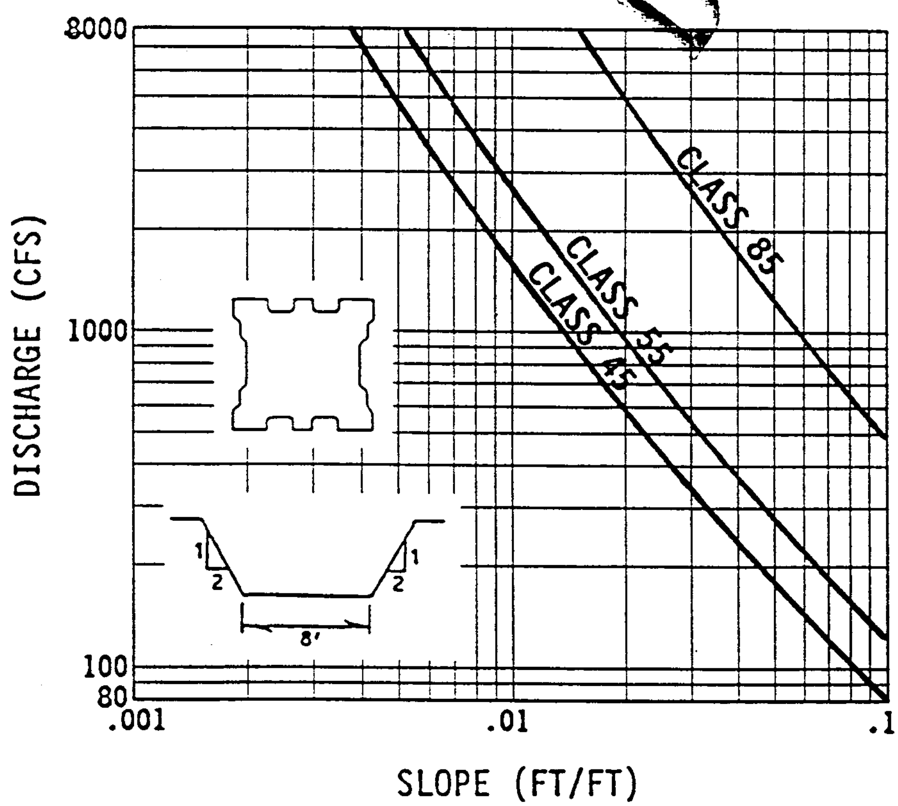
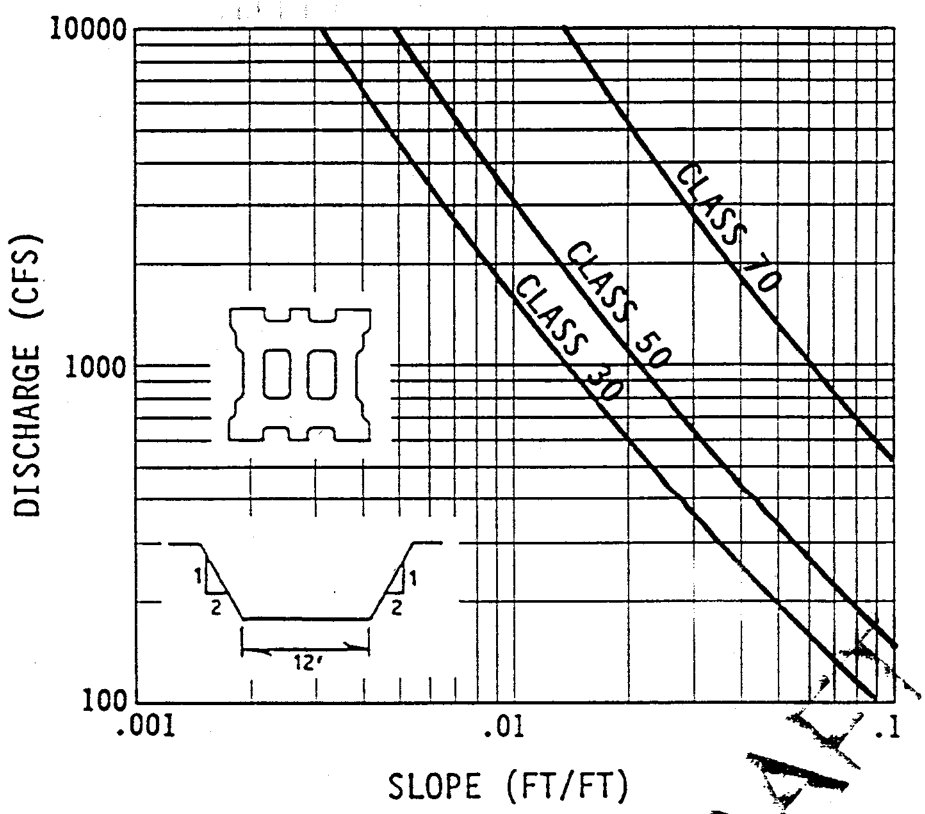

8000
1000
100
80
.001
.01
.1
DISCHARGE (CFS)
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
2
8'

CHART 3.2


10000
1000
100
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
2
1
2
12'

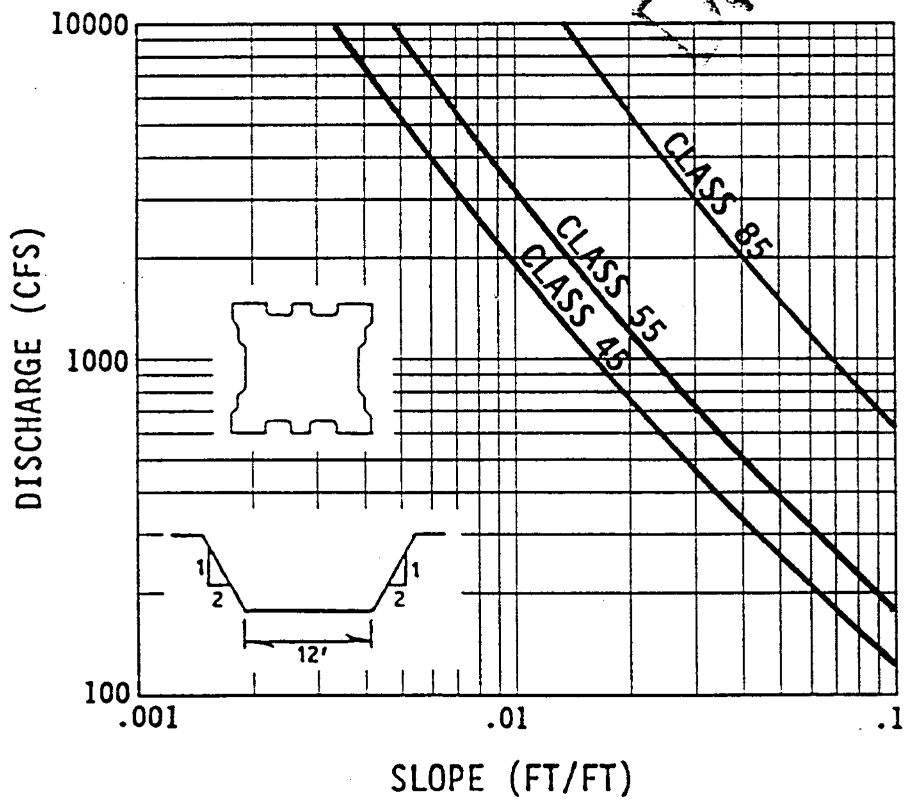
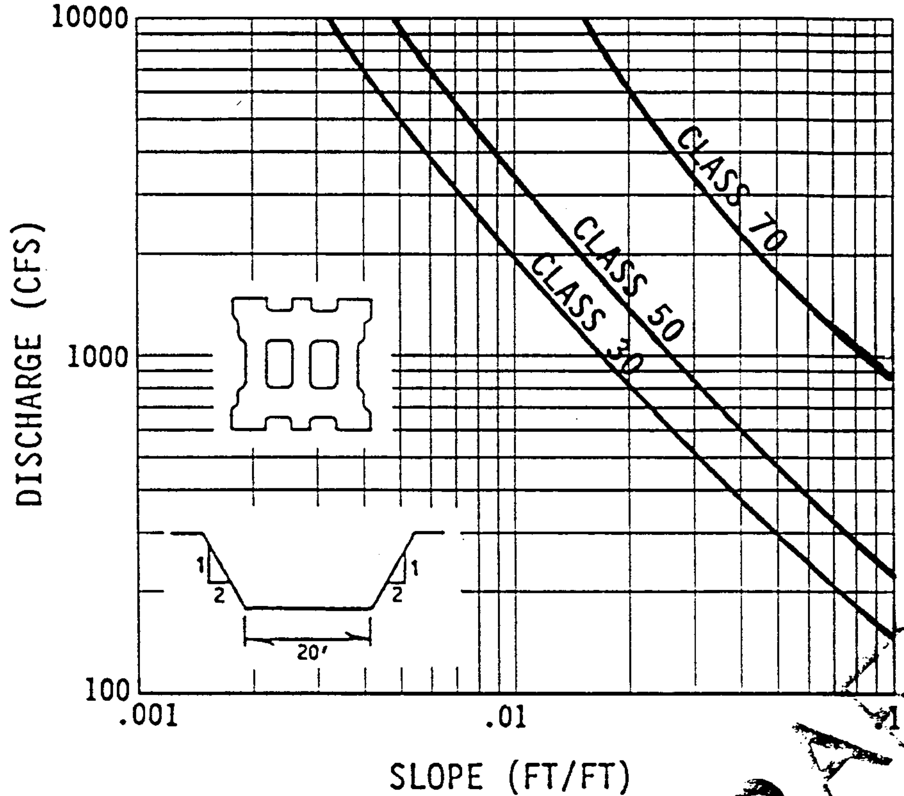

10000
1000
100
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
2
1
2
12'

CHART 3.3


10000
1000
100
.001
.01
.1
DISCHARGE (CFS)
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
2
20'

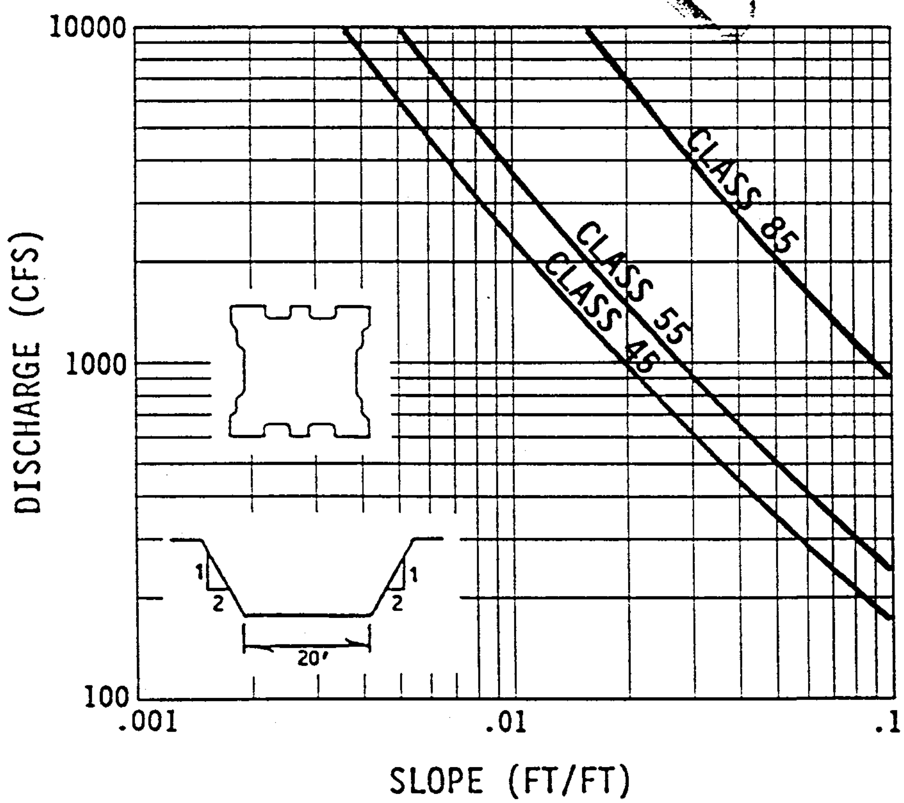
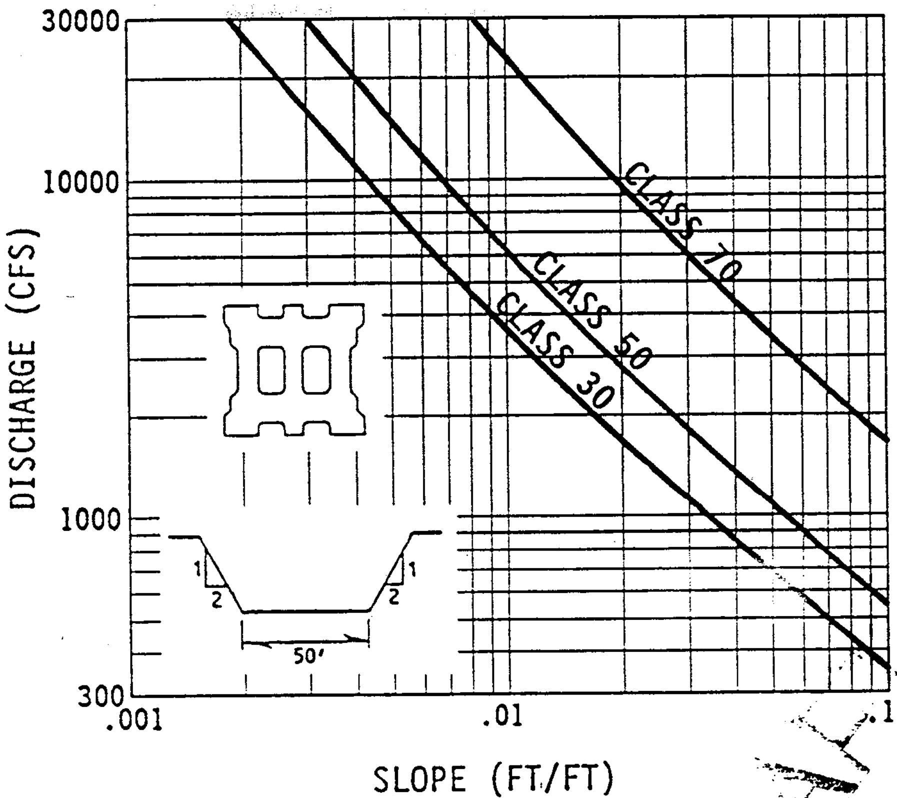

10000
1000
100
.001
.01
.1
DISCHARGE (CFS)
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
2
20'

CHART 3.4


30000
10000
1000
300
.001
.01
.1
DISCHARGE (CFS)
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
2
1
2
50'

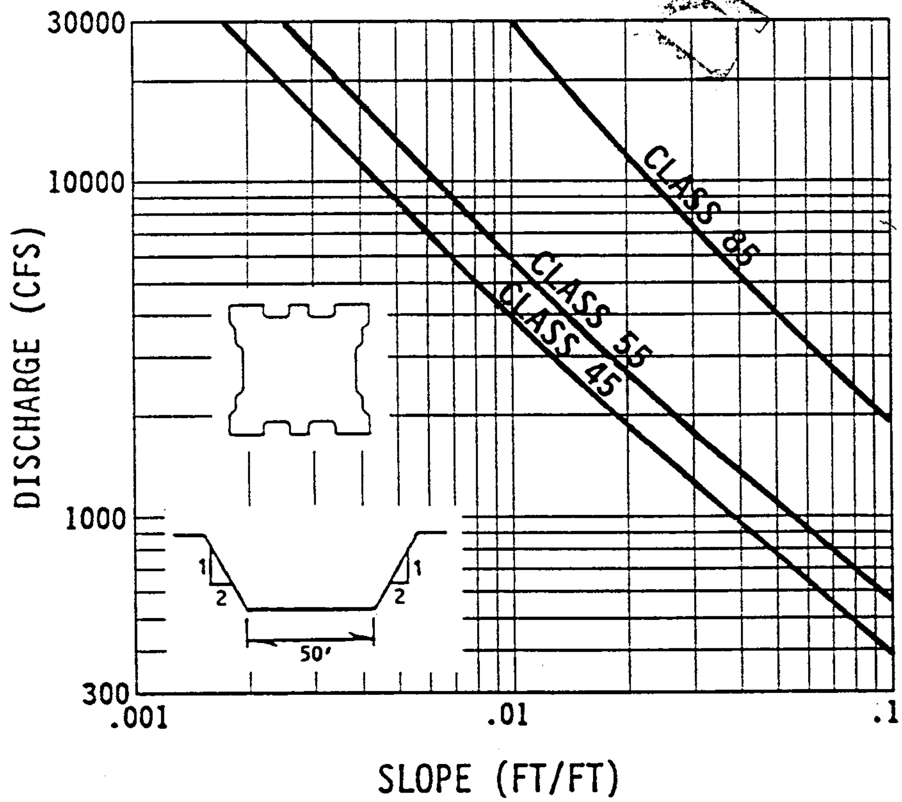
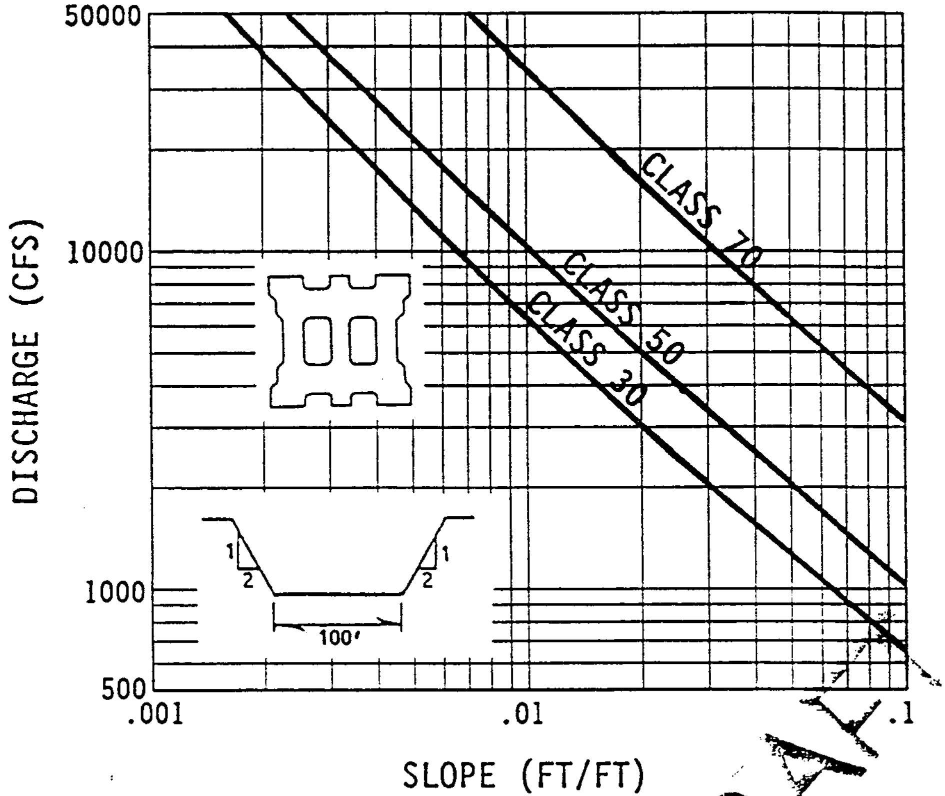

30000
10000
1000
300
.001
.01
.1
DISCHARGE (CFS)
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
2
1
2
50'

CHART 3.5


50000
10000
1000
500
DISCHARGE (CFS)
CLASS 70
CLASS 50
CLASS 30
1
2
1
2
100'
.001
.01
.1
SLOPE (FT/FT)

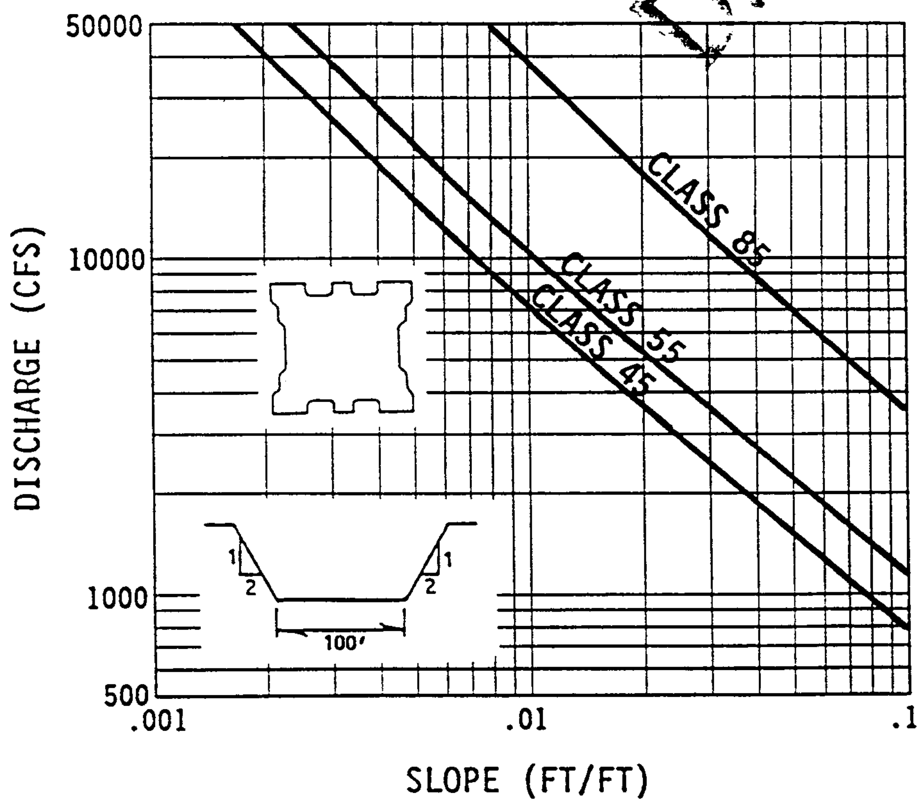
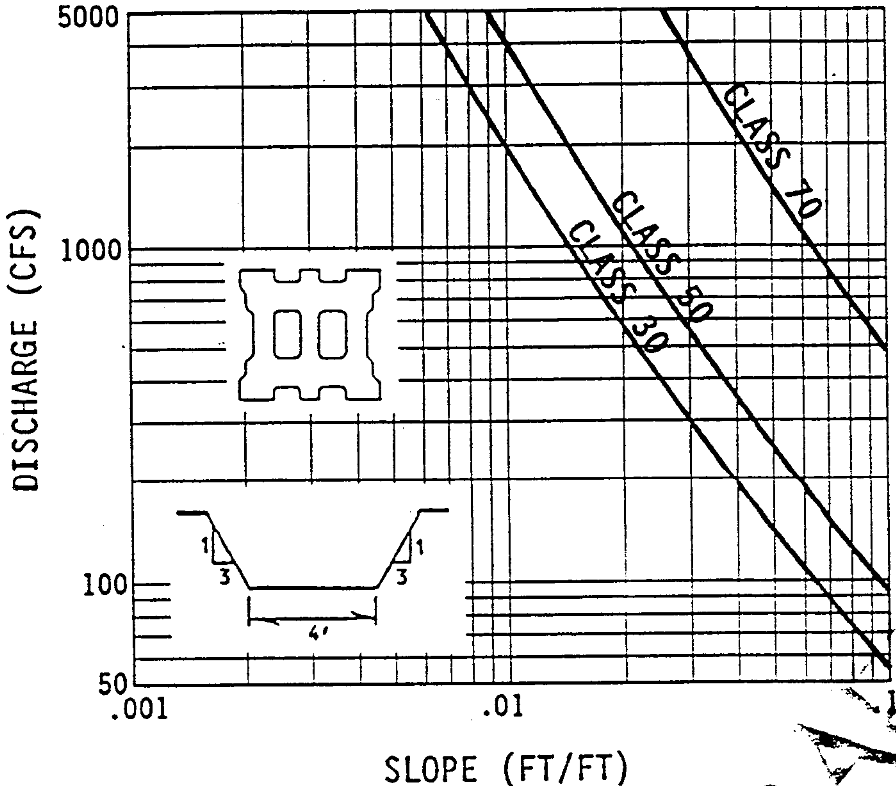
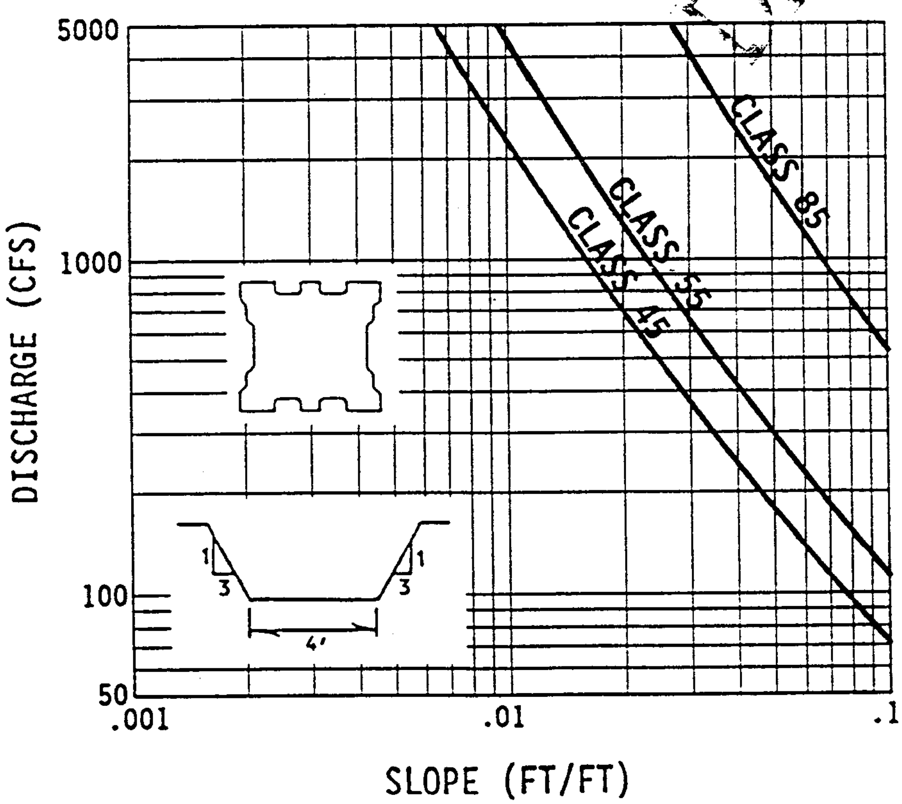

50000
10000
1000
500
DISCHARGE (CFS)
CLASS 85
CLASS 55
CLASS 45
1
2
1
2
100'
.001
.01
.1
SLOPE (FT/FT)

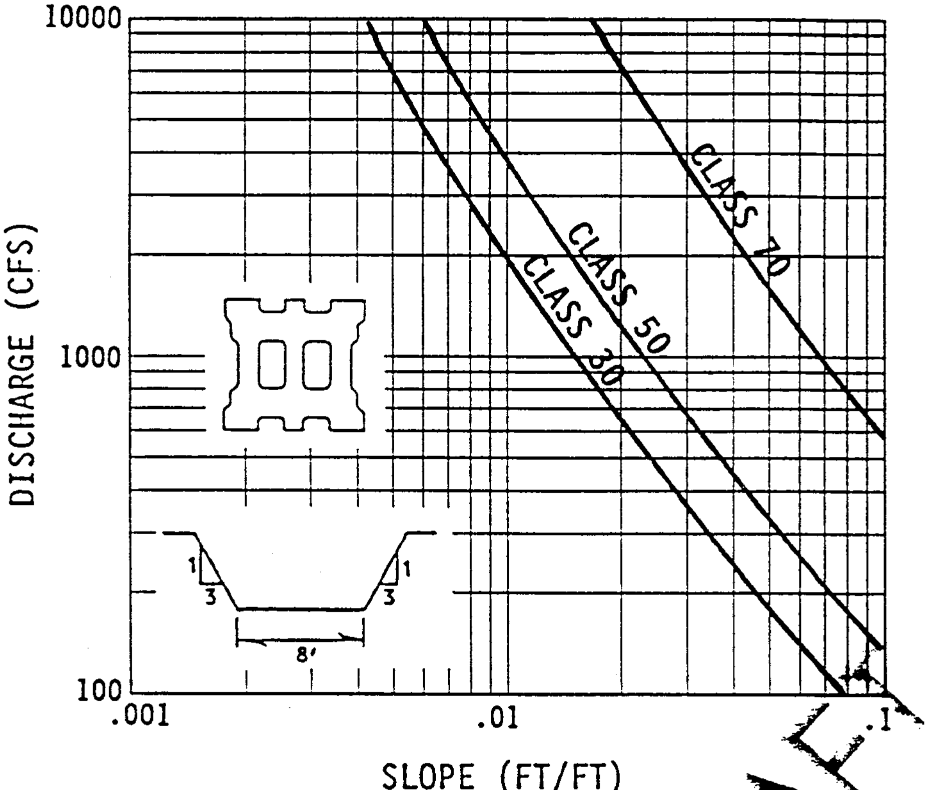
CHART 3.6





DRAFT

CHART 3.7


10000
1000
100
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
3
1
3
8'

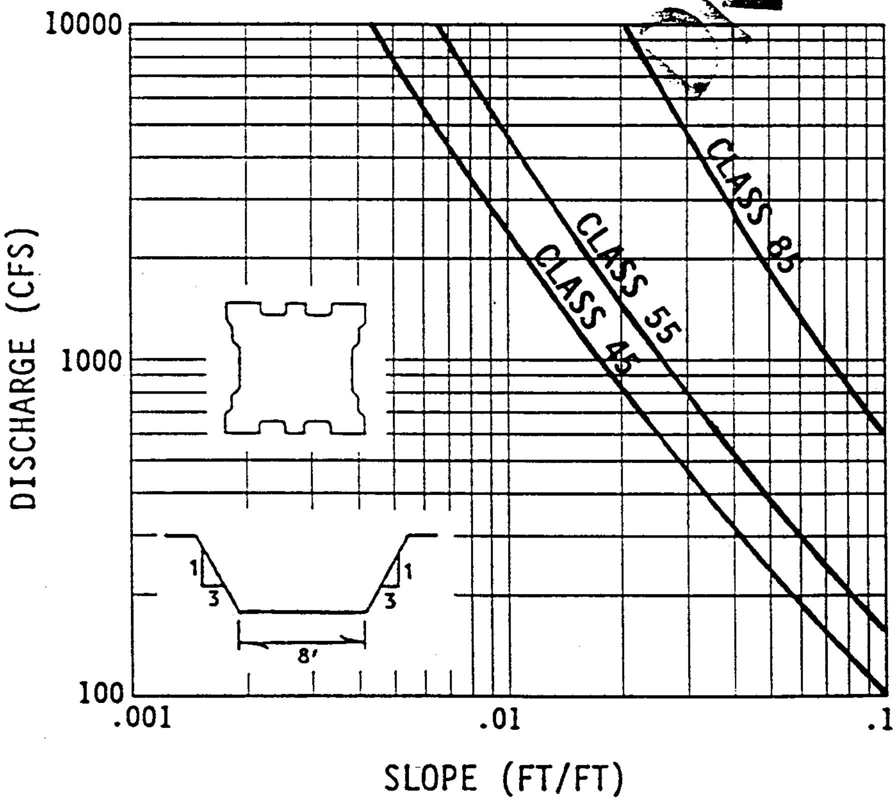
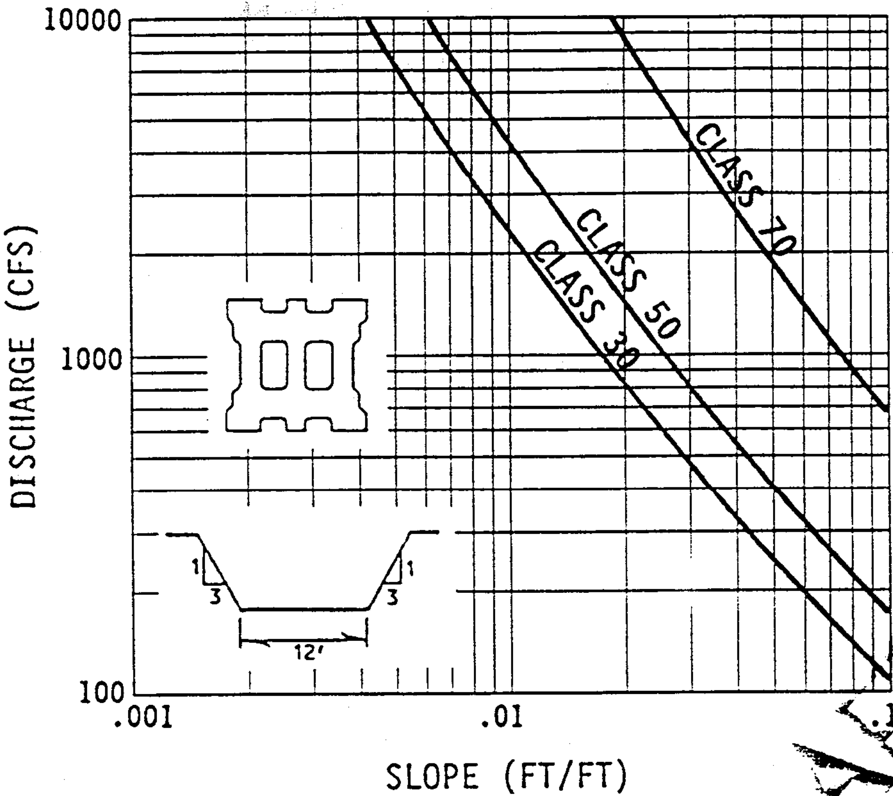

10000
1000
100
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
3
1
3
8'

CHART 3.8


10000
1000
100
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
3
1
3
12'

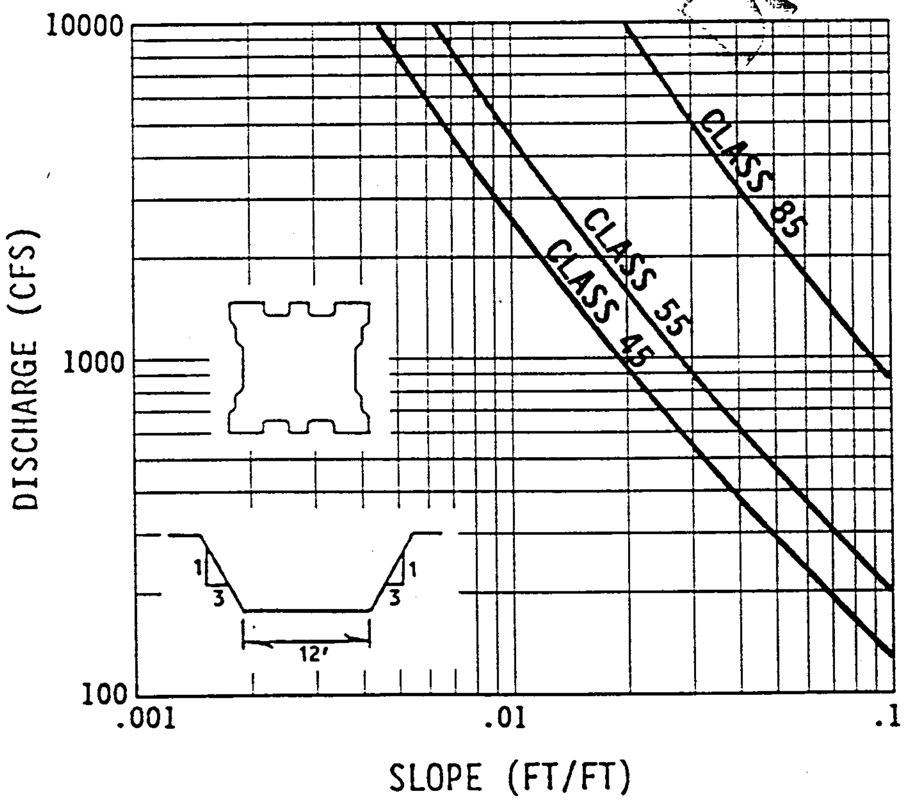
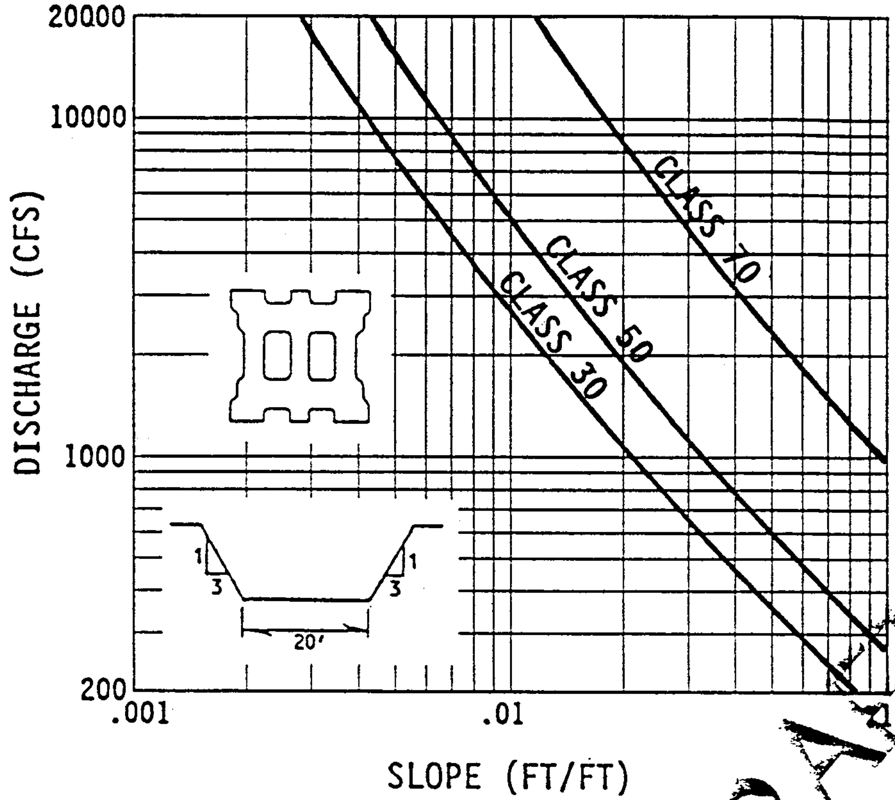
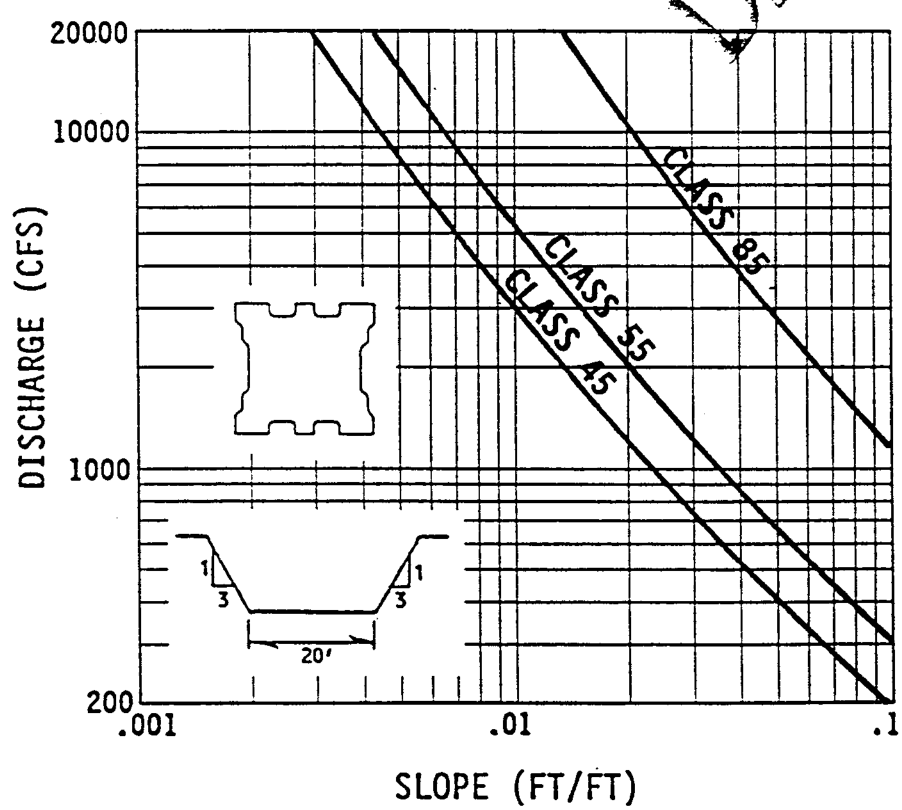

10000
1000
100
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
3
1
3
12'

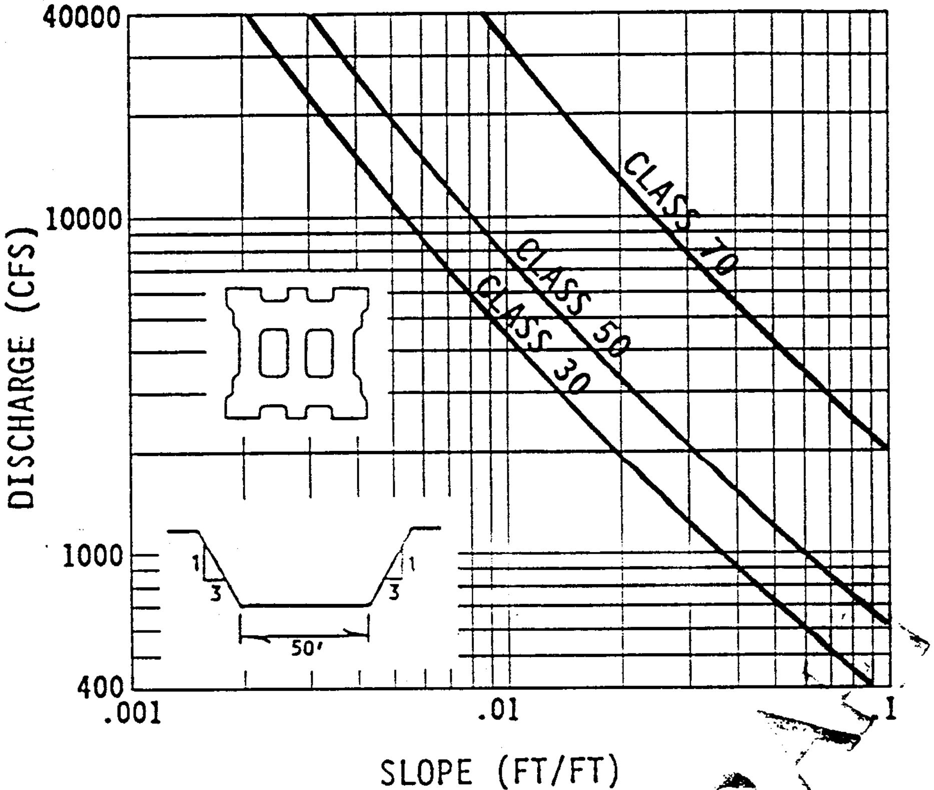
CHART 3.9





DRAFT

CHART 3.10


40000
10000
1000
400
.001
.01
.1
DISCHARGE (CFS)
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
3
50'

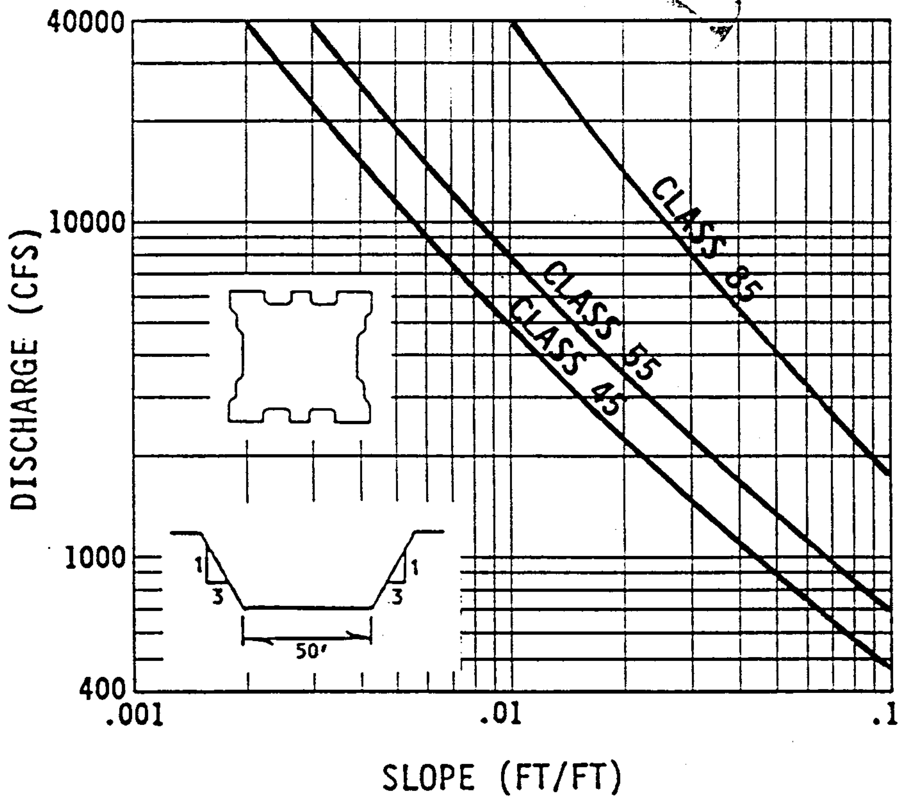
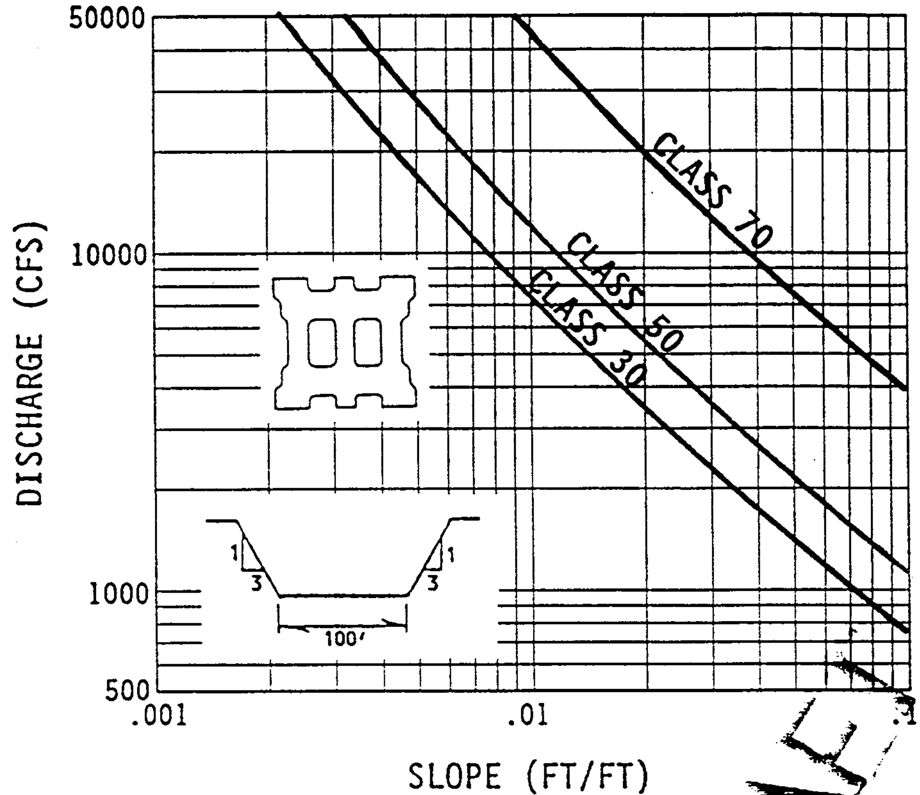

40000
10000
1000
400
.001
.01
.1
DISCHARGE (CFS)
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
3
50'

CHART 3.11


50000
10000
1000
500
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
3
1
3
100'

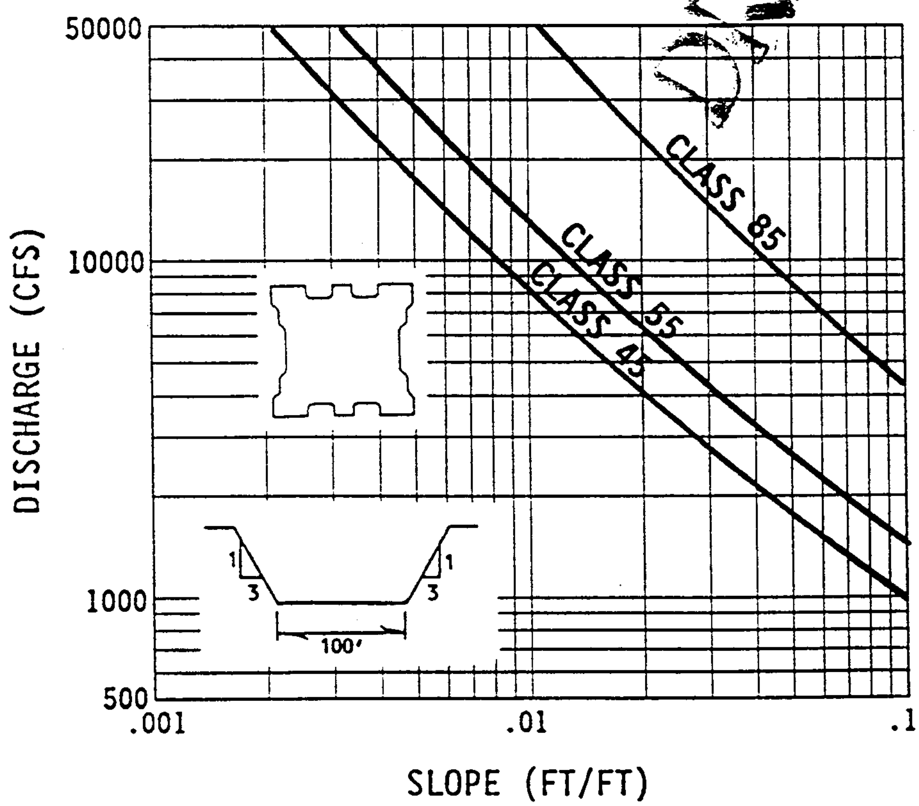
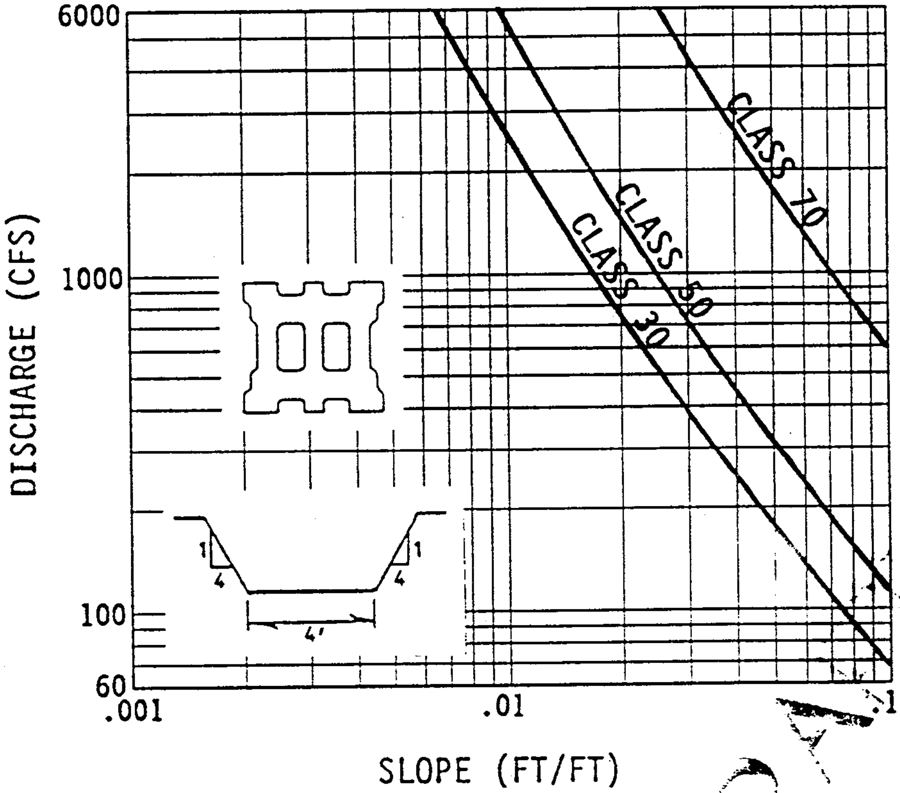

50000
10000
1000
500
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 43
1
3
1
3
100'

CHART 3.12


6000
1000
100
60
.001
.01
.1
DISCHARGE (CFS)
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
4
4'

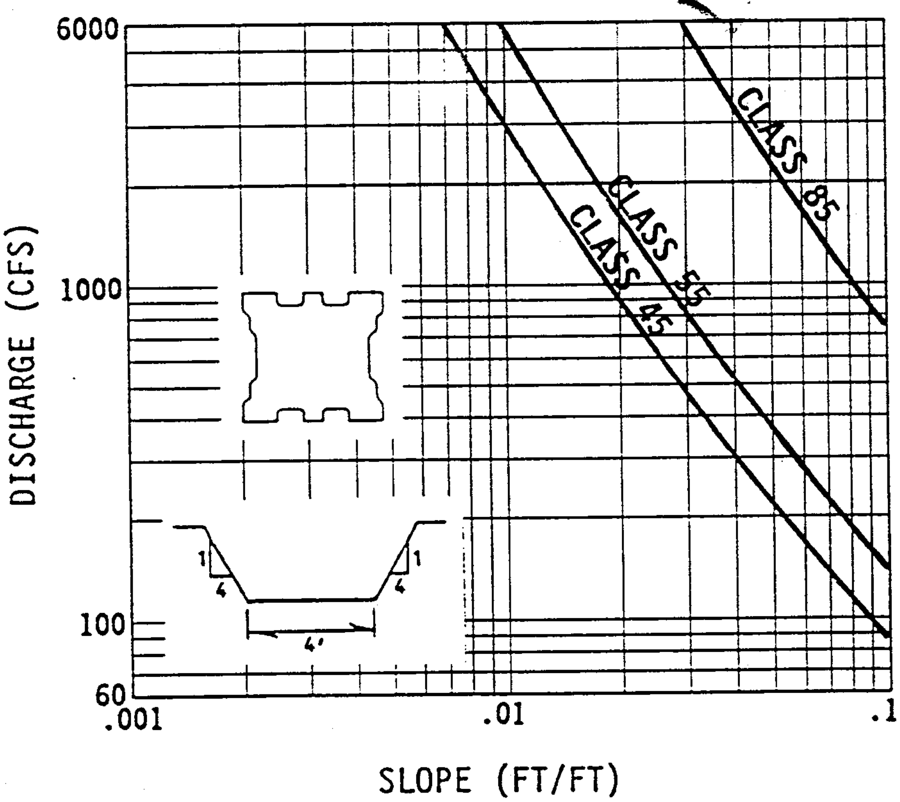
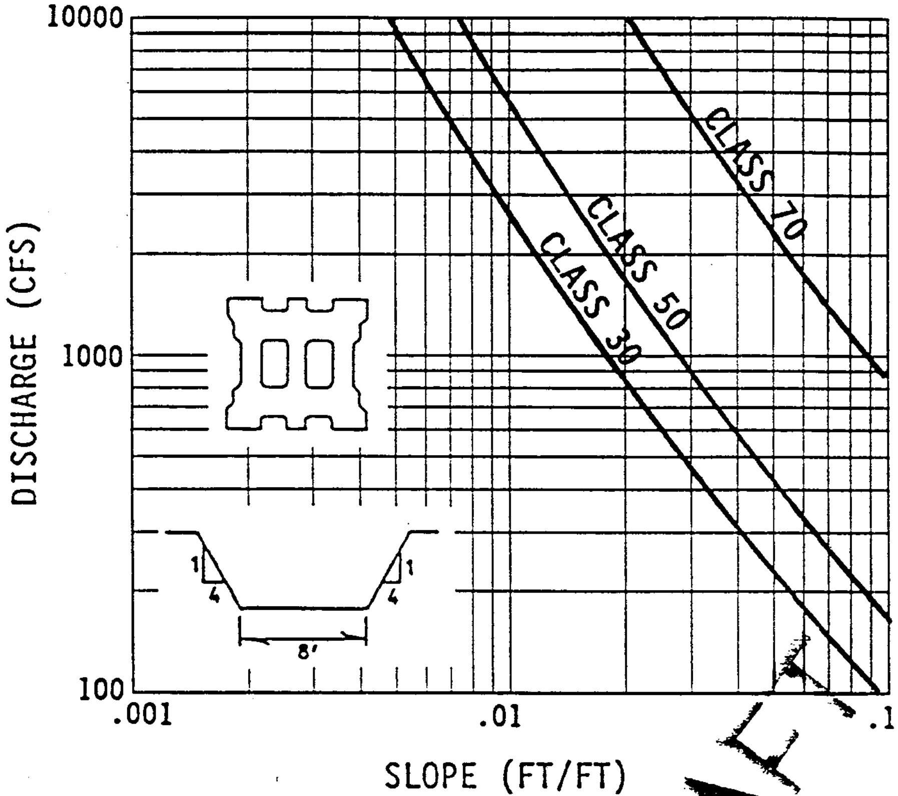

6000
1000
100
60
.001
.01
.1
DISCHARGE (CFS)
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
4
4'

CHART 3.13


10000
1000
100
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
4
1
4
8'

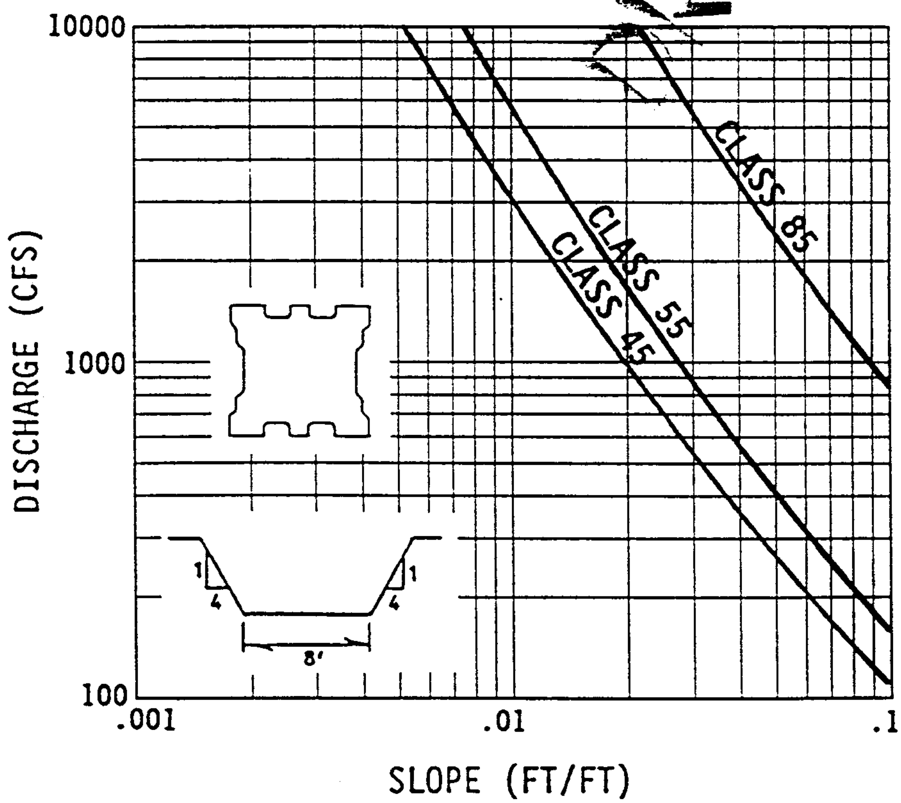
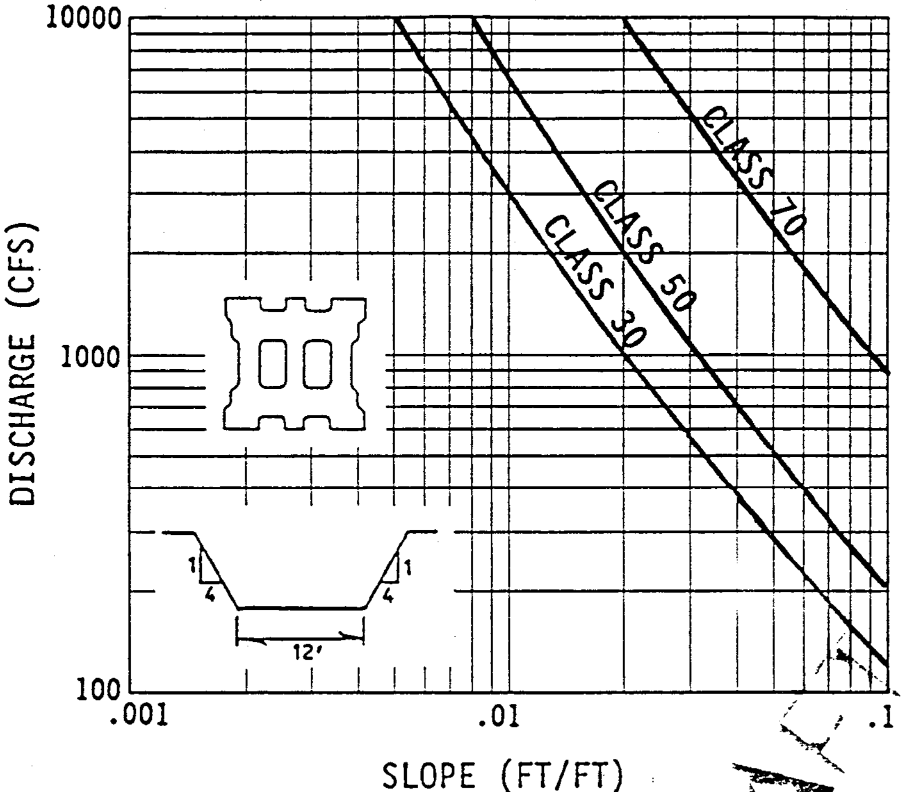

10000
1000
100
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
4
1
4
8'

CHART 3.14


10000
1000
100
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
4
1
4
12'

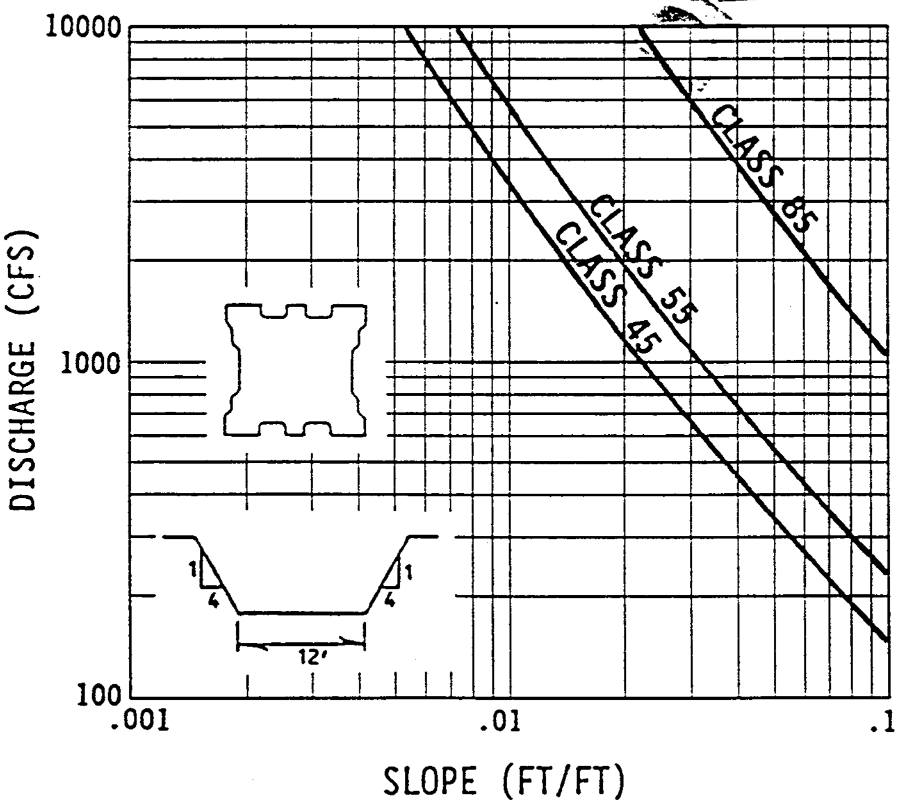
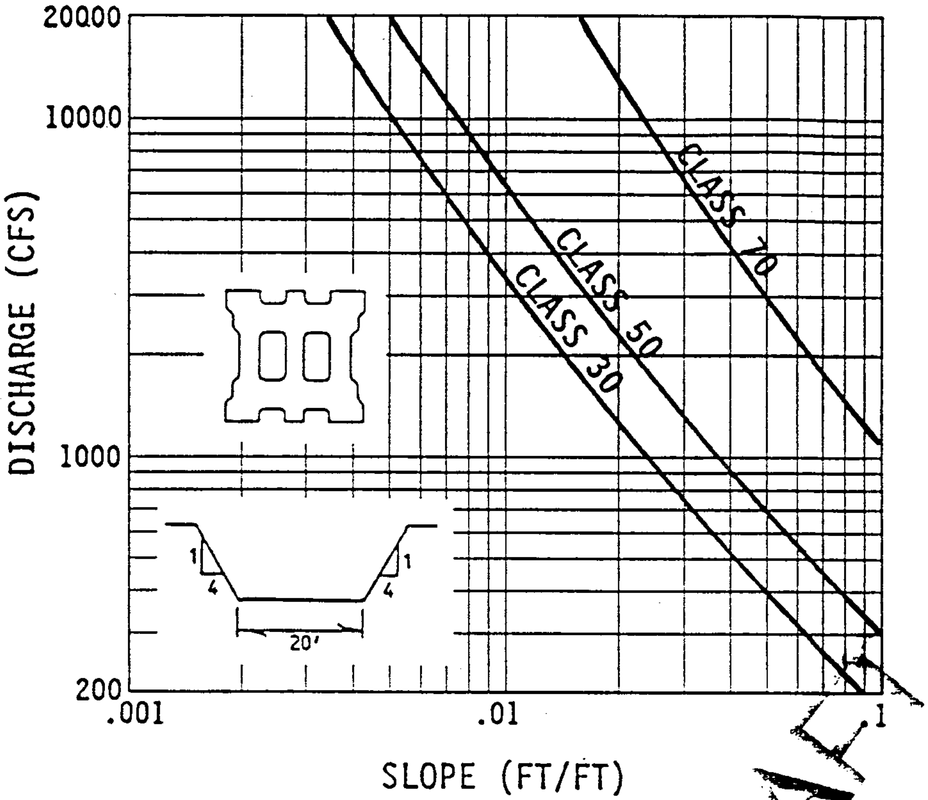

10000
1000
100
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
4
1
4
12'

CHART 3.15


20000
10000
1000
200
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
4
1
4
20'

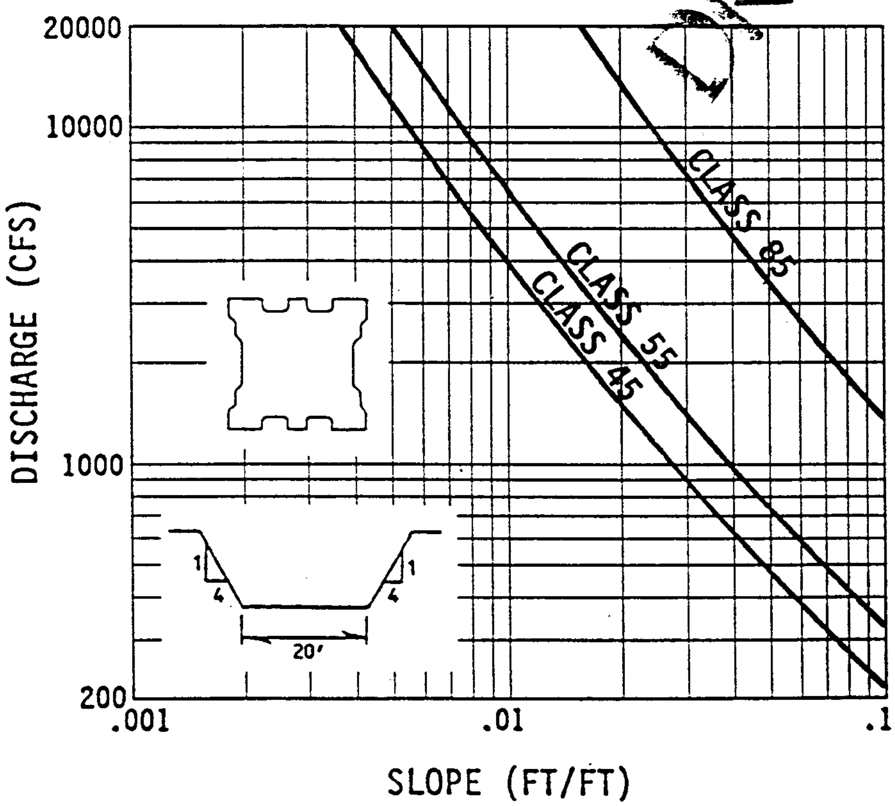
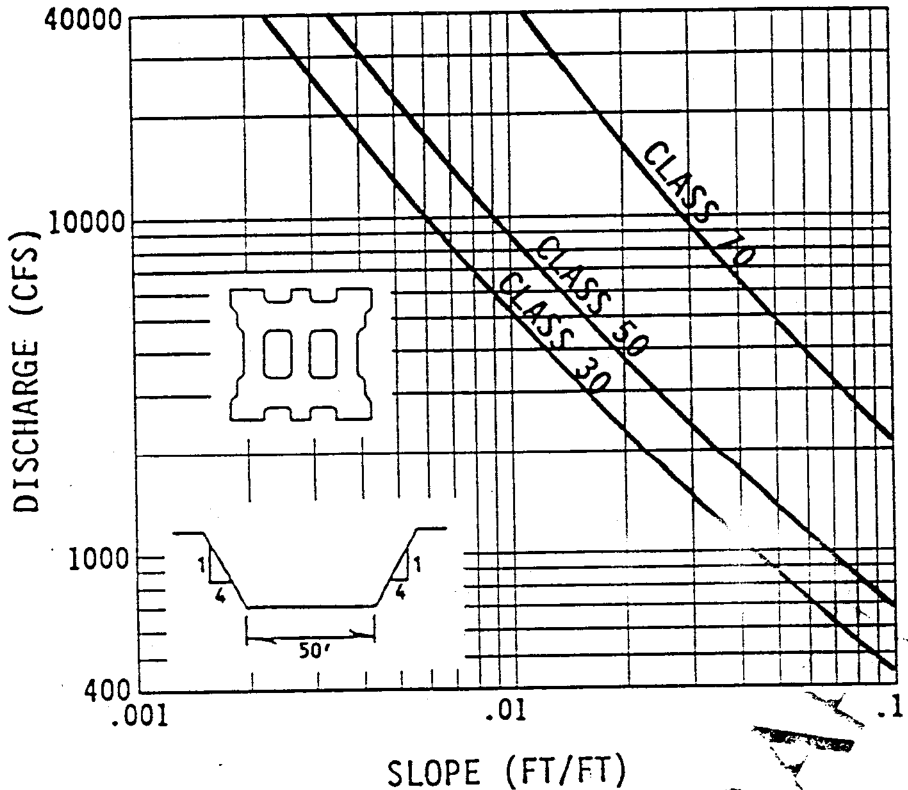

20000
10000
1000
200
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
4
1
4
20'

CHART 3.16


40000
10000
1000
400
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
4
50'

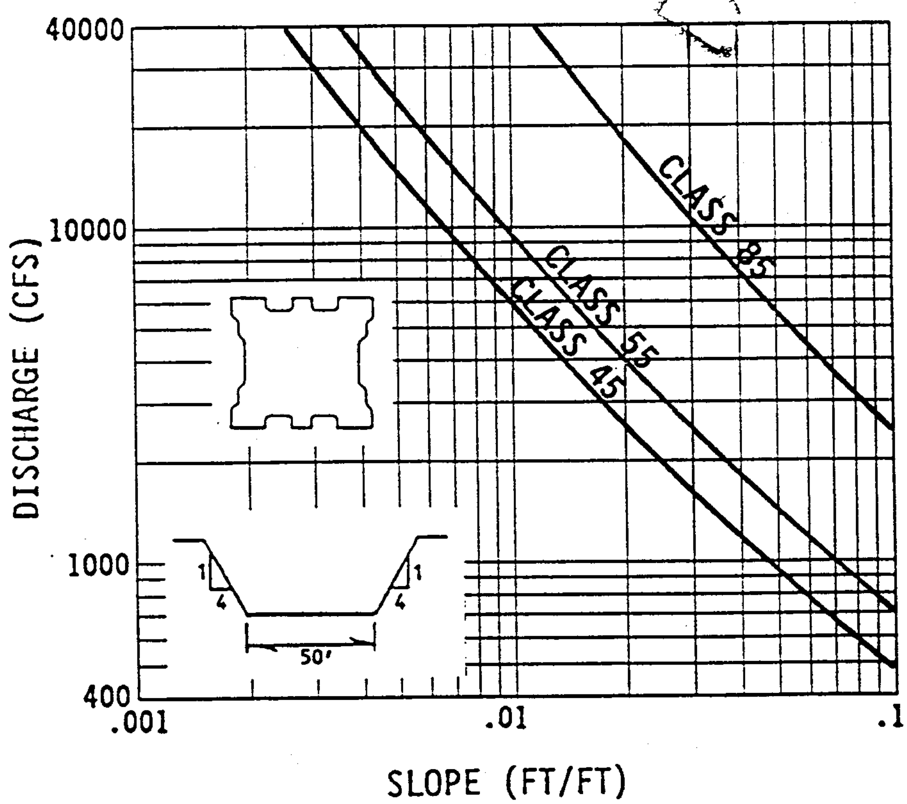
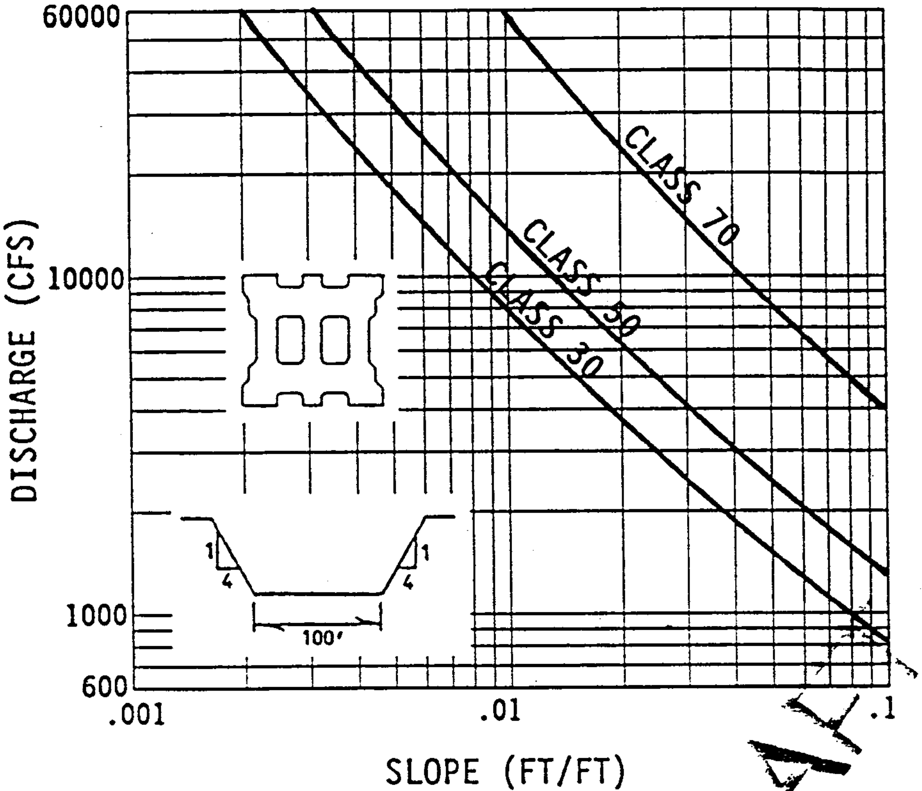

40000
10000
1000
400
DISCHARGE (CFS)
.001
.01
.1
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
4
50'

CHART 3.17


60000
10000
1000
600
.001
.01
.1
DISCHARGE (CFS)
SLOPE (FT/FT)
CLASS 70
CLASS 50
CLASS 30
1
4
100'

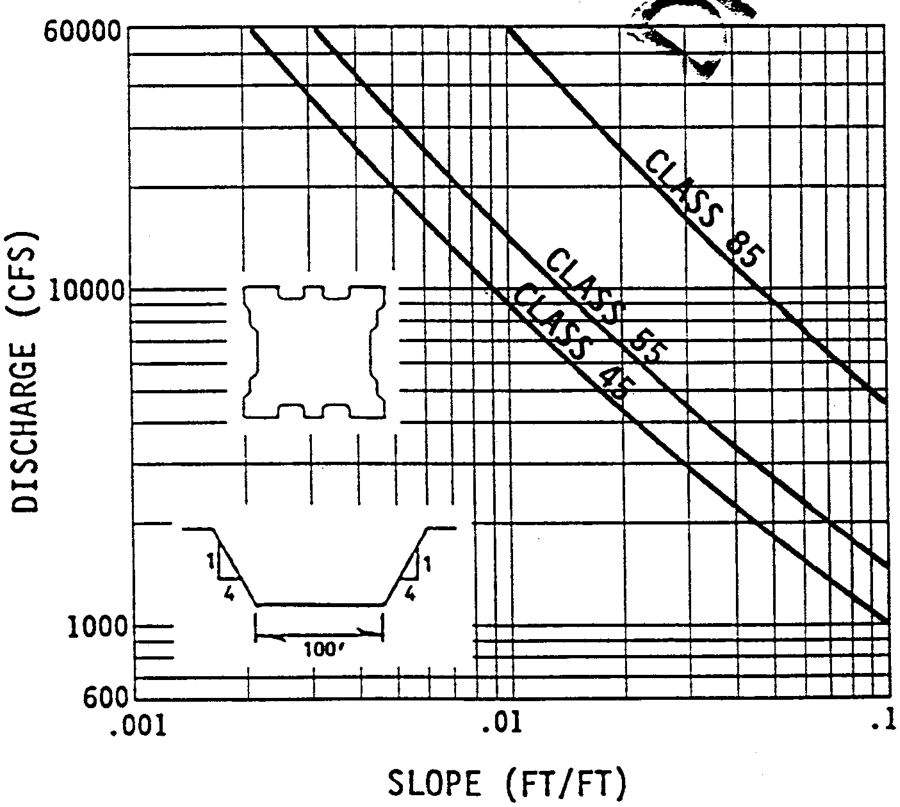

60000
10000
1000
600
.001
.01
.1
DISCHARGE (CFS)
SLOPE (FT/FT)
CLASS 85
CLASS 55
CLASS 45
1
4
100'

CHART 3.18

APPENDIX A

FACTOR OF SAFETY METHOD FOR EVALUATING THE STABILITY OF ARMORFLEX BLOCKS

A.1 General

The design of **Armorflex** systems is currently accomplished with the use of hydraulic design criteria contained within a technical bulletin published by the manufacturer (Armortec, Inc., 1981). The design procedures in this bulletin are based on standard hydraulic analysis techniques for open-channel flow and channel stability. These techniques, while based on sound hydraulic principals, do not take into account the most recent hydraulic test data for the product. Full-scale hydraulic test of the **Armorflex** Class 30 system have recently been conducted by SLA for the Federal Highway Administration and the U.S. Bureau of Reclamation. These tests indicate that **Armorflex** Class 30 blocks are considerably more stable than shown by the current design procedure. The current design procedure is based in part on the Shields relationship, developed to evaluate the stability of natural particles on a stream bed. This relationship does not take into account the greater stability of **Armorflex** blocks which are specifically designed to resist motion.

A revised design procedure for **Armorflex** systems has been developed utilizing the recent test data. The procedure is based on incorporation of the test data into a force balance calculation for the movement of a single **Armorflex** block. The approach is similar to that used to derive the "factor of safety" method of riprap design as described in <u>Sediment Transport Technology</u> (Simons and Senturk, 1977). The force balance has been recomputed considering the properties of **Armorflex** blocks with the Shields relationship utilized in the Simons and Senturk approach to compute the critical shear stress replaced with the recent test results.

The following sections describe the development of the force balance for **Armorflex** blocks and how the test results for Class 30 blocks (the only class of blocks tested) can be extrapolated to other classes of **Armorflex** blocks. Included is the development of the theory for considering additional drag forces caused by projecting blocks in the force balance. The hydraulic tests were conducted on carefully placed blocks without projections, a condition which may not always be achieved in field installations.

A.2 Stability of a Single Armorflex Block on a Sloping Surface

The stability of a single **Armorflex** block on a sloping surface is a function of the magnitude and direction of the stream velocity, the depth of flow, the angle of the inclined surface on which it rests, and its geometric properties and weight.

Consider flow along a channel bank as shown on **Figure A.1**. The forces acting on an **Armorflex** block resting on the sloping surface are the lift force F_L, the drag force F_D, and the weight of the block W_A. The block's stability is determined by evaluating the moments about the point 0 about which rotation can take place. The components of forces relative to the plane of motion (assumed to act along the resultant force R) are shown in Figure A.1c. The relationship that defines the equilibrium of the block is:

$$\ell_2 W_A \cos\theta = \ell_1 W_A \sin\theta \cos\beta + \ell_3 F_d \cos\delta + \ell_4 F_L \qquad \text{(A.1)}$$

The symbols are defined in Figure A.1. The factor of safety SF for the Armorflex block is defined as the ratio of the moments resisting motion to those tending to rotate the block out of its resting position. Accordingly:

$$SF = \frac{\ell_2 W_A \cos\theta}{\ell_1 W_A \sin\theta \cos\beta + \ell_3 F_d \cos\delta + \ell_4 F_L} \qquad \text{(A.2)}$$

If there is no flow (F_L and $F_D = 0$) and if the sideslope angle is increased to incipient failure of the block (call this angle ϕ), the factor of safety becomes unity. Then,

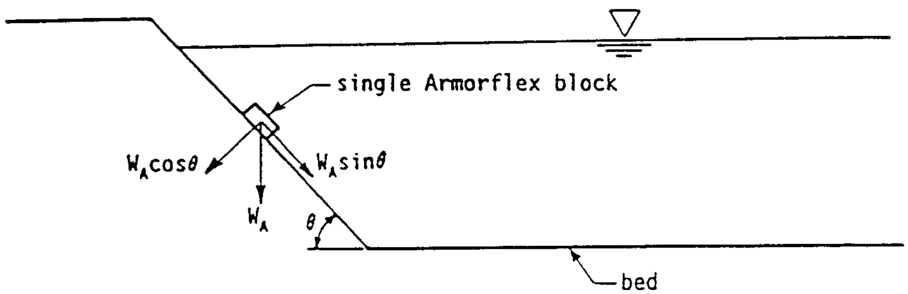
$SF = 1.0$

$\theta = \phi$

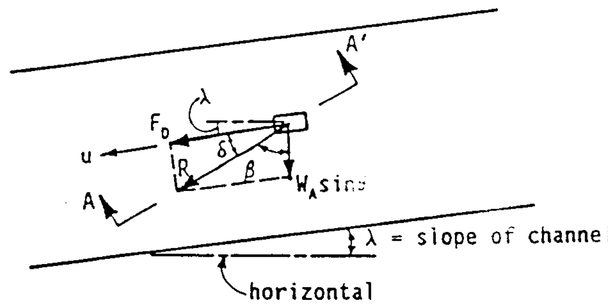
$\beta = 0°$

$\lambda = 0°$

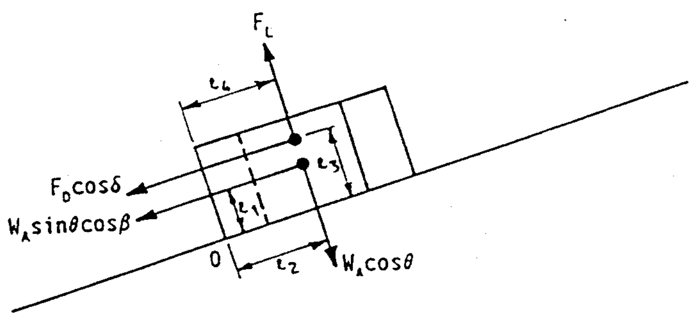
With these values, Equation A.2 becomes:



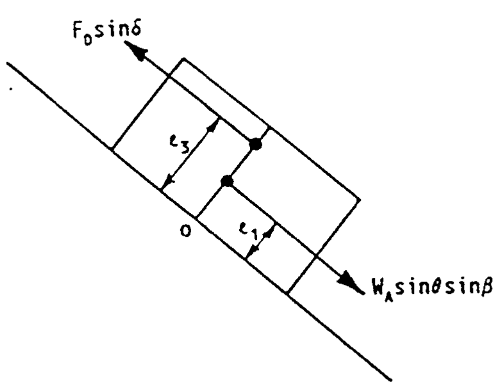
a. Cross section view.



b. View normal to the sideslope.



c. Section A-A'.



d. View normal to Section A-A'.

Figure A.1. Forces acting on a single Armorflex block resting on the sideslope of a channel.

$$\frac{\ell_2\ W_A\ \cos\phi}{\ell_1\ W_A\ \sin\phi} = 1 \qquad \text{(A.3)}$$

or

$$\tan\phi = \frac{\ell_2}{\ell_1} \qquad \text{(A.4)}$$

That is, the ratio of the moment arms ℓ_2/ℓ_1 is characterized by the angle at which the block would tip over on a sloping surface (assuming that it would not slide first).

Dividing both numerator and denominator by $\ell_1\ W_A$, Equation A.2 becomes:

$$SF = \frac{\cos\theta\ (\frac{\ell_2}{\ell_1})}{\eta'\ \frac{\ell_2}{\ell_1} + \sin\theta\ \cos\beta} \qquad \text{(A.5)}$$

where

$$\eta' = \frac{\ell_3\ F_d}{\ell_2\ W_A}\cos\delta + \frac{\ell_4\ F_L}{\ell_2\ W_A} \qquad \text{(A.6)}$$

The angle λ shown in Figure A.1 is the angle between the horizontal and the velocity vector (or drag force) measured in the plane of the sideslope. Then

$$\cos\delta = \cos(90 - \lambda - \beta) = \sin(\lambda + \beta) \qquad \text{(A.7)}$$

Also

$$\sin\delta = \sin(90 - \lambda - \beta) = \cos(\lambda + \beta) \qquad \text{(A.8)}$$

and

$$\sin\delta = \cos\lambda\ \cos\beta - \sin\lambda\ \sin\beta \qquad \text{(A.9)}$$

For motion along R, the moments of the drag force F_D and the component of the submerged weight $W_A \sin\theta$ normal to the path R must be balanced. Then

$$\ell_3 F_D \sin\delta = \ell_1 W_A \sin\theta \sin\beta \tag{A.10}$$

it follows from Equations A.9 and A.10 that:

$$\sin\beta = \frac{\ell_3 F_D \sin\delta}{\ell_1 W_A \sin\theta} = \frac{\ell_3 F_D (\cos\lambda \cos\beta - \sin\lambda \sin\beta)}{\ell_1 W_A \sin\theta} \tag{A.11}$$

or

$$\tan\beta = \frac{\cos\lambda}{\dfrac{\ell_1 W_A}{\ell_3 F_D} \sin\theta + \sin\lambda} \tag{A.12}$$

For flow over a plane flat bed ($\theta = 0$, $\delta = 0$):

$$\eta = \frac{\ell_3 F_D}{\ell_2 W_A} + \frac{\ell_4 F_L}{\ell_2 W_A} \tag{A.13}$$

Also Equation A.5 becomes:

$$SF = \frac{1}{\eta} \tag{A.14}$$

For incipient motion conditions for flow over a plane flat bed, SF = 1.0 by definition. From Equation A.14, $\eta = 1.0$. For flow conditions other than incipient:

$$\eta = \frac{\tau_o}{\tau_c} \tag{A.15}$$

The critical shear stress τ_c is derived from physical model tests (see Section A.5). For convenience, let:

$$M = \frac{\ell_4 F_L}{\ell_2 W_A} \tag{A.16}$$

and

$$N = \frac{\ell_3 F_D}{\ell_2 W_A} \tag{A.17}$$

In terms of the new variables, Equation A.6 becomes:

$$\eta' = (M + N \cos\delta) \tag{A.18}$$

and Equation A.13 becomes:

$$\eta = M + N \tag{A.19}$$

Thus η' and η are related by:

$$\frac{\eta'}{\eta} = \frac{\frac{M}{N} + \cos\delta}{\frac{M}{N} + 1} \tag{A.20}$$

or

$$\eta' = \{\frac{\frac{M}{N} + \cos\delta}{\frac{M}{N} + 1}\} \eta \tag{A.21}$$

From Equations A.16 and A.17, the ratio M/N can be written:

$$\frac{M}{N} = \frac{\ell_4 F_L}{\ell_3 F_D} \tag{A.22}$$

In Equation A.12, the term $\ell_1 W_A/\ell_3 F_D$ can be written as:

$$\frac{\ell_1 W_A}{\ell_3 F_D} = \frac{\ell_2 W_A \ell_1}{\ell_3 F_D \ell_2} = \frac{1}{N} \frac{\ell_1}{\ell_2} \tag{A.23}$$

according to Equation A.17. From Equation A.13:

$$N = \frac{\eta}{(\frac{M}{N} + 1)} \tag{A.24}$$

Substituting Equations A.22 and A.23 into A.12:

$$\tan\beta = \frac{\cos\lambda}{(\frac{\frac{M}{N} + 1}{\eta} \frac{\ell_1}{\ell_2}) \sin\theta + \sin\lambda} \tag{A.25}$$

In summary the factor of safety for **Armorflex** blocks on the sideslopes of a channel can be computed using the following equations:

$$SF = \frac{\cos\theta \ (\frac{\ell_2}{\ell_1})}{\eta' \ (\frac{\ell_2}{\ell_1}) + \sin\theta \cos\beta} \tag{A.26}$$

$$\beta = \tan^{-1} \{\frac{\cos\lambda}{(\frac{\frac{M}{N} + 1}{\eta} \frac{\ell_1}{\ell_2}) \sin\theta + \sin\lambda}\} \tag{A.27}$$

$$\eta = \frac{\tau_o}{\tau_c} \tag{A.28}$$

$$\eta' = \left\{\frac{\frac{M}{N} + \sin(\lambda + \beta)}{\frac{M}{N} + 1}\right\} \eta \qquad (A.29)$$

$$\frac{M}{N} = \frac{\ell_4 \, F_L}{\ell_3 \, F_D} \qquad (A.30)$$

The above equations can be solved by knowing τ_o and τ_c and the angles θ and λ, and assuming the ratios ℓ_1/ℓ_2, ℓ_3/ℓ_4, and F_L/F_D. These assumptions are discussed in Section A.5.

A.3 Extrapolation of Model Test Data to Different Size Blocks

The full-scale hydraulic tests conducted using the **Armorflex** Class 30 system provide the necessary data to determine the critical shear stress for this class of blocks. The model test data indicate that a reliable and conservative value for the critical shear stress for the Class 30 system is 15 lb/ft^2. No tests were conducted using other classes of **Armorflex** blocks, and none are known to exist. As such it is necessary to extrapolate the test results for the Class 30 blocks to other classes so that their stability may be evaluated. This has been done using a force balance approach which utilizes known physical characteristics of the different classes of blocks.

The extrapolation procedure is developed by assuming that the critical shear stress for each class of **Armorflex** is proportional to the forces necessary to initiate motion of a single block in that class resting on a horizontal bed. The forces acting on such a block are shown in **Figure A.2**. Considering the moments about point O at equilibrium (it is assumed that the block will rotate before it slides):

$$\ell_2 \, W_A = F_L \, \ell_4 + F_D \, \ell_3 \qquad (A.31)$$

The variables ℓ_2, ℓ_4, and W_A are known from the physical properties of each class of **Armorflex** block. Equation A.31 can be solved for F_D and F_L by assuming the location of the drag and lift forces (length ℓ_3 in Figure A.2) and a relationship between F_D and F_L. The drag and lift forces are assumed

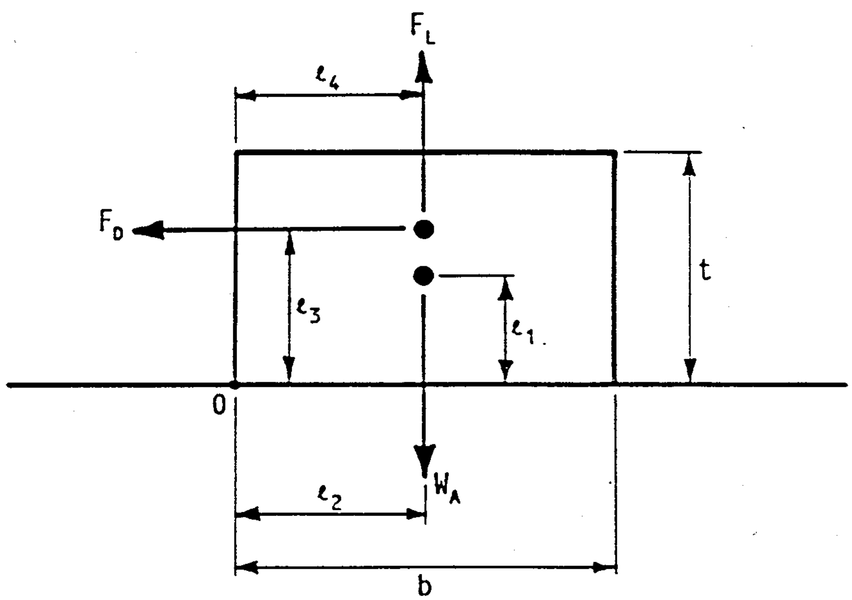


Figure A.2. Forces acting on a single Armorflex block resting on a plane flat bed.

to act at eight-tenths of the block thickness (ℓ_3 = 0.8t in Figure A.2). While the relationship between F_D and F_L is unknown, it is assumed that F_D = F_L. These assumptions were arrived at during numerical testing which showed the results are not very sensitive to the assumptions made.

With the critical shear stress known for the Class 30 system, the critical shear stress for other classes can be computed as follows:

$$\tau_{cu} = \tau_{c30} \frac{W_u}{W_{30}} \frac{\ell_{2u}}{\ell_{230}} \frac{(\ell_{430} + \ell_{330})}{(\ell_{4u} + \ell_{3u})} \qquad \text{(A.32)}$$

where τ_{cu} is the unknown critical shear stress for the class of **Armorflex** in question, subscripts "u" denote values for the untested block, subscripts "30" denote values for the Class 30 block, and τ_{c30} is the critical shear stress for Class 30. **Table A.1** summarizes the computation of critical shear stress for each class of **Armorflex**.

A.4 Consideration of Additional Forces Due to Projecting Blocks

The hydraulic model studies used to establish the critical shear stress for Class 30 **Armorflex** blocks were conducted using carefully placed blocks on a specially prepared subgrade. In actual field conditions, the placement uniformity achieved in the laboratory may not be attained. To account for this possibility, the force balance equations were reformulated considering additional drag and lift forces caused by possible irregularities in placement. The additional forces were computed using hydraulic theory.

Assuming that the additional lift and drag forces act at the same location as the original forces, the factor of safety equation describing the equilibrium of an **Armorflex** block can be rewritten as follows:

$$SF = \frac{\ell_2 W_A \cos\theta}{\ell_1 W_a \sin\theta \cos\beta + \ell_3 (F_D + F_D') \cos\delta + \ell_4(F_L + F_L')} \qquad \text{(A.33)}$$

where F_D' and F_L' are the additional lift and drag forces. Simplifying to a form consistent with the previous derivation:

Table A.1. Summary of Computation of Critical Shear Stress for Each Class of Armorflex.

Standard Armorflex Class	Gross Weight W (lbs)	Submerged Weight W_A (lbs)	ℓ_2 (ft)	ℓ_3 (ft)	ℓ_4 (ft)	F (lb)	τ_c (lb/ft^2)
30	34	19.8	0.54	0.32	0.54	21.3	15**
50	49	28.6	0.54	0.40	0.54	28.1	20
70	129	75.3	0.73	0.60	0.73	70.8	50
45	42	24.5	0.54	0.32	0.54	26.4	18
55	57	33.3	0.54	0.40	0.54	32.7	23
85	156	91.0	0.73	0.60	0.73	85.6	60

*$F = F_L = F_D$

**Known from physical model tests

$$SF = \frac{\cos\theta\left(\frac{\ell_2}{\ell_1}\right)}{\sin\theta\ \cos\beta + \frac{\ell_3(F_D + F_D')\ \cos\delta + \ell_4(F_L + F_L')}{\ell_1\ W_A}} \qquad (A.34)$$

which simplifies after rearrangement to:

$$SF = \frac{\cos\theta\left(\frac{\ell_2}{\ell_1}\right)}{\eta'\ \frac{\ell_2}{\ell_1} + \sin\theta\ \cos\beta} \qquad (A.35)$$

where

$$\eta' = \frac{1}{\ell_2\ W_A}\left[\ell_3(F_D + F_D')\ \cos\delta + \ell_4(F_L + F_L')\right] \qquad (A.36)$$

as before. Equation A.35 replaces Equation A.26 when additional forces for projecting blocks are considered.

The additional drag caused by a projecting block is computed using the principal of conservation of momentum. This principal states that the net force acting on a control volume in a particular direction is equal to the change in momentum in that direction. Mathematically, for direction x:

$$\Sigma F_x = \Delta(\rho QV)_x \qquad (A.37)$$

where ΣF_x is the net force acting on the control volume in direction x and $\Delta(\rho QV)_x$ is the net change in momentum flux in direction x (Q is discharge, ρ is the fluid density, and V is velocity). An exact solution of Equation A.37 requires defining a control volume that extends to the water surface as shown in **Figure A.3** to avoid an unknown momentum flux crossing the sides of the control volume. This requires knowing the depth of flow at locations 1 and 2 in Figure

A.3. Numerical tests indicate that it is sufficiently accurate to compute the drag force F_D acting on the block in the following simplified manner:

$$F_D' = C\ (\Delta Z \omega \rho V^2) \tag{A.38}$$

where ΔZ is the projection height, ω is the width of the projection, and C is a momentum transfer coefficient assumed equal to 0.5. When one considers the flow lines for flow through a control volume just upstream of the projection the simplified equation appears reasonably conservative.

The additional uplift force F_L' due to the projecting area is assumed to equal F_D', which is conservative. The projection height ΔZ was set equal to 0.5 inches which is a reasonable maximum value to allow in installation specifications, given typical construction techniques and installation requirements.

A.5 Solution of the Force Balance Equations

Equations A.27 through A.30, A.35, and A.38 define the stability of Armorflex blocks on the sideslope of a channel with projections. To solve these equations the following variables must be known or assumed: θ. λ, ℓ_1, ℓ_2, ℓ_3, ℓ_4, F_L/F_D, τ_o, τ_c, W_A, ΔZ, and ω.

The angles θ and λ are equal to the sideslope and bed slope of the channel which are known. The lengths ℓ_1 through ℓ_4 are determined from the geometry of each block with the additional assumption that the drag force acts at eight tenths of the block thickness above the base of the block. The ratio F_L/F_D was set equal to 1.0 which, in conjunction with the assumption on the location of the drag force, was found to produce the most conservative estimate of the factor of safety for a range of assumptions tested by way of numerical sensitivity analysis. The length ω is the width of the projection into the flow for a projecting block. **Table A.2** summarizes the values for each of these variables for the various standard classes of **Armorflex**.

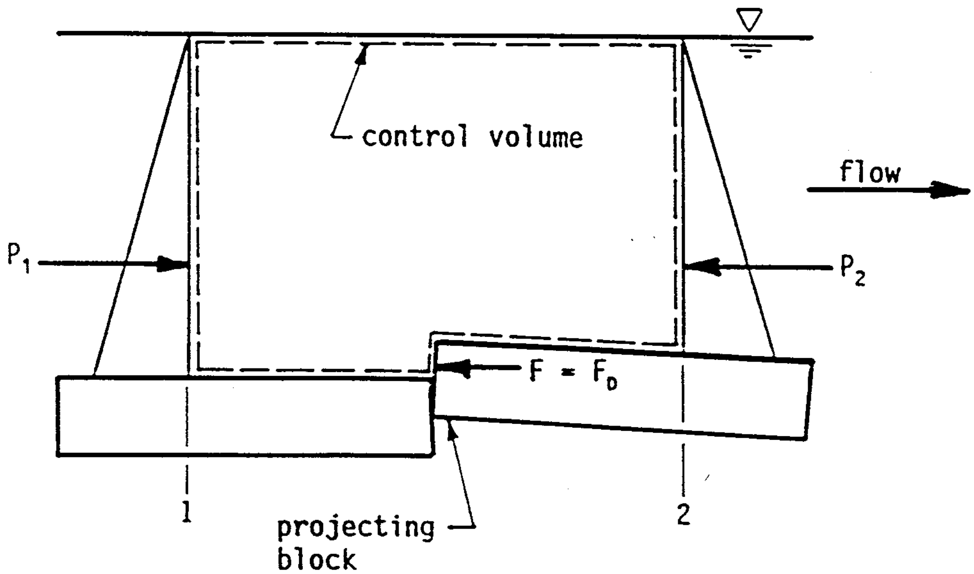


Figure A.3. Control volume for computing horizontal force on a projecting block.

Table A.2. Values of Variables Used to Define the Stability of Armorflex Blocks.

Standard Armorflex Class	Submerged Weight W_A (lbs)	ℓ_1 (ft)	ℓ_2 (ft)	ℓ_3 (ft)	ℓ_4 (ft)	ΔZ (in)	ω (ft)	τ_c (lb/ft^2)
30	19.8	0.20	0.73	0.32	0.73	0.50	0.97	15.0
50	28.6	0.25	0.73	0.40	0.73	0.50	0.97	20.0
70	75.3	0.38	0.97	0.60	0.97	0.50	1.29	50.0
45	24.5	0.20	0.73	0.32	0.73	0.50	0.97	18.0
55	33.3	0.25	0.73	0.40	0.73	0.50	0.97	23.0
85	91.0	0.38	0.97	0.60	0.97	0.50	1.29	60.0

TOM BASIS

COE - 12.70