Design Manual for

Articulating Concrete Block (ACB) Revetment Systems

Third Edition

NATIONAL
CONCRETE MASONRY
ASSOCIATION

DESIGN MANUAL FOR ARTICULATING CONCRETE BLOCK (ACB) REVETMENT SYSTEMS

ACKNOWLEDGEMENT

The National Concrete Masonry Association *Design Manual for Articulating Concrete Block (ACB) Revetment Systems* addresses articulating concrete block design and construction, building upon previous versions of this manual with new research and expanded analyses. The National Concrete Masonry Association (NCMA) acknowledges with appreciation Dr. Amanda L. Cox, P.E. of Saint Louis University for her significant contributions to this manual.

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ABOUT NCMA

Founded in 1918, the National Concrete Masonry Association (NCMA) unites, supports, and represents the producers and suppliers of concrete masonry systems – including concrete masonry, manufactured stone veneer, segmental retaining walls, articulating block systems and other hardscape systems. From small family-owned businesses to large corporations, our membership reflects the full spectrum of companies that provide the foundation for resilient building construction.

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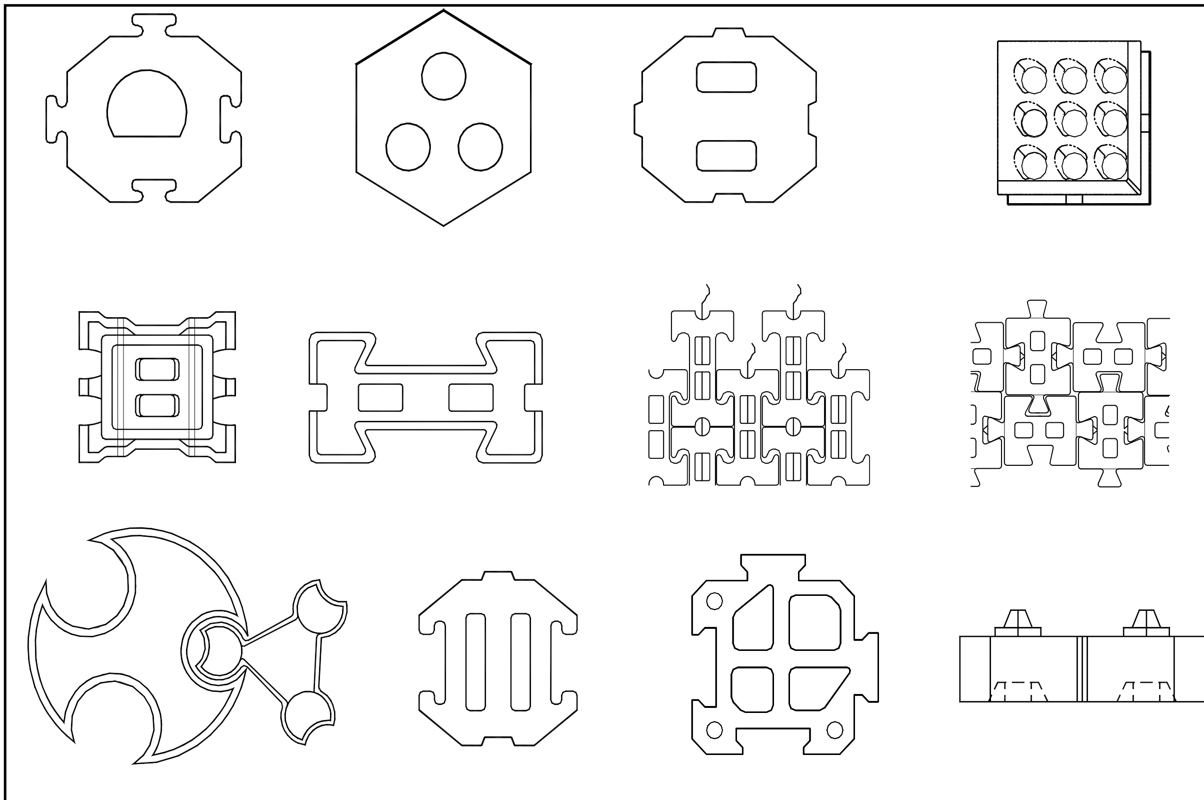
Section 1. INTRODUCTION

This design manual provides guidelines and procedures for the design and installation of articulating concrete block revetment systems. Articulating concrete block (ACB) systems are used to provide erosion protection to underlying soil from the hydraulic forces of moving water. An ACB system is comprised of a matrix of individual concrete blocks placed together to form an erosion-resistant revetment with a geotextile underlay for subsoil retention. The term "articulating" implies the ability of the matrix to conform to minor changes in the subgrade while remaining connected with or without the use of cables, geotextiles or geogrids. Several varieties of ACB systems are available: interlocking, cable-tied and non-cable-tied matrices, and open cell and closed cell varieties. Open cell units contain open voids within individual units that facilitate the placement of aggregate and/or vegetated soil. Closed cell units are solid, but may be capable of allowing vegetation growth between adjacent units. Figure 1.1 shows a variety of ACB units in plan view.



Scale varies between block types

Figure 1.1: Examples of proprietary ACB systems shown in plan view. This is not all inclusive of available configurations. No endorsement or recommendation is intended.

The ACB system includes a filter component that allows infiltration and exfiltration of water to occur while retaining the soil subgrade. The filter layer requires a geotextile and may include a granular transition layer. In some cases a highly permeable drainage layer, either granular or synthetic, may be included in the system to provide sub-block pressure relief, particularly in turbulent flows or wave-attack environments.

Articulating concrete blocks can be used in a broad range of erosion control applications with success. Because ACB systems are highly effective at erosion protection, applications are not limited to subcritical flow or locations of low turbulence. ACB systems have been used with excellent success at installations generating high velocities such as culvert outlets, spillways, and grade control structures. In many laboratory studies, ACB systems have maintained stability in flow velocities conditions exceeding 20 ft/s (6 m/s), where stability failure was defined as any loss of contact between the block and the subgrade. In many applications, ACB systems offer a less expensive and more aesthetically appealing alternative to other treatments such as riprap, structural concrete, rigid grout filled mats (pump mats), and soil cement. The design and construction of these alternative systems is not addressed in this manual.

The permeable characteristic of ACBs allow their use to preserve or enhance natural drainage and treatment systems. ACBs installed on filter media are pervious surfaces that reduce the water runoff and flooding risks, improve water quality, reduce pollutants, recharge aquifers, and prevent erosion. These environmental characteristics encourage the use of ACBs on sustainable developments to preserve or improve existing sites and maybe eligible for credits in some green building rating systems.

ACB systems are well suited to channel lining applications, in particular for lateral stream stability. The articulating characteristic allows the systems to be placed effectively at bends and regions of vertical change, such as sloping grade control structures.

ACB systems are intended for erosion control, not slope stabilization. As such, these systems should not be placed on slopes that are geotechnically unstable or exhibit bedslope angles steeper than that used during hydraulic performance testing. Geotechnical engineering and slope stabilization references should be sought for solutions to these topics.

This manual is intended to provide a standardized basis for the analysis, design, and installation of ACB systems for erosion control applications in open channels or similar hydraulic flow conditions. If ACBs are used for other uses besides erosion control, the design should follow the applicable design requirements for the intended application. Design provisions in this manual are applicable, but not limited, to the following:

- Areas of channelized flow – flumes, channels, waterways;
- Spillways, dam overtopping, and levees; and
- Stormwater control and infiltration.

This manual can be used for the design of ACBs on subcritical and supercritical flow conditions. On spillways, if a hydraulic jump over the ACBs is anticipated, the recommendations of *210-NEH-628-54 - Articulated Concrete Block Armored Spillways* (ref. 40) and *Hydraulic Jump Stability of Articulating Concrete Block Systems* (ref. 44) should be reviewed. Most hydraulic jumps are caused by abrupt changes in channel slope, stilling basins or unexpected debris in the channel that changes the flow.

This manual presents the *Hydraulic Stability Method* applicable for the design of ACBs exposed to design velocities below 8ft/s (2.43 m/s) in Section 3 and the new *Shear and Velocity Stability Method* for the design of ACBs exposed to design velocities over 8ft/s (2.43 m/s) in Section 4. The new methodology, developed in recent years, is applied to channelized flow and overtopping projects.

Section 2. GENERAL CONSIDERATIONS FOR ACB DESIGN

2.1 Open Channel Hydraulics for ACB Design

Effective design of ACB revetment systems depends upon proper characterization of the hydraulic conditions expected during the design event. The vast majority of revetment failures, whether riprap or manufactured systems, occurred in cases where the designer did not adequately quantify the hydraulics of flow.

The two design procedures presented in this ACB design manual are based on an approach that considers the hydraulic forces imposed on a single block at incipient failure of the system. In formulating the equations for practical use, a ratio of design shear stress (τ_{des}) to "critical" shear stress (τ_C) is used. Although shear stress and flow velocity are important variables in ACB system design, the referenced design procedure incorporates flow velocity as an input variable when considering block protrusion/placement tolerance and its effect on stability. Flow velocity is a critical variable in the laboratory and field performance of the system. Therefore, it is important that the maximum stable tested velocity (V_{test}) determined during full-scale flume testing be reported and that the design velocity (V_{des}) not exceed the laboratory test velocity associated with the reported "critical" shear stress (τ_C). The average cross-section shear stress can be calculated using the following simple equation:

$$\tau_0 = \gamma R S_f \qquad \text{(Eqn. 2.1)}$$

where:

τ_0	=	Cross-section-averaged shear stress, lb/ft^2
γ	=	Unit weight of water, 62.4 lb/ft^3
R	=	Hydraulic radius, ft
S_f	=	Energy grade line or bed slope, ft/ft

Historically, full-scale testing results published by the Federal Highway Administration (FHWA), *Minimizing Embankment Damage During Overtopping Flow* (ref. 23) and *Hydraulic Stability of Articulated Concrete Block Revetment Systems During Overtopping Flow* (ref. 21) were originally used to provided performance data on ACB systems. Two ASTM standards have been developed based on the FHWA testing: ASTM D7276, *Standard Guide for Analysis and Interpretation of Test Data for Articulating Concrete Block (ACB) Revetment Systems in Open Channel Flow* (ref. 18) and ASTM D7277, *Standard Test Method for Performance Testing of Articulating Concrete Block (ACB) Revetment Systems for Hydraulic Stability in Open Channel Flow* (ref. 19). These standards provide recommended guidance for the performance testing of ACB systems. The data developed from the full-scale tests are then provided to the designer in the form of critical shear stress (τ_C). Results provided to the designer should also include the maximum test velocity (V_{test}), tested bed slope geometry, and the block lift coefficient (C_{BL}). A background discussion of laboratory flume testing of ACB systems is provided later in this manual (Section 2.2.1). A bed slope of 2H:1V is used for performance testing. The designer should also verify that the bed slope angle used in the performance test to determine the block shear stress value (τ_C) is more than the application's slope.

For some applications, cross-section-averaged shear stress (τ_{des}) is not suitable for design. Such cases include bends, confluences, constrictions, and flow obstructions. An example of how shear stress can vary in a complex flow field is illustrated in the river meander bend of Figure 2.1. The superelevation of the water surface against the outside bank of the bend produces a locally steep downstream water surface slope and, as a result, a region of increased shear stress. A similar phenomenon can occur at bridge crossings where approach embankments encroach on a floodplain. A locally steep water surface is developed near the bridge abutment between the water backed up behind the embankment and the water moving through the bridge opening at a much higher velocity.

For complex hydraulic systems, more sophisticated modeling is generally an appropriate solution. For example, a two-dimensional model may be the appropriate method for determining shear stress through a bridge where the approach embankment(s) constrict a wide floodplain. A two-dimensional model showing velocity vectors through a constricted waterway is shown in Figure 2.2. More sophisticated modeling tools are discussed in the annotated bibliography provided at the end of this manual along with their availability and ordering information.

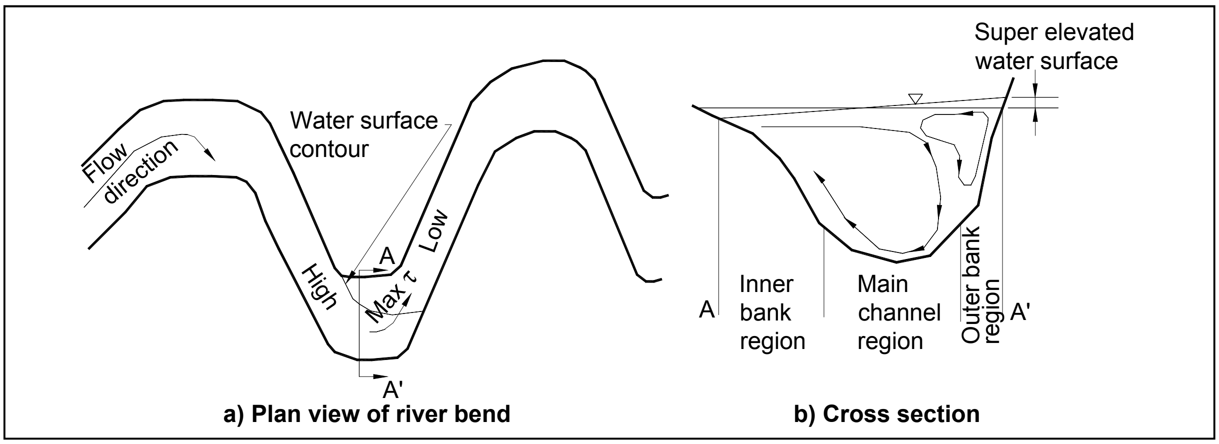


Figure 2.1: (a) Plan view of a river meander bend with region of increased shear stress indicated (b) Cross section A-A' illustrating super elevation at outer bank of the bend.

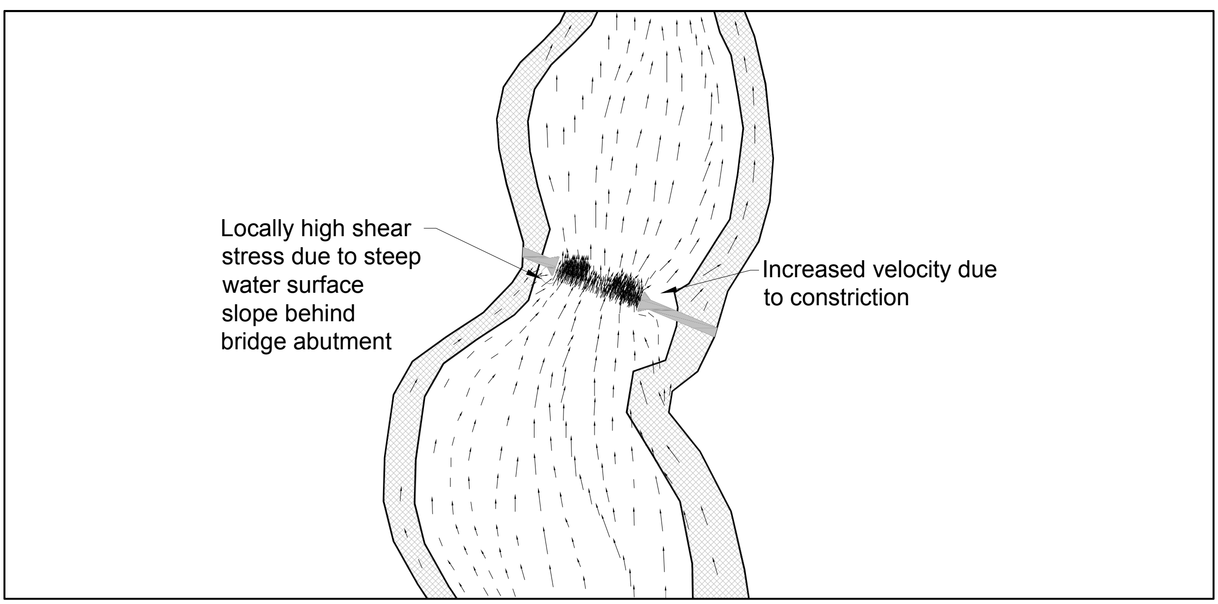


Figure 2.2: Two-dimensional model results with velocity vectors at a waterway constricted by bridge approach embankments.

If a simplified modeling approach, such as the Manning equation or the HEC-2 model, is used to model a complex hydraulic system, then conservatism should be incorporated into the design shear stress (τ_{des}) and selection of the safety factor (SF) reviewed in Section 2.2.3). In the case of flow around a bend, actual velocities can range between 0.9 and 1.7 times the cross-section-averaged velocity (V_{avg}) (ref. 37). Because shear stress is proportional to the square of velocity, the range of multipliers that is suggested for application to the average shear stress, τ_0, vary from is 0.8 to 2.9. Some example shear stress multipliers are provided as follows:

- 0.8 for a location near the bank of a straight reach
- 1.4 for a location in the main current of flow of a meander bend
- 2.9 for a location in the main current of flow of an extreme bend

Given the array of variables involved, there is limited comprehensive information available for quantifying how velocity and shear stress increase locally at obstructions to a flow field, such as bridge piers or pipelines. Flow around local obstructions is very turbulent and generally results in some vortex flow pattern, both contributing to very erosive conditions. A schematic of the horseshoe shaped vortex often observed at flow around bridge piers is provided in Figure 2.3. The rearranged Isbash riprap equation for piers from *Bridge Scour and Stream Instability Countermeasures, Experience Selection, and Design Guidance, 3rd Edition* (ref. 37) uses a velocity multiplier of 1.5 for round piers and 1.7 for rectangular piers. These values correspond to shear stress multipliers of 2.3 and 2.9 for round and square piers, respectively. It is suggested that these values be used along with an increased factor of safety for bridge piers.

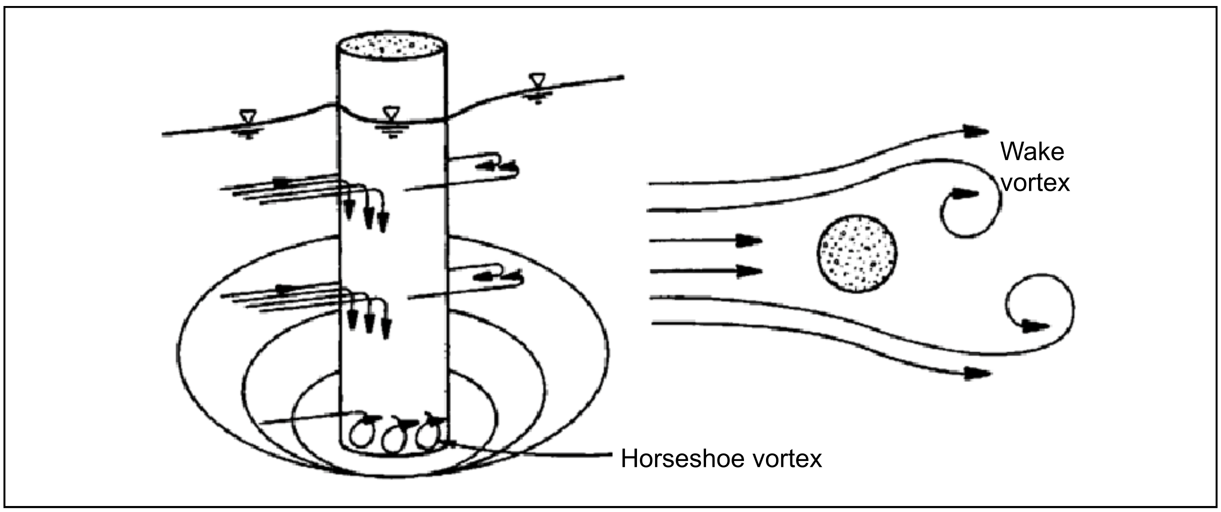


Figure 2.3: Horseshoe vortex flow pattern observed at bridge piers.

Flow velocity becomes a significant hydraulic variable when considering the potential for destabilizing forces on individual blocks, which can result from blocks protruding above the surrounding ACB matrix due to local subgrade irregularities or imprecise placement. The problem is presented in the schematic of Figure 2.4. The added drag on the block is a function of the velocity of the water squared according to the following relationship:

$$F'_D = 1/2 \cdot C_D(\Delta Z)b\rho V^2 \quad \text{(Eqn. 2.2)}$$

where:

F'_D	=	Drag force due to block protrusion, lb
C_D	=	Drag coefficient ($C_D \approx 1.0$)
ΔZ	=	Height of protrusion, ft
b	=	Block width perpendicular to flow, ft (see Section 2.3.1)
ρ	=	Density of water, 1.94 slugs/ft^3
V	=	Velocity, ft/s

Note that V must be less than or equal to the maximum tested velocity (V_{test}) used in determining the critical shear stress (τ_C) for the block system. Figure 2.5 illustrate the effect of drag force for various velocities and protrusion heights.

The added lift force (F'_L) due to the block protruding above the ACB matrix is conservatively assumed equal to the drag force (F'_D). With the added drag force imposed on the block proportional to velocity squared, proper subgrade preparations and installation quality control are very important, especially in regions of high flow velocity, such as supercritical reaches and overtopping spillways. In the design procedure that follows, allowable height of block protrusion is specified by the designer and should be used by inspectors as a criterion for acceptance or rejection of the installation.

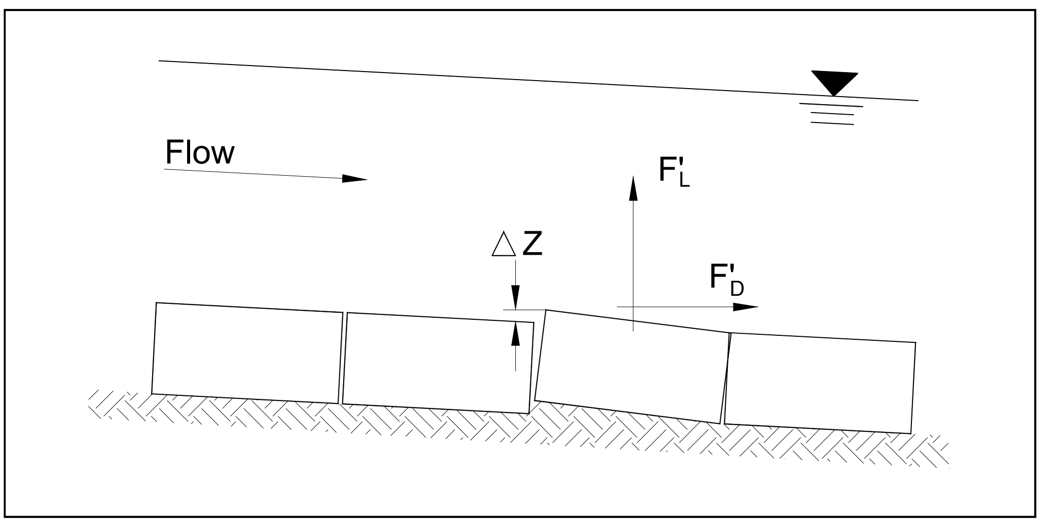


Figure 2.4: Schematic of a block protruding above ACB matrix resulting in added drag and lift forces overturning the block.

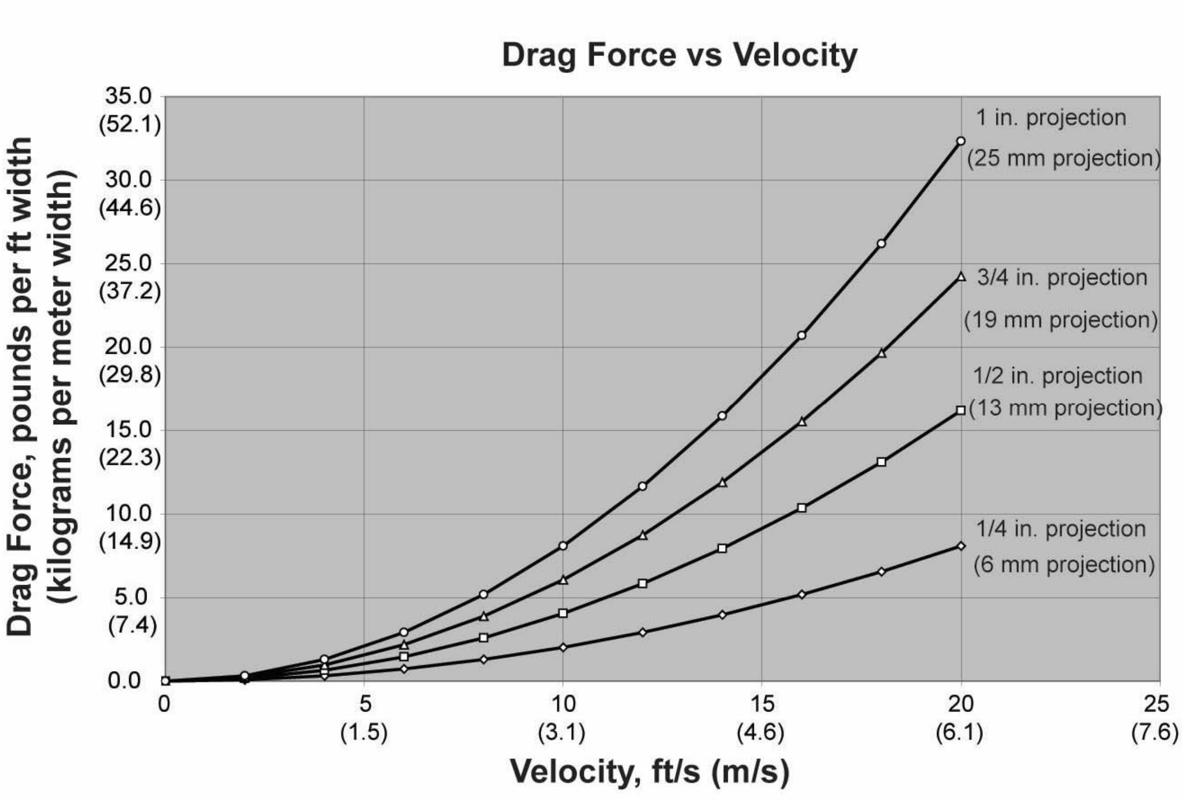


Figure 2.5: Relationship between drag force, velocity and protrusion height – Inch-Pound units (SI units).

2.2 Designing Considerations for ACB Systems

This section describes the linkage between performance testing in laboratory flumes and real-world field applications. It also defines a rational approach to pre-selecting a target factor of safety for a project and special topics related to ACB design are also addressed.

2.2.1 Performance Testing of ACB Systems

Starting in 1983, the Federal Highway Administration (FHWA) led a group of federal agencies in a multi-year research program to evaluate the performance of different erosion control systems for embankment overtopping flow. *Minimizing Embankment Damage During Overtopping Flow* (ref. 23) summarizes the results from the investigation. The erosion control systems in that 1988 report included three proprietary articulating concrete block systems. Test results indicated that ACB systems showed promise as an erosion control countermeasure under severe hydraulic loading; however, the performance of tested systems varied significantly. The scope of the 1988 study does not provide a thorough understanding of the failure mechanisms associated with ACB systems and does not provide reasons for the broad range in system performance. *Hydraulic Stability of Articulated Concrete Block Revetment Systems During Overtopping Flow* (ref. 21) provides a follow up report that more thoroughly addresses these issues.

Concurrent with FHWA testing, researchers in Great Britain were evaluating the performance of similar erosion control systems. Both the FHWA and British researchers agreed that a suitable definition of "failure" for ACB systems is the localized loss of intimate contact between the ACB and the subgrade that it protects. Ref. 21 outlines four causative mechanisms that will result in this definition of failure:

1. Loss of embankment soil beneath the system by gradual erosion along the slope beneath the system or washout through the system at joints and open cells;
2. Deformation of the underlying embankment through liquefaction and shallow slip of the embankment soil caused by the ingress of water beneath the system;
3. Loss of a block or group of blocks (uncabled systems) that directly exposes the subgrade to the flow;
4. Local uplift of a block or group of blocks due to hydraulic loading.

Refinements to the original FHWA test procedures *Minimizing Embankment Damage During Overtopping Flow* (ref. 23) have resulted in new test protocols. ASTM D7277, *Standard Test Method for Performance Testing of Articulating Concrete Block (ACB) Revetment Systems for Hydraulic Stability in Open Channel Flow* (ref. 19) is based on the mentioned procedure and is currently recommended for testing ACB systems.

The loss of intimate contact is most often the result of overturning of a block or group of blocks, in which incipient failure occurs when the overturning moments equal the restraining moments about the downstream contact point of an individual block. The hydraulic stability of a block is thus a function of its restraining moments (block weight and inter-block restraint) versus the applied overturning moments from hydrodynamic drag and lift. Inter-block restraint is the force resulting from block-to-block contact that resists overturning. The process of incipient failure is illustrated in the moment balance of Figure 2.6.

Summing moments acting on the block at incipient failure produces an equation defining hydraulic stability. The following equation, which conservatively ignores inter-block restraint is recommended; with the restraining moments on the left side of the equation and the overturning moments on the right side:

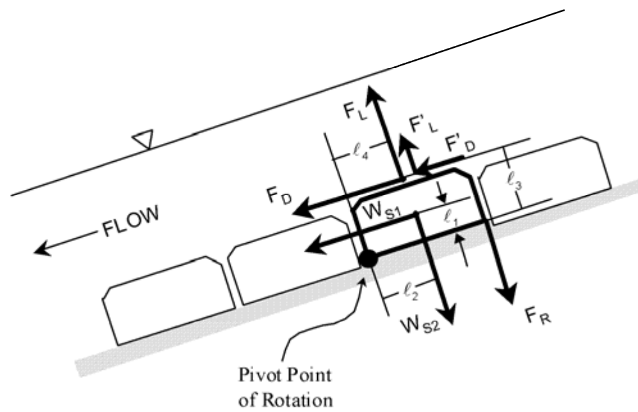
$$\ell_2 W_{S2} = \ell_1 W_{S1} + \ell_3 (F_D + F'_D) + \ell_4 (F_L + F'_L) \qquad \text{(Eqn. 2.3)}$$

where:

W_{S1}	=	Gravity force parallel to slope, lb
W_{S2}	=	Gravity force normal to slope, lb
F_D & F_L	=	Drag and lift forces, lb
F'_D & F'_L	=	Additional drag and lift force from block protruding above ACB matrix, lb
ℓ_x	=	Moment arms, ft; Refer to Figure 3.2.

See Figure 2.6 for notations.

Figure 2.6 illustrates that the ability of any ACB system to provide a stable erosion resistant boundary under a given set of hydraulic conditions is a function of its weight, inter-block restraint, geometry, and quality of installation. In addition, the ability of a system to provide a degree of flexibility through block-to-block articulation is an important factor in maintaining intimate contact between the system and the subgrade that it protects. Because these characteristics can vary greatly between ACB systems, laboratory flume testing of a system is necessary to quantify the performance of a particular system. Using test results, the manufacturer can provide performance data in the form of "critical" shear stress, maximum test velocity, and test bed slope geometry to the designer of the ACB system. The term critical applies to the condition at the brink of failure (loss of intimate contact) of a single block.



Overturning Forces

F_D & F_L = Drag & lift forces

F'_D & F'_L = Additional drag & lift force from block protruding above ACB matrix

W_{S1} = Gravity force parallel to slope

Restraining Forces

F_R = Inter-block restraint

W_{S2} = Gravity force normal to slope

Figure 2.6: Moment balance on an ACB at incipient failure.

A schematic of a typical laboratory flume is shown in Figure 2.7a, along with photographs of actual testing facilities in Figure 2.7b and 2.7c. Flume configurations vary greatly depending on the laboratory setting provided by the testing contractor, but are most commonly used for full scale testing of the blocks. Reference can be made to the annotated bibliography provided at the end of this ACB Design Manual for further documentation on laboratory flume testing of ACB systems.

2.2.2 Extrapolation of Test Data

Often, laboratory flume testing of ACB systems is conducted using a steep bed slope. In order to use the design procedure that follows, the critical shear stress for a horizontal surface must be known. An equation for extrapolation of test results from a steeper bed slope to results for a shallower bed slope has been developed. The equation is based on a moment balance approach that assumes inter-block restraint to be the same for the tested and untested configurations. The following equation is suggested for extrapolation of test results obtained from a steeper bed slope to that of a shallower bed slope for the same ACB system:

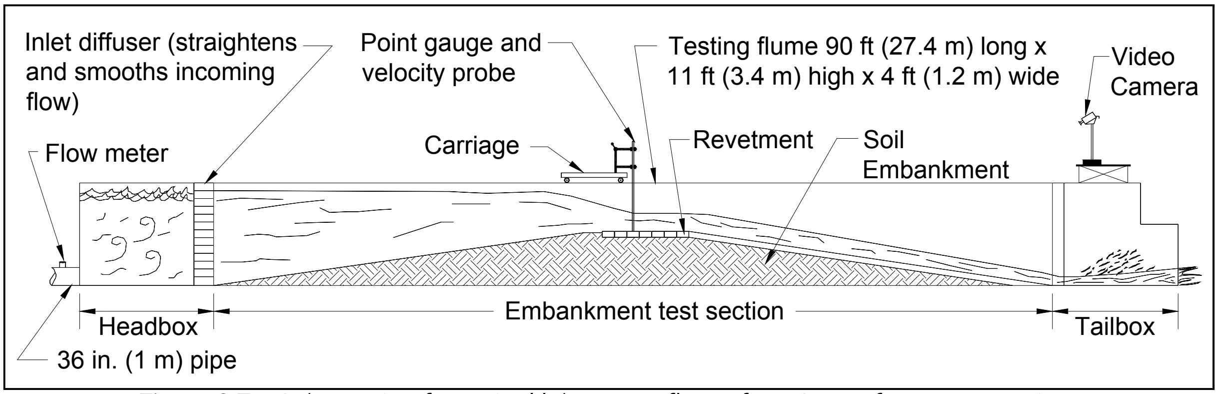


Figure 2.7a: Schematic of a typical laboratory flume for ACB performance testing.

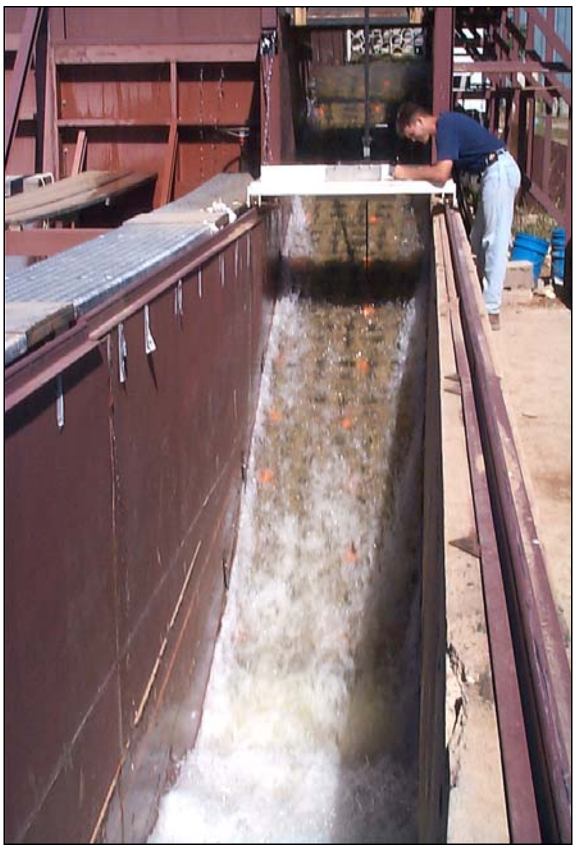


Figure 2.7b: Photograph of full-scale flume test (courtesy of Colorado State University).

Figure 2.7c: Photograph of subgrade inspection after a series of full-scale tests (courtesy of Colorado State University).

$$\tau_{C\theta U} = \tau_{C\theta T} \cdot \left(\frac{\ell_2 \cos \theta_U - \ell_1 \sin \theta_U}{\ell_2 \cos \theta_T - \ell_1 \sin \theta_T} \right) \qquad \text{(Eqn. 2.4)}$$

where:

$\tau_{C\theta U}$	=	Critical shear stress for untested bed slope, lb/ft^2
$\tau_{C\theta T}$	=	Critical shear stress for tested bed slope, lb/ft^2

θ_U = Untested bed slope (degrees)
Where θ_U less than or equal to θ_T; and where design velocity (V_{des}) less than or equal to the test velocity (V_{test})
θ_T = Tested bed slope (degrees)
ℓ_x = Moment arms, ft; Refer to Figure 3.2.

Note that the moment arms used in this equation should apply to the orientation of the block during testing and are not necessarily the same as those recommended later in this document for design.

Similar to extrapolation based on bed slope, an equation for extrapolating test results from a tested block to a thicker untested block has been developed for block of identical characteristics (i.e., only different in height and weight, but having identical footprint area, geometry and interlock mechanism). This extrapolation is only applicable when considering a block height greater than that of the tested block height and should not be used for determining the characteristics of units with heights less than the tested block. This equation is also based on a moment balance approach that neglects inter-block restraint. The following equation is suggested for extrapolation of test results from one block height to another within the same family:

$$\tau_{CU} = \tau_{CT} \cdot \left(\frac{W_{SU}\ell_{2U}}{W_{ST}\ell_{2T}} \cdot \frac{\ell_{3T} + \ell_{4T}}{\ell_{3U} + \ell_{4U}} \right) \qquad \text{(Eqn. 2.5)}$$

Note: Extrapolated critical shear stress, τ_{CU}, is only applicable when considering an untested block height greater than that of the tested block height.

Note:
τ_{CU} = Critical shear stress for untested block, lb/ft^2
τ_{CT} = Critical shear stress for tested block, lb/ft^2
W_{SU} = Submerged weight of untested and tested blocks, lb
W_{ST} = Submerged weight of untested and tested blocks, lb
ℓ_{XU} = Moment arms of untested blocks, ft
ℓ_{XT} = Moment arms of tested blocks, ft

This extrapolation method has been used for many years for the Hydraulic Stability Method. The designer is recommended to carefully review the extrapolation options if the Shear and Velocity Stability Method is being used because there is no experience with extrapolation in this new method yet.

2.2.3 Factor of Safety Methodology for ACB Design

There are several factors that need to be understood and considered when evaluating the appropriate target safety factor for design purposes. These can be categorized into two groups; “external” and “internal” factors. The external group consists of factors such as the complexity of the hydraulic system, the uncertainty of the input hydraulics, and the overall consequence of failure. The concepts behind these factors are well understood, even though calculating how each one of these considerations contributes to an overall target factor of safety can be very challenging. More commonly understood are the internal factors related directly to the safety factor methodology for ACB design. As discussed below, there are multiple facets of the safety factor methodology that are *inherently conservative* as they relate to external and internal design factors.

External Factors

1. Complexity of the hydraulic system and uncertainty of the input hydraulics – Obviously, all hydraulic systems are not of the same complexity. Modeling the flow characteristics of a stream bank or channel is much different than the design of scour protection around bridge piers. If the flow is relatively uniform and predictable, then a lower value for the target safety factor can be used for design. As the complexity of the system increases, so too should the sophistication of the model used to determine the hydraulic parameters. Utilizing a simplistic model in a complex environment may warrant an increase in the target safety factor (i.e. >1.5). Conversely, if a complex model is used to analyze a simplistic design scenario, then a lower target safety factor may be adequate (i.e. <1.5).
2. Consequence of failure – As with the complexity of the hydraulic system, the overall consequence of failure needs to be understood. Failure that results in loss of life is much different from a failure resulting in soil erosion along a stream bank in which no loss of life or property is imminent. Increasing the target safety factor is one way of potentially offsetting environmental conditions that are considered high risk.

Internal Factors

1. Conservatism associated with the safety factor methodology – The safety factor methodology is considered to be a conservative approach based on the following reasons:
   a. Extrapolation of Test Data. In order to use the safety factor methodology, the critical shear stress of the unit along a horizontal surface must be understood and quantified. An equation is used for the extrapolation of test results from a steeper bed slope to a horizontal slope. A second extrapolation takes place from the tested units to thicker, untested units. In both processes, it is assumed that the intra-block restraint is the same for all heights of the units. Under this assumption, the extrapolation equations only consider the weight and height of the units. This moment balance approach (obtained from the geometry of the unit) neglects any intra-block restraint. This assumption can be *very* conservative given the fact that thicker units have much more intra-block friction than thinner units given the shape of the blocks. As illustrated in Figure 2.8, the bottom half of an ACB unit is essentially a rectangle of concrete with adjacent units resting against the surrounding units. As the unit increases in height, so too does the intra-block friction. Currently, the safety factor methodology does not account for this variable, which only increases the conservatism of this design approach for such conditions.

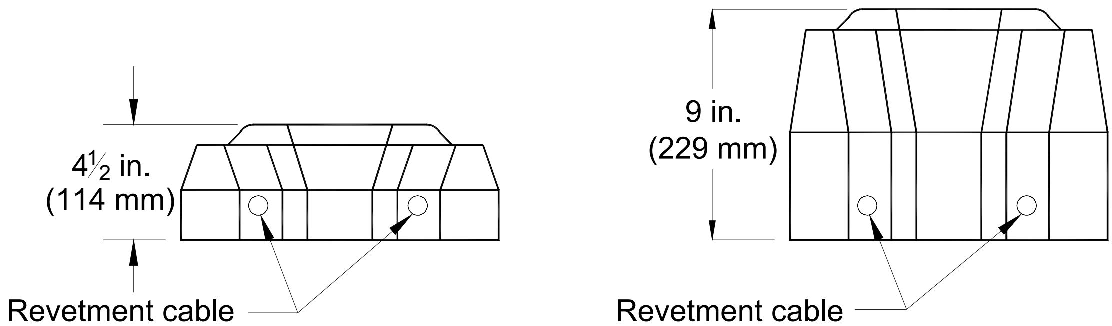


Figure 2.8: Comparison between the potential intra-block friction between 4.5 in. (114 mm) and 9.0 in. (229 mm) ACB units. (Courtesy of Submar, Inc.)

b. Performance Values. Hydraulic testing on different "footprint" or classes of blocks and tapers for a variety of dam overtopping and spillway applications has been performed. In many of these tests, the testing facility was unable to fail the system under a range of scenarios. Nevertheless, the resulting shear stresses obtained from the tests are used within the safety factor methodology as a threshold, or failure, shear stress. This issue is compounded when extrapolating to thicker units. Without being able to reach a threshold condition in the testing flume, licensors and manufacturers extrapolate shear stress value from a stable value. A large degree of conservatism in the performance values of the units is the result of not being able to fail these systems under laboratory conditions.

c. Interaction between Velocity and Shear Stress. In flume testing of the units, two of the most important results obtained are; 1. a stable shear stress; and 2. velocity at a downstream point under the highest flow conditions. Consider for example testing results whereby the highest boundary shear stress and velocity obtained was 22.2 lb/ft^2 (1,063 Pa) and 26.1 ft/s (7.96 m/s), respectively. In the safety factor methodology one utilizes a shear stress of 22.2 lb/ft^2 (1,063 Pa) regardless of the expected design velocity for every design utilizing this particular unit (provided that the design velocity is less than or equal to the tested velocity). Conservatively, if the velocity was only 12 ft/s (3.66 m/s) for a given application, then the system could withstand a much larger shear stress than 22.2 lb/ft^2 (1,063 Pa). Therefore, an additional degree of conservatism is present when the design velocity is less than the tested velocity and the design utilizes the maximum shear stress generated during the higher velocity event.

d. Allowable shear stress in a vegetative state. All of the testing on existing ACB systems has taken place in a non-vegetative state. Many ACB applications for overtopping and spillway applications, however, seek a final system that is fully vegetated. A series of hydraulic tests conducted by the U.S. Army Corp of Engineers investigated the performance of identical ACB systems in both vegetated and un-vegetated conditions (ref. 38). In this investigation, the end result was an increase in the allowable shear stress of 41% when vegetated.

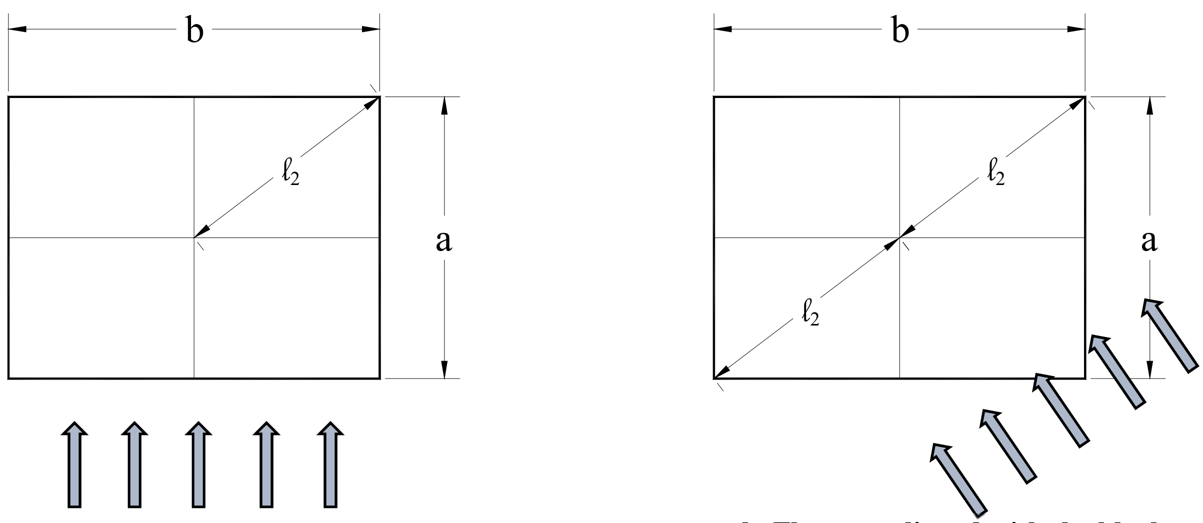
Taking into consideration all of the points addressed above, what is the proper target safety factor required for a dam overtopping or spillway application? It is safe to state that the methodology used for ACB design is full of conservative assumptions. From the fact that tapered ACB systems have not reached their threshold condition in the testing flume to the fact that vegetation increases the allowable shear stress, it is apparent that the resulting design can be conservative. Therefore, a target safety factor of 1.3 – 1.5 is adequate for applications in which the design hydraulics and site geometry are *clearly* understood. *Ultimately, the "external" factors and overall design of the project will need to be evaluated and decided on by the engineer of record.* It may also be appropriate for an individual experienced in ACB design to offer an opinion on how these factors should be incorporated into an overall target safety factor.

2.3 Other Considerations

2.3.1 Direction of the Flow

In the field not all ACB applications have the flow aligned with the sides of the block. To address this variable the *Hydraulic Engineering Circular No. 23 (HEC-23, 3rd edition, September 2009)* (ref. 37), introduced a recommendation for ACB Systems to account for the flow direction in the drag force calculation. If the flow direction is uncertain, use b in Equation 2.2 as the diagonal distance of the block ($2\ell_2$) in the drag force calculations (see Figure 2.9b). If the flow aligns with the block use b as the width perpendicular to the flow (Figure 2.9a).

It is recommended that the designer analyze the project conditions and determine the appropriate dimension for determining the drag forces (F'_D) and safety factors on each project. Examples of non-parallel flow conditions are open channel and levees where the flow alignment is uncertain during the life of the project.



a. Flow perfectly aligned with the block
Use "b" as the width perpendicular to the flow

b. Flow not aligned with the block
Use "$2\ell_2$" as the width perpendicular to the flow

Figure 2.9: Block dimensions and flow direction.

2.3.2 Extent of Revetment Coverage

Longitudinal Extent—The revetment should be continuous for a distance that extends upstream and downstream of the region that experiences hydraulic forces severe enough to cause dislodging and/or transport of bed or bank material. The minimum distances recommended are an upstream distance of 1.0 multiplied by the channel width and a downstream distance of 1.5 multiplied by the channel width. The channel reach that experiences severe hydraulic forces is usually identified by site inspection, examination of aerial photography, hydraulic modeling, or a combination of these methods.

Many site-specific factors have an influence on the actual length of channel that should be protected. Channel obstructions (such as bridge abutments) may produce local areas of relatively high velocity and shear stress due to channel constriction, but may also create areas of ineffective flow further upstream and downstream in "shadow zone" areas of slack water. In straight reaches, field reconnaissance may reveal erosion scars on the channel banks that will assist in determining the protection length required. In meandering reaches, because the natural progression of bank erosion is in the downstream direction, the present limit of erosion may not necessarily define the ultimate downstream limit. Guidance for the assessment of lateral migration is provided in HEC-20 (ref. 36). The design engineer is encouraged to review this reference for proper implementation.

Vertical Extent—The vertical extent of the revetment should provide ample freeboard above the design water surface. A minimum freeboard of 1.5 ft (0.5 m) should be used for unconstricted reaches and minimum of 2.5 ft (0.76 m) for constricted reaches. The freeboard height shall be taken above the energy grade line. The revetment system should either cover the entire channel bottom or, in the case of unlined channel beds, extend below the bed far enough so that the revetment is not undermined from local scour or degradation. Techniques for estimating local scour are provided in *HEC-18, Evaluating Scour at Bridges* (ref. 41) and long-term degradation is discussed in more detail in Section 2.3.6.

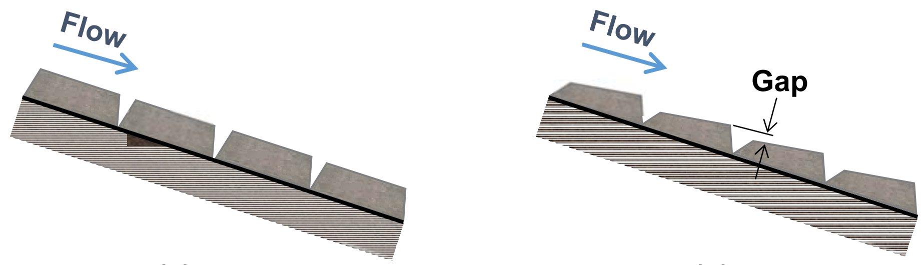
2.3.3 Cabled Versus Non-Cabled ACB Systems

Some manufacturers of ACB systems provide the option of cables or other connection devices for installation convenience and block-to-block connection. Under the precepts of the definition of failure and the factor of safety design procedure, cables are not considered to increase the hydraulic stability of the ACB system and no explicit terms are incorporated into the procedure for block-to-block connections.

2.3.4 Considerations for Tapered Block Systems

Tapered block systems have a larger downstream height relative to the upstream height resulting in a vertical gap between the top of the upstream and downstream block within a system. A schematic illustrating the difference between a tapered block system and an untapered block system is shown in Figure 2.10. This tapered feature reduces the potential for additional lift and drag associated with blocks protruding above adjacent blocks (i.e., F'_L and F'_D), computed based on an acceptable tolerance for block protrusion above the ACB matrix (ΔZ) for field installation. Minor block protrusions are expected for ACB systems installed in the field because of nonidealized subgrade conditions. The following should be considered when evaluating stability of tapered block systems:

- For tapered block systems with a gap height greater than the acceptable variation in installation height for the block system, the additional lift and drag forces due to block protrusion should not be included in the factor of safety calculations.
- For tapered block systems with a gap height less than the acceptable variation for block installation, the height of block protrusion (ΔZ) used for computing F'_L and F'_D should be estimated as the acceptable installation height variation minus the tapered block gap height.



(a) (b)

Figure 2.10: Profile view of block system illustrations: (a) untapered block system and (b) tapered block system (dimensions are exaggerated for illustration).

2.3.5 Drainage Layers

A drainage layer may be used in conjunction with an ACB system. A drainage layer lies between the blocks and the geotextile and/or granular filter. This layer allows "free" flow of water beneath the block system while still holding the filter material to the subsoil surface under the force of the block weight.

Drainage layers can be comprised of coarse, uniformly sized granular material, or can be synthetic mats that are specifically manufactured to permit flow within the plane of the mat. Granular drainage layers are typically comprised of 1- to 2-inch (25 to 51 mm) crushed rock in a layer 4 inches (102 mm) or more in thickness. The uniformity of the rock provides significant void space for flow of water. Synthetic drainage mats typically range in thickness from 0.25 to 0.75 inches (6 to 19 mm) and are manufactured using polymeric materials.

Many full-scale laboratory performance tests have been conducted with a drainage layer in place. When evaluating an ACB system, for which performance testing was conducted with a drainage layer and/or polymeric materials, a drainage layer and/or polymeric materials must also be used in the design and construction. *The drainage layers and/or polymeric materials tested dimensions are to be replicated in the field.* This recommendation is based on the apparent increase in the hydraulic stability of systems that have incorporated a drainage layer in the performance testing.

Vertical components of velocity in highly turbulent flow can create conditions where detrimental quantities of flow may penetrate beneath the block system in local areas. For this reason, the designer may wish to incorporate a drainage layer with any ACB system design in areas where very turbulent flows are expected.

ACBs installed over drainage layers can be used in a Best Management Practices (BMP) plan to preserve or improve existent sites, or in new developments. The system installed over a drainage layer preserves the natural drainage and treatment systems of the soil reducing the water runoff and flooding risks, improving water quality, reducing pollutants, recharging aquifers, preventing erosion, and when vegetated will also generate habitat. All the mentioned advantages make ACBs a great candidate for its use in sustainable projects where water quantity and quality control are extremely important.

Research done on permeable systems similar to ACBs with drainage layers has made known the excellent benefits on water quantity and quality control. A study in North Carolina (ref. 30) demonstrated the ability of the system to reduce runoff, mitigate the peak flow, and reduce water nutrients like total phosphorus (TP), ammonium-nitrogen (NH4-N) and total Kjeldahl nitrogen (TKN). A similar study in Ireland (ref. 34) also showed the ability of permeable systems over aggregate to remove heavy metals and hydrocarbons efficiently from industrial water.

2.3.6 Geomorphic Considerations For ACB Design

Ascertaining whether or not a stream is stable requires a functional definition of stability. In the context of ACB design, stability implies that the geomorphic state of the stream, with the ACB system in place, is such that adverse conditions to the revetment do not develop over time.

Hydraulic Engineering Circular No. 20 (HEC-20), *Stream Stability at Highway Structures* (ref. 36) provides a stability characterization system that classifies several stream properties as being unstable or stable. The system is qualitative in nature, but provides a quick method for ascertaining stability of a stream using very little data, which includes, annual hydrograph characteristics, soil properties, aerial photography, and land topography. Thirteen stream properties are used in the method, which can be categorized into temporal flow characteristics, channel boundary characteristics, topographic relief, plan geometry, and cross-section geometry.

Many natural streams migrate laterally without impacting the stream as a system (i.e., effects of migration do not propagate upstream and downstream). However, lateral migration becomes a concern when the security of nearby infrastructure from erosion is jeopardized. In such cases, ACB systems can be used as a countermeasure or as a component of a countermeasure to arrest lateral migration. The designer is referred to *HEC-23, Bridge Scour and Stream Instability Countermeasures* (ref. 37) for lateral instability countermeasure options.

In many applications, an ACB system is used for embankment and streambank lining while a "soft" channel bed is maintained for environmental, habitat, or economic reasons. The vertical stability of the project site, in terms of aggradation or degradation, should be quantified to determine the sufficient toe-down depth for the revetment. Long-term bed elevation changes are usually the result of change(s) to the watershed system, such as: urbanization, deforestation, channelization, meander cutoff, and changes to downstream base level control elevation. Because vertical instability is typically indicative of system-wide response, local use of articulating concrete blocks should not be used as the sole countermeasure to arrest degradation.

Prediction of long-term bed elevation changes is a multi-disciplinary problem that must be solved using a system analysis approach. Analysis of the problem requires the consideration of all influences to the system: runoff from the watershed (hydrology), sediment delivery to the channel reach (sedimentology), sediment transport capacity of the reach (hydraulics), and the response of the channel to these factors (geomorphology). *HEC-20, Stream Stability at Highway Structures* (ref. 36) offers a three level system approach to fully characterize stream stability:

Level 1: Application of simple geomorphic concepts and other qualitative analyses.

Level 2: Application of basic hydrologic, hydraulic, and sediment transport engineering concepts.

Level 3: Application of mathematical or physical modeling studies.

Not all three levels of analysis must be completed. Instead, it is suggested that each level of analysis be carried out until adequate characterization of stream stability is achieved. Given adequate characterization of stream stability, the designer can then utilize *HEC-23, Bridge Scour and Stream Instability Countermeasures* (ref. 37) for countermeasure design, if needed.

Section 3. ACB DESIGN – HYDRAULIC STABILITY METHOD

3.1 Introduction

Two methods are available for computing a factor of safety for an application of an ACB system for revetment. The original hydraulic stability method that uses only shear stress for computing the hydrodynamic forces (ref. 34 and 22) reviewed in this section and the Shear and Velocity Stability Assessment (SVSA) method that uses both the shear stress and flow velocity to quantify the hydrodynamic forces (ref. 24) that is addressed in Section 5. The hydraulic stability method presented here is recommended for design velocities (V_{des}) up to 8 ft/s (2.43 m/s). Higher design velocities should follow the SVSA method detailed in the next section.

3.2 Design Equations

The following design equations quantify a factor of safety for application to an ACB system based on an approach that considers the hydraulic forces imposed on a single block. The procedure was originally presented in *Stability Analysis for Coarse Granular Material on Slopes* (ref. 42) for riprap design and has been modified in *Erosion and Sedimentation* (ref. 32) to account for the case of riprap placed on a steep longitudinal slope and a steep lateral side slope (e.g., a revetment system protecting the bank of an overtopping spillway). The ref. 32 equations are the most general formulation and can be applied to any hydraulic system where the water surface slope is approximately equal to the bed slope (i.e., gradually varied flow). These equations have been modified slightly for this procedure to consider the known geometric dimensions of concrete blocks and the critical shear stress determined from performance testing. *Protecting Embankment Dams with Concrete Block Systems,* (ref. 22) first presented the process of adapting the factor of safety equations to ACB systems.

Changes have also been incorporated into the design procedure to account for the additional forces imposed on a block that protrudes above the surrounding ACB matrix due to local subgrade irregularities or imprecise placement. Because a slight disruption of intimate contact between a block and the subgrade constitutes failure, the equations do not account for the restraining forces due to cables. The potential restraining force imposed on the block matrix by cables is intentionally limited so that block-to-block articulation is permitted. Similarly, the additional stabilizing forces offered by vegetation and/or mechanical-anchoring devices are ignored in the procedure because such effects are difficult to quantify and are assumed to be of limited value, which contributes to the inherent design conservatism of the modeling approach presented in this manual.

The safety factor (SF) for a single block in the ACB system is defined as the ratio of restraining (stabilizing) moments to the overturning (destabilizing) moments. Rearranging Equation 2.3 and adding terms to account for a block placed on a three-dimensional surface, results in the following equation for SF:

$$SF = \frac{\ell_2 W_S a_\theta}{\ell_1 W_S \sqrt{1 - a_\theta^2} \cos\beta + \ell_3 F_D \cos\delta + \ell_4 F_L + \ell_3 F'_D \cos\delta + \ell_4 F'_L} \quad \text{(Eqn. 2.4)}$$

where:

a_θ = Projection of W_S into subgrade beneath block

F_D & F_L	=	Drag and lift forces, lb
F'_D & F'_L	=	Additional drag and lift force from block protruding above ACB matrix, lb
ℓ_x	=	Moment arms, ft; Refer to Figure 3.2.
W_S	=	Gravity force parallel to slope, lb
β	=	Angle of block projection from downward direction, once in motion
δ	=	Angle between drag force and block motion

The nomenclature, forces, dimensions, and angles in the equation for SF are presented in Figure 3.1. Dividing Equation 3.1 by $\ell_1 W_S$ and substituting terms yields the final form of the factor of safety equations as presented in Table 3-1. The equations can be used in any consistent set of units.

The submerged block weight, W_S, is the weight of the block after subtracting out the force of buoyancy. The moment arms ℓ_1, ℓ_2, ℓ_3, and ℓ_4 are determined from the block dimensions shown in Figure 3.2. In the general case, the pivot point of overturning will be at the front corner of the block; therefore, the horizontal distance from the center of the block to the corner should be used for both ℓ_2 and ℓ_4. Because the resultant of weight is through the block center of gravity, one half the block height should be used for ℓ_1. The drag force acts both on the top surface of the block (shear drag) and on the body of the block (form drag). Considering both elements of drag, eight-tenths the height of the block is considered a good estimate of ℓ_3.

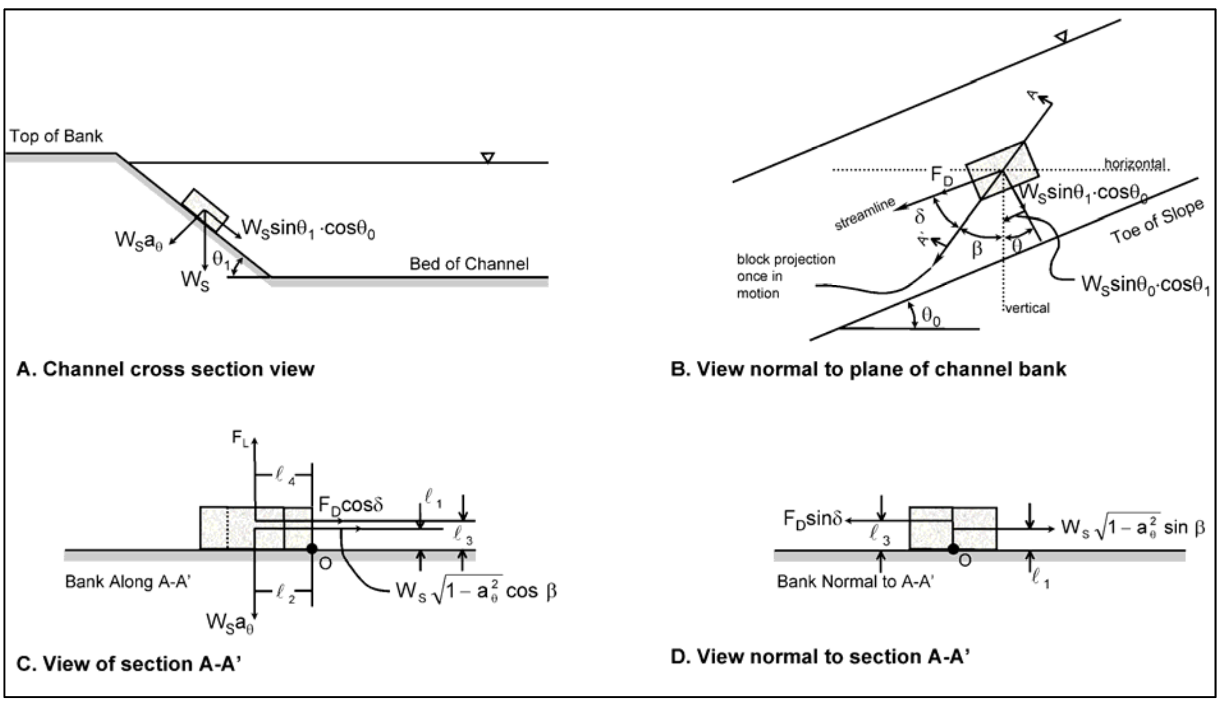


Figure 3.1: Three-dimensional view of a block on a channel side slope with factor of safety variables defined.

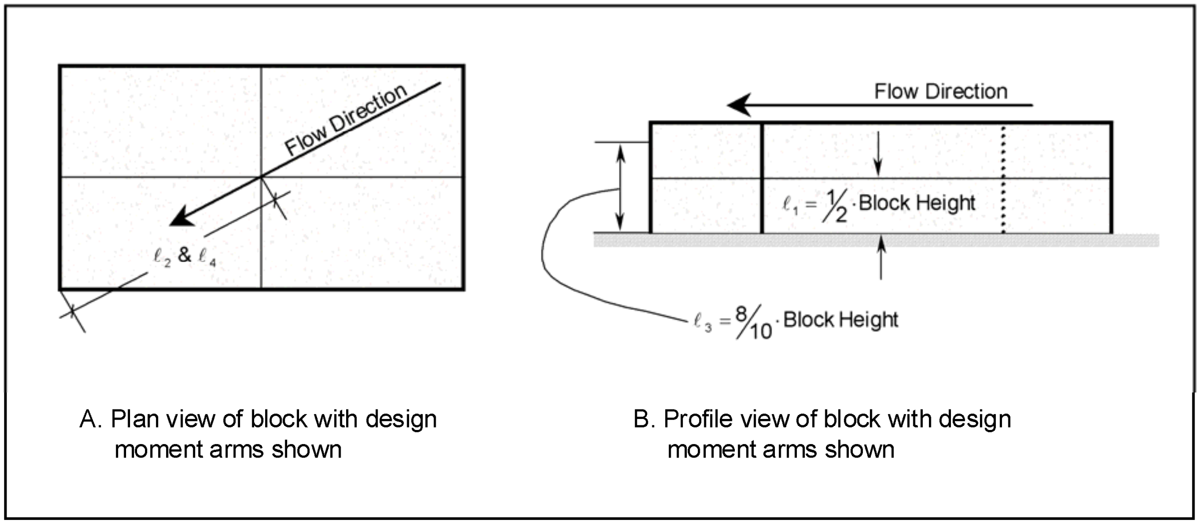


Figure 3.2: Figure of a block showing moment arms ℓ_1, ℓ_2, ℓ_3, and ℓ_4.

Extensive research has been conducted to determine the critical shear stress for virtually all sizes of granular soil particles and riprap, but there are limited test data available for proprietary ACB products. Therefore, critical shear stress for a block on a horizontal surface, τ_C, should come from performance testing or be extrapolated for the ACB system being considered. Determination of critical shear stress, τ_C, is discussed in Section 2.2.

Table 3-1: Hydraulic Stability Method Design Equations – Customary U.S. Units.

$\mathrm{SF} = \dfrac{(\ell_2/\ell_1)a_\theta}{\sqrt{1-a_\theta^2}\cos\beta + \eta_1(\ell_2/\ell_1) + \dfrac{\ell_3 F'_D \cos\delta + \ell_4 F'_L}{\ell_1 W_S}}$	3.2	a_θ = Projection of W_S into subgrade beneath block b = Block width, ft F'_D & F'_L = additional drag and lift forces, lb ℓ_x = Block moment arms, ft S_C = Specific gravity of concrete (assume 2.1) SF = Calculated factor of safety V_{des} = Design velocity, ft/s (V_{des} less than or equal to V_{test}) V_{test} = Maximum tested Velocity, ft/s W = Weight of block, lb W_S = Submerged weight of block, lb ΔZ = Height of block protrusion above ACB matrix, ft β = Angle of block projection from downward direction, once in motion δ = Angle between drag force and block motion η_0 = Stability number for a horizontal surface η_1 = Stability number for a sloped surface θ = Angle between side slope projection of W_S and the vertical θ_0 = Channel bed slope (degrees or radians) (less than or equal to test bed slope) θ_1 = Channel side slope (degrees or radians) Note - the equations cannot be solved for $\theta_1 = 0$ (i.e., division by 0); therefore, a negligible side slope must be entered for the case of $\theta_1 = 0$. ρ = Mass density of water, 1.94 slugs/ft^3 τ_C = Critical shear stress for block on a horizontal surface, lb/ft^2 τ_{des} = Design shear stress, lb/ft^2
$\delta + \beta + \theta = 90°\text{ or }\frac{\pi}{2}\text{ radians}$	3.3	
$\eta_1 = \left(\dfrac{\ell_4/\ell_3 + \sin(\theta_0+\theta+\beta)}{\ell_4/\ell_3 + 1}\right)\eta_0$	3.4	
$\beta = \arctan\left(\dfrac{\cos(\theta_0+\theta)}{(\ell_4/\ell_3+1)\dfrac{\sqrt{1-a_\theta^2}}{\eta_0(\ell_2/\ell_1)} + \sin(\theta_0+\theta)}\right)$	3.5	
$\theta = \arctan\left(\dfrac{\sin\theta_0}{\sin\theta_1}\cdot\dfrac{\cos\theta_1}{\cos\theta_0}\right) = \arctan\left(\dfrac{\tan\theta_0}{\tan\theta_1}\right)$	3.6	
$a_\theta = \sqrt{\cos^2\theta_1 - \sin^2\theta_0}$	3.7	
$F'_L = F'_D = 0.5\cdot(\Delta Z)b\rho V_{des}^2$	3.8	
$\eta_0 = \dfrac{\tau_{des}}{\tau_C}$	3.9	
$W_S = W\cdot\left(\dfrac{S_C - 1}{S_C}\right)$	3.10	

3.3 Required Design Variables for the Hydraulic Stability Method

Values for block geometry, block weight, specific gravity of block material, design velocity, and design shear stress are required to use the hydraulic stability method. This Section details how each of the required design variables can be determined. All other variables can be calculated from the equations provided in Table 3-1.

3.3.1 ACB System Variables

Submerged block weight (W_S): Block weight (W) and specific gravity (S_C) are provided by the ACB system manufacturer. The submerged block weight is computed using Eq. 3.10:

$$W_S = W \cdot \left(\frac{S_C - 1}{S_C}\right) \qquad \text{(Eqn. 3.10)}$$

Block moment arms (ℓ_x): The block moment arms (ℓ_X) are computed based on the block length, width, and height as shown in Figure 3.2 and defined by the following equations:

$$\ell_1 = 0.5 \cdot \text{Block Height} \qquad \text{(Eqn. 3.11)}$$

$$\ell_2 = \ell_4 = 0.5 \cdot \sqrt{{\ell_p}^2 + {\ell_n}^2} \qquad \text{(Eqn. 3.12)}$$

$$\ell_3 = 0.8 \cdot \text{Block Height} \qquad \text{(Eqn. 3.13)}$$

3.3.2 Hydrodynamic Variables

Both **design shear stress (τ_{des})** and **design flow velocity (V_{des})** are determined from hydraulic analysis of the open-channel system design. Several numerical modeling programs are available for hydraulic analysis. They generally require information on channel geometry, hydraulic roughness coefficient (Manning's *n*) of the block system, and design discharge.

3.4 Hydraulic Stability Design Procedure and Example

The following example illustrates an ACB design procedure that uses the design equations presented in Table 3-1. The procedure is presented in a series of steps that can be followed by the designer in order to select the appropriate ACB system based on a pre-selected target safety factor. The major criterion for product selection is if the computed factor of safety for the ACB system meets or exceeds the pre-selected target value.

Problem Statement

A hydraulic structure is to be constructed at the downstream end of a reach on Meandering River, Texas. The river has a history of channel instability, both vertically and laterally. A quantitative assessment of channel stability has been conducted using the multi-level analysis from *HEC-20, Stream Stability at Highway Structures* (ref. 36). Using guidelines from *HEC-23, Bridge Scour and Stream Instability Countermeasures* (ref. 37), a drop structure has been designed at the indicated reach to control bed elevation changes. However, there is concern that lateral channel migration will threaten the integrity of the structure.

An ACB system is proposed to arrest lateral migration. Figure 3.3 illustrates this design example problem. The design example presented in the following discussion uses inch-pound units, however, the design would proceed identically when using S.I. units.

The design discharge for the revetment is the 100-year event, which is 6,444 ft^3/s. The bed slope of the reach upstream of the proposed drop structure is 0.01 ft/ft (due to the drop structure the energy grade line is changed so the value on Table 3-2 will be used for design). The bed material is clay and the bank material is silty clay with sand.

The design procedure assumes that appropriate assessment of hydraulic and geomorphic conditions has been made prior to the design process. The HEC-RAS package has been used to model the design hydraulics for the reach upstream of the proposed drop structure. Table 3-2 presents pertinent results from the hydraulic model at the cross-section that is exposed to the most severe hydraulic conditions.

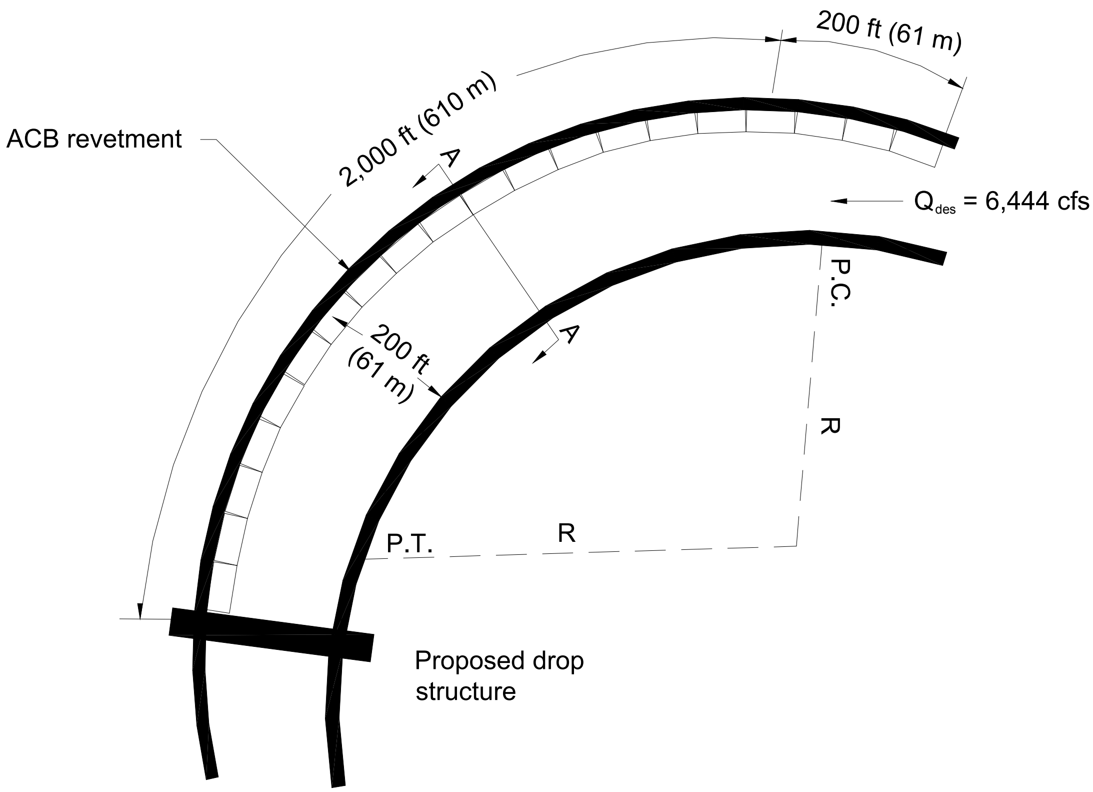
Table 3-2: HEC-RAS Model Output at Critical Design Section.	
Channel Discharge (ft^3/s)	6,444
Cross-Section-Averaged Velocity (ft/s)	6.5
Hydraulic Radius (ft)	4.3
Bed Slope upstream of the structure (ft/ft)	0.01
Energy Grade Line or Bed Slope (ft/ft)	0.007

A horizontal velocity distribution was calculated at the critical (most severe) section using HEC-RAS. Figure 3.4 presents a reduced form of the velocity distribution with 9 velocity subsections derived from the HEC-RAS analysis, which originally calculated a distribution of 20 velocity subsections. The distribution indicates that the maximum velocity expected at the bend is 8.0 ft/s (2.44 m/s), which will be used as the design value in the factor of safety calculations. The cross-section-averaged shear stress can be calculated with Equation 2.1 as $\tau_0 = \gamma R S_f = 62.4(4.3)(0.007) = 1.9\ lb/ft^2$.

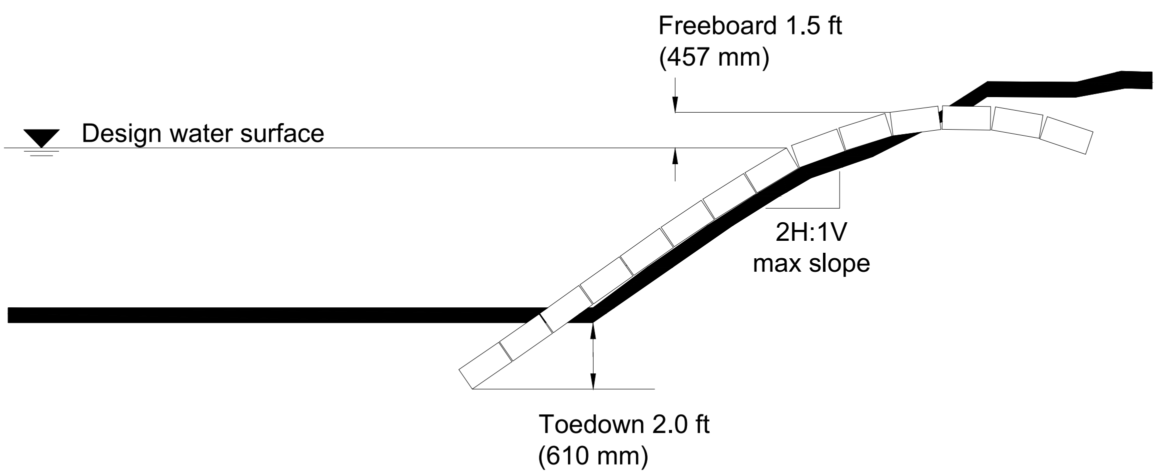
Section 2 provides guidance for increasing cross-section-averaged shear stress at meander bends. For this example, the velocity distribution in Figure 3.4 can be used instead, knowing that shear stress is proportional to the square of velocity. The maximum shear stress for design can be estimated as follows:

$$\tau_{des} = \tau_0 \cdot \left(\frac{V_{des}}{V_{avg}}\right)^2 = 1.9 \cdot \left(\frac{8.0}{6.5}\right)^2 = 2.88\ \mathrm{lb/ft^2} \qquad \text{(Eqn. 3.14)}$$

Verify that V_{des} and V_{avg} are less than or equal to V_{test} determined during full-scale flume testing and used to define the critical shear stress of the revetment systems (τ_C). For this example, the estimated maximum shear stress is used as the design value ($\tau_{des} = \tau_{max}$).



(A) Plan view of problem setting and ACB system installation



(B) Cross section view of A-A looking downstream

Figure 3.3: Example problem setting and ACB installation (not to scale).

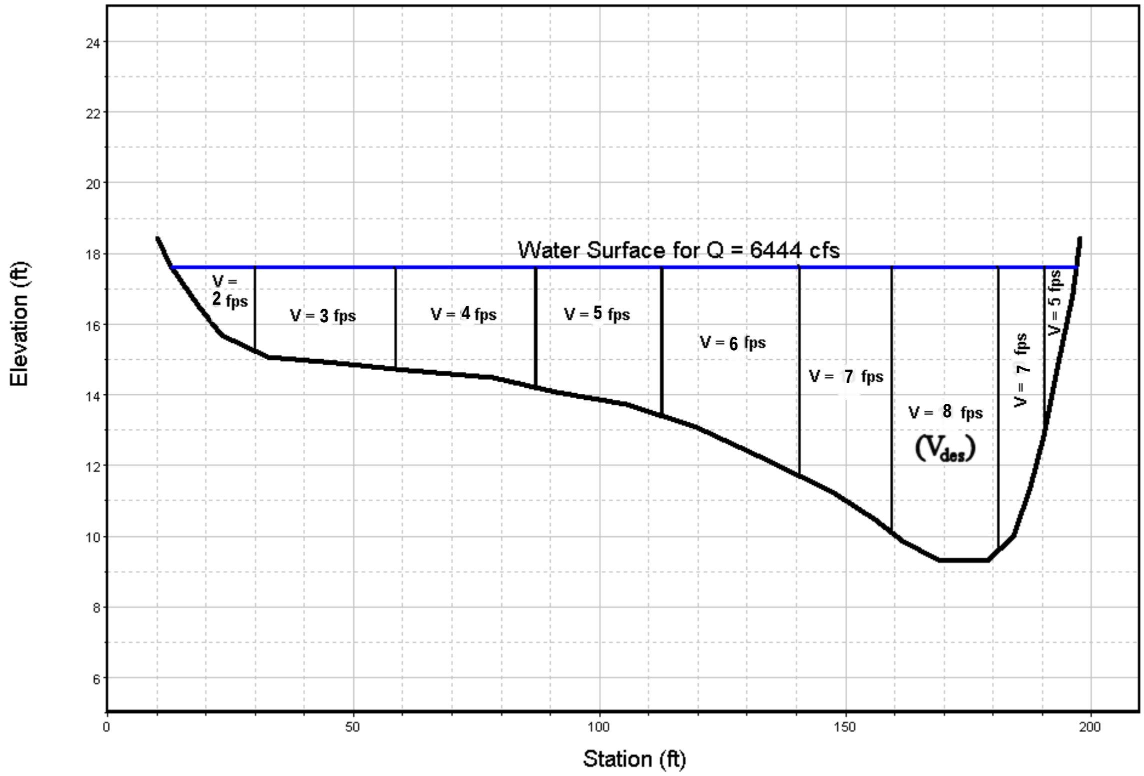


Figure 3.4: Velocity Distribution at Critical Cross-Section from HEC-RAS Model.

The suggested design procedure follows.

Step 1. Select a target factor of safety

For this example a target safety factor of 2.4 is selected. This safety factor was selected by the design engineer based on consideration of the project's complexity and flow characteristics, consequences of failure, and overall understanding of the site conditions and modeling accuracy.

Step 2. Select potential ACB products for design

Contact ACB manufacturers and/or review ACB catalogs and select several systems that are appropriate for the given application based on a preliminary assessment of the hydraulic conditions. At the same time, obtain the block properties necessary for design. These properties generally include the moment arms in Figure 3.2, the submerged weight of the block, the critical shear stress for the block on a horizontal surface, the maximum test velocity, and the test bed slope.

For this example, three products from ACB Systems, Inc. are selected based on guidance from the manufacturer. ACB Systems, Inc. suggests that the Type-A, Type-B or Type-C blocks would be appropriate for velocities in the range of 8 ft/s (2.44 m/s). The block properties provided by the manufacturer are shown on the worksheet accompanying this design example.

Step 3. Calculate the factor of safety for each product

Use the *NCMA ACB Design Spreadsheet* for the Hydraulic Stability Method to assist in the factor of safety calculations using the equations from Table 3-1. For this example the calculations are presented for the Type-A block and a completed worksheet with all the blocks is included.

a) Assuming a specific gravity of 2.1 for the concrete, calculate the submerged unit weight:

$$W_S = W \cdot \left(\frac{S_C - 1}{S_C}\right) \qquad \text{(see Eqn. 3.10)}$$

$$W_S = 67.5 \cdot \left(\frac{2.1 - 1}{2.1}\right) = 35.4 \text{ lb}$$

b) Calculate the stability number on a horizontal surface:

$$\eta_0 = \frac{\tau_{des}}{\tau_C} \qquad \text{(see Eqn. 3.9)}$$

$$\eta_0 = \frac{2.88}{25.0} = 0.115$$

c) Calculate the additional lift and drag forces from block protrusion out of the ACB matrix:

$$F'_L = F'_D = 0.5 \cdot (\Delta Z) b \rho V_{des}^2 \qquad \text{(see Eqn. 3.8)}$$

Note: The design velocity shall be less than or equal to the maximum test velocity used in full-scale hydraulic testing. b is selected based on the direction of the flow and mentioned in Section 2.3.1.

$$F'_L = F'_D = 0.5 \cdot (0.04)(1.25)(1.94)(8.0)^2 = 3.10 \text{ lb}$$

d) Calculate a_θ:

$$a_\theta = \sqrt{\cos^2\theta_1 - \sin^2\theta_0} \qquad \text{(see Eqn. 3.7)}$$

$$a_\theta = \sqrt{\cos^2(26.57) - \sin^2(0.57)} = 0.8943$$

e) Calculate angle θ:

$$\theta = \arctan\left(\frac{\sin\theta_0}{\sin\theta_1}\cdot\frac{\cos\theta_1}{\cos\theta_0}\right) = \arctan\left(\frac{\tan\theta_0}{\tan\theta_1}\right)$$ (see Eqn. 3.6)

$$\theta = \arctan\left(\frac{\sin(0.57)}{\sin(26.57)}\cdot\frac{\cos(26.57)}{\cos(0.57)}\right) = 1.14 \text{ degrees}$$

f) Calculate angle β:

$$\beta = \arctan\left(\frac{\cos(\theta_0+\theta)}{(\ell_4/\ell_3+1)\frac{\sqrt{1-a_\theta^2}}{\eta_0(\ell_2/\ell_1)} + \sin(\theta_0+\theta)}\right)$$ (see Eqn. 3.5)

$$\beta = \arctan\left(\frac{\cos(0.57+1.14)}{(0.88/0.33+1)\frac{\sqrt{1-0.8943^2}}{0.115(0.88/0.21)} + \sin(0.57+1.14)}\right) = 16.51 \text{ degrees}$$

g) Calculate the stability number on a sloped surface:

$$\eta_1 = \left(\frac{\ell_4/\ell_3 + \sin(\theta_0+\theta+\beta)}{\ell_4/\ell_3+1}\right)\eta_0$$ (see Eqn. 3.4)

$$\eta_1 = \left\{\frac{0.88/0.33 + \sin(0.57+1.14+8.88)}{0.88/0.33+1}\right\}0.115 = 0.094$$

h) Calculate angle δ:

$$\delta + \beta + \theta = 90° \text{ or } \pi/2 \text{ radians}$$ (see Eqn. 3.3)

$$\delta = 90 - (16.51 + 1.14) = 72.35 \text{ degrees}$$

i) Calculate the actual factor of safety for the Type-A block under these hydraulic conditions:

$$\mathrm{SF} = \frac{(\ell_2/\ell_1)\mathrm{a}_\theta}{\sqrt{1-\mathrm{a}_\theta^2}\cos\beta + \eta_1(\ell_2/\ell_1) + \dfrac{(\ell_3 \mathrm{F}'_\mathrm{D}\cos\delta + \ell_4 \mathrm{F}'_\mathrm{L})}{\ell_1 \mathrm{W}_\mathrm{S}}} \qquad \text{(see Eqn. 3.2)}$$

$$\mathrm{SF} = \frac{(0.88\ /\ 0.21)0.8943}{\sqrt{1-0.8943^2}\cos(16.51) + 0.094(0.88/0.21) + \dfrac{(0.33(3.10)\cos(72.35) + 0.88(3.10))}{0.21(35.4)}}$$

$$= 3.06$$

Steps a) through i) are then repeated for the Type-B and C blocks, the results of which are shown in the accompanying worksheet to this design example.

Step 4. Assess the suitability of each product and select a final ACB System

Compare the calculated factors of safety for the considered blocks with the design factor of safety and select the product that best meets the design needs. Other factors for consideration are: *1) the blocks open area relative to vegetative potential and manning's n variation; 2) the block's ability to articulate; 3) the block's ability to expand and contract; 4) block interlock and tapering characteristics.* For this example the Type A, and B products satisfied the target factor of safety, but Type A was selected as it resulted in a SF closest to the target SF. Once a product has been selected, the block specifications of the block selected are entered.

NATIONAL CONCRETE MASONRY ASSOCIATION

ARTICULATING CONCRETE BLOCK DESIGN CALCULATIONS FOR OPEN CHANNEL AND OVERTOPPING FLOW

NATIONAL CONCRETE MASONRY ASSOCIATION

EQUIPPING BETTER BUILDING

General Information

Company:	*ACB Consultants, Inc.*	Description:	*Meandering River*
Designer:	*John Doe*	Date:	*1/10/2019*
Project Name/Number:	*10-466-077*	**Hydraulic Design Data**	
Client:	*Harris County, TX*	Discharged (cfs):	*6444*
Target Factor of Safety:	*2.4*	Flow Depth (ft):	*4.3*

Project Information for ACB Design

TABLE 1: CHANNEL CONDITIONS FOR ACB DESIGN

	ENTER VALUES	Degrees	Radians
Longitudinal (bed) Slope θ_0, percent	1.00	0.57	0.0100
Maximum Side Slope θ_1, percent	50.00	26.57	0.4636
Design Maximum Velocity V, ft/s	8.00	**==> Use Hydraulic Stability Method**	
Design Maximum Shear Stress τ_0, lb/ft^2	2.88		
Maximum Block Placement Tolerance, inches	0.48		
Flow Direction: (select from dropdown)	a) Perpendicular to block width (b)		
Unit Weight of Water, lb/ft^3	62.4	NOTE: Recommended values for density of water are 62.4 lb/ft^3 for fresh water, 64.2 lb/ft^3 for seawater	
Unit Weight of Concrete, lb/ft^3	131		

Sheet 1: Block Characteristics

TABLE 2: NOMINAL BLOCK DIMENSIONS AND WEIGHTS

Block Designation	Length, a inches	Width, b inches	Height, inches	Open area at base of system, percent	Weight in air, lb
5-in. open cell - Type A	15	15	5.0	21	67.5
5-in. open cell- Type B	18	15	5.0	21	81.0
4.5-in. open cell - Type C	12	12	4.5	10	44.0

TABLE 3: PERFORMANCE DATA FOR CRITICAL SHEAR STRESS AND VELOCITY

Block type	τ_{test} at horizontal, lb/ft^2	Maximum velocity, V_{test} ft/s	Comments
5-in. open cell - Type A	25.0	18	Tested at 2H:1V
5-in. open cell- Type B	30.0	20	Tested at 2H:1V
4.5-in. open cell - Type C	11.0	10	Tested at 2H:1V

Project Name/Number:	*Meandering River / 10-466-077*
Company:	*ACB Consultants, Inc.*
Designer:	*John Doe*
Date:	*1/10/2019*

NATIONAL NCMA CONCRETE MASONRY ASSOCIATION

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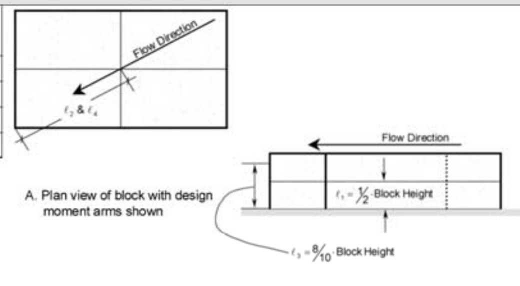
Sheet 2: Hydraulic Stability Method Calculations

TABLE 4: MOMENT ARMS AND CRITICAL SHEAR STRESS

Block Designation	ℓ_1, inches	ℓ_2, inches	ℓ_3, inches	ℓ_4, inches	τ_{test} at horiz., lb/ft^2
5-in. open cell - Type A	2.500	10.607	4.000	10.607	25.000
5-in. open cell- Type B	2.500	11.715	4.000	11.715	30.000
4.5-in. open cell - Type C	2.250	8.485	3.600	8.485	11.000



A. Plan view of block with design moment arms shown

B. Profile view of block with design moment arms shown

TABLE 5: CHANNEL CONDITIONS

	Design Inputs	Degrees	Radians
Longitudinal (bed) slope θ_0, percent	1.00	0.57	0.0100
Maximum side slope θ_1, percent	50.00	26.57	0.4636
Design maximum velocity V, ft/s	8.00		
Design maximum shear stress τ_{des}, lb/ft^2	2.88		
Maximum block placement tolerance, inches	0.48		

Flow direction parallel to the block*:	a) Perpendicular to block width (b)

Unit weight of water, lb/ft^3	62.4	NOTE: Recommended values for density of water are: 62.4 lb/ft^3 for fresh water, 64.2 lb/ft^3 for seawater
Unit weight of concrete, lb/ft^3	131	
Mass density of water, slugs/ft^3	1.94	

TABLE 6: SAFETY FACTOR CALCULATIONS

Block Designation	$\eta_0 = \tau_{des}/\tau_{test}$	a_θ	ratio ℓ_2/ℓ_1	ratio ℓ_4/ℓ_3	angle θ (radians)	angle β (rad)	η_1	Drag F'_d, lbs	Submerged weight (lb)	**Safety Factor**
5-in. open cell - Type A	0.115	0.894	4.243	2.652	0.020	0.288	0.093	3.10	35.35	**3.06**
5-in. open cell- Type B	0.096	0.894	4.686	2.929	0.020	0.249	0.078	3.10	42.42	**3.57**
4.5-in. open cell - Type C	0.262	0.894	3.771	2.357	0.020	0.572	0.228	3.10	23.04	**1.81**

Block Designation	SF ≥ SF_{goal}	Velocity Check	Bed Slope Check	Shear Stress Check
5-in. open cell - Type A	Ok	Ok	Ok	Ok
5-in. open cell- Type B	Ok	Ok	Ok	Ok
4.5-in. open cell - Type C	Not Ok	Ok	Ok	Ok

DESIGN NOTES:

Selected System: **5-in. open cell - Type A**

Step 5. Design horizontal and vertical extent of the ACB system

Following guidelines from Section 2.3.2, the ACB system should terminate against the drop structure and extend 2200 ft (671 m) upstream, which is more than one channel width beyond the observed limits of channel erosion. The drop structure is expected to arrest vertical degradation; therefore, bed erosion is not expected to undermine the revetment. A toe down into the bed of 2 ft (61 cm) is specified so that lateral movement of the lowest point in the channel will not undermine the revetment. The specified freeboard for this application is 1.5 ft (45.72 cm) above the water surface profile computed in the HEC-RAS model. *The maximum side slope for any ACB system should be 2H:1V.*

Step 6. Design the filtration component of the ACB system

The procedure outlined in Section 5. should be followed for filtration design. A worked example problem is provided in Section 5.5 to illustrate the procedure. If performance testing of the selected ACB system was conducted with a drainage layer in place, then a drainage layer of the same type is required for the design.

Section 4. ACB DESIGN – SHEAR AND VELOCITY STABILITY METHOD

4.1 Introduction

This new method is intended for application where the velocity of the flow is higher than 8 ft/s. This methodology includes the shear and velocity in the calculations. This method is not conservative for project with velocities less than 8 ft/s and the hydraulic stability method should be used in those cases.

Design equations for the shear and velocity stability assessment (SVSA) method quantify a factor of safety for application of an ACB system based on a moment stability analysis of a single block. The SVSA method was originally provided in *Moment Stability Analysis Method for Determining Safety Factors for Articulated Concrete Blocks* (ref. 24). The moment-stability analysis method computes a factor of safety by taking the ratio of the sum of the moments caused by stabilizing forces to the sum of moment caused by destabilizing forces. This analysis procedure was originally presented in *Stability Analysis for Coarse Granular Material on Slopes* (ref. 42). The first moment-stability method for calculating factors of safety for individual rectangular blocks within a matrix was presented in *Protecting Embankment Dams with Concrete Block Systems* (ref. 22). The ref. 22 method was based on the ref. 42 factor of safety method for particles resting on a side slope with modifications to account for block geometry. The factor of safety method detailed in Section 3.2 of this NCMA ACB Design Manual is a derivative of the ref. 22 method.

Similar to the factor of safety calculation method presented in the Section 3. , the SVSA factor of safety design method incorporates the following considerations:

1. additional forces imposed on a block that protrudes above the surrounding ACB matrix are included;
2. potential restraining forces imposed on a block by cables are excluded; and
3. additional stabilizing forces provided by vegetation and/or mechanical anchoring devices are excluded in the moment stability analysis.

The SVSA factor of safety design method differs from the hydraulic stability method (Section 3.) by the following:

1. the block rotation angle (β) for rotation about block corner is computed from the block geometry, where as the hydraulic stability method computes the block rotation angle based on hydrodynamic forces and uses the computed angle to determine force components for the moment stability analysis then couples those forces with a moment arm length to the block corner; this is an erroneous residual from the method's original application for riprap where the rotation angle is not defined by particle geometry;
2. the lift and drag forces are directly calculated and employed instead of using a stability number (η_1) to represent the lift and drag forces in the moment stability analysis;
3. the mathematical expressions for determining the portions of the submerged weight force for each of the submerged weight moments are different than those used in the hydraulic stability method; and

4. the full block height (ℓ_3') is used as the moment arm for the drag force instead of eight-tenths the block height.
5. Inter-block friction is not represented in the moment stability analysis method and is encompassed within a calibrated block system lift coefficient.

4.2 Channelized Flow Equations

The moment-stability analysis approach computes a safety factor (SF) from the ratio of stabilizing to destabilizing moments. Stabilizing and destabilizing forces on an individual block within an ACB system resting on a channel side-slope plane are illustrated in Figure 4.1. The forces represented in the free-body diagrams include the lift force (F_L), the drag force (F_D), and the submerged weight force of the block (W_S), which combines the block weight force with the associated buoyancy force. To simplify the equations, the portions of the submerged weight force which act in the defined x, y, and z coordinates are labeled with the variables W_{SX}, W_{SY}, and W_{SZ}, respectively.

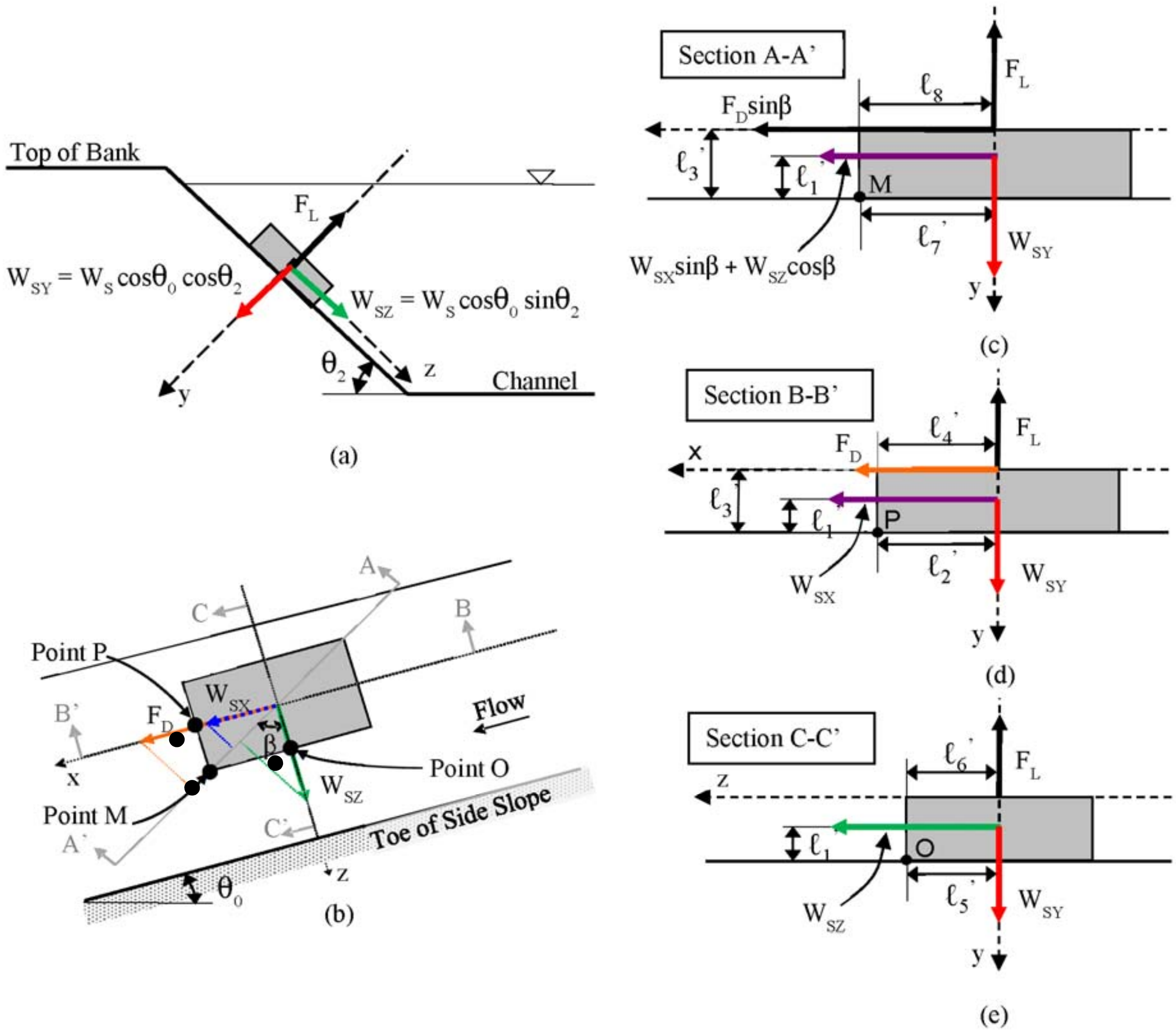


Figure 4.1: Force diagrams for safety factor analysis: (a) cross-section view normal to bed slope, (b) view normal to side slope, (c) rotation about Point M along Section A-A', (d) rotation about Point P along Section B-B', and (e) rotation about Point O along Section C-C'.

Three potential rotation points exist for a block resting on a side-slope plane: Point M, Point P, and Point O. These points are identified in Figure 4.1. Point M represents the location for rotation about the block corner; Point P represents the location for rotation about the block edge in the flow direction; and Point O represents the location for rotation about the block edge laterally into the channel. Rotation could occur about any of the three points depending on the combination of channel slope, side slope, and hydraulic conditions. Free-body diagrams for rotation about Point M, Point P, and Point O are shown in Figure 4.1c, Figure 4.1d and Figure 4.1e, respectively. Moment arms ℓ_1', ℓ_2', ℓ_3', ℓ_4', ℓ_5', ℓ_6', ℓ_7', and ℓ_8', for the forces are determined from block dimensions as shown in

Figure 4.2. Variables for block length normal to the bed slope ℓn, and block length parallel to the bed slope ($\ell_{p,}$) are also defined in

Figure 4.2.

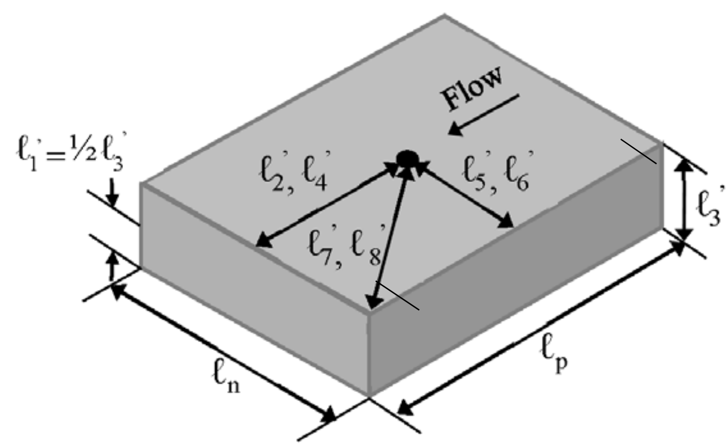


Figure 4.2: Definition sketch of block-length and moment arm variables.

The factor of safety equations for rotation about each of the three points are based on the moments in the free-body diagrams presented in Figure 4.1. and include the additional lift and drag force caused by a block protruding above adjacent blocks (i.e., F'_L and F'_D). The full set of equations used for the SVSA factor of safety design method for channelized flow are provided in Table 4-1. The equations are presented in chronological order for calculation and can be used with any consistent set of units. Equations for the drag force, lift force, and the additional drag and lift force are provided in by Eq. 4.6, Eq. 4.7, and Eq. 3.8, respectively. The additional lift and drag force are assumed to be equal and are a function of the flow velocity.

Factors of safety should be computed for rotation about each of the three points (Point M, Point P and Point O) using Eq. 4.8, Eq. 4.9, and Eq. 4.10, respectively. The minimum computed factor of safety (SF_{Min}) is controlling and should be used for design as shown by Eq. 4.11. The *NCMA ACB Design Spreadsheet* can be used to assist in the design process for channelized flow conditions.

Table 4-1: SVSA Design Equations for ACB Systems with Channelized Flow – US Customary

Equation	No.
$Ws = W \cdot \left(\frac{S_C - 1}{S_C}\right)$	3.10
$\theta_2 = \arctan[\tan(\theta_1)\cos(\theta_0)]$	4.1
$\beta = \arctan \frac{\ell_p}{\ell_n}$	4.2
$W_{SX} = W_S \cdot \sin(\theta_0)$	4.3
$W_{SY} = W_S \cdot \cos(\theta_0) \cdot \cos(\theta_2)$	4.4
$W_{SZ} = W_S \cdot \cos(\theta_0) \cdot \sin(\theta_2)$	4.5
$F_D = \tau_{des} \cdot A_B$	4.6
$F_L = (0.5) \cdot C_{BL}\rho A_B V_{des}^2$	4.7
$F_L' = F_D' = (0.5) \cdot (\Delta Z) b \rho V_{des}^2$	3.8
$SF_M = \frac{\ell_7' W_{SY}}{\left[\begin{array}{l}\ell_1'(W_{SX} \cdot \sin\beta + W_{SZ} \cdot \cos\beta) + \\ \ell_3'(F_D + F_D')\sin\beta + \ell_8'(F_L + F_L')\end{array}\right]}$	4.8
$SF_P = \frac{\ell_2' W_{SY}}{\ell_1' W_{SX} + \ell_3'(F_D + F_D') + \ell_4'(F_L + F_L')}$	4.9
$SF_O = \frac{\ell_5' W_{SY}}{\ell_1' W_{SZ} + \ell_6'(F_L + F_L')}$	4.10
$SF_{MIN} = \mathrm{Min}[SF_M, SF_P, SF_O]$	4.11

A_B = Block area parallel to the direction of flow, ft^2 (m^2)
b = Block width normal to the direction of flow, ft (m)
C_{BL} = Block lift coefficient (Section 4.4.2)
F_D = Drag force, lb (N)
F'_D & F'_L = additional drag and lift forces, lb (N)
F_L = Lift force, lb (N)
S_C = Specific gravity of concrete
SF_M = Factor of safety for rotation about Point M
SF_P = Factor of safety for rotation about Point P
SF_O = Factor of safety for rotation about Point O
SF_{Min}= Minimum factor of safety for all rotation points
V_{des} = Design velocity, ft/s (m/s) (V_{des} less than or equal to V_{test} or V_{max})
W = Weight of block, lb (N)
W_S = Submerged weight of block, lb (N)
W_{SX} = W_S component parallel to side-slope plane in the x direction, lb (N)
W_{SY} = W_S component normal to side-slope plane in the y direction, lb (N)
W_{SZ} = W_S component parallel to side-slope plane in the positive z **direction**, lb (N)
β = Angle to block corner, degrees
ΔZ = Height of block protrusion above ACB matrix, ft (m)
θ_0 = Bed slope angle, degrees
θ_1 = Side slope angle, degrees
θ_2 = Side slope angle normal to bed slope plane, degrees
ℓ_n = Block length normal to flow direction, ft (m)
ℓ_p = Block length parallel to flow direction, ft (m)
ℓ_X' = Moment arms corresponding to forces, ft (m)
ρ = Mass density of water 1.94 slugs/ft^3 (1 x 10^6 g/m^3)
τ_{des} = Design shear stress, lb/ft^2 (Pa)

4.3 Overtopping Flow Equations

A simplified SVSA safety factor equation can be used to compute a factor of safety for overtopping flow (SF_{Bed}). The equation for overtopping flow applications is based on Eq. 4.9, the safety factor equation for rotation about Point P for channelized flow applications, but uses a side-slope angle of zero. The SVSA design equations for ACB systems with overtopping flow are provided in Table 4-2. The *NCMA ACB Design Spreadsheet* for Overtopping Flow can be used to assist in the design process for overtopping flow conditions.

Table 4-2: SVSA Design Equations for ACB Systems with Overtopping Flow – US Customary

Equation	No.	Variables
$W_S = W \cdot \left(\frac{S_C - 1}{S_C}\right)$	3.10	A_B = Block area parallel to the direction of flow, ft^2 (m^2) b = Block width normal to the direction of flow, ft (m) C_{BL} = Block lift coefficient (Section 4.4.2) F_D = Drag force, lb (N) F'_D & F'_L = additional drag and lift forces, lb (N) F_L = Lift force, lb (N) S_C = Specific gravity of concrete SF_{Bed} = Factor of safety for overtopping flow V_{des} = Design velocity, ft/s (m/s) (V_{des} less than or equal to V_{test} or V_{max}) W = Weight of block, lb (N) W_S = Submerged weight of block, lb (N) ΔZ = Height of block protrusion above ACB matrix, ft (m) θ_0 = Bed slope angle, degrees ℓ_X' = Moment arms corresponding to forces, ft (m) ρ = Mass density of water 1.94 $slugs/ft^3$ (1×10^6 g/m^3) τ_{des} = Design shear stress, lb/ft^2 (Pa)
$F_D = \tau_{des} \cdot A_B$	4.6	
$F_L = (0.5) \cdot C_{BL} \rho A_B V_{des}^2$	4.7	
$F'_L = F'_D = (0.5) \cdot (\Delta Z) b \rho V_{des}^2$	3.8	
$SF_{BED} = \dfrac{\ell'_2 W_S \cdot \cos\theta_0}{\left[\ell'_1 W_S \cdot \sin\theta_0 + \ell'_3(F_D + F'_D) + \ell'_4(F_L + F'_L)\right]}$	4.12	

4.4 Required Design Variables for the SVSA Factor of Safety Design Method

Values for bed slope, side slope, block geometry, block weight, specific gravity of block material, design velocity, design shear stress, and calibrated lift coefficient are required to use the new safety factor method. This Section details how each of the required design variables can be determined. All other variables can be calculated from the equations provided in Section 4.1.

4.4.1 Channel Geometry Variables

Bed slope (S_0): The bed slope is measured in the channel along the flow direction using the vertical to horizontal ratio. This can be obtained from survey data or design specifications. The bed slope angle (θ_0) is computed from the bed slope using the following equation:

$$\theta_0 = \arctan(S_0) \quad \text{(Eqn. 4.13)}$$

Side slope (z): The side slope is measured across the channel using the horizontal to vertical ratio. This can be obtained from survey data or design specifications. The vertical side slope angle (θ_1) and the side slope angle relative to the bed slope plane (θ_2) are computed using Eq. 4.14 and Eq. 4.1, respectively:

$$\theta_1 = \arctan\left(\frac{1}{z}\right) \quad \text{(Eqn. 4.14)}$$

$$\theta_2 = \arctan(\tan\theta_1 \cdot \cos\theta_0) \quad \text{(Eqn. 4.1)}$$

4.4.2 ACB System Variables

Submerged block weight (W_S): Block weight (W) and specific gravity (S_C) are provided by the ACB system manufacturer. The submerged block weight is computed using Eq. 3.10:

$$W_S = W \cdot \left(\frac{S_C - 1}{S_C}\right) \quad \text{(Eqn. 3.10)}$$

Block moment arms (ℓ_x'): The block length measured perpendicular to the flow direction (ℓ_p), the block width measured normal to the flow direction (ℓ_n), and the block height (ℓ_3') are provided by the block system manufacturer. The block moment arms (ℓ_X') are computed based on the block length, width, and height as shown in

Figure 4.2 and defined by the following equations:

$$\ell_1' = 0.5 \cdot \ell_3' \quad \text{(Eqn. 4.15)}$$

$$\ell_2' = \ell_4' = 0.5 \cdot \ell_p \quad \text{(Eqn. 4.16)}$$

$$\ell_5' = \ell_6' = 0.5 \cdot \ell_n \quad \text{(Eqn. 4.17)}$$

$$\ell_7' = \ell_8' = 0.5 \cdot \sqrt{{\ell_p}^2 + {\ell_n}^2} \quad \text{(Eqn. 4.18)}$$

The rotation angle within the side slope plane (β) is defined by Eq. 4.2:

$$\beta = \arctan\left(\frac{\ell_p}{\ell_n}\right) \quad \text{(Eqn. 4.2)}$$

Block area parallel to flow direction (A_B): The block area parallel to the flow direction (A_B) is provided by the ACB system manufacturer. The area is determined as the total block footprint from a plan view perspective. Open-celled systems do not include the open areas as part of the block area.

Block width normal to the direction of flow (b): The block width normal to the direction of flow (b) is used in the calculation of the additional lift and drag forces (F'_L and F'_D). The diagonal distance of the block is recommended for this block width to account for the uncertainty in the flow direction relative to the block system installation following the same recommendations on Section 2.3.1. The block width normal to the direction of flow (b) is computed using Eq. 4.19:

$$b = \sqrt{\ell_p^{\,2} + \ell_n^{\,2}} \qquad \text{(Eqn. 4.19)}$$

Block system lift coefficient (C_{BL}): Block system lift coefficients, which are unique to a given system, can be calculated using embankment-overtopping laboratory test data. The equation to compute the block system lift coefficient (C_{BL}) is derived from the factor of safety equation for overtopping flow (Eq. 4.12). The safety factor is set to a value of 1.00 and the equation is rearranged to solve for the block system lift coefficient. To be conservative, the block system lift coefficient is computed using the highest stable flow velocity (V_S) and boundary shear stress (τ_{0S}) values, which results in a conservative known maximum value for the lift coefficient (i.e., based on laboratory testing, the lift coefficient must be less than or equal to the computed value). The following equation is used to compute block system lift coefficients from overtopping test data:

$$C_{BL} = \frac{\ell'_2 W_S \cos\theta_0 - \ell'_1 W_S \sin\theta_0 - \ell'_3 \tau_{0S} A_B}{0.5 \ell'_4 A_B V_S^2} \qquad \text{(Eqn. 4.20)}$$

where:

C_{BL}	=	Block system lift coefficient
W_S	=	Submerged weight of the block, lb (N)
τ_{0S}	=	Highest stable boundary shear stress, lb/ft^2 (Pa)
A_B	=	Block area parallel to flow direction, ft^2 (m^2)
V_S	=	Highest stable flow velocity, ft/s (m/s)
ℓ_1'	=	Moment arm for destabilizing submerged weight force, ft (m)
ℓ_2'	=	Moment arm for stabilizing submerged weight force, ft (m)
ℓ_3'	=	Moment arm for drag force, ft (m)
ℓ_4'	=	Moment arm for lift force, ft (m)
θ_0	=	Bed slope angle (equal to the arctan of the bed slope), degrees
ρ	=	Density of water, 1.94 slugs/ft^3 (1 x 10^6 g/m^3)

The ASTM D7276 standard provides guidance for analysis and interpretation of laboratory test data for ACB systems (ASTM, 2016). The ASTM D7276 standard can be used to determine flow velocities and shear stresses from recorded test data.

Inter-block friction is not represented in the moment stability analysis method and is encompassed within the calibrated block system lift coefficient. Thus, coefficient extrapolations for varying block heights, block footprints, and block weights, such as those presented in Section 2.2.2 should be carefully employed.

4.4.3 Hydrodynamic Variables

Both **design shear stress (τ_{des})** and **design flow velocity (V_{des})** are determined from hydraulic analysis of the open-channel system design. Several numerical modeling programs are available for hydraulic analysis. They generally require information on channel geometry, hydraulic roughness coefficient (Manning's *n*) of the block system, and design discharge.

4.5 Design Calculation Examples for the SVSA Method

4.5.1 Channelized Flow

The example problem for channelized flow presented in Section 0 is used for the channelized flow example design problem for the SVSA factor of safety calculation method with higher design velocities. This section details how Steps 1 through 3 of the design example are done using the SVSA factor of safety calculation method.

Table 4-3: HEC-RAS Model Output at Channel Critical Design Section Channel	
Channel Discharge (ft^3/s)	6,444
Cross-Section-Averaged Velocity (ft/s)	8.1
Hydraulic Radius (ft)	4.3
Energy Grade Line or Bed Slope (ft/ft)	0.007

A horizontal velocity distribution was calculated at the critical (most severe) section using HEC-RAS. Figure 4.3 presents a velocity distribution derived from the HEC-RAS analysis. The distribution indicates that the maximum velocity expected at the bend is 11.0 ft/s (3.35 m/s), which will be used as the design value in the factor of safety calculations. The cross-section-averaged shear stress can be calculated with Equation 2.1 as $\tau_0 = \gamma R S_f = 62.4(4.3)(0.007) = 1.9$ lb/ft^2.

The maximum shear stress for design (τ_{des}) can be estimated as follows:

$$\tau_{des} = \tau_0 \cdot \left(\frac{V_{des}}{V_{avg}}\right)^2 = 1.9 \cdot \left(\frac{11.0}{8.1}\right)^2 = 3.5\ \mathrm{lb/ft^2} \qquad \text{(Eqn. 3.14)}$$

Verify that V_{des} and V_{avg} are less than or equal to V_{test} (from full-scale flume testing) and used to define the critical shear stress of the revetment systems (τ_C). For this example, the estimated maximum shear stress is used as the design value ($\tau_{des} = \tau_{max}$).

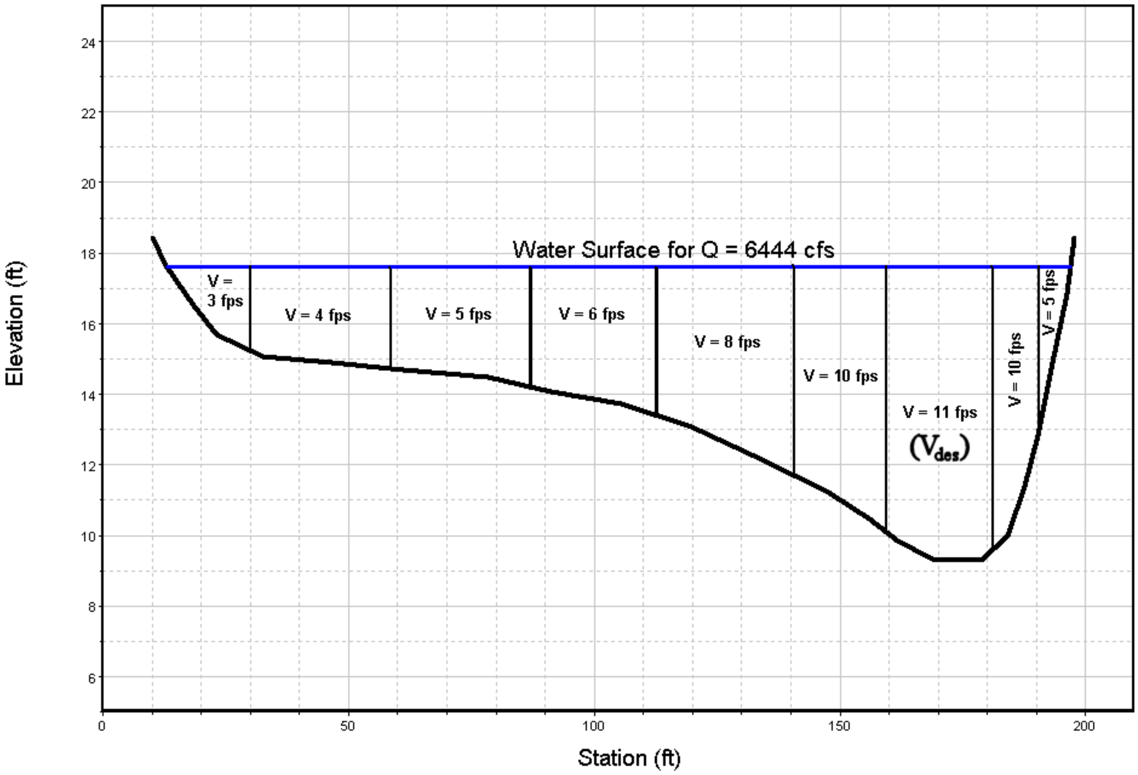


Figure 4.3: Velocity Distribution at Critical Cross-Section from HEC-RAS Model.

Step 1. Select a target factor of safety

For this example a target factor of safety of 2.4 is selected. This safety factor was selected by the design engineer based on consideration of the project's complexity and flow characteristics, consequences of failure, and overall understanding of the site conditions and modeling accuracy.

Step 2. Select potential ACB products for design

Contact ACB manufacturers and/or review ACB catalogs and select several systems that are appropriate for the given application based on a preliminary assessment of the hydraulic conditions. At the same time obtain the block properties necessary for design. These properties generally include the moment arms in Figure 4.2, the submerged weight of the block, the block system lift coefficient, the maximum test velocity, and the test bed slope.

For this example, three products from ACB Systems, Inc. are selected based on guidance from the manufacturer. ACB Systems, Inc. suggests that the Type-A, Type-B or Type-C blocks would be appropriate for velocities in the range of 11.0 ft/s (3.35 m/s),. The block properties provided by the manufacturer are shown on the worksheet accompanying this design example.

Step 3. Calculate the factor of safety for each product

Use the *NCMA ACB Design Spreadsheet* for the Shear and Velocity Stability Method in channels to assist in the factor of safety calculations using the equations from Table 4-1. For this example, the calculations are presented for the Type-A block and a completed worksheet with Type-A, Type-B and Type-C is included.

a) Assuming a specific gravity of 2.1 for the concrete, calculate the submerged weight:

$$W_S = W \cdot \left(\frac{S_C - 1}{S_C}\right) \qquad \text{(Eqn. 3.10)}$$

$$W_S = (67.50\ \text{lb}) \cdot \left(\frac{2.1 - 1}{2.1}\right) = 35.40\ \text{lb}$$

b) Calculate the side slope angle perpendicular to the bed slope:

$$\theta_2 = \arctan[\tan(\theta_1)\cos(\theta_0)] \qquad \text{(see Eqn. 4.1)}$$

$$\theta_2 = \arctan[\tan(26.57°)\cos(0.57°)] = 26.56°$$

c) Calculate the rotation angle in the side slope plane:

$$\beta = \arctan\left(\frac{\ell_p}{\ell_n}\right) \qquad \text{(Eqn. 4.2)}$$

$$\beta = \arctan\left(\frac{1.25\ \text{ft}}{1.25\ \text{ft}}\right) = 45.0°$$

d) Compute submerged weight forces in the x, y, and z axis:

$$W_{SX} = W_S \cdot \sin(\theta_0) \qquad \text{(see Eqn. 4.3)}$$

$$W_{SX} = (35.40\ \text{lb}) \cdot \sin(0.57°) = 0.35\ \text{lb}$$

$$W_{SY} = W_S \cdot \cos(\theta_0) \cdot \cos(\theta_2) \qquad \text{(see Eqn. 4.4)}$$

$$W_{SY} = (35.40\ \text{lb}) \cdot \cos(0.57°) \cdot \cos(26.56°) = 31.61\ \text{lb}$$

$$W_{SZ} = W_S \cdot \cos(\theta_0) \cdot \sin(\theta_2) \qquad \text{(see Eqn. 4.5)}$$

$$W_{SZ} = (35.40\ \text{lb}) \cdot \cos(0.57°) \cdot \sin(26.56°) = 15.81\ \text{lb}$$

e) Compute the drag force:

$$F_D = \tau_{des} \cdot A_B \qquad \text{(see Eqn. 4.6)}$$

$$F_D = (3.5\ lb/ft^2) \cdot (1.11\ ft^2) = 3.9\ lb$$

f) Compute the lift force:

$$F_L = (0.5) \cdot C_{BL} \rho A_B V_{des}^2 \qquad \text{(see Eqn. 4.7)}$$

$$F_L = (0.5) \cdot (0.0135) \cdot (1.94\ slugs/ft^3) \cdot (1.11\ ft^2) \cdot (11.0\ ft/s)^2 = 1.8\ lb$$

g) Compute the additional lift and drag force due to projecting block edge:

$$F'_L = F'_D = (0.5) \cdot (\Delta Z) b \rho V_{des}^2 \qquad \text{(see Eqn. 3.8)}$$

Note: b is selected based on the direction of the flow and mentioned in Section 2.3.1.

$$F'_L = F'_D = (0.5) \cdot (0.04\ ft) \cdot (1.26\ ft) \cdot (1.94\ slugs/ft^3) \cdot (11.0\ ft/s)^2 = 5.9\ lb$$

h) Compute SF for rotation about Point M, Point P, and Point O:

$$SF_M = \frac{\ell'_7 \cdot W_{SY}}{[\ell'_1(W_{SX} \cdot \sin\beta + W_{SZ} \cdot \cos\beta) + \ell'_3(F_D + F'_D)\sin\beta + \ell'_8(F_L + F'_L)]} \quad \text{(see Eqn. 4.8)}$$

$$SF_M = \frac{(0.88\ ft) \cdot (31.61\ lb)}{\begin{bmatrix} (0.21\ ft) \cdot [(0.35\ lb) \cdot \sin(45.0°) + (15.81 lb) \cdot \cos(45.0°)] + \\ (0.42\ ft) \cdot (3.9\ lb + 5.9\ lb)\sin(45.0°) + (0.88\ ft) \cdot (1.8\ lb + 5.9\ lb) \end{bmatrix}} = 2.3$$

$$SF_P = \frac{\ell'_2 W_{SY}}{\ell'_1 W_{SX} + \ell'_3(F_D + F'_D) + \ell'_4(F_L + F'_L)} \quad \text{(see Eqn. 4.9)}$$

$$SF_P = \frac{(0.63\ ft) \cdot (31.61\ lb)}{\begin{bmatrix} (0.21\ ft) \cdot (0.35\ lb) + (0.42\ ft) \cdot (3.9\ lb + 5.9\ lb) + \\ (0.63\ ft) \cdot (1.8\ lb + 5.9\ lb) \end{bmatrix}} = 2.2$$

$$SF_O = \frac{\ell'_5 W_{SY}}{\ell'_1 W_{SZ} + \ell'_6(F_L + F'_L)} \qquad \text{(see Eqn. 4.10)}$$

$$SF_O = \frac{(0.63\ \text{ft}) \cdot (31.61\ \text{lb})}{[(0.21\ \text{ft}) \cdot (15.81\ \text{lb}) + (0.63\ \text{ft}) \cdot (1.8\ \text{lb} + 5.9\ \text{lb})]} = 2.4$$

i) Identify minimum SF from computed values for rotation about the three points:

$$SF_{Min} = \text{Min}[SF_M, SF_P, SF_O]$$ (see Eqn. 4.11)

$$SF_{Min} = \text{Min}[2.3, 2.2, 2.4] = 2.2$$

j) Compare minimum SF to target SF to determine if system is acceptable for the application:

$SF_{Min} \leq SF_{Target}$
$2.2 \leq 2.4$

Design is NOT OK for the Type-A block system.

Steps a) through j) are then repeated for the Type-B and C blocks. Type-C block is discounted because the maximum tested velocity is lower than the design velocity of the project. All the results of which are shown in the accompanying worksheet to this design example.

NATIONAL CONCRETE MASONRY ASSOCIATION

ARTICULATING CONCRETE BLOCK DESIGN CALCULATIONS FOR OPEN CHANNEL AND OVERTOPPING FLOW

NATIONAL NCMA CONCRETE MASONRY ASSOCIATION

EQUIPPING BETTER BUILDING

General Information

Company:	*ACB Consultants, Inc.*	Description:	*Meandering River*
Designer:	*John Doe*	Date:	*1/10/2019*
Project Name/Number:	*10-466-077*	**Hydraulic Design Data**	
Client:	*Harris County, TX*	Discharged (cfs):	*6444*
Target Factor of Safety:	*2.4*	Flow Depth (ft):	*4.3*

Project Information for ACB Design

TABLE 1: CHANNEL CONDITIONS FOR ACB DESIGN

	ENTER VALUES	Degrees	Radians
Longitudinal (bed) Slope θ_0, percent	1.00	0.57	0.0100
Maximum Side Slope θ_1, percent	50.00	26.57	0.4636
Design Maximum Velocity V, ft/s	11.00	**==> Use Shear and Velocity Method**	
Design Maximum Shear Stress τ_0, lb/ft^2	3.50		
Maximum Block Placement Tolerance, inches	0.48		

Flow Direction: (select from dropdown)	a) Perpendicular to block width (b)	
Unit Weight of Water, lb/ft^3	62.4	NOTE: Recommended values for density of water are 62.4 lb/ft^3 for fresh water, 64.2 lb/ft^3 for seawater
Unit Weight of Concrete, lb/ft^3	131	

Sheet 1: Block Characteristics

TABLE 2: NOMINAL BLOCK DIMENSIONS AND WEIGHTS

Block Designation	Length, a inches	Width, b inches	Height, inches	Open area at base of system, percent	Weight in air, lb
5-in. open cell - Type A	15	15	5.0	21	67.5
5-in. open cell- Type B	18	15	5.0	21	81.0
4.5-in. open cell - Type C	12	12	4.5	10	44.0

BLOCK AREA AND LIFT

Block Designation	Block area parallel to flow A_B, ft^2	Block lift coefficient, C_{BL}
5-in. open cell - Type A	1.110	0.01350
5-in. open cell- Type B	1.320	0.01350
4.5-in. open cell - Type C	1.000	0.01150

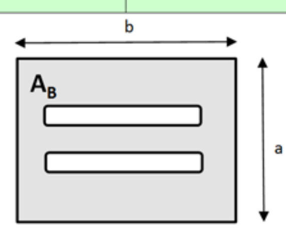


TABLE 3: PERFORMANCE DATA FOR CRITICAL SHEAR STRESS AND VELOCITY

Block type	τ_{test} at horizontal, lb/ft^2	Maximum velocity, V_{test} ft/s	Comments
5-in. open cell - Type A	25.0	18	Tested at 2H:1V
5-in. open cell- Type B	30.0	20	Tested at 2H:1V
4.5-in. open cell - Type C	11.0	10	Tested at 2H:1V

Project Name/Number:	*Meandering River / 10-466-077*
Company:	*ACB Consultants, Inc.*
Designer:	*John Doe*
Date:	*1/10/2019*
Client:	*Harris County, TX*

NATIONAL NCMA CONCRETE MASONRY ASSOCIATION

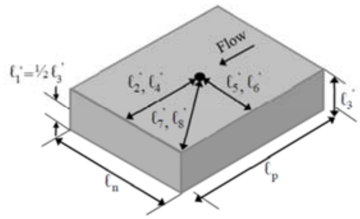
EQUIPPING BETTER BUILDING

Sheet 3a: Shear Velocity Method Calculations - Channel Flow

TABLE 4: MOMENT ARMS AND CRITICAL SHEAR STRESS

Block Designation	ℓ_1, ft	ℓ_2, ft	ℓ_3, ft*	ℓ_4, ft	ℓ_5, ft	ℓ_6, ft	ℓ_7, ft	ℓ_8, ft
5-in. open cell - Type A	0.208	0.625	0.417	0.625	0.625	0.625	0.884	0.884
5-in. open cell- Type B	0.208	0.750	0.417	0.750	0.625	0.625	0.976	0.976
4.5-in. open cell - Type C	0.188	0.500	0.375	0.500	0.500	0.500	0.707	0.707

Block Designation	ℓ_p, ft	ℓ_n, ft	C_{BL}	W (lb)	A_B, ft^2	τ_{test} at horiz., lb/ft^2
5-in. open cell - Type A	1.250	1.250	0.01350	67.5	1.110	25.0
5-in. open cell- Type B	1.500	1.250	0.01350	81.0	1.320	30.0
4.5-in. open cell - Type C	1.000	1.000	0.01150	44.0	1.000	11.0



* ℓ_3 considers the whole height of the block.

TABLE 5: CHANNEL CONDITIONS

	COPIED VALUES	Degrees	Radians
Longitudinal (bed) slope θ_0, percent	1.00	0.57	0.0100
Maximum side slope θ_1, percent	50.00	26.57	0.4636
Side slope relative to bed θ_2, percent	50.00	26.56	0.4636
Design maximum velocity V, ft/s	11.00		
Design maximum shear stress τ_{des}, lb/ft^2	3.50		
Maximum block placement tolerance, inches	0.48		

Unit weight of water, lb/ft^3	62.4
Unit weight of concrete, lb/ft^3	131
Mass density of water, slugs/ft^3	1.94

NOTE: Recommended values for density of water are: 62.4 lb/ft^3 for fresh water, 64.2 lb/ft^3 for seawater

Flow direction parallel to the block*: a) Perpendicular to block width (b)

TABLE 6: SAFETY FACTOR CALCULATIONS

Block Designation	angle θ_2 (radians)	Drag F_d, lbs	Lift F_L, lbs	angle β (rad)	b (ft)	Extra Drag F'_d and F'_L, lbs	Submerged weight W_s, lb	W_{sx}, lb	W_{sy}, lb	W_{sz}, lb	**SF_M**	**SF_P**	**SF_O**	**SF_{MIN}**
5-in. open cell - Type A	0.464	3.89	1.76	0.785	1.250	5.87	35.35	0.35	31.61	15.81	2.33	2.22	2.45	**2.22**
5-in. open cell- Type B	0.464	4.62	2.09	0.876	1.250	5.87	42.42	0.42	37.94	18.97	2.70	2.73	2.66	**2.66**
4.5-in. open cell - Type C	0.464	3.50	1.35	0.785	1.000	4.69	23.04	0.23	20.61	10.30	1.86	1.68	2.08	**1.68**

Block Designation	SF ≥ SF_{goal}	Velocity Check	Bed Slope Check	Shear Stress Check
5-in. open cell - Type A	Not Ok	Ok	Ok	Ok
5-in. open cell- Type B	Ok	Ok	Ok	Ok
4.5-in. open cell - Type C	Not Ok	Not Ok	Ok	Ok

DESIGN NOTES:

Selected System: **5-in. open cell- Type B**

4.6 Overtopping Flow

An emergency spillway is to be constructed for a small reservoir. The geometric spillway design has a length of 120 ft and crest width of 150 ft. The design discharge for the revetment is the 100-year event, which is 410 ft^3/s. Hydraulic analysis of the spillway design was conducted using HEC-RAS. Table 4-4 presents pertinent results from the hydraulic model.

Table 4-4: HEC-RAS Model Output for Overtopping	
Channel Discharge (ft^3/s)	410
Maximum Shear Stress (lb/ft^2)	3.1
Maximum Cross-Section-Averaged Flow Velocity (ft/s)	10.7
Maximum Energy Grade Line Slope (ft/ft)	0.20

The suggested design procedure follows.

Step 1. Select a target factor of safety

A target factor of safety of 2.4 is selected for this example. This safety factor was selected by the design engineer based on consideration of the project's complexity and flow characteristics, consequences of failure, and overall understanding of the site conditions and modeling accuracy.

Step 2. Select potential ACB products for design

Contact ACB manufacturers and/or review ACB catalogs and select several systems that are appropriate for the given application based on a preliminary assessment of the hydraulic conditions. At the same time obtain the block properties necessary for design. These properties generally include the moment arms in

Figure 4.2, the submerged weight of the block, the block system lift coefficient, the maximum test velocity, and the test bed slope.

For this example, three products from ACB Systems, Inc. are selected based on guidance from the manufacturer. ACB Systems, Inc. suggests that the Type-A, Type-B or Type-C blocks would be appropriate for velocities in the range of 10 to 15 ft/s. The block properties provided by the manufacturer are shown on the worksheet accompanying this design example.

Step 3. Calculate the factor of safety for each product

Use the *NCMA ACB Design Spreadsheet* to assist in the factor of safety calculations using the equations from Table 4-2. For this example, the calculations are presented for the Type-A block and a completed worksheet with Type-A, Type-B and Type-C is included.

a) Assuming a specific gravity of 2.1 for the concrete, calculate the submerged weight:

$$W_S = W \cdot \left(\frac{S_C - 1}{S_C}\right) \qquad \text{(see Eqn. 3.10)}$$

$$W_S = 67.5 \cdot \left(\frac{2.1 - 1}{2.1}\right) = 35.4 \text{ lb}$$

b) Compute the drag force:

$$F_D = \tau_{des} \cdot A_B \qquad \text{(see Eqn. 4.6)}$$

$$F_D = (3.1\ \text{lb}/\text{ft}^2) \cdot (1.11\ \text{ft}^2) = 3.4\ \text{lb}$$

c) Compute the lift force:

$$F_L = (0.5) \cdot C_{BL} \rho A_B V_{des}^2 \qquad \text{(see Eqn. 4.7)}$$

$$F_L = (0.5) \cdot (0.0135) \cdot (1.94\ \text{slugs}/\text{ft}^3) \cdot (1.11\ \text{ft}^2) \cdot (10.7\ \text{ft}/\text{s})^2 = 1.7\ \text{lb}$$

d) Compute the additional lift and drag force due to projecting block edge:

$$F'_L = F'_D = (0.5) \cdot (\Delta Z) b \rho V_{des}^2 \qquad \text{(see Eqn. 4.8)}$$

$$F'_L = F'_D = (0.5) \cdot (0.04\ \text{ft}) \cdot (1.26\ \text{ft}) \cdot (1.94\ \text{slugs}/\text{ft}^3) \cdot (10.7\ \text{ft}/\text{s})^2 = 5.6\ \text{lb}$$

e) Compute the factor of safety:

$$SF_{BED} = \frac{\ell'_2 W_S \cdot \cos\theta_0}{\ell'_1 W_S \cdot \sin\theta_0 + \ell'_3 (F_D + F'_D) + \ell'_4 (F_L + F'_L)} \qquad \text{(See Eqn. 4.12)}$$

$$SF_{Bed} = \frac{(0.63\ \text{ft}) \cdot (35.4\ \text{lb}) \cdot \cos(11.31°)}{\begin{bmatrix} (0.21\ \text{ft}) \cdot (34.6\ \text{lb}) \cdot \cos(11.31°) + (0.42\ \text{ft}) \cdot (3.4\ \text{lb} + 5.6\ \text{lb}) + \\ (0.63\ \text{ft}) \cdot (1.7\ \text{lb} + 5.6\ \text{lb}) \end{bmatrix}} = 2.6$$

f) Compare minimum SF to target SF to determine if system is acceptable for the application:

$$SF_{Bed} \leq SF_{Target}$$
$$2.6 \geq 2.4$$

Design is OK for the Type-A block system.

Steps a) through f) are then repeated for the Type-B and Type-C blocks, the results of which are shown in the accompanying worksheet to this design example. Type-C block is discounted because the maximum tested velocity is lower than the design velocity of the project.

NATIONAL CONCRETE MASONRY ASSOCIATION

ARTICULATING CONCRETE BLOCK DESIGN CALCULATIONS FOR OPEN CHANNEL AND OVERTOPPING FLOW

NATIONAL NCMA CONCRETE MASONRY ASSOCIATION
EQUIPPING BETTER BUILDING

General Information

Company:	*ACB Consultants, Inc.*	Description:	*Meandering River*
Designer:	*John Doe*	Date:	*1/10/2019*
Project Name/Number:	*10-466-077*	**Hydraulic Design Data**	
Client:	*Harris County, TX*	Discharged (cfs):	*6444*
Target Factor of Safety:	*2.4*	Flow Depth (ft):	*4.3*

Project Information for ACB Design

TABLE 1: CHANNEL CONDITIONS FOR ACB DESIGN

	ENTER VALUES	Degrees	Radians
Longitudinal (bed) Slope θ_0, percent	1.00	0.57	0.0100
Maximum Side Slope θ_1, percent	50.00	26.57	0.4636
Design Maximum Velocity V, ft/s	10.70	**==> Use Shear and Velocity Method**	
Design Maximum Shear Stress τ_0, lb/ft^2	3.10		
Maximum Block Placement Tolerance, inches	0.48		

Flow Direction: (select from dropdown)	a) Perpendicular to block width (b)	

Unit Weight of Water, lb/ft^3	62.4	NOTE: Recommended values for density of water are 62.4 lb/ft^3 for fresh water, 64.2 lb/ft^3 for seawater
Unit Weight of Concrete, lb/ft^3	131	

Sheet 1: Block Characteristics

TABLE 2: NOMINAL BLOCK DIMENSIONS AND WEIGHTS

Block Designation	Length, a inches	Width, b inches	Height, inches	Open area at base of system, percent	Weight in air, lb
5-in. open cell - Type A	15	15	5.0	21	67.5
5-in. open cell- Type B	18	15	5.0	21	81.0
4.5-in. open cell - Type C	12	12	4.5	10	44.0

BLOCK AREA AND LIFT

Block Designation	Block area parallel to flow A_B, ft^2	Block lift coefficient, C_{BL}
5-in. open cell - Type A	1.110	0.01350
5-in. open cell- Type B	1.320	0.01350
4.5-in. open cell - Type C	1.000	0.01150

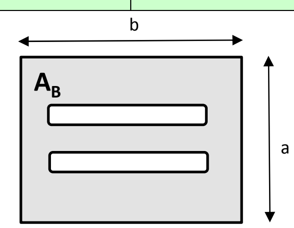


TABLE 3: PERFORMANCE DATA FOR CRITICAL SHEAR STRESS AND VELOCITY

Block type	τ_{test} at horizontal, lb/ft^2	Maximum velocity, V_{test} ft/s	Comments
5-in. open cell - Type A	25.0	18	Tested at 2H:1V
5-in. open cell- Type B	30.0	20	Tested at 2H:1V
4.5-in. open cell - Type C	11.0	10	Tested at 2H:1V

Project Name/Number:	*Meandering River / 10-466-077*
Company:	*ACB Consultants, Inc.*
Designer:	*John Doe*
Date:	*1/10/2019*
Client:	*Harris County, TX*

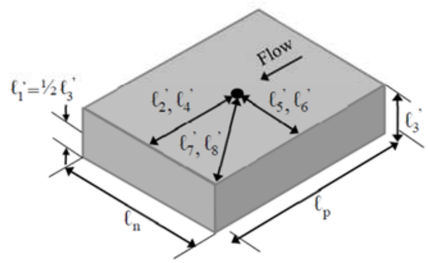
NATIONAL NCMA CONCRETE MASONRY ASSOCIATION
EQUIPPING BETTER BUILDING

Sheet 3b: Shear Velocity Method Calculations - Overtopping Flow

TABLE 4: MOMENT ARMS AND CRITICAL SHEAR STRESS

Block Designation	ℓ_1, ft	ℓ_2, ft	ℓ_3, ft*	ℓ_4, ft	ℓ_5, ft	ℓ_6, ft	ℓ_7, ft	ℓ_8, ft
5-in. open cell -	0.208	0.625	0.417	0.625	0.625	0.625	0.884	0.884
5-in. open cell-	0.208	0.750	0.417	0.750	0.625	0.625	0.976	0.976
4.5-in. open cell -	0.188	0.500	0.375	0.500	0.500	0.500	0.707	0.707

Block Designation	ℓ_p, ft	ℓ_n, ft	C_{BL}	W (lb)	A_B, ft^2	τ_{test} at horiz., lb/ft^2
5-in. open cell -	1.250	1.250	0.01350	67.5	1.110	25.0
5-in. open cell-	1.500	1.250	0.01350	81.0	1.320	30.0
4.5-in. open cell -	1.000	1.000	0.01150	44.0	1.000	11.0



* ℓ_3 considers the whole height of the block.

TABLE 5: CHANNEL CONDITIONS

	COPIED VALUES	Degrees	Radians
Longitudinal (bed) slope θ_0, percent	1.00	0.57	0.0100
Maximum side slope θ_1, percent	50.00	26.57	0.4636
Side slope relative to bed θ_2, percent	50.00	26.56	0.4636
Design maximum velocity V, ft/s	10.70		
Design maximum shear stress τ_{des}, lb/ft^2	3.10		
Maximum block placement tolerance, inches	0.48		

Unit weight of water, lb/ft^3	62.4
Unit weight of concrete, lb/ft^3	131
Mass density of water, slugs/ft^3	1.94

NOTE: Recommended values for density of water are: 62.4 lb/ft^3 for fresh water, 64.2 lb/ft^3 for seawater

Flow direction parallel to the block*:	a) Perpendicular to block width (b)

TABLE 6: SAFETY FACTOR CALCULATIONS

Block Designation	Drag F_d, lbs	Lift F_L, lbs	angle β (rad)	b (ft)	Extra Drag F'_d and F'_L, lbs	Submerged weight W_s, lb	SF_{BED}	SF ≥ SF_{goal}	Velocity Check	Bed Slope Check	Shear Stress Check
5-in. open cell - Type A	3.44	1.66	0.785	1.250	5.553	35.35	**2.65**	Ok	Ok	Ok	Ok
5-in. open cell- Type B	4.09	1.98	0.876	1.250	5.553	42.42	**3.26**	Ok	Ok	Ok	Ok
4.5-in. open cell - Type C	3.10	1.28	0.785	1.000	4.442	23.04	**2.01**	Not Ok	Not Ok	Ok	Ok

DESIGN NOTES:

Selected System: **5-in. open cell - Type A**

Section 5. GEOTEXTILE AND GRANULAR FILTER DESIGN

The importance of the filter component of an ACB system should not be underestimated. If laboratory testing of an ACB system was conducted with a granular filter in place, then the design should include a filter. Geotextiles and granular layers perform the filtration function. Some situations call for a composite filter consisting of both a granular layer and a geotextile. The specific characteristics of the existing base soil determine whether a granular filter is required.

The filter is installed between the ACB and the base soil (Figure 5.1). The primary role of a filter component is to retain the base soil particles while allowing the flow of water through the interface between the ACB system and the underlying soil. A granular filter also provides a smooth and free-draining surface to rocky or otherwise irregular subgrades, thereby maximizing intimate contact between the ACB system and its base. The installation of the granular material is fully addressed in the installation section 7.2. Careful design, selection, and installation of the appropriate filter material all play an important role in the overall performance of ACB systems.

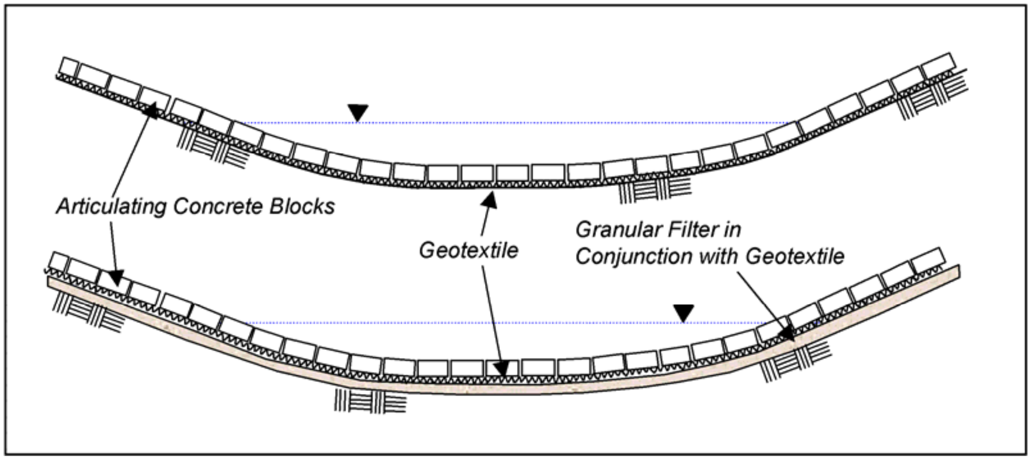


Figure 5.1: Channel cross-sections showing filter and bedding orientation.

5.1 Filter Functions

The primary function of filter components is to prevent fine particles from washing away while allowing water flow through the filter material. These two objectives must be considered to achieve an effective functional balance between retention and permeability.

Filters assist in maintaining intimate contact between the revetment and the subgrade by providing stability at the interface. Depending upon the internal stability of the soil, several processes can occur over time along the interface of the base soil and filter material. The filter pore size and the base soil stability dictate these processes. As an example, consider the process of "piping." Piping is basically the washing away of very fine particles, resulting in greater void space in the soil structure. Piping is more likely to occur in non-cohesive/unstable soils that are in contact with a filter material that has large openings. The large openings do not retain the smaller particles and therefore these particles are removed by flowing water and only the larger particles remain. This process increases the potential for soil erosion by weakening the soil structure. Correct filter design reduces the effects of piping by limiting the loss of fines. Figure 5.2 illustrates a stable versus unstable soil and several common filtering processes that can occur (modified from Koerner 2005, ref. 35). The large arrows in Figure 5.2 indicate the direction of flow.

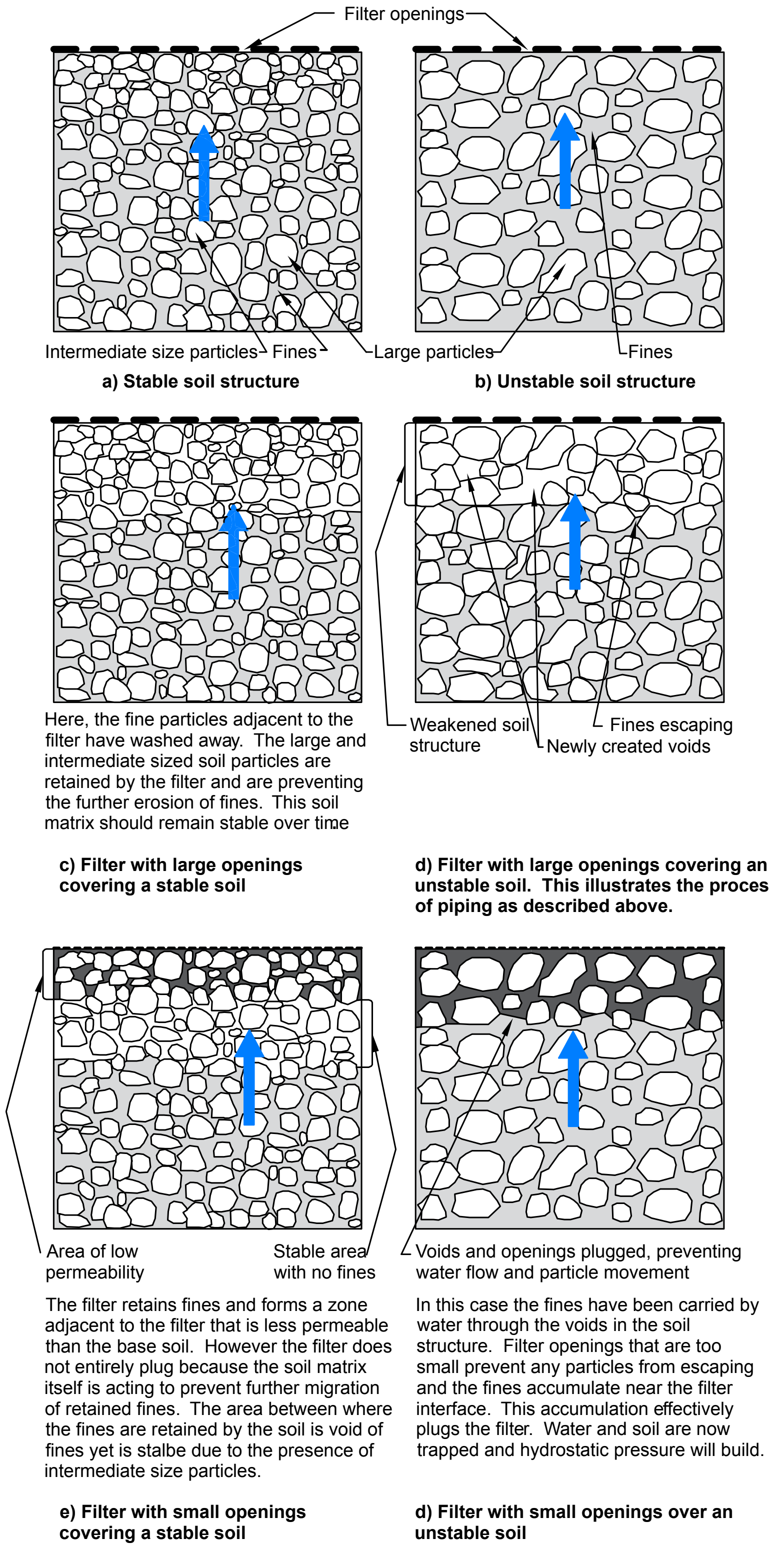


Figure 5.2: Examples of soil and filter subgrades.

As illustrated in Figure 5.2, matching the correct filter opening to the characteristics of the base soil is critical to obtaining the desired retention of the filter component.

Filters should be permeable enough to allow flow of water through the filter material. This is necessary for two reasons: regulation of the filtration process along the base soil and filter interface, as illustrated above, and reduction of hydrostatic pressure build-up from local groundwater fluctuations in the vicinity of the channel bed and banks (e.g., seasonal water level changes and storm events) that can weaken the channel soil structure. The permeability of the filter should never be less than the layer below it (whether base soil or another filter layer).

Figure 5.3 illustrates a process that can result in an increase of hydrostatic pressure beneath the filter. The figure is a time series view of channel cross-sections showing changing water levels and seepage resulting from a storm event. A properly designed filter will help alleviate problems associated with fluctuating water levels.

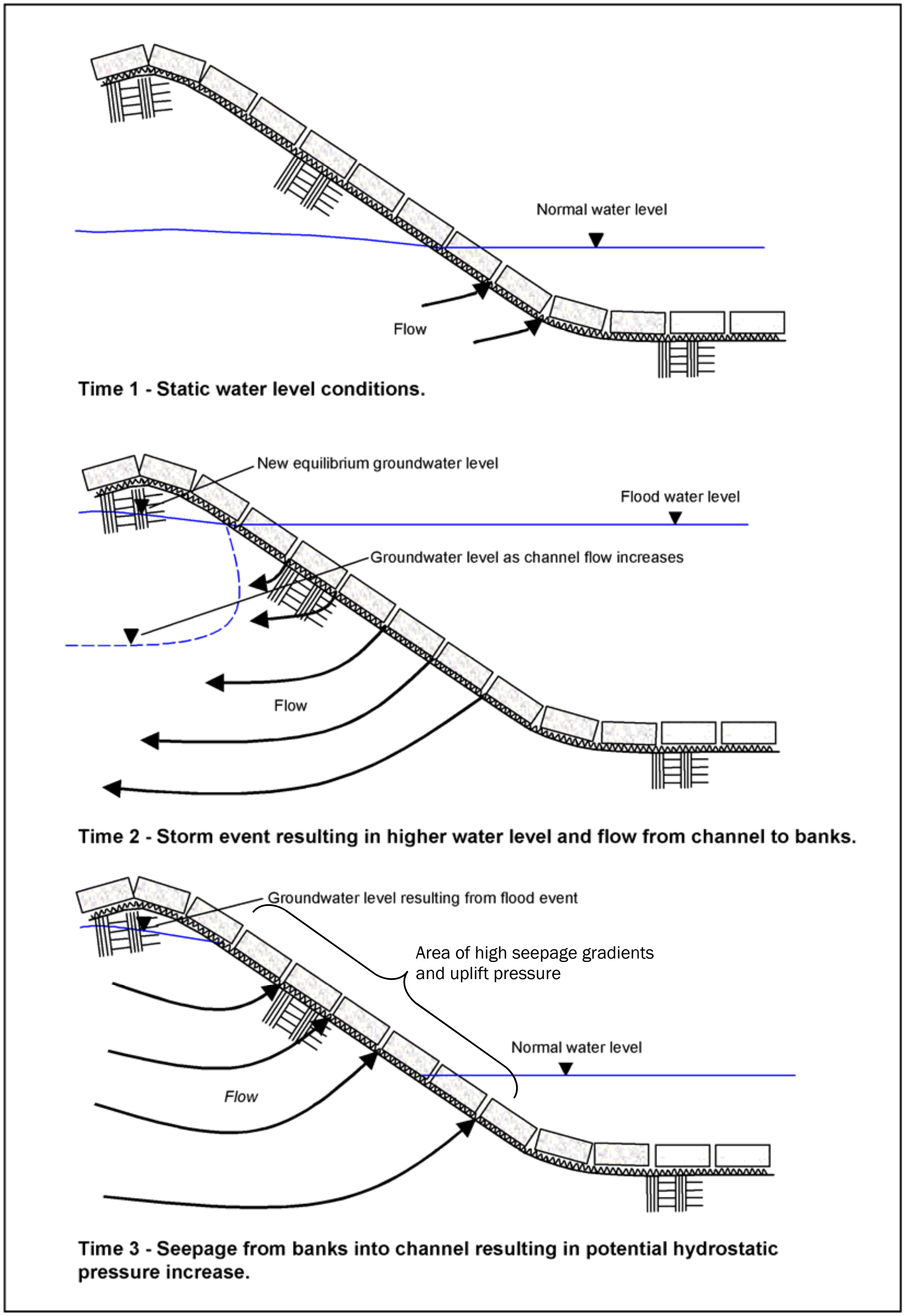


Figure 5.3: Time series of channel and groundwater level changes due to a flood event.

5.2 Base Soil Properties

Base soil is defined here as the subgrade material upon which the filter or the ACB system will be placed. Base soil can be existing material of the channel bed and banks, or imported and recompacted fill. The following properties represent a minimum level of information that should be obtained for the base soil for use in the design process:

General Soil Classification. Soils are classified based on laboratory determinations of particle size characteristics and the physical effects of varying water content on soil properties. Typically, soils are described as coarse-grained if more than 50 percent by weight of the particles are larger than a #200 sieve (0.075 mm mesh), and fine-grained if more than 50 percent by weight is smaller than this size. Sands and gravels are examples of coarse-grained soils, while silts and clays are examples of fine-grained soils.

The fine-grained fraction of a soil is further described by changes in its consistency caused by varying water content and by the percentage of organic matter present. Soil classification methodology is described in ASTM D2487, *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)* (ref. 4).

Particle Size Distribution. The single most important soil property for the design of ACB systems is the range of particle sizes in the soil. Particle size is a convenient and relatively simple way to assess soil properties. Also, particle size tends to be an indication of other properties such as permeability. Characterizing soil particle size involves determining the relative proportions of sand, silt, and clay in the soil. This characterization is usually done using either a technique called sieve analysis for coarse-grained soils or sedimentation (hydrometer) analysis for fine-grained soils. ASTM D6913, *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis* (ref. 17) outlines these standardized procedures.

Plasticity. Plasticity is defined as the property of a material that allows it to be deformed rapidly, without rupture, without elastic rebound, and without volume change. A measure of plasticity is the Plasticity Index (PI), which should be determined for soils with a large percentage of fines or clay particles. The results associated with plasticity testing are referred to as the Atterberg Limits. ASTM D4318, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils* (ref. 6) defines these testing procedures.

Porosity. Porosity is that portion of a representative volume of soil that is interconnected void space. It is typically reported as a dimensionless fraction or a percentage. The porosity of soils is affected by the particle size distribution, the particle shape (e.g., round vs. angular), and degree of compaction and/or cementation.

Permeability. Permeability is a measure of the ability of soil to transmit water. Permeability is related to particle size distribution, dominated by the finest 20 percent, and can be determined using an equation that has been developed for this purpose or through laboratory analysis. ASTM provides two standard test methods for determining permeability: ASTM D2434, *Standard Test Method for Permeability of Granular Soils (Constant Head)* (ref. 3) or ASTM D5084, *Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter* (ref. 12). Soil permeability is used as part of the design process to help select an appropriate filter material.

For granular soils, the permeability may be estimated by the Fair-Hatch Equation in lieu of performing laboratory testing. The Fair-Hatch Equation relates permeability to soil porosity and the particle size distribution. Porosity is defined as the ratio of void space to the total volume of the soil. The pores in the soil are the means by which water is conducted; therefore, permeability of soil is influenced by the soil porosity. The Fair-Hatch Equation in SI units is:

$$K_S = 1.958 \times 10^6 \frac{\phi^3}{(1-\phi)^2}\left(\frac{1}{49\left(\sum_{n=1}^{N}\frac{P_n}{d_n}\right)^2}\right) \quad \text{(SI Units)} \qquad \text{(Eqn. 5.1)}$$

where:

K_s	=	Permeability of the base soil or granular filter, cm/s
ϕ	=	Dimensionless soil porosity determined from Equation 5.2 or Table 5-1, both shown below
P	=	Percentage of material in the distribution between adjacent particle sizes
d	=	Geometric mean of adjacent particle sizes in the distribution, mm
N	=	Number of intervals between adjacent particle sizes

If the particle size distribution does not include a particle size at 0 percent, this value should be estimated by extrapolation and included in the calculation. This is important because the presence of small particles representing the fine end of the particle size distribution significantly influences permeability.

Commonly observed values of porosity and permeability for alluvial soils are presented in Table 5-1. If the soil has been compacted in place rather than naturally deposited, the following equation that relates porosity to compaction and dry unit weight of the soil is recommended:

$$\phi = 1 - \left(\frac{C}{100} \cdot \frac{\gamma_d}{165.4\ \text{lb/ft}^3}\right) \quad \text{(Inch-Pound Units)} \qquad \text{(Eqn. 5.2)}$$

where:

ϕ	=	Soil porosity (dimensionless)
C	=	Soil compaction in percent of Standard Proctor Density (90 to 100)
γ_d	=	Maximum dry unit weight of the soil at 100 percent of Standard Proctor Density, lb/ft^3

Table 5-1: Typical Porosity and Permeability for Alluvial Soils (ref. 37).

Type of Material	**Porosity**	**Permeability (cm/s)**
Gravel, coarse	0.28	$4x10^{-1}$
Gravel, fine	0.34	Varies
Sand, coarse	0.39	$5x10^{-2}$
Sand, fine	0.43	$3x10^{-3}$
Silt	0.46	$3x10^{-5}$
Clay	0.42	$9x10^{-8}$

5.3 Geotextile Filter Properties

For compatibility with site-specific soils, geotextiles must exhibit the appropriate values of permittivity (hydraulic conductivity), pore size (otherwise known as Apparent Opening Size, or AOS), and porosity (for non-woven geotextiles) or percent open area (for woven geotextiles). In addition, geotextiles must be sufficiently strong to withstand the stresses during installation. These properties are available from geotextile manufacturers.

Only woven monofilament or nonwoven needle-punched geotextiles should be considered for filter applications. Slit-film, spun-bonded, or other types of geotextiles are not suitable as filters. If a woven monofilament fabric is chosen, it should have a Percent Open Area (POA) greater than or equal to 4%. If a nonwoven needle-punched fabric is chosen, it should have a porosity greater than or equal to 30% and a mass per unit area of at least 12 ounces per square yard (400 grams per square meter). The following list briefly describes the most relevant properties of geotextiles for filter applications that are available from manufacturers. The ASTM standard test is cited where applicable.

Permittivity. This is a measure (used to compare geotextiles of various thicknesses) of a material's cross-plane permeability that when multiplied by the geotextile thickness gives a traditional permeability value. (ASTM D4491/D4491M; ref. 7)

Apparent Opening Size (AOS). Also known as Equivalent Opening Size, this measure is generally reported as O_{95}. O_{95} represents the aperture size such that 95 percent of the openings are smaller. In similar fashion to a soil gradation curve, a geotextile hole distribution curve can be derived. (ASTM D4751; ref. 10)

Porosity. Porosity is a comparison of the total volume of voids to the total volume of geotextile. This measure is applicable to non-woven geotextiles only. Porosity is used to estimate the potential for long term clogging, and is typically reported as a percentage.

Percent Open Area (POA). POA is a comparison of the total open area to the total geotextile area. This measure is applicable to woven geotextiles only. POA is used to estimate the potential for long term clogging.

Thickness. Thickness is used to calculate traditional permeability based upon permittivity. It is typically reported in millimeters or mils (thousandths of an inch).

Grab Strength and Elongation. Force required to initiate a tear in the fabric when pulled in tension. Typically reported in Newtons or pounds as measured in a testing apparatus having standardized dimensions. The elongation measures the amount the material stretches before it tears, and is reported as a percent of its original (unstretched) length. (ASTM D4632/D4632M; ref. 9)

Tear Strength. Force required to propagate a tear once initiated. Typically reported in Newtons or pounds. (ASTM D4533/D4533M; ref. 8)

Puncture Strength. Force required to puncture a geotextile using a standard penetration apparatus. Typically reported in pounds or Newtons. (ASTM D4833/D4833M; ref. 11)

There are many other tests to determine various characteristics of geotextiles; only those deemed most relevant to applications involving countermeasures have been discussed here. As previously mentioned, geotextiles should be able to withstand the rigors of installation without suffering degradation. Long-term endurance due to exposure to ultraviolet light or continual abrasion are considered of secondary importance, because once the geotextile has been installed and covered by the armor layer, these conditions do not represent the long-term environment that the geotextile will experience. Table 5-5 provides recommended tests and minimum design values for various geotextile properties.

5.4 Granular Filter Properties

Generally speaking, most required granular filter properties can be obtained from the particle size distribution curve for the material. Granular filters serve as a transitional layer between a predominantly fine-grained base soil and a geotextile.

Particle size distribution. As a rule of thumb, the gradation curve of the granular filter material should be approximately parallel to that of the base soil. Parallel gradation curves minimize the migration of particles from the finer material into the coarser material. *HEC-23, Bridge Scour and Stream Instability Countermeasures* (ref. 37) proposes a procedure whereby the d_{50} size of the filter is selected based on the coefficients of uniformity (d_{60}/d_{10}) of both the base soil and the filter material. This new methodology allows the grain size distribution curves to not necessarily be parallel.

Permeability. Refer to Section 5.2 for an explanation of soil permeability. Often, the permeability for a granular filter material is estimated by the Fair-Hatch equation or determined by laboratory analysis. The permeability of a granular layer is used to select a geotextile when designing a composite filter. The permeability of the granular filter should be at least 10 times the permeability of the soil.

Thickness. Practical issues of placement suggest that a typical minimum thickness of 6 to 8 inches (152 to 203 mm) be specified. For placement under water, thickness should be increased by 50 percent.

Quality and Durability. Aggregate used for a granular filter should be hard, dense, and durable.

Note: If the required AOS is smaller than that of available geotextiles, then a granular transition layer is required, even if the base soil is not clay. However, this requirement can be waived if the base soil exhibits the following conditions for hydraulic conductivity K_s, plasticity index PI, and undrained shear strength c:

K_s < 1 x 10-7 cm/s

PI > 15

c > 10 kPa

Under these soil conditions there is sufficient cohesion to prevent soil loss through the geotextile. A geotextile with an AOS less than a #70 sieve (approximately 0.2 mm) can be used with soils meeting these conditions, and essentially functions more as a separation layer than a filter.

5.5 Geotextile and Granular Filter Design Procedure and Example

The following example illustrates a six-step design procedure for the filter component of an ACB system. The major criteria for geotextile and granular filter design are permeability and retention, which need to be compatible with the base soil.

Problem Statement:

A filter needs to be designed for the ACB system that was designed in Section 3.4 for Meandering River, Texas. Table 5-2 and Table 5-3 provide the local soil properties from geotechnical laboratory testing for this example problem. If a granular filter is necessary, consider the Pit Run material with the gradation shown in Table 5-4.

Table 5-2: Base Soil Sample Information and Classification	
Sample ID	No. 3 (in Channel)
Test Date	6/18/09
Soil description	Silty Clay with Sand
USCS Classification	CL-ML
Moisture Content	9.9%
Liquid Limit (LL)	26%
Plastic Limit (PL)	19%
Plasticity Index (PI)	7%
Permeability	7.5×10^{-7} cm/s

Table 5-3: Results From Sieve Analysis of Base Soil		
Sieve Size	**Particle Size (mm)**	**Percent Finer**
3/4 inch	19.05	100.0
1/2 inch	12.70	100.0
3/8 inch	9.52	100.0
No. 4	4.75	100.0
No. 10	2.00	100.0
No. 20	0.85	99.8
No. 40	0.425	99.6
No. 80	0.180	99.6
No. 100	0.150	99.0
No. 200	0.075	71.9
0.005 mm	0.005	24.2

Step 1. Obtain base soil information

Section 5.2 can be consulted for a definition of common soil properties. Typically, the necessary base soil information is a grain size distribution curve, permeability, and the Plasticity Index (PI is required only if the base soil is more than 20 percent clay). For this example, the information is provided in the problem statement and a gradation curve is shown in Figure 5.4.

Document the percentages of gravel, fines, and clay that were observed in the base soil sample. Gravel is characterized by particle sizes greater than 4.75 mm, fines are defined as the particles that passed the No. 200 sieve, and clay is characterized by particle sizes less than 0.005 mm per ASTM D6913 (ref. 17). Also, document the plasticity index (PI) if the percentage of clay is greater than 20 percent and the median grain size d_{50}, d_{60} and d_{10}. Due to the inherent variability of natural soils, these parameters should be determined for a number of samples and a representative value, or range of values, should be used for design based on engineering judgment.

For this example, the sample contains no gravel, 71.9 percent fines, and 24.2 percent clay.

d_{10} = 0.0017 mm
d_{30} = 0.0074 mm
d_{50} = 0.025 mm
d_{60} = 0.04 mm
K_s = 7.5×10^{-7} cm/s
PI = 7%
Gravel: 0 %
Fines: 71.9%
Clay: 24.2%

Step 2. Determine the geotextile retention criterion

Use the decision tree in Figure 5.5 to assist in determining the appropriate soil retention criterion for the geotextile. The figure has been modified to include guidance when a granular transition layer (i.e., composite filter) is necessary. A composite filter is typically required when the base soil is greater than 30% clay having relatively low cohesion, or is predominantly fine-grained soil (more than 50% passing the #200 sieve). If a granular transition layer is required, the geotextile should be designed to be compatible with the properties of the granular layer.

From Figure 5.5, determine if a granular transition layer will be necessary. If a granular filter is used, the remaining steps in the geotextile selection should be based on the granular filter properties. Go to Step 2a to design the granular filter before continuing on with geotextile selection.

For this example, there is less than 30% of clay and more than 50% fines; the Plasticity Index (PI) is higher than 5 and the soil parameters do not meet the Ks < 1 x 10-7 cm/s, PI > 15, and c > 10 kPa requirements. Under these conditions, this example needs a granular layer designed following Figure 5.6. The *NCMA ACB Design Spreadsheet* could be used for documenting the geotextile selection process.

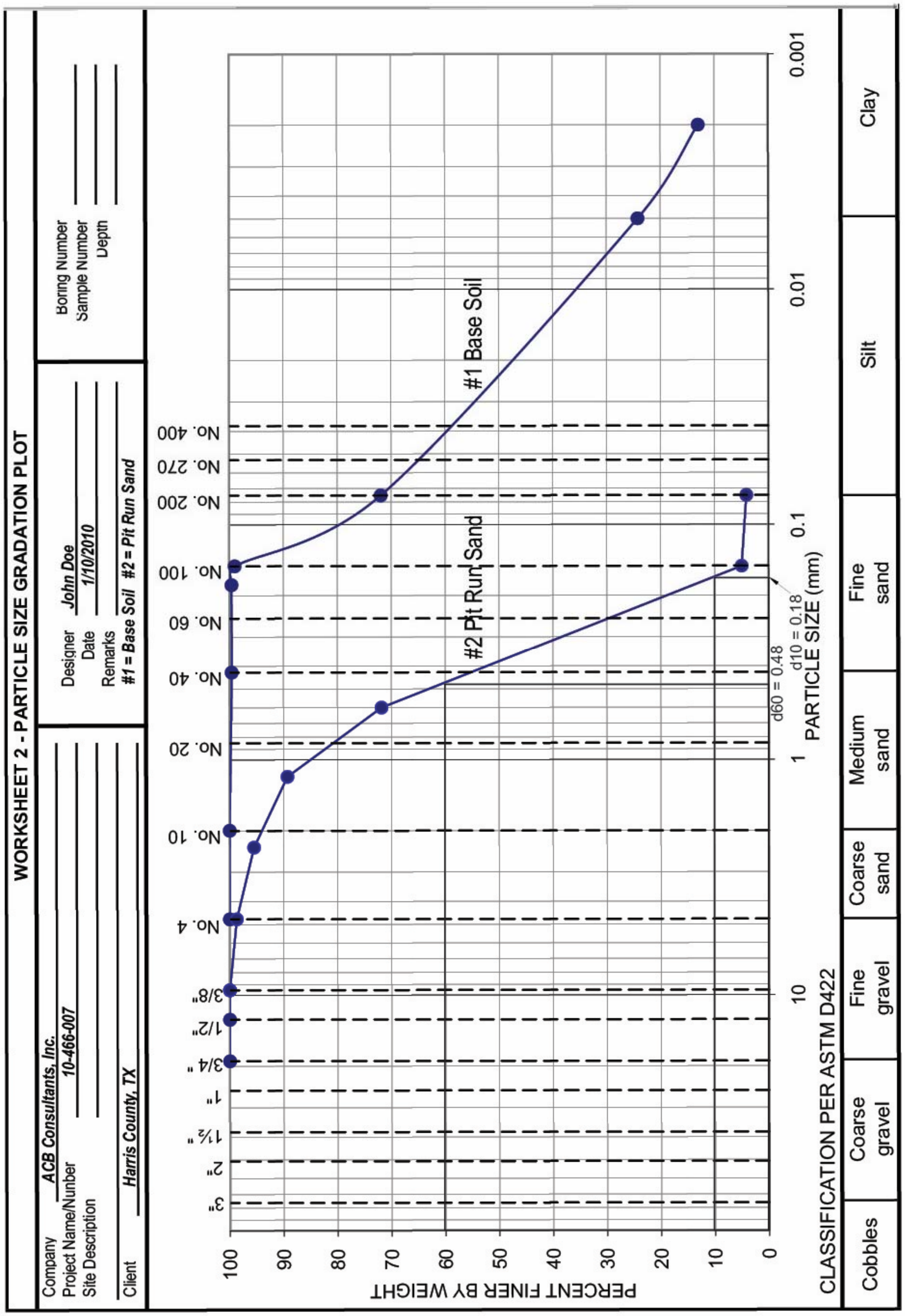


Figure 5.4: Grain size distribution curve

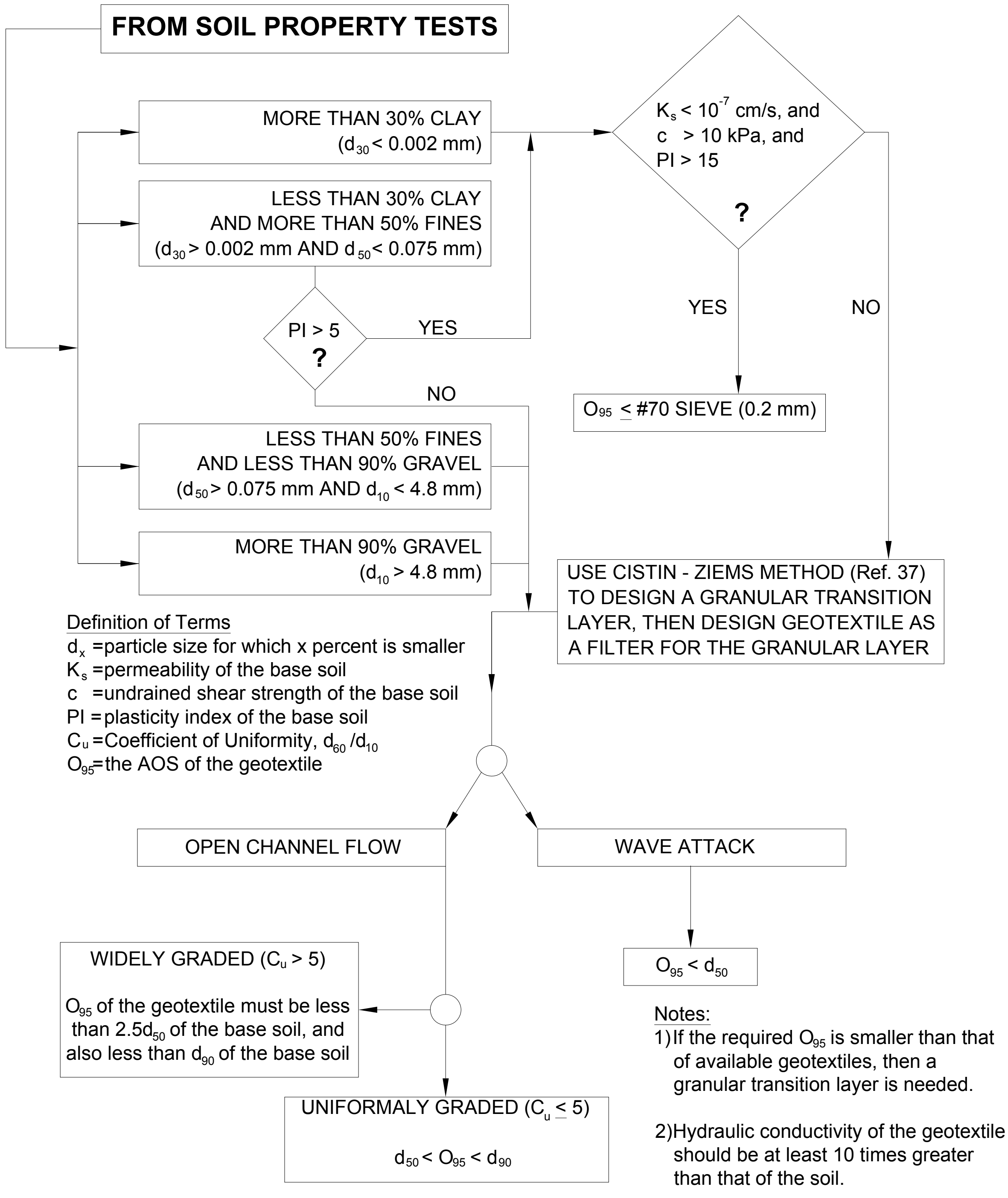


Figure 5.5: Geotextile selection based on soil retention (ref. 37).

No wave attack is expected at Meandering River, therefore the Uniformity Coefficient of the granular filter will be used for the final step in determining the retention criteria. The Uniformity Coefficient, C_u, is defined as follows:

(Eqn. 5.3)

$$C_u = \frac{d_{60}}{d_{10}}$$

where:

d_x = Particle size of which X percent is smaller

For this example, the uniformity coefficient of the base soil is:

$C_u = d_{60}/d_{10} = 0.04$ mm/0.0017 mm = 23.53

For this example, the uniformity coefficient of the granular filter material (see Table 5-4) is:

$C_u = d_{60}/d_{10} = 0.48$ mm/0.18 mm = 2.7 (d_{60} and d_{10} determined from Figure 5.4)

Because C_u of the granular filter is less than 5, it is considered "uniformly graded".

Therefore, the Apparent Opening Size of the geotextile filter should meet the following condition:

$d_{50} < O_{95} < d_{90}$

The geotextile retention criterion is shown on Sheet 4 of the *NCMA ACB Design Spreasheet*.

Step 2a. Determine the granular filter retention and permeability criteria

Where project condition warrant, use the following to determine the properties of the granular filter. Determine Maximum Allowable d_{50f} for Filter. Enter the Cistin - Ziems design chart (Figure 5.6) with the Coefficient of Uniformity for the base soil on the x-axis. Find the curve that corresponds to the Coefficient of Uniformity for the filter in the body of the chart, and from that point determine the maximum allowable A_{50} from the y-axis (A_{50} is the ratio between the particle size diameter at 50% in the gradations for the filter d_{50f} and the base soil, d_{50s}). Compute the maximum allowable d_{50f} of the filter using $d_{50f(max)} = A_{50max}$ times d_{50s}. Check to see if the candidate filter material conforms to this requirement. If it does not, continue checking alternate candidates until a suitable material is identified.

Enter the Cisten – Ziems chart (Figure 5.6) with $C_u = 23.53$ of the base soil on the x-axis (in this case data have been extrapolated). Chart vertically up to a location corresponding to a C_u of 2.7 for the candidate filter. Read a maximum allowable value A_{50} of approximately 8.5 on the y-axis.

For this example, $d_{50s} = 0.025$ mm, $d_{50f} = 0.42$ mm and the

Max. allowable $d_{50f} = A_{50}(d_{50s}) = 8.5 \times 0.025 = 0.213$ mm

Because the granular filter has a d_{50} greater than this value ($d_{50f} = 0.42$ mm > 0.213 max. allowable), a second (coarser) granular filter layer could be designed and placed on top of the first filter layer or alternatively, a geotextile filter may be considered.

The gradation curve of the granular transition layer does not need to be parallel (or close to) to the base soil curve. At this point the granular transition layer design, when required, is complete. For practical considerations related to constructability and inspection, the granular filter thickness should not be less than 6 inches (152 mm). For placement under water, thickness should be increased by 50 percent.

For this example, a granular filter is required and should be 9 inches (229 mm) thick because the revetment will be continuously under water. The particle size gradation of the selected pit run sand is provided in Table

5-4 and is plotted on Figure 5.4. Notice that the gradation of the pit run sand is approximately parallel to that of the base soil for this example. Calculations for the granular filter are presented below.

Table 5-4: Pit Run Gradation for Granular Filter

Sieve Size	Particle Size (mm)	Percent Finer
3/8 in.	9.52	100
No. 4	4.75	98.7
No. 8	2.36	95.5
No. 16	1.18	89.3
No. 30	0.600	71.8
No. 50	0.300	26.0
No. 100	0.150	5.0
No. 200	0.075	4.1

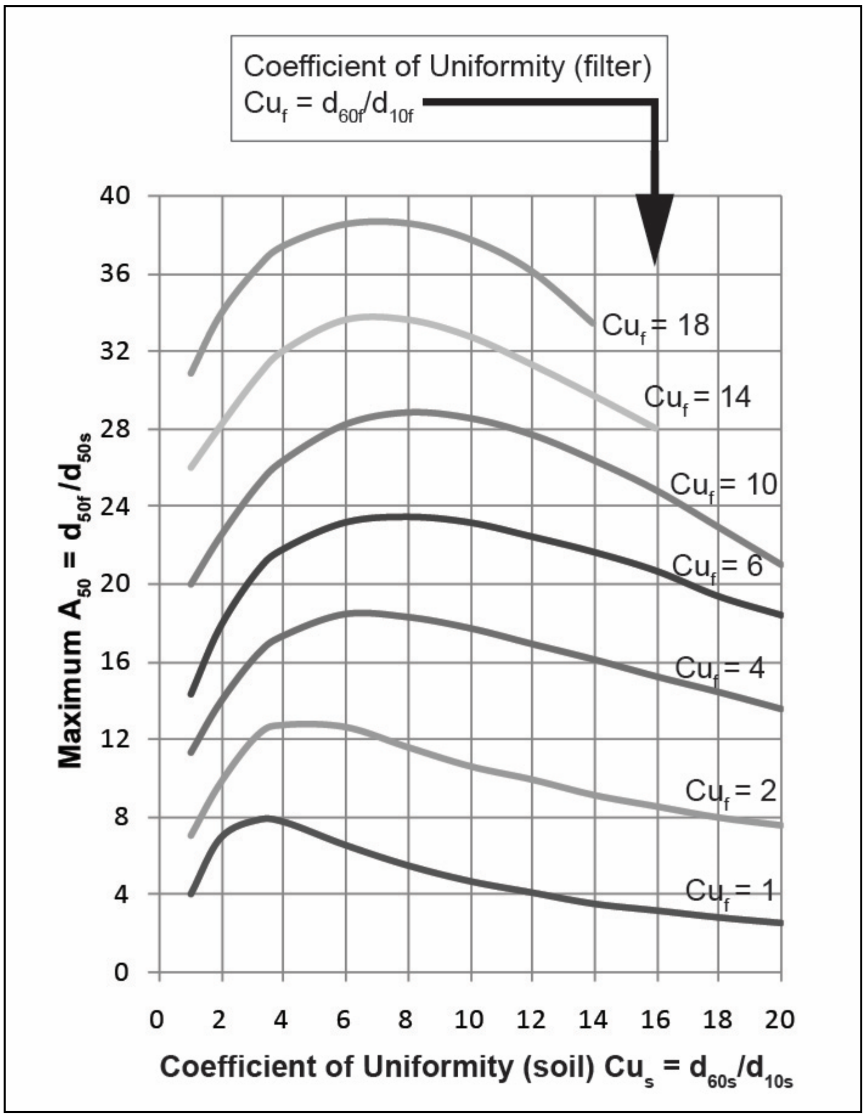


Figure 5.6: Granular filter design chart according to Cistin and Ziems (ref. 37).

Step 3. Determine the geotextile permeability criterion

The permeability criterion is specified as a function of the base soil permeability as follows:

$$K_g \geq 10K_s \qquad \text{(Eqn. 5.4)}$$

where:

K_g	=	Permeability of the geotextile, cm/s
K_s	=	Permeability of the base soil or granular filter, cm/s

To obtain the permeability of a geotextile in cm/s, multiply the thickness of the geotextile in cm by its permittivity in s^{-1}. Typically, the designer will need to contact the geotextile manufacturer to obtain values of permittivity.

Generally speaking, if the permeability of the base soil or granular filter has been determined from laboratory testing, that value should be used. If testing was not conducted, then the Fair-Hatch Equation should be used. For this example, the calculation of permeability of the granular filter using the Fair-Hatch Equation is shown below. A dry unit weight of 115 lb/ft^3 and 95 percent compaction are assumed for the selected pit run sand filter material.

Calculate the porosity:

$$\phi = 1 - \frac{C}{100} \cdot \frac{\gamma_d}{165.4} \qquad \text{(see Eqn. 5.2)}$$

$$\phi = 1 - \frac{95}{100} \cdot \frac{115.0}{165.4} = 0.339$$

Calculate the permeability for the pit run sand. For the gradation in Table 5.4 there will be eight particle size intervals, the seven shown in the table plus one to extrapolate down to 0 percent (particle size 0.008 mm scaled from Figure 5.4).

$$K_s = 1.958 \times 10^6 \frac{\phi^3}{(1-\phi)^2} \left(\frac{1}{49\left(\sum_{n=1}^{N} \frac{P_n}{d_n}\right)^2} \right) \qquad \text{(see Eqn. 5.1)}$$

$$\sum_{n=1}^{8} \frac{P_n}{d_n} = \frac{100-98.7}{\sqrt{(9.52)(4.75)}} + \frac{98.7-95.5}{\sqrt{(4.75)(2.36)}} + \frac{95.5-89.3}{\sqrt{(2.36)(1.18)}} + \frac{89.3-71.8}{\sqrt{(1.18)(0.600)}} + \frac{71.8-26.0}{\sqrt{(0.600)(0.300)}}$$

$$+ \frac{26.0-5.0}{\sqrt{(0.300)(0.150)}} + \frac{5.0-4.1}{\sqrt{(0.150)(0.075)}} + \frac{4.1-0}{\sqrt{(0.075)(0.008)}} = 408.476 \text{ mm}^{-1}$$

$$K_s = 1.958 \times 10^6 \frac{0.339^3}{(1-0.339)^2}\left(\frac{1}{49(408.476)^2}\right) = 0.02\,\text{cm/s}$$

The permeability for the granular filter and the calculated criterion for the geotextile are recordded on Sheet 4.

Step 4. Select potential geotextiles for design

Using results obtained in Steps 2 and 3 select several geotextile candidates. A valuable reference is the annual *Geotechnical Fabrics Report - Specifier's Guide*, published by the Industrial Fabrics Association International (ref. 31).

For this example, three products from three different manufacturers are selected as candidates for design. The selected systems are 121F, 113-004, and XW45. All three products satisfy the retention and permeability criteria.

Step 5. Screen potential geotextiles using the following considerations

Geotextile strength relating to installation. This refers to the ability of the geotextile to withstand damage during installation, the weight of the block system, and additional compaction. Minimum strength requirements for geotextile should be in accordance with the specification requirements of ASTM D6684 (ref. 15):

Table 5-5: Geotextile Strength Requirements[A]

			Class 1		Class 2		Class 3	
Property	**ASTM Test Methods**	**Units**	**Elongation <50%[A]**	**Elongation >50%[A]**	**Elongation <50%[A]**	**Elongation >50%[A]**	**Elongation <50%[A]**	**Elongation >50%[A]**
Grab Strength	D4632/ D4632M	lb N	315 (1400)	200 (900)	250 (1100)	160 (700)	180 (800)	110 (500)
Sewn Seam Strength[B]	D4632/ D4632M	lb N	285 (1260)	180 (810)	220 (990)	140 (630)	160 (720)	100 (450)
Tear Strength	D4533/ D4533M	lb N	110 (500)	80 (350)	90 (400)[C]	55 (250)	70 (300)	40 (180)
Puncture Strength	D4833/ D4833M	lb N	620 (2750)	435 (1925)	495 (2200)	310 (1375)	370 (1650)	220 (990)

[A] Percent elongation as measured in accordance with ASTM D4632/D4632M (ref. 9).

[B] Seam strength determined in accordance with ASTM D4632 when seams are required.

[C] Woven monofilament geotextiles should have a required Minimum Average Roll Value (MARV) of not less than 55 lb (250 N).

Note A:

Class 1 recommended for harsh or severe installation conditions where there is a greater potential for geotextile damage, including irregular sections where repeated mattress lifting, realignment, and replacing is expected, or when vehicular traffic on the installation is anticipated.

Class 2 recommended for installation conditions where mattress placement in regular, even reaches is expected and little or no vehicular traffic on the installation will occur, or when hand-placing on a graded surface of native soils.

Class 3 specified for the least severe installation environments, typically hand-placed systems (zero drop height) on a bedding layer of graded sand, road base aggregate, or other select imported material.

1. Durability and the ability to withstand long-term degradation. This is particularly a concern for geotextiles exposed to ultraviolet light during installation. Follow manufacturer recommendations for protection against ultraviolet light degradation. For additional guidelines regarding the selection of durability test methods refer to ASTM D5819, *Standard Guide for Selecting Test Methods for Experimental Evaluation of Geosynthetic Durability* (ref. 14).

2. Minimize Long-Term Clogging Potential. When a woven geotextile is used, its percent open area (POA) should be greater than, or equal to, 4% by area (POA $\geq$ 4%). Woven slit film geotextiles are not recommended for use under ACB systems. If a non-woven geotextile is used, its porosity should be greater than, or equal to, 30% by volume. A good rule of thumb suggests that the geotextile having the largest AOS that satisfies the particle retention criteria should be used (provided of course that all other minimum allowable values described in this section are met as well).

For this example, the application is assumed to satisfy the condition for a Class 3 geotextile, least severe installation environments, typically hand-placed systems (zero drop height) on a bedding layer of graded sand, road base aggregate, or other select imported material.

Step 6. Make a final geotextile selection by assessing compliance with permeability, retention and durability requirements.

The XW45 system from Geotextile Fabrics, Inc. is selected because it satisfies the material and design requirements necessary for the assumed design conditions.

Note: During construction, but before the geotextile is placed, collect soil samples for analysis to ensure that the geotextile selected in the design process is still appropriate, see the introduction of Section 7. for required testing frequency and laboratory tests.

Project Name/Number:	*Meandering River / 10-466-077*	NATIONAL NCMA CONCRETE MASONRY ASSOCIATION EQUIPPING BETTER BUILDING
Company:	*ACB Consultants, Inc.*	
Designer:	*John Doe*	
Date:	*1/10/2019*	
Client:	*Harris County, TX*	

Sheet 4: Geotextile Selection and Granular Filter Design

1. BASE SOIL INFORMATION

Description: Reddish Brown Clayey Silt

Percent of Gravel: 0 Fines: 71.9 Clay: 24.2

Plasticity Index: 7

Permeability of base soil, Ks (cm/s): 7.50E-07 Undrained Cohesion, c (kPa): 0

FILTER DESIGN

2. From Figure 5.5 – Geotextile Criterion Based on (mark with an X)

Base Soil Properties: Granular Filter Properties: X

For Granular Filter Only from Figure 5.5

Base Soil Properties		Potential Granular Fill Properties	
$d_{10\ BASE}$ (mm):	*0.0017*	$d_{10\ FILTER}$ (mm):	*0.18*
$d_{50\ BASE}$ (mm):	*0.0025*	$d_{50\ FILTER}$ (mm):	*0.42*
$d_{60\ BASE}$ (mm):	*0.04*	$d_{60\ FILTER}$ (mm):	*0.48*

$$C_{U\ BASE}: \frac{d_{60}}{d_{10}} = \frac{0.04}{0.0017} = 23.53 \qquad C_{U\ FILTER}: \frac{0.48}{0.18} = 2.7$$

2a. Granular Filter Retention and Permeability Criteria from Fig. 5.6

Max. all. $d_{50\ FILTER}$: $A_{50} \times d_{50\ BASE}$ 8.5 x 0.0025 = 0.0213

Is the granular fill appropriate?: ***The granular filter does not meet the requirements and a second granular filter or a geotextile will be necessary.***

Description of Selected Material: ***Pit Run Sand***

Geotextile Retention Criterion from Figure 5.5

$$C_U = \frac{d_{60}}{d_{10}} = \frac{0.48}{0.18} = 2.7$$

Base Soil or Granular Filter Particle Sizes

d_{10} (mm):	*0.18*
d_{50} (mm):	*0.41*
d_{60} (mm):	*0.48*
d_{90} (mm):	*1.2*

currents are (mark with an X)

mild: X severe:

geotextile retention criteria for O_{95}

0.41 mm < O95 < 1.2 mm

continued on next page →

Project Name/Number:	*Meandering River / 10-466-077*
Company:	*ACB Consultants, Inc.*
Designer:	*John Doe*
Date:	*1/10/2019*
Client:	*Harris County, TX*

NATIONAL CONCRETE MASONRY ASSOCIATION
EQUIPPING BETTER BUILDING

3. Geotextile Permeability Criterion

Soil permeability determined from (mark with an X)

Fair-Hatch Equation **X** laboratory testing of soil

Other Explain

K_s (cm/s): *0.02* geotextile permeability criterion: $K_g \geq 10K_s \geq$ *0.2* cm/s

4 and 5. Geotextile Strength Screening Table (Table 5-5)

Application Condition?(select): Class 3 Elongation (select): Elongation <50%

Geotextile Strength Properties*	Selected Woven Geotextile Products					
	121F		*113-004*		*XW45*	
	Value	Satisfactory?	Value	Satisfactory?	Value	Satisfactory?
Grab Strength (lb) 180	*81*	*No*	*200*	*Yes*	*310*	*Yes*
Elongation (%) 160	*45*	*No*	*160*	*Yes*	*180*	*Yes*
Trapezoidal Tear Strength (lb) 70	*34*	*No*	*80*	*Yes*	*85*	*Yes*
Puncture Strength (lb) 370	*43*	*No*	*385*	*Yes*	*405*	*Yes*

* Grab strength, Puncture Strength and Trapezoidal Tear Strength minimum values based on requirements for Class 3 geotextile with Elongation <50% (ASTM D6684 – Table 2).

Note: use additional tables if more than three products are being evaluated

6. Select the Final Geotextile

Manufacturer/Selected Geotextile *Geotextile Fabrics, Inc./XW45*

Type of geotextile structure (mark with an X):	***Woven*** **X**	***Non - Woven***
O_{95} (mm):	***0.6***	
K_g (cm/s):	***0.4***	
Percent Open Area ³ 4%:	***4***	
Porosity ³ 30%:	***N/A***	
Mass per unit Area ³ 400g/m^2 (12 oz/yd^2)	***N/A***	

Section 6. ASTM D6684 REQUIREMENTS FOR ACB SYSTEMS

ASTM D6684, *Standard Specification for Materials and Manufacture of Articulating Concrete Block (ACB) Systems* (ref. 15), provides specifications for structural components, material composition and physical properties of ACB systems that are essential to long term durability and structural performance. The job site acceptance or rejection of the ACB units can be made based on these physical properties and the requirements for quality assurance, all of which should be incorporated into the job site specification.

Articulating concrete blocks may be produced at a block plant or onsite using either wet-cast or dry-cast production techniques, provided that the composition and physical characteristics of the furnished units meet the following requirements:

The compressive strength requirements for the ACB units in ASTM D6684 are governed by the durability requirements of a particular application. The standard specifies an average minimum compressive strength of three units be no less than 4,000 psi (27.58 MPa), with no individual unit less than 3,500 psi (24.13 MPa). The maximum water absorption is 9.1 lb/ft^3 (145.8 kg/m^3) (average of three units) and no individual unit more than 11.7 lb/ft^3 (187.4 kg/m^3). The standard further requires an average minimum density of three units of 130 lb/ft^3 (2082.4 kg/m^3) and no individual unit less than 125 lb/ft^3(2002.3 kg/m^3). When freeze thaw durability testing is required, the testing is performed following the test methods C67/C67M, C666/C666M, or C1262/C1262M, at the direction of the Owner. The number of freeze-thaw cycles and the corresponding weight loss criterion for pass-fail determination shall be specified by the Owner along with the test method. Overall dimensions for width, height, and length shall differ by not more than $\pm ^1/_8$ in. (3.2 mm) from the specified standard dimensions.

Geotextile filters must meet minimum standards for grab strength, sewn seam strength, tear strength and puncture strength. Geotextile must also satisfy subsoil compatibility assessment as detailed in *Section 5. Geotextile and Granular Filter Design*.

The standard further requires, if the system is cabled, that the cables and fittings (which facilitate lifting and placing of large mattresses) demonstrate a minimum factor of safety of 5.0 with respect to lifting. This applies to cable or rope, splice fittings, sleeves, and stops.

Section 7. INSTALLATION GUIDELINES

The proper installation of an ACB revetment system is essential to achieve suitable hydraulic performance and maintain stability against the erosive force of flowing water during the design hydrologic event. These guidelines are intended to maximize the conformity between the design intent and the actual field-finished conditions of the project. Quality workmanship is important to the ultimate performance of the system. The following sections address the subgrade preparation, geotextile placement, block system placement, backfilling and finishing, and inspection. These guidelines apply to the installation of ACB revetment systems, whether hand-placed or placed as a mattress, in compliance with ASTM D6884, *Standard of Practice for the Installation of Articulating Concrete Block (ACB) Revetment Systems* (ref. 16).

These guidelines do not purport to address the safety issues associated with installation of ACB revetment systems, including use of hazardous materials, mechanical equipment, and operations. It is the responsibility of the contractor to establish and adopt appropriate safety and health practices. Also, the contractor is obligated to comply with prevalent regulatory codes, such as OSHA (Occupational Health and Safety Administration) regulations, while using these guidelines.

At the completion of rough grading, soil samples representative of subgrade conditions shall be obtained at a minimum frequency of one sample for each 50,000 blocks to be installed, or additional fraction thereof, and tested for the following properties:

1. Grain size distribution – ASTM D6913, *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis* (Ref. 17)
2. Atterberg Limits – ASTM D4318, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils* (Ref. 6)
3. Standard Proctor Density – ASTM D698, *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3))* (Ref. 2)

Results of laboratory tests shall be submitted to the engineer to ensure conformance with design parameters prior to placement of the geotextile and ACB revetment system. When a granular filter is used, it shall be tested for grain size distribution at the same frequency as the subgrade soil testing.

7.1 Subgrade Preparation

Stable and compacted subgrade soil should be prepared to the lines, grades, and cross sections shown on the contract drawings. Termination trenches and transitions between slopes and embankment crests, benches, berms, and toes should be compacted, shaped and uniformly graded to facilitate the development of intimate contact between the ACB revetment system and the underlying grade. Secure the revetment in a manner that prevents soil migration when the ACB matrix is terminated at a structure, such as a concrete slab or wall.

Subgrade soil should be approved by the engineer to confirm that the actual subgrade soil conditions meet the required material and compaction standards. Soils not meeting the required standards should be removed and replaced with acceptable material.

Care should be exercised so as not to excavate below the grades shown on the contract drawings, unless directed by the engineer to remove unsatisfactory material. Any excessive excavation should be filled with compacted backfill material as approved by the engineer. Where it is impractical, in the opinion of the engineer, to dewater the area to be filled, over-excavations should be backfilled with crushed rock or stone conforming to the grading and quality requirements of well-graded coarse aggregate in ASTM C33, *Standard Specification for Concrete Aggregates* (ref. 1), or as directed by the engineer.

When preparing areas to receive the ACB system, the surface should be graded smooth to ensure that intimate contact is achieved between the subgrade surface and the geotextile and between the geotextile and the bottom surface of the ACB revetment system. Unsatisfactory soils, soils too wet to achieve desired compaction, and soils containing roots, sod, brush, or other organic materials, should be removed and replaced with an approved, compacted material. The subgrade should be uniformly compacted to a minimum 90 percent of the Standard Proctor density in accordance with ASTM D698 (ref. 2) or as required by the project specification, whichever is more stringent. Should the subgrade surface for any reason become rough, eroded, corrugated, uneven, textured, or traffic marked prior to ACB installation, such unsatisfactory portion should be scarified, reworked, recompacted, or replaced as directed by the engineer.

Excavation of the subgrade, above the water line, should not be more than 2 inches (51 mm) below the grade indicated on the contract drawings. Excavation of the subgrade below the water line should not be more than 4 inches (102 mm) below the grade indicated on the contract drawings.

Where such areas are below the allowable grades, they should be brought to grade by placing approved material and compacting in lifts not exceeding 6 inches (152 mm) in thickness. Where such areas are above the allowable grades they should be brought to grade by removing material, or reworking existing material, and compacting as directed by the engineer. The subgrade should be raked, screeded, or rolled by hand or machine to achieve a smooth compacted surface that is free of loose material, clods, rocks, roots, or other materials that would prevent satisfactory contact between the geotextile and the subgrade. Immediately prior to placing the geotextile and ACB system, the prepared subgrade should be inspected and approved by the engineer.

7.2 Placement of Geotextile

The geotextile should be placed directly on the prepared area, in intimate contact with the subgrade, and free of folds or wrinkles. The geotextile shall be placed in such a manner that placement of the overlying materials will not excessively stretch or tear the geotextile. After geotextile placement, the work area should not be disturbed so as to result is a loss of intimate contact between the articulating concrete block and the geotextile, or between the geotextile and the subgrade. The geotextile should not be left exposed longer than the manufacturer's recommendation to minimize damage due to exposure to ultraviolet radiation.

The geotextile should be placed so that the upstream strips of fabric overlap downstream strips and so that upslope strips overlap down slope strips. Overlaps should be in the direction of flow wherever possible. The joints should be overlapped a minimum 3 ft (1 m) for below-water installations and a minimum 1.5 feet (0.5 m) for dry installations in accordance with ASTM D6884 (ref. 15). When a sewn seam is used for geotextile seaming, the thread should consist of high strength, U.V. resistant polypropylene or polyester.

When a granular filter transition layer is used, the geotextile should be placed so as to encapsulate the granular filter material as shown in Figure 7.1. The distance between encapsulation points should not exceed 20 feet (6 m). The geotextile should extend to the edge of the revetment within the top, toe, and side termination points of the revetment. If necessary to expedite construction and to maintain the recommended overlaps, anchoring pins or 11 gauge (3 mm), 6- by 1-inch (152 by 25 mm) U-staples may be used; however, weights (e.g., sand filled bags) are preferred to prevent creating holes in the geotextile.

7.3 Placement of ACB System

The articulating concrete block system should be placed on the geotextile in such a manner as to produce a smooth plane surface in intimate contact with the geotextile. For blocks within the mat and blocks that are hand set, the joint spacing between adjacent blocks is to be maintained so that binding of blocks does not occur and block-to-block interlock is achieved. In curvature and grade change areas, alignment of the individual block and the orientation of the neighboring adjacent block is to provide for intimate block-to-fabric contact and block-to-block interlock. Care shall be taken during block installation so as to avoid damage to the geotextile or subgrade during the installation process. Preferably, when a geotextile is used, the ACB system placement should begin at the upstream end and proceed downstream. If an ACB system is to be installed from downstream up, a contractor option is to place a temporary toe on the front edge of the ACB system to protect against undermining when flows are anticipated. On sloped sections, where practical, placement shall begin at the toe of the slope and proceed up the slope. Block placement shall not bring block-to-block interconnections into tension. Individual blocks within the plane of the finished system shall not exceed the protrusion tolerance beyond that used in the design of the system. The typical protrusion tolerance is 0.5 inches (13 mm).

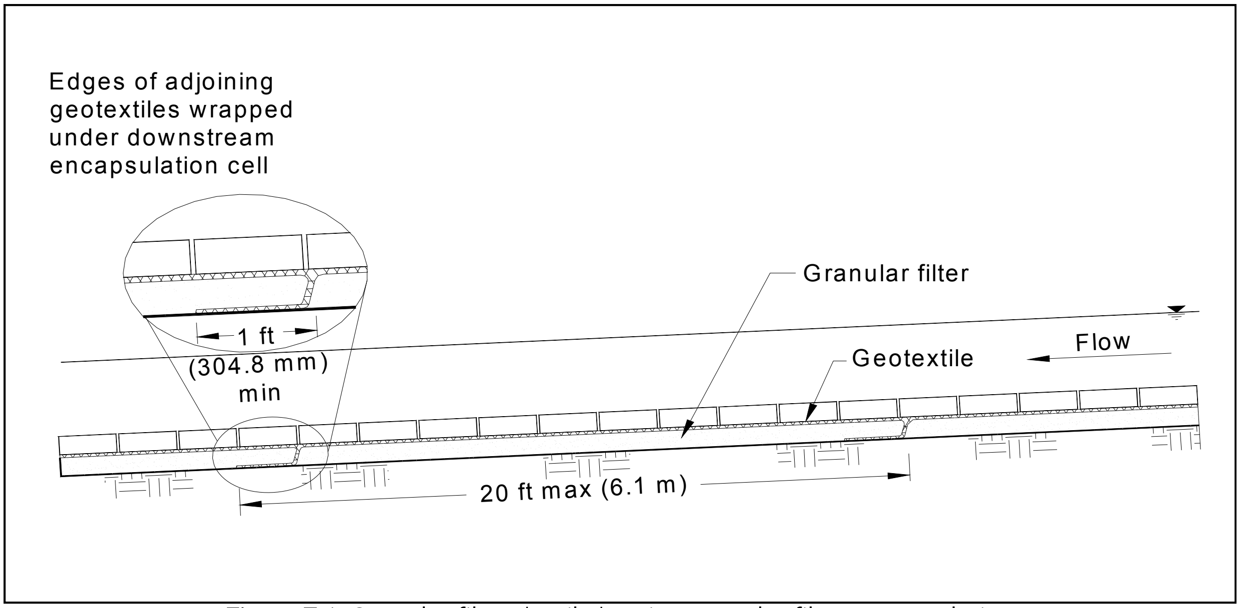


Figure 7.1: Granular filter detail showing granular filter encapsulation.

Do not use the ACB revetment system as a road for heavy construction traffic unless designed as a flexible pavement that can handle the expected wheel loads. Light traffic, such as single axle trucks and mowing equipment, may operate on installed ACB systems.

If assembled and placed as large mattresses, the articulating mats can be attached to a spreader bar to aid in the lifting and placing of the mats in their proper position with a crane. Figure 7.2 contains a photo of a crane placing bank protection with a spreader bar while Figure 7.3 is a close-up of an ACB mat and spreader bar. The mats should be placed side-by-side and/or end-to-end.

Mat seams or openings between mats creating voids or separations greater than 2 inches (51 mm) between blocks in the matrix should be filled with grout. Whether placed by hand or in large mattresses, distinct grade changes should be accommodated with a well-rounded transition (i.e., minimum radius determined by individual system characteristics). Figure 7.4 is a conceptual detail showing a minimum radius for a top-of-slope and toe-of-slope transition for bed and bank protection. The trapezoidal channel in Figure 7.5 shows a properly finished ACB revetment system with minimum radius-of-curvature. A top-of-slope transition and a typical toe detail for bank protection is shown in Figure 7.6. Figure 7.7 is a conceptual detail for spillways or embankment overtopping flow and Figure 7.8 is a photo of an ACB system that has been installed to protect an embankment during overtopping flow.

Figure 7.2: ACB mats being placed with a crane and spreader bar.

Figure 7.3: Close-up of spreader bar and ACB mat.

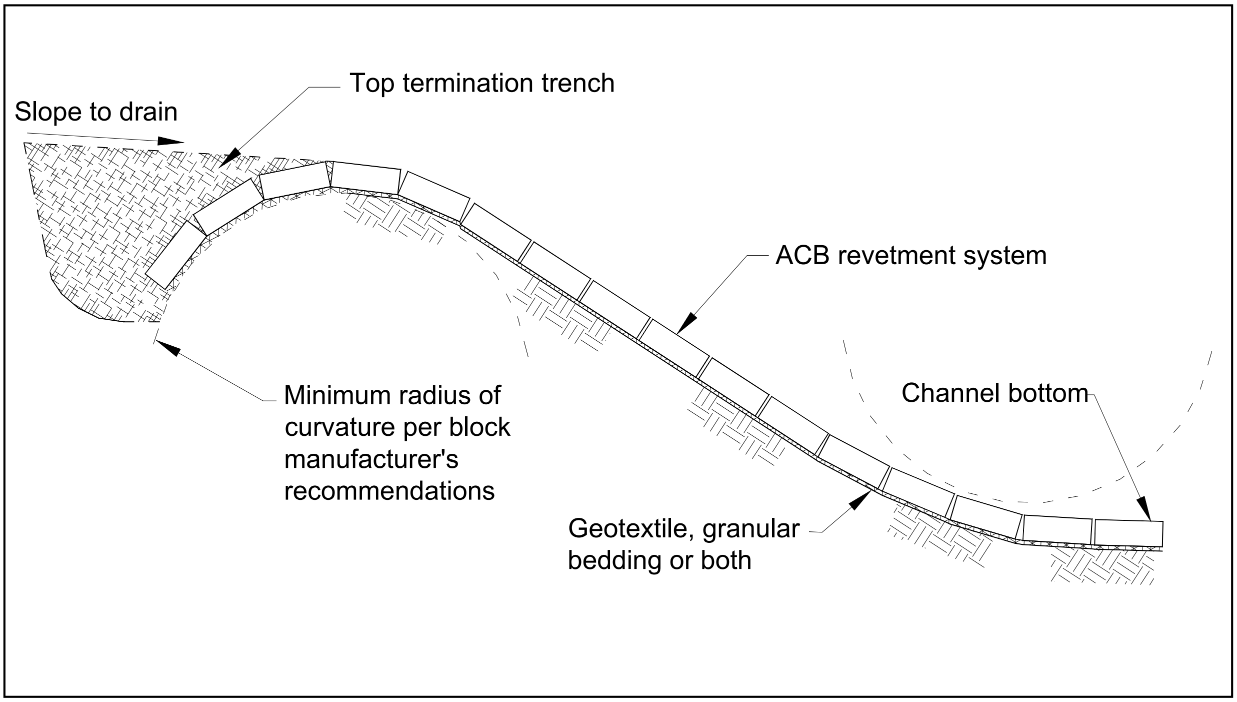


Figure 7.4: Conceptual detail of minimum radius-of-curvature for bed and bank protection.

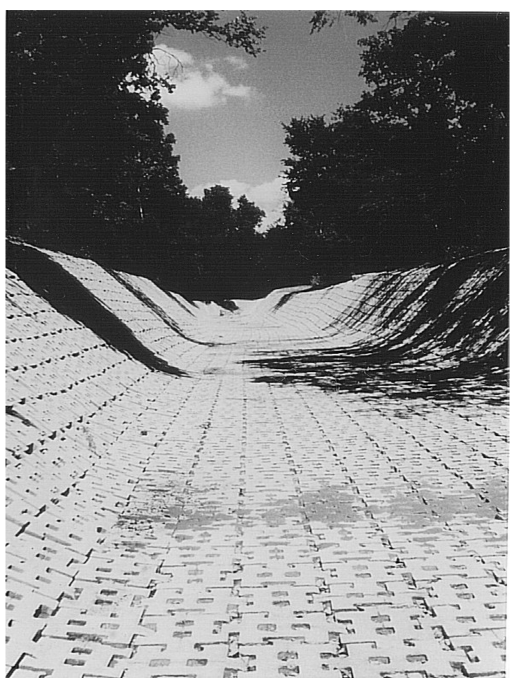


Figure 7.5: Bed and bank protection with minimum radius-of-curvature at grade changes and top-of-slope termination points.

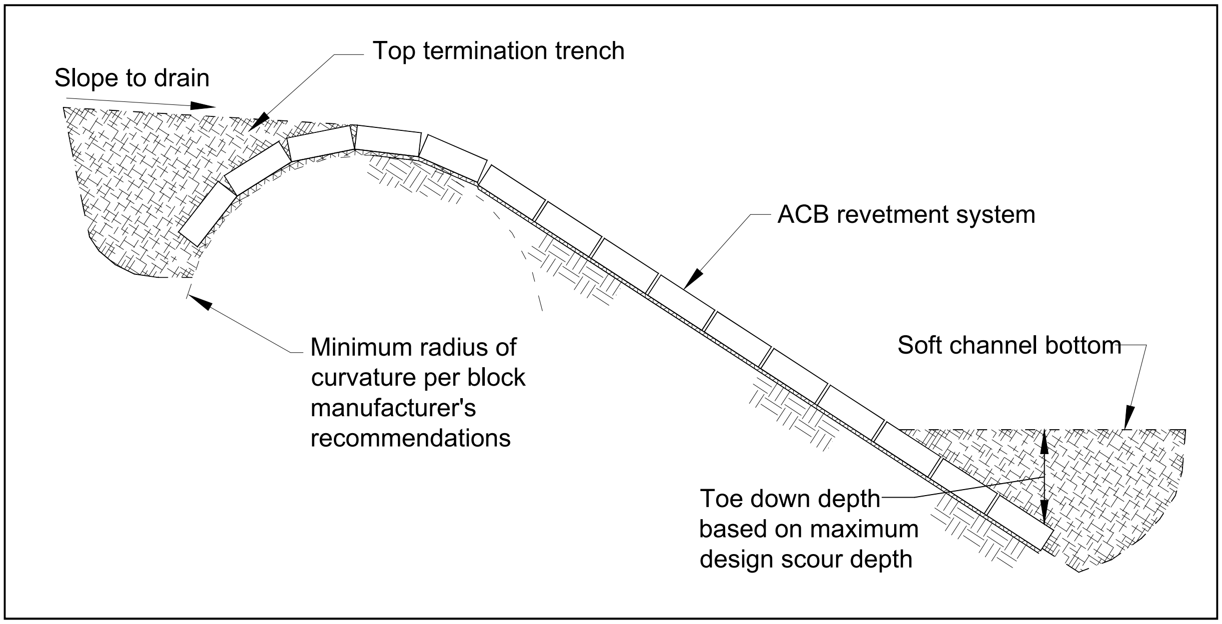


Figure 7.6: Conceptual detail of minimum radius-of-curvature for bank protection.

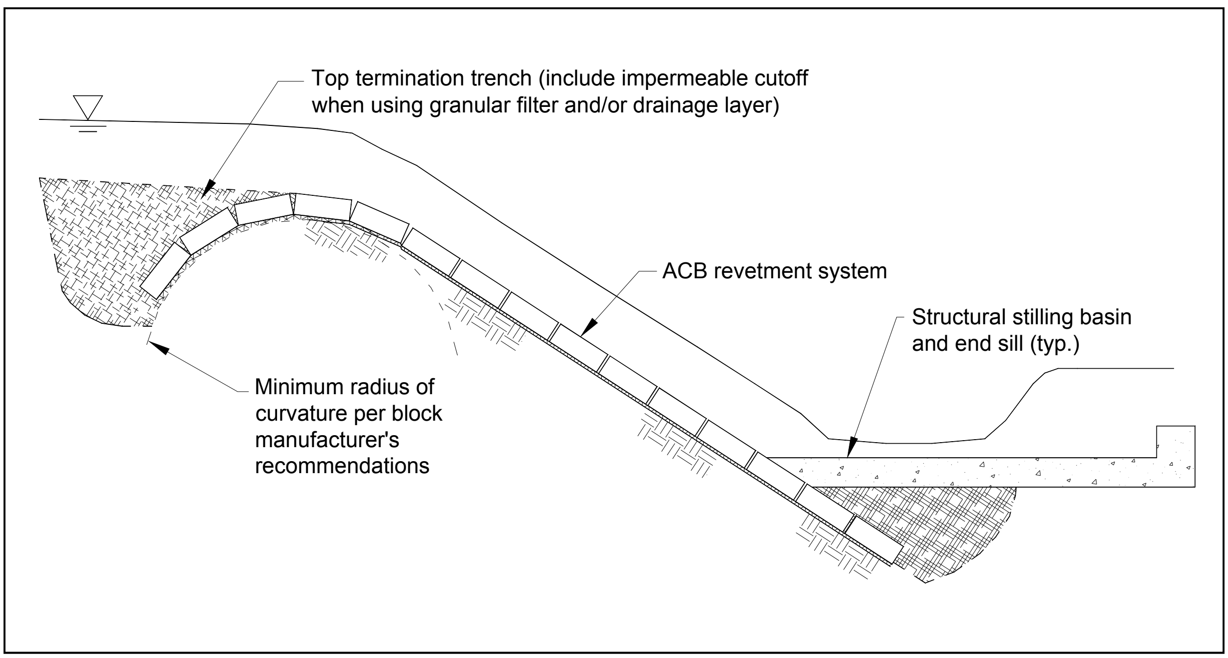


Figure 7.7: Conceptual detail of toe termination for spillways or embankment overtopping flow.

Figure 7.8: Embankment dam overtopping protection with radius-of-curvature at top-of-slope termination.

If a discontinuous revetment surface exists in the direction of flow, a grout seam at the grade change location should be provided to produce a continuous, flush finished surface. Grout seams should not be wider than one-half the maximum dimension of a single block.

Termination trenches should be backfilled with approved fill material and compacted flush with the top of the blocks. The integrity of a soil trench backfill must be maintained so as to ensure a surface that is flush with the top surface of the articulating blocks for its entire service life. Top, toe, and side termination trenches should be backfilled with suitable fill material and compacted immediately after the block system has been placed.

Anchors or other penetrations through the geotextile should be grouted or otherwise repaired in a permanent fashion to prevent migration of subsoil through the penetration point.

7.4 Finishing

The open area of the articulating concrete block system is typically either backfilled with suitable soil for revegetation or with 3/8- to 3/4-inch (9.5 to 19 mm) diameter uniform crushed stone or a mixture thereof. Crushed stone can enhance the interlock restraint, but can make the ACB revetment system less flexible. Backfilling with soil or granular fill within the cells of the system should be completed as soon as possible after the revetment has been installed. When topsoil is used as a fill material above the normal waterline, overfilling by 1 to 2 inches (25 to 51 mm) may be desirable to allow for consolidation.

7.5 Inspection

Each step of installation, including subgrade preparation, geotextile and granular filter placement, ACB revetment placement, and the overall finished condition, including termination points, should be inspected and approved by the engineer.

Section 8. ANNOTATED BIBLIOGRAPHY

Hydraulics	ACB Design	Filtration	Reference
			ASTM standard specifications, standard test methods, standard classifications, and standard guides. The following are the ASTM standards that are referenced in this manual and others that are related to ACB design, filter design, and system installation: **1.** C33/C33M-18 *Standard Specification for Concrete Aggregates* **2.** D698-12e2 *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3))* **3.** D2434-68(2006*) Standard Test Method for Permeability of Granular Soils (Constant Head) (Withdrawn 2015)* **4.** D2487-17 *Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System)* **5.** D4221-18 *Standard Test Method for Dispersive Characteristics of Clay Soil by Double Hydrometer* **6.** D4318-17e1 *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils* **7.** D4491/D4491M-17 *Standard Test Methods for Water Permeability of Geotextiles by Permittivity* **8.** D4533/D4533M-15 *Standard Test Method for Trapezoid Tearing Strength of Geotextiles* **9.** D4632/D4632M-15a *Standard Test Method for Grab Breaking Load and Elongation of Geotextiles* **10.** D4751-16 *Standard Test Method for Determining Apparent Opening Size of a Geotextile* **11.** D4833/D4833M-07(2013)e1 *Standard Test Method for Index Puncture Resistance of Geotextiles, Geomembranes, and Related Products* **12.** D5084-16a *Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter* **13.** D5101-12(2017) *Standard Test Method for Measuring the Soil-Geotextile System Clogging Potential by the Gradient Ratio* **14.** D5819-18 *Standard Guide for Selecting Test Methods for Experimental Evaluation of Geosynthetic Durability* **15.** D6684-18 *Standard Specification for the Materials and Manufacture of Articulating Concrete Block (ACB) Systems* **16.** D6884-03(2015)e1 *Standard of Practice for the Installation of Articulating Concrete Block (ACB) Revetment Systems* **17.** D6913-17 *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis* **18.** D7276-16 *Standard Guide for Analysis and Interpretation of Test Data for Articulating Concrete Block (ACB) Revetment Systems in Open Channel Flow* **19.** D7277-16 *Standard Test Method for Performance Testing of Articulating Concrete Block (ACB) Revetment Systems for Hydraulic Stability in Open Channel Flow* ASTM standards are avilable through the ASTM web site at www.astm.org.

Hydraulics	ACB Design	Filtration	Reference
Y			**20. Chow, V.T. *Open-Channel Hydraulics*. McGraw-Hill, New York, 1959.** This famous textbook has been the definitive reference in open channel hydraulics since the time it was published. It was reissued in 1988 in response to a high demand after discontinued printing. The textbook is a good reference for any design professional working in open channel hydraulics, including erosion control and ACB design. Open-Channel Hydraulics covers a wide range of topics related to ACB design, including evaluation of shear stress, uniform flow, hydraulic backwater profiles, flow over spillways, hydraulic jumps, and flow in meandering channels. The reasons for its popularity probably include the broad range of topics and the fact that the textbook provides a useful balance between theory and application.
	Y		**21. Clopper, P.E. *Hydraulic Stability of Articulated Concrete Block Revetment Systems During Overtopping Flow*, Technical Report FHWA RD-89 199. Federal Highway Administration, Washington, D.C., 1989.** This document summarizes findings from full-scale laboratory testing of five proprietary ACB systems. The research was conducted as a follow up study from FHWA (1988) testing to provide a more comprehensive understanding of ACB performance. The goal of the testing was to define hydraulic processes causing ACB failure and isolate the hydraulic conditions at failure for each system. A secondary goal of the testing was to develop preliminary design guidelines for protection of embankments against erosion. The research conducted for this document has become the industry standard practice and set the starting point for continued research and development by ACB manufacturers.
	Y		**22. Clopper, P.E., *Protecting Embankment Dams with Concrete Block Systems*. Hydro Review, April, 1991.** The article represents the first time the factor of safety equations, as applied to ACB system, were published in a peer-reviewed journal. This document provides a good background and history of concrete block testing programs. Particular emphasis has been placed on research conducted by Simons, Li & Associates, Inc. that evaluated a number of methods for protecting embankments from erosion caused by overtopping flow. From this research a method was developed for assessing the stability of block systems under field hydraulic conditions. A thorough explanation introduces the resulting method referred to as the "factor of safety" procedure. This procedure has been adapted from previous research on the stability of riprap. Application of the factor of safety method is illustrated through a design example.
	Y		**23. Clopper, P.E. And Y. Chen, *Minimizing Embankment Damage During Overtopping Flow*, Technical Report FHWA RD-88 181. Federal Highway Administration, Washington, D.C., 1988.** This document provides a discussion and background literature review on the mechanics of overtopping flow (steep slope, high velocity conditions) and summarizes findings from full-

Hydraulics	ACB Design	Filtration	Reference
			scale tests of bare soil, gabion, geosynthetics, soil cement, asphalt, cellular confinement systems, and ACB system on a 6 foot high earthen test embankment. The FHWA and the Bureau of Reclamation sponsored the research to provide pilot testing of each of the systems so that their performance and feasibility could be evaluated for field applications. Since the research was so broad in scope, the document does not provide substantial information related to ACB performance; however, it does define some of the observed failure mechanisms. A broad range of performance was observed between the three proprietary ACB systems that were tested, indicating the need for further research and development of the technology.
	Y		**24. Cox, A. L. (2010).** ***"Moment stability analysis method for determining safety factors for articulated concrete blocks."*** **Ph.D. dissertation, Colorado State University, Fort Collins, CO.** This document provides a review of the existing ACB design methodology and defines a new moment stability analysis based on a database of twenty-four test for both channelized and overtopping condition for three different ACB systems. The new safety factor design methodology was developed using a moment stability analysis coupled with the computation of hydrodynamic forces using both boundary shear stress and flow velocity.
	Y		**25. Cox, A.L., Thornton, C.I., and Abt, S.R. (2014). "*Articulated Concrete Block Stability Assessment for Embankment-Overtopping Conditions*." ASCE Journal of Hydraulic Engineering, 140(5). DOI: 10.1061/(ASCE)HY.1943-7900.0000844** This document provides a review of the existing ACB design methodology and defines a new moment stability analysis for embankment-overtopping based on two data sets for a given ACB sisyem. The new safety factor design methodology was developed using a moment stability analysis coupled with the computation of hydrodynamic forces using both boundary shear stress and flow velocity. A database was developed that included overtopping tests for three ACB systems with varying embankment slopes and lengths.
	Y		**26. Cox, A.L., Thornton, C.I., and Abt, S.R. (2019).** ***"Articulated Concrete Block Stability Assessment for Channelized Flow." ASCE Journal of Hydraulic Engineering,*** **154(4). DOI: https://doi.org/10.1061/(ASCE)HY.1943-7900.0001579** This article summarizes the moment stability analysis method which computes a safety factor using shear stress and flow velocity was previously developed for assessing the stability of articulated concrete block (ACB) systems during overtopping flow. The study used the shear and velocity stability assessment (SVSA) method to derive safety factor equations for evaluating channelized flow. The stability analysis method for channelized flow excludes several assumptions used in previous methods, including calculating the rotation angle for movement and using a ratio of the boundary shear stress to critical shear stress to account for all hydrodynamic forces.

Hydraulics	ACB Design	Filtration	Reference
Y	Y	Y	**27. Escarameia, M., *River and Channel Revetments: A Design Manual.* Thomas Telford Ltd., Heron Quay, London, 1988.** Escarameia begins with background information including geotechnical factors affecting bank stability and the modes of bank failure most common in river engineering. A concise section on geotechnical stability addresses soil characteristics and applicable geotechnical parameters. The design manual identifies common revetment types and design equations for each, including ACB systems. Escarameia separates the discussion of block revetments into two sections: interlocking blocks and cabled blocks, and provides design equations for both. Parameters for these two design equations differ. Additional parameters included with the cabled block design equation include porosity of the revetment, water depth, and a slope factor. These two design equations determine required thickness only. The equations are empirical in form and very simple to apply. However, given the large variability in block performance observed in laboratory testing, the equations may not be suitable for all ACB systems. The manual does provide useful information related to the suitability of each block type to various applications. As an indication of the relative importance of bedding component design within the overall framework of revetment design, an individual Chapter entitled, "Use of granular filters and geotextiles," is included in this manual. The provided flowchart for filter design can be used to compare/contrast with the design steps recommended in this design manual. The explanation of geotextile types is brief yet very informative and useful. Also, provided are several examples of situations where drainage layers are not advisable. In summary, Escarameia provides a compact presentation on filter design that is to the point and easy to follow.
Y	Y	Y	**28. Harris County Flood Control District, Harris County, Texas. *Design Manual for Articulating Concrete Block Systems*, 2001.** Ayres Associates prepared this design manual for The Harris County Flood District and it was the base for the first and the current edition of NCMA's Design Manual for Articulated Concrete Block. The manual was the first document that addressed some of the design issues and constructions of ACB systems.
Y	Y	Y	**29. Hewlett, H.W.M., L.A. Boorman, and M.E. Bramley, *Design Of Grassed Waterways.* Construction Industry Research and Information Association, London, 1987.** This manual addresses a number of issues relating to grassed waterway design. Methods to reinforce grassed waterways are outlined and basic channel design is reviewed. Within the erosion resistance section, a recommendation is made to use a 2-dimensional woven fabric when the channel design process specifies a geotextile underlayer. A lower limit on the geotextile opening size of $O_{90} > 0.5$ mm is recommended here as well. Several field and laboratory experiences with erosion resistance reinforcement systems are reviewed within the ACB Design Manual.

Hydraulics	ACB Design	Filtration	Reference
	Y	Y	**30. Hunt, W.F., Collins, K.A., Hathaway, J.M. "Hydrologic and Water Quality Evaluation of Four Permeable Pavements in North Carolina, USA"** This paper summarizes the research conducted on permeable pavement parking lot in eastern North Carolina consisting of four types of permeable pavement and standard asphalt. The research examined hydrologic differences in pavement surface runoff volumes, total outflow volumes, peak flow rates, and time to peak, and water quality concentrations.
		Y	**31. Industrial Fabrics Association International, "2017 Specifiers Guide."** ***Geotechnical Fabrics Report*****, v. 34, No. 6, December, 2017.** This guide is a special edition of the trade journal "Geosynthetic Magazine." It is updated annually, and provides tables of values for various physical properties of geotextiles. Tables are organized by manufacturer and product name (or alphanumeric acronym), and include most geotextiles typically specified for use in conjunction with articulating concrete block revetment systems. http://www.ifai.com
Y	Y		**32. Julien, P.Y.,** ***Erosion and Sedimentation*****. Cambridge University Press, Cambridge, UK, 1995.** This sediment transport textbook is referenced because it provides the most general form of the factor of safety equations (i.e., steep slope in both longitudinal and lateral directions). The equations presented in the text are formulated for riprap design, and therefore can not be used to replace this design manual as an ACB design reference. The text is an important reference for subjects related to hydraulics and sediment transport. In particular, Julien's book gives an excellent presentation of turbulent velocity profiles and incipient motion analysis, both subjects pertinent to erosion control applications.
Y	Y		**33. Julien, P.Y., Anthony, D.J. (2002).** ***Bed Load Motion and Grain Sorting in a Meandering Stream*****. Journal of Hydraulic Research, 40(2):125-134.** This sediment transport article is an expansion of Julien, 1998. This three-dimensional moment analysis expanded the weight components on side sloes and defined a more complete set of equations. The equations are formulated for riprap design. The article is an important reference for the shear and velocity stability assessment methodology.
	Y	Y	**34. Kirkpatrick, R., Campbell, R, Smyth, J., Murtagh, J., Knapton, J. "Improvement Of Water Quality By Coarse Graded Aggregates In Permeable Pavements"** The paper summarizes a research completed in Ireland to investigate the ability of permeable pavements to remove heavy metals and hydrocarbons from industrial water.

Hydraulics	ACB Design	Filtration	Reference
		Y	**35. Koerner, Robert M., *Designing with Geosynthetics*, 5th edition. Prentice Hall, Upper Saddle River, New Jersey, 2005.** Koerner presents a thorough coverage of geosynthetic design. Individual Chapters are devoted to designing with geotextiles, geogrids, geomembranes, geosynthetic clay liners, geopipes, and geocomposites. Specifically for purposes of design with geotextiles, Koerner details the functions and mechanisms of geotextiles as well as their properties and related test methods. A section addressing geotextile design for filtration proves somewhat useful although the applicable example problem is of a geotextile below riprap used as a coastal inlet protection. The description and analysis of geotextile property test methods is the strength of this reference. The soil retention function of geotextiles presented here parallels the method chosen for the HCFCD design manual.
Y			**36. Lagasse, P.F., J.D. Schall, and E.V. Richardson, *Stream Stability At Highway Structures*, 3rd edition. Hydraulic Engineering Circular No. 20. Federal Highway Administration, Washington, D.C., 2001.** This FHWA publication is most often referred to as HEC-20. The document provides background and methodology for stream reconnaissance and restoration projects. HEC-20 uses a multi-disciplinary approach including methods from geomorphology, sedimentology, hydrology, and hydraulics. An excellent feature of HEC-20 is that it is written for a broad range of audiences; it provides sufficient background for general planning, technical analysis, and design. It presents quantitative procedures for assessing local scour at piers, local scour at abutments, contraction scour, and long term degradation scour. The document suggests a three level approach to stream analysis/restoration projects that is systematic and general enough to apply to most projects. To date, HEC-20 is the most comprehensive and applied document related to stream reconnaissance and restoration projects.
Y	Y		**37. Lagasse, P.F., P.E. Clopper, J.E. Pagan-Ortiz, L.W. Zevenbergen, L.A. Arneson, J.D. Schall, and L.G. Girard, Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance - 3rd Edition. Hydraulic Engineering Circular No. 23. Federal Highway Administration, Washington, D.C., 2009.** This FHWA publication is most often referred to as HEC-23. The document provides guidance for scour countermeasure designs at bridge crossings. HEC-23 was developed in response to the recognized need for FHWA support to design professionals related to scour countermeasures. Included is a countermeasure matrix that provides tabular information related to scour type and river environment suitability. The matrix also provides states where each countermeasure has been used successfully. HEC-23 provides specific design guidance for ACB systems that is similar to that presented in this document. However, this design manual is much more comprehensive and the design

Hydraulics	ACB Design	Filtration	Reference
			procedure presented here uses a more general set of equations. The 3rd edition of HEC-23 presents the Factor of Safety design equations for hydraulic stability of ACB systems that are identical to those presented in this manual.
	Y	Y	**38. Lipscomb, C.M, C.I. Thornton, S.R. Abt, and J. R. Leech. "Performance of Articulated Concrete Blocks in Vegetated and Un-vegetated Conditions"** This paper summarizes the research conducted by the U.S. Army Corps of Engineers investigating the performance of ACB system vegetated and un-vegetated showing an increase in the allowable shear stress of 41% when vegetated.
		Y	**39. Luettich, Scott M., Geotextile Filter Design Manual. Nicolon Mirafi Group, 1991.** This design manual was prepared for the Nicolon Corporation by Luettich and reviewed by Dr. Robert C. Bachus and Dr. Jean-Pierre Giroud of GeoSyntec Consultants. The document closely follows a similarly titled article, "Geotextile Filter Design Guide", authored by the three individuals just mentioned, that appeared in the "Journal of Geotextiles and Geomembranes" in 1992. The manual covers many of the same topics and procedures as those presented in the HCFCD Criteria Manual bedding section. A good overview of the filtration processes associated with bedding components is presented. A step by step design procedure shows in detail the process for selecting an appropriate geotextile. Many topics relating to geotextile application design are briefly introduced and references for further information are provided. A number of design examples are included addressing a broad range of applications.
	Y		**40. Fripp, J., Visser, K., National Engineering Handbook - Part 628 - Dams: Chapter 54-Articulated Concrete Block Armored Spillways (210-NEH-628-54), National Resources Conservation Service (NRCS), Washington, D.C., 2019.** This section of the NRCS National Engineering Handbook provides the guidelines for the design of spillways with articulating concrete block (ACB). The resource covers hydraulic, geotechnical, design, construction considerations and maintenance of this type of spillways.
Y			**41. Richardson, E.V. and S.R. Davis, *Evaluating Scour At Bridges*, 4th edition. Hydraulic Engineering Circular No. 18. Federal Highway Administration, Washington, D.C., 2001.** This FHWA publication is most often referred to as HEC-18. The document provides guidelines for estimating scour at riverine and tidal bridges under hydraulic loading. HEC-18 presents two major classifications for scour: live-bed and clear water (indicating if sediment is being transported into the subject reach). Scour is also classified into three sub-types: contraction scour, pier scour, and degradation. In terms of ACB design, the scour of greatest interest is contraction scour and degradation. These variables need to be estimated when considering toe-down depth of the ACB revetment, as discussed in Sections C.3 and C.4.5.

Hydraulics	ACB Design	Filtration	Reference
	Y		**42. Stevens, M.A. and D.B. Simons, "Stability Analysis For Coarse Granular Material On Slopes". *River Mechanics*, Shen, H.W. (ed.), Fort Collins, Colorado, 1971.** This document provides background information and development of the factor of safety design procedure. Stevens is the original developer/inventor of the design procedure for stability analysis using the moment balance approach. The document provides thorough insight into the development of the factor of safety equations; however, it is of limited use for ACB design purposes because the original equations are not tailored to analysis of blocks of known geometric dimensions.
		Y	**43. Terzaghi, K., G. Mesri, and R.B. Peck, *Soil Mechanics In Engineering Practice*, 3rd edition. John Wiley & Sons, New York, 1996.** This widely used and renowned textbook covers in great detail many of the soil mechanic topics critical to the field of civil engineering. Of particular importance to filter design are Articles One through Nine devoted to the index properties of soils and several articles included within Chapter 3 (permeability of soils, and particle migration and erosion). The Terzaghi rules used to determine the appropriate grain size of granular filter material are presented and briefly explained. These are the same rules used to design granular bedding components as presented within the HCFCD Design Manual. This text is particularly useful at providing definitions and explanations of the background soil information required by the bedding component design procedure.
	Y		**44. Thornton, C. and Nadeau, J., "Hydraulic Jump Stability of Articulating Concrete Block Systems". Association of State Dam Safety Officials, Dam Safety 2019 Conference Proceedings, Orlando, Florida 2019** This paper summarizes the research conducted on 7 full scale ACB assemblies subjected to the turbulent flow under a hydraulic jump. The different ACB/gravel systems were tested to failure or until the flume reached capacity. This research proposed a design methodology where the determined threshold Specific Energy (SE_i) for each particular ACB assembly is compared to the project's specific energy to select an ACB assembly that could meet the project's requirements.
Y			**45. United States Army Corps of Engineers, *RMA2 Version 4.5*. USACE Waterways Experiment Station, Vicksburg, Mississippi, 2008.** RMA2 is a sophisticated 2-dimensional model for free surface flow applications. RMA2 is a two-dimensional, depth-averaged finite element hydrodynamic numerical model. RMA2 solves the 2-dimensional version of the momentum and continuity equations at each node in a finite element mesh to calculate depth and velocity. The program is limited to sub-critical flow and longitudinal bed slopes less than 10 percent. Time dependent wind fields can also be added to the model as a boundary condition. RMA2 was originally developed by Resource Management Associates but is currently maintained by Waterways Experiment Station. The program itself does not provide editing utilities for the input file or a post processor for viewing model results. The most efficient way to develop the model and interpret results is using Surface-Water Modeling System (SMS) developed and supported

Hydraulics	ACB Design	Filtration	Reference
			by the Aquaveo, LLC of Provo, Utah. SMS is a pre- and post-processor that can be used to develop the finite element mesh geometry and boundary condition/run control file and view the model solution using several graphical tools. The RMA-2 source code, program, and manuals can be downloaded from the Aquaveo LLC web site: http//www.aquaveo.com The SMS program is not free but can be purchased at the above web address.
Y			**46. United States Army Corps of Engineers, *HEC-RAS Version 4.1*. USACE Hydrologic Engineering Center, Davis, CA, January 2010.** This is a widely used software package for 1-dimensional hydraulic modeling of open channel flow. A feature that makes HEC-RAS suitable for ACB design is that it will provide a horizontal velocity distribution at a cross section for a specified number of intervals that is based on the conveyance of each interval. However, this procedure can not replace 2-dimensional modeling for complex systems because the velocity distribution is not based on principals of momentum. The unsteady flow feature of HEC-RAS will make it suitable for tidal applications, where time dependent tide elevations can be used as a boundary condition. The HEC-RAS program and manuals are available free of charge from the HEC web site: http://www.wrc-hec.usace.army.mil/
		Y	**47. Wilson-Fahmy, R.F., G.R. Koerner, and R.M. Koerner (1996). "Geotextile Filter Critique". *Recent Developments in Geotextile Filters and Prefabricated Drainage Geocomposites*, ASTM STP 1281, Shobha K. and L. David Suits, Eds., American Society for Testing and Materials, 1996.** This paper compares data collected from exhumed highway drainage field sites with existing geotextile design criteria for permeability, soil retention, and long term performance (clogging). The purpose here is to verify current design practices with actual in-field performance. The exhumed sites were each given a letter grade based on a visual assessment of their performance. This rating is followed by a review of the three primary requirements of geotextile filter design. Each of the specific design criteria widely in use (permeability, soil retention, and long term performance) are then presented in tabular form. These design criteria are assessed through comparison with actual in-field performance. The authors conclude by recommending a set of design criteria based upon the results of the comparison. This paper presents a very good summary of the current design methods in practice and provides some useful insight into observed behavior of geotextiles under actual field conditions.

APPENDIX A: DESIGN EQUATIONS – SI UNITS

A.1 The average cross-section shear stress:

$$\tau_0 = \gamma R S_f \qquad \text{(Eqn. 2.1)}$$

where:

τ_0	=	Cross-section-averaged shear stress, Pa
γ	=	Unit weight of water, 9,810 N/m^3
R	=	Hydraulic radius, m
S_f	=	Energy grade line or bed slope, m/m

A.2 The drag force on the block:

$$F'_D = 1/2 \cdot C_D(\Delta Z) b \rho V^2 \qquad \text{(Eqn. 2.2)}$$

where:

F'_D	=	Drag force due to block protrusion, N
C_D	=	Drag coefficient ($C_D \approx 1.0$)
ΔZ	=	Height of protrusion, m
b	=	Block width perpendicular to flow, m
ρ	=	Density of water, 1,000 kg/m^3
V	=	Velocity, m/s

A.3 Hydraulic Stability Equation for the ACB block:

$$\ell_2 W_{S2} = \ell_1 W_{S1} + \ell_3(F_D + F'_D) + \ell_4(F_L + F'_L) \qquad \text{(Eqn. 2.3)}$$

where:

W_{S1}	=	Gravity force parallel to slope, N
W_{S2}	=	Gravity force normal to slope, N
F_D & F_L	=	Drag and lift forces, N
F'_D & F'_L	=	Additional drag and lift force from block protruding above ACB matrix, N
ℓ_x	=	Moment arms, m; Refer to Figure 3.2.

See Figure 2.6 for nomenotaionsnclature.

A.4 Critical Shear Stress extrapolation from a steeper bed slope to that of a shallower bed slope for the same ACB system:

$$\tau_{C\theta U} = \tau_{C\theta T} \cdot \left(\frac{\ell_2 \cos\theta_U - \ell_1 \sin\theta_U}{\ell_2 \cos\theta_T - \ell_1 \sin\theta_T} \right) \qquad \text{(Eqn. 2.4)}$$

where:

$\tau_{C\theta U}$	=	Critical shear stress for untested bed slope, Pa
$\tau_{C\theta T}$	=	Critical shear stress for tested bed slope, Pa
θ_U	=	Untested bed slope (degrees)

		Where θ_U less than or equal to θ_T; and where design velocity (V_{des}) less than or equal to the test velocity (V_{test})
θ_T	=	Tested bed slope (degrees)
ℓ_x	=	Moment arms, m; Refer to Figure 3.2.

Note that the moment arms used in this equation should apply to the orientation of the block during testing and are not necessarily the same as those suggested later in this document for design.

A.5 Critical Shear Stress interpolation from one block height to another within the same family:

$$\tau_{CU} = \tau_{CT} \cdot \left(\frac{W_{SU}\ell_{2U}}{W_{ST}\ell_{2T}} \cdot \frac{\ell_{3T} + \ell_{4T}}{\ell_{3U} + \ell_{4U}} \right) \qquad \text{(Eqn. 2.5)}$$

Note: Extrapolated critical shear stress, τ_{CU}, is only applicable when considering an untested block height greater than that of the tested block height.

where:

τ_{CU}	=	Critical shear stress for untested block, Pa
τ_{CT}	=	Critical shear stress for tested block, Pa
W_{SU}	=	Submerged weight of untested blocks, N
W_{ST}	=	Submerged weight of tested blocks, N
ℓ_{XU}	=	Moment arms of untested, m
ℓ_{XT}	=	Moment arms of tested blocks, m

A.6 Factor of Safety of the ACB block for the Hydraulic Stability Method:

$$SF = \frac{\ell_2 W_S a_\theta}{\ell_1 W_S \sqrt{1 - a_\theta^2}\cos\beta + \ell_3 F_D \cos\delta + \ell_4 F_L + \ell_3 F'_D \cos\delta + \ell_4 F'_L} \qquad \text{(Eqn. 3.1)}$$

The nomenclature, forces, dimensions, and angles in the equation for SF are presented in Figure 3.1.

where:

a_θ	=	Projection of W_S into subgrade beneath block
F_D & F_L	=	Drag and lift forces, N
F'_D & F'_L	=	Additional drag and lift force from block protruding above ACB matrix, N
ℓ_x	=	Moment arms, m; Refer to Figure 3.2.
W_S	=	Gravity force parallel to slope, N
β	=	Angle of block projection from downward direction, once in motion
δ	=	Angle between drag force and block motion

<table>
<tr><th colspan="3">Table A-1: Hydraulic Stability Method Design Equations – SI Units</th></tr>
<tr><td>$$SF = \frac{(\ell_2/\ell_1)a_\theta}{\sqrt{1-a_\theta^2}\cos\beta + \eta_1(\ell_2/\ell_1) + \frac{(\ell_3 F'_D \cos\delta + \ell_4 F'_L)}{\ell_1 W_S}}$$</td><td>3.2</td><td rowspan="9">a_θ = Projection of W_S into subgrade beneath block
b = Block width, m
F'_D & F'_L = additional drag and lift forces, N
ℓ_x = Block moment arms (m)
S_C = Specific gravity of concrete (assume 2.1)
SF = Calculated factor of safety
V_{des} = Design velocity, m/s (V_{des} less than or equal to V_{test})
V_{test} = Maximum tested Velocity, m/s
W = Weight of block, N
W_S = Submerged weight of block, N
ΔZ = Height of block protrusion above ACB matrix, m
β = Angle of block projection from downward direction, once in motion
δ = Angle between drag force and block motion
η_0 = Stability number for a horizontal surface
η_1 = Stability number for a sloped surface
θ = Angle between side slope projection of W_S and the vertical
θ_0 = Channel bed slope (degrees or radians) (less than or equal to test bed slope)
θ_1 = Channel side slope (degrees or radians) Note - the equations cannot be solved for $\theta_1 = 0$ (i.e., division by 0); therefore, a negligible side slope must be entered for the case of $\theta_1 = 0$
ρ = Mass density of water, 1,000 kg /m^3
τ_C = Critical shear stress for block on a horizontal surface, Pa
τ_{des} = Design shear stress, Pa</td></tr>
<tr><td>$$\delta + \beta + \theta = 90^\circ \text{ or } \pi/2 \text{ radians}$$</td><td>3.3</td></tr>
<tr><td>$$\eta_1 = \left(\frac{\ell_4/\ell_3 + \sin(\theta_0 + \theta + \beta)}{\ell_4/\ell_3 + 1}\right)\eta_0$$</td><td>3.4</td></tr>
<tr><td>$$\beta = \arctan\left(\frac{\cos(\theta_0 + \theta)}{(\ell_4/\ell_3 + 1)\frac{\sqrt{1-a_\theta^2}}{\eta_0(\ell_2/\ell_1)} + \sin(\theta_0 + \theta)}\right)$$</td><td>3.5</td></tr>
<tr><td>$$\theta = \arctan\left(\frac{\sin\theta_0}{\sin\theta_1}\cdot\frac{\cos\theta_1}{\cos\theta_0}\right) = \arctan\left(\frac{\tan\theta_0}{\tan\theta_1}\right)$$</td><td>3.6</td></tr>
<tr><td>$$a_\theta = \sqrt{\cos^2\theta_1 - \sin^2\theta_0}$$</td><td>3.7</td></tr>
<tr><td>$$F'_L = F'_D = 0.5\cdot(\Delta Z)b\rho V_{des}^2$$</td><td>3.8</td></tr>
<tr><td>$$\eta_0 = \frac{\tau_{des}}{\tau_C}$$</td><td>3.9</td></tr>
<tr><td>$$W_S = W\cdot\left(\frac{S_C - 1}{S_C}\right)$$</td><td>3.10</td></tr>
</table>

A.7 Maximum shear stress:

$$\tau_{des} = \tau_0 \cdot \left(\frac{V_{des}}{V_{avg}}\right)^2 \qquad \text{(Eqn. 3.14)}$$

where:

τ_{des}	=	Design shear stress on the designed section, Pa
τ_0	=	Cross-section-averaged shear stress, Pa
V_{des}	=	Design velocity on the designed section, m/s
V_{avg}	=	Average velocity on the designed section, m/s

A.8 Factor of Safety of the ACB block for the Shear and Velocity Method with Channelized Flow:

$$SF_M = \frac{\ell'_7}{\begin{bmatrix} \ell'_1(W_{SX} \cdot \sin\beta + W_{SZ} \cdot \cos\beta) + \\ \ell'_3(F_D + F'_D)\sin\beta + \ell'_8(F_L + F'_L) \end{bmatrix}} \qquad \text{(Eqn. 4.8)}$$

$$SF_P = \frac{\ell'_2 W_{SY}}{\ell'_1 W_{SX} + \ell'_3(F_D + F'_D) + \ell'_4(F_L + F'_L)} \qquad \text{(Eqn. 4.9)}$$

$$SF_O = \frac{\ell'_5 W_{SY}}{\ell'_1 W_{SZ} + \ell'_6(F_L + F'_L)} \qquad \text{(Eqn. 4.10)}$$

$$SF_{MIN} = \mathrm{Min}[SF_M, SF_P, SF_O] \qquad \text{(Eqn. 4.11)}$$

<table>
<tr><th colspan="3">Table A-2: SVSA Design Equations for ACB Systems with Channelized Flow – SI Units</th></tr>
<tr><td>$W_S = W \cdot \left(\frac{S_C - 1}{S_C}\right)$</td><td>3.10</td><td rowspan="13">A_B = Block area parallel to the direction of flow, m^2
b = Block width normal to the direction of flow, m
C_{BL} = Block lift coefficient
F_D = Drag force, N
F'_D & F'_L = additional drag and lift forces, N
F_L = Lift force, N
S_C = Specific gravity of concrete
SF_M = Factor of safety for rotation about Point M
SF_P = Factor of safety for rotation about Point P
SF_O = Factor of safety for rotation about Point O
SF_{Min}= Minimum factor of safety for all rotation points
V_{des} = Design velocity, m/s (V_{des} less than or equal to V_{test} or V_{max})
W = Weight of block, N
W_S = Submerged weight of block, N
W_{SX} = W_S component parallel to side-slope plane in the x direction, N
W_{SY} = W_S component normal to side-slope plane in the y direction, N
W_{SZ} = W_S component parallel to side-slope plane in the positive z direction, N
β = Angle to block corner, degrees
ΔZ = Height of block protrusion above ACB matrix, m
θ_0 = Bed slope angle, degrees
θ_1 = Side slope angle, degrees
θ_2 = Side slope angle normal to bed slope plane, degrees
ℓ_n = Block length normal to flow direction, m
ℓ_p = Block length parallel to flow direction, m
ℓ_X’ = Moment arms corresponding to forces, m
ρ = Mass density of water 1,000 kg/m^3
τ_{des} = Design shear stress, Pa</td></tr>
<tr><td>$\theta_2 = \arctan[\tan(\theta_1)\cos(\theta_0)]$</td><td>4.1</td></tr>
<tr><td>$\beta = \arctan\frac{\ell_p}{\ell_n}$</td><td>4.2</td></tr>
<tr><td>$W_{SX} = W_S \cdot \sin(\theta_0)$</td><td>4.3</td></tr>
<tr><td>$W_{SY} = W_S \cdot \cos(\theta_0) \cdot \cos(\theta_2)$</td><td>4.4</td></tr>
<tr><td>$W_{SZ} = W_S \cdot \cos(\theta_0) \cdot \sin(\theta_2)$</td><td>4.5</td></tr>
<tr><td>$F_D = \tau_{des} \cdot A_B$</td><td>4.6</td></tr>
<tr><td>$F_L = (0.5) \cdot C_{BL}\rho A_B V_{des}^2$</td><td>4.7</td></tr>
<tr><td>$F'_L = F'_D = (0.5) \cdot (\Delta Z) b \rho V_{des}^2$</td><td>3.8</td></tr>
<tr><td>$SF_M = \frac{\ell'_7}{\left[\begin{array}{c}\ell'_1(W_{SX} \cdot \sin\beta + W_{SZ} \cdot \cos\beta) + \\ \ell'_3(F_D + F'_D)\sin\beta + \ell'_8(F_L + F'_L)\end{array}\right]}$</td><td>4.8</td></tr>
<tr><td>$SF_P = \frac{\ell'_2 W_{SY}}{\ell'_1 W_{SX} + \ell'_3(F_D + F'_D) + \ell'_4(F_L + F'_L)}$</td><td>4.9</td></tr>
<tr><td>$SF_O = \frac{\ell'_5 W_{SY}}{\ell'_1 W_{SZ} + \ell'_6(F_L + F'_L)}$</td><td>4.10</td></tr>
<tr><td>$SF_{MIN} = \mathrm{Min}[SF_M, SF_P, SF_O]$</td><td>4.11</td></tr>
</table>

A.9 Factor of Safety of the ACB block for the Shear and Velocity Method with Overtopping Flow:

$$\mathrm{SF_{BED}} = \frac{\ell'_2 \mathrm{W_S} \cdot \cos\theta_0}{\begin{bmatrix} \ell'_1 \mathrm{W_S} \cdot \sin\theta_0 + \ell'_3(\mathrm{F_D} + \mathrm{F'_D}) + \\ \ell'_4(\mathrm{F_L} + \mathrm{F'_L}) \end{bmatrix}} \qquad \text{(Eqn. 4.12)}$$

Table A-3: SVSA Design Equations for ACB Systems with Overtopping Flow – SI Units		
$\mathrm{W_S} = \mathrm{W} \cdot \left(\frac{\mathrm{S_C} - 1}{\mathrm{S_C}}\right)$	3.10	A_B = Block area parallel to the direction of flow, m^2 b = Block width normal to the direction of flow, m C_{BL} = Block lift coefficient F_D = Drag force, N F'_D & F'_L = additional drag and lift forces, N F_L = Lift force, N S_C = Specific gravity of concrete SF_{Bed} = Factor of safety for overtopping flow V_{des} = Design velocity, m/s (V_{des} less than or equal to V_{test} or V_{max}) W = Weight of block, N W_S = Submerged weight of block, N ΔZ = Height of block protrusion above ACB matrix, m θ_0 = Bed slope angle, degrees ℓ_X' = Moment arms corresponding to forces, m ρ = Mass density of water 1,000 kg/m^3 τ_{des} = Design shear stress, Pa
$\mathrm{F_D} = \tau_{des} \cdot \mathrm{A_B}$	4.6	
$\mathrm{F_L} = (0.5) \cdot \mathrm{C_{BL}} \rho \mathrm{A_B} \mathrm{V_{des}^2}$	4.7	
$\mathrm{F'_L} = \mathrm{F'_D} = (0.5) \cdot (\Delta Z) \mathrm{b} \rho \mathrm{V_{des}^2}$	3.8	
$\mathrm{SF_{BED}} = \frac{\ell'_2 \mathrm{W_S} \cdot \cos\theta_0}{\begin{bmatrix} \ell'_1 \mathrm{W_S} \cdot \sin\theta_0 + \ell'_3(\mathrm{F_D} + \mathrm{F'_D}) + \\ \ell'_4(\mathrm{F_L} + \mathrm{F'_L}) \end{bmatrix}}$	4.12	

A.10 Permeability of soil

$$\mathrm{K_S} = 1.958 \times 10^6 \frac{\phi^3}{(1-\phi)^2} \left(\frac{1}{49\left(\sum_{n=1}^{N} \frac{P_n}{d_n}\right)^2} \right) \qquad \text{(Eqn. 5.1)}$$

where:

K_s = Soil permeability, cm/s

ϕ = Dimensionless soil porosity determined from Equation 3.2 or

Table 3-1

P = Percentage of material in the distribution between adjacent particle sizes
d = Geometric mean of adjacent particle sizes in the distribution, mm
N = Number of intervals between adjacent particle sizes

A.11 Porosity of soil:

$$\phi = 1 - \left(\frac{C}{100} \cdot \frac{\gamma_d}{25.99\ \mathrm{kN/m^3}}\right) \quad \text{(Eqn. 5.2)}$$

where:

ϕ = Soil porosity (dimensionless)
C = Soil compaction in percent of Standard Proctor Density (90 to 100)
γ_d = Maximum dry unit weight of the soil at 100 percent of Standard Proctor Density, kN/m^3

A.12 Uniformity Coefficient, C_U:

$$C_U = \frac{d_{60}}{d_{10}} \quad \text{(Eqn. 5.3)}$$

where:

d_x = Particle size of which X percent is smaller

A.13 Geotextile Permeability Criterion:

$$K_g \geq 10K_s \quad \text{(Eqn. 5.4)}$$

where:

K_g = Permeability of the geotextile, cm/s
K_s = Permeability of the base soil or granular filter, cm/s

CONVERSION TABLE

Inch-Pound	To	Metric	
1 inch (in.)	=	25.4	millimeters (mm)
1 foot (ft)	=	0.3048	meters (m)
1 yard (yd)	=	0.9144	meters (m)
1 square foot (ft^2)	=	0.0929	square meters (m^2)
1 square yard (yd^2)	=	0.8361	square meters (m^2
1 ounce (oz)	=	28.35	grams (gm)
1 pound (lb)	=	0.4536	kilogram (kg)
1 pound (force) (lbs)	=	4.448	newtons (N)
1 pound/foott (lbs/ft)	=	0.0146	kilonewtons/meter (kN/m)
1 pound/inch (lbs/in.)	=	0.1751	kilonewtons/meter (kN/m)
1 pound/sq. inch (psi)	=	6.895	kilopascal (kPa)
1 pound/sq. foot (psf)	=	0.0479	kilopascal (kPa)
1 pound/cu. foot (pcf)	=	0.1571	kilonewtons/cubic meter (kN/m^3)

Metric	To	Inch-Pound	
1 millimeter (mm)	=	0.03937	inches (in.)
1 meter (m)	=	39.37	inches (in.)
1 meter (m)	=	3.281	feet (ft)
1 square meter (m^2)	=	10.76	sq. feet (ft^2)
1 square meter (m^2)	=	1.196	sq. yards (yd^2)
1 gram (gm)	=	0.0353	ounces (oz)
1 kilogram (kg)	=	2.205	pounds (lb)
1 newton (N) (1 kg, force)	=	0.2248	pounds force (lb)
1 kilonewton/meter (kN/m)	=	68.5	pounds/foot (lbs/ft)
1 kilonewton/meter (kN/m)	=	5.71	pounds/inch (lbs/in.)
1 kilopascal (kPa)	=	0.145	pounds/sq. inch (psi)
1 kilopascal (kPa)	=	20.87	pounds/sq. foot (psf)
1 kilonewton/cubic meter (kN/m^3)	=	6.365	pounds/cu. foot (pcf)

NOTATIONS AND ABBREVIATIONS

a = Block length, ft (m)
a_θ = Projection of W_S into subgrade beneath block
A_B = Block area parallel to direction of flow, ft^2 (m^2)
A_{50} = Ratio between the particle size diameter at 50% in the gradations for the filter d_{50f} and the base soil, d_{50s}
b = Block width, ft (m)
c = Undrained shear strength, lb/ft^2 (Pa)
C = Soil compaction in percent of Standard Proctor Density (90 to 100)
C_{BL} = Block lift coefficient
C_D = Drag coefficient ($C_D \approx 1.0$)
C_u = Coefficient of uniformity
C_{uf} = Coefficient of uniformity of the granular filter
C_{us} = Coefficient of uniformity of the base soil
d = Geometric mean of adjacent particle sizes in the distribution (mm)
d_x = Particle size of which X percent is smaller
d_{xf} = Particle size of which X percent is smaller in the granular filter
d_{xs} = Particle size of which X percent is smaller in the base soil
F_D = Drag force, lb (N)
F'_D = Drag force due to block protrusion, lb (N)
F_L = Lift force, lb (N)
F'_L = Lift force due to block protrusion, lb (N)
h = Block height, ft (m)
K_g = Permeability of the geotextile, cm/s
K_s = Permeability of the base soil or granular filter, cm/s
ℓ_x = Moment arms, ft (m)
ℓ_x' = Moment arms corresponding to forces for SVSA factor of safety method, ft (m)
ℓ_p = Block length parallel to flow direction, ft (m)
ℓ_n = Block length normal to flow direction, ft (m)
ℓ_{XT} = Moment arms of tested blocks, ft (m)
ℓ_{XU} = Moment arms of untested blocks, ft (m)
N = Number of intervals between adjacent particle sizes
P = Percentage of material in the distribution between adjacent particle sizes
P.C. = Point of Curvature (beginning of the curve)
PI = Plasticity Index
P.T. = Point of Tangent (end of the curve)
R = Hydraulic radius, ft (m)
S_C = Specific gravity of concrete (assume 2.1)
SF = Calculated factor of safety
S_f = Energy grade line or bed slope, ft/ft (m/m)
SF_{Bed} = Factor of safety for overtopping flow analysis
SF_M = Factor of safety for rotation about Point M
SF_{Min} = Minimum factor of safety for all rotation points
SF_P = Factor of safety for rotation about Point P
SF_O = Factor of safety for rotation about Point O
V = Velocity, ft/s (m/s)
V_{avg} = Average velocity on the designed section, ft/s (m/s)
V_{des} = Design velocity on the designed section, ft/s (m/s)
V_{test} = Test velocity determined during full-scale flume testing, ft/s (m/s)

W	=	Weight of block, lb (kg)
W_S	=	Submerged weight of block, lb (kg)
W_{ST}	=	Submerged weight of tested blocks, lbs (N)
W_{SU}	=	Submerged weight of untested blocks, lbs (N)
W_{SX}	=	Block submerged weight force component parallel to the side-slope plane along the x axis, lb (N)
W_{SY}	=	Block submerged weight force component normal to the side-slope plane along the y axis, lb (N)
W_{SZ}	=	Block submerged weight force component parallel to the side-slope plane along the z axis, lb (N)
β	=	Angle of block projection from downward direction, once in motion
γ	=	Unit weight of water, 62.4 lb/ft^3 (9,810 N/m^3)
γ_d	=	Dry unit weight of the soil at 100 percent of Standard Proctor Density lbs/ft^3 (kN/m^3)
ΔZ	=	Height of block protrusion above ACB matrix, ft (m)
δ	=	Angle between drag force and block motion
η_0	=	Stability number for a horizontal surface
η_1	=	Stability number for a sloped surface
θ	=	Angle between side slope projection of W_S and the vertical
θ_0	=	Channel bed slope (degrees or radians)
θ_1	=	Channel side slope (degrees or radians)
θ_2	=	Side-slope angle measured perpendicular to the bed-slope plane (degrees)
θ_T	=	Tested bed slope (degrees)
θ_U	=	Untested bed slope (degrees)
ρ	=	Density of water, 1.94 slugs/ft^3 (1,000 kg/m^3)
τ_C	=	Critical shear stress for block on a horizontal surface (lb/ft^2)
τ_{CT}	=	Critical shear stress for tested block, lb/ft^2 (Pa)
τ_{CU}	=	Critical shear stress for untested block, lb/ft^2 (Pa)
$\tau_{C\theta U}$	=	Critical shear stress for untested bed slope, lb/ft^2 (Pa)
$\tau_{C\theta T}$	=	Critical shear stress for tested bed slope, lb/ft^2
τ_{des}	=	Design shear stress at the critical section, lb/ft^2 (Pa)
τ_{max}	=	Maximum shear stress on the designed section, lb/ft^2 (Pa)
τ_0	=	Cross-section-averaged shear stress, lb/ft^2(Pa)
ϕ	=	Soil porosity (dimensionless)

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