

NEH Part 628 Dams National Engineering Handbook

Chapter 54 Articulated Concrete Block Armored Spillways



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Cover photograph is of an ACB lined spillway under construction in Virginia. Photograph on table of contents page is of a flat-top tapered ACB.

Part 628 – Dams

Chapter 54 – Articulated Concrete Block Armored Spillways

628.5400 Introduction and Scope

A. A dam is an artificial barrier that impounds water for one or more beneficial purposes (NRCS Conservation Practice Standard (CPS) Dam 402). NRCS Technical Release (TR) 210-60, “Earth Dams and Reservoirs,” provides design criteria for NRCS dams. NRCS CPS 378 provides design criteria for low hazard potential earthen dams. Title 210, National Engineering Handbook, Part 628, Chapter 54,¹ defines the criteria used to design an **articulated concrete block (ACB) system** for armoring an auxiliary spillway.

B. The NRCS designs do not allow water to pass over a dam without being contained in a designated spillway. An auxiliary spillway conveys runoff flows that are more than what the principal spillway can convey. The auxiliary spillway is designed to operate infrequently and only during exceptionally large rainfall events as defined by agency policy. The public often refers to the auxiliary spillway as an “emergency spillway.” Spillway operation during these infrequent events is for adequate capacity and stability. The spillway must function with minimal risk of a dam breach. NRCS typically constructs auxiliary spillways as open channels excavated into natural materials, or a combination of excavation and earth fill, rock fill, or both. Preference is given to placement of auxiliary spillways adjacent to and around the dam rather than over the dam. Auxiliary spillways may be unlined or lined. The lining for spillways on NRCS dams is typically grass, roller-compacted concrete, or reinforced concrete.

C. An ACB system is a matrix of interconnected concrete block units installed to provide an erosion-resistant lining with specific hydraulic characteristics. The connection between the individual units is by geometric interlock, cables, ropes, geotextiles, geogrids, or a combination thereof. Under the blocks is a filter system for subgrade retention. There are a variety of commercially manufactured blocks with unique features and design considerations. The literature often refers to these systems as “cellular concrete mats” (CCMs).

D. An ACB armored spillway has elements of strength and durability that a vegetated spillway does not have, but often with tangible cost savings compared to a traditional structural spillway. However, the matrix of blocks contains a percentage of open space potentially allowing spillway flows to reach subgrade materials. For this reason, the in-situ subgrade materials as well as the designed filter, geosynthetic, and bedding materials are critical elements of the design and may require greater monitoring and maintenance efforts to keep the structure functioning properly.

E. ACBs can provide channel protection, scour protection around bridge piers, grade stabilization, and spillway protection. The term “articulated” describes the ability of the matrix to conform to minor changes in the subgrade while maintaining geometric interlock (Hepler et al. 2012). An example of ACBs being installed for spillway lining is shown in figure 1.

¹ Referenced as 210-NEH-628-54, “Articulated Concrete Block Armored Spillways”

Figure 1: ACB-Lined Spillway (NRCS-VA)



F. This chapter provides guidance for the design of ACB for lining auxiliary spillways. The focus is on hydraulic design of ACBs for high-velocity applications. Example calculations using manufacturer-specific data are included, but no endorsement of specific products is implied. The specific data used in the example calculations merely provide realism for the analysis and reiterate the importance of using specific product-appropriate information for each product assessed. Designers may use other products of this type if appropriate testing and data analysis (similar to what this document describes later) form the basis of the design criteria.

G. The design approach described in this document for determining the stability of the ACB units is a simplification of the **Colorado State University (CSU) methodology**, which is based upon the PhD dissertation of Dr. Amanda Cox (Cox 2010) and described in Cox, Thornton, and Apt (2014). The coefficient of lift is the basis of the CSU methodology. The NRCS finds that this is the most appropriate method for design of ACB lining in spillways. Manufacturer and practitioner guidance is included. While this chapter contains many different photographs of ACBs in use for a variety of circumstances to illustrate particular design issues, it does not address the use of ACBs for wave protection or low-velocity applications. A planned update of TR 210-69, “RipRap for Slope Protection Against Wave Action,” will include specific design guidance for ACB use as wave protection.

H. **210-NEH-654, “Stream Restoration Design”** (2007), includes Technical Supplement 14L, “**Use of Articulating Concrete Block Systems for Stream Restoration and Stabilization Projects**” (210-NEH-654-TS14L). This 210-NEH-654-TS14L technical design document provides equations for calculating the stability of ACB systems, provides guidance for the selection of factors of safety, and addresses issues in the context of stream and river design. These formulas are appropriate for *low-velocity* (<10 fps) applications. 210-NEH-654-TS14L is not directly applicable if high-velocity conditions are expected in **auxiliary spillway design**.

I. While the blocks in an ACB system are the most prominent feature of an ACB-lined spillway, they are not the only essential element that requires careful design. This chapter provides guidance for the design of the subgrade, drain and filter system that is part of an ACB lining. This is a critical element of ACB spillway lining. Example calculations are included.

J. This document provides guidance for other design considerations including climate, vegetation, transitions, and ends. Construction issues specific to ACB spillway lining are included. Maintenance and inspection issues are discussed. Finally, this document includes a summary of recommended documentation that should be used to support the design of an ACB lined auxiliary spillway.

628.5401 Basic Concepts of ACB Armored Spillway Materials

A. The proper design and installation of all components of an ACB armored spillway system are critical to its successful performance. In addition to the concrete blocks and connection materials covered in this section, an ACB system may consist of materials such as geotextiles, geogrids, granular filter materials, or some combination of these. Other NRCS documents address the design of these elements in more detail. Discussion in this document is limited to the considerations relevant to ACBs. Figure 2 shows several components of an ACB system under construction.

Figure 2: Placement of an ACB Armor System Showing Subgrade, Drain, Geotextile, and Block



B. Blocks

- (1) The most prominent feature of an ACB system is the articulating concrete blocks. These blocks must meet ASTM D6684, Standard Specification for Materials and Manufacture of Articulating Concrete Block (ACB) Systems. Any block specified for use in an NRCS project must meet ASTM D7277, Standard Test Method for Performance Testing of Articulating Concrete Block (ACB) Systems for Hydraulic Stability in Open Channel Flow. Blocks used where freeze-thaw issues are a consideration must meet ASTM C666/C666M for verifying conformance with freeze-thaw durability requirements for wet-cast products or ASTM C1262 for dry-cast products. Testing is required within 24 months of ACB delivery. The materials, mix proportioning, manufacturing process, and curing method used for the tested materials must be the same as the delivered blocks.

- (2) Several proprietary ACB systems are available. The cast blocks can have a variety of shapes and thicknesses. The thickness of available blocks typically ranges from 4 inches to 9 inches. The blocks can have interlocking or noninterlocking shapes. The blocks may be cabled into mats or noncabled. Cabled blocks usually have preformed holes cast in them for placement of the cable. However, some systems have the blocks cast directly onto the cables. The holes should be smooth to prevent damage to the cable. Tapered and wedge-shaped blocks are also available and are discussed in more detail later in this document.
- (3) Blocks can be open-cell or closed cell. The open area ranges from approximately 17 to 23 percent for open-cell blocks. The soil placed during installation or deposited sediments will become vegetated in the open areas. Closed cell block systems provide less open area (approximately 10 percent) for growing vegetation.
- (4) Originally, all ACBs were untapered or uniform in thickness. The tapered or wedge-shaped block has been developed more recently to provide improved hydraulic performance over untapered block on auxiliary spillways. However, spillway lining can use either style of block. Examples of both types of block are shown in figure 3.
- (5) Tapered ACBs provide significant hydraulic performance advantages over untapered blocks. Designs utilizing tapered blocks have become more common since the release of 210-NEH-654-TS14L in 2007. Figure 4 provides a schematic of a tapered block installation. As can be seen in this figure, the downstream edge of a wedge-shaped tapered block rises above the upstream edge of the next block. With proper subgrade and installation, the taper prevents any portion of a block from protruding into the flow and thus eliminates the destabilizing impact forces of water flow. In effect, the leading edge of a tapered block is in the hydraulic shadow of the next block upstream. The taper significantly increases the stability of an ACB installation. As a result, tapered blocks provide a much higher factor of safety than untapered blocks of the same weight. The installation shown in figure 1 used tapered blocks.
- (6) The stability advantages of the taper are realized only if the flows are uniform and in one direction. This hydraulic condition is characteristic of spillway flow. The tapered ACBs are becoming the industry standard for ACB lining of spillways while untapered blocks are frequently used for fluvial and low-velocity applications. However, a designer can use the untapered blocks for high velocity spillway situations if the appropriate factors of safety calculations are satisfied. The design methodology presented in this document considers the hydraulic conditions of both tapered and untapered blocks.

Figure 3: Untapered (Dome Top²) ACB (left) and Flat-Top Tapered³ ACB (right)

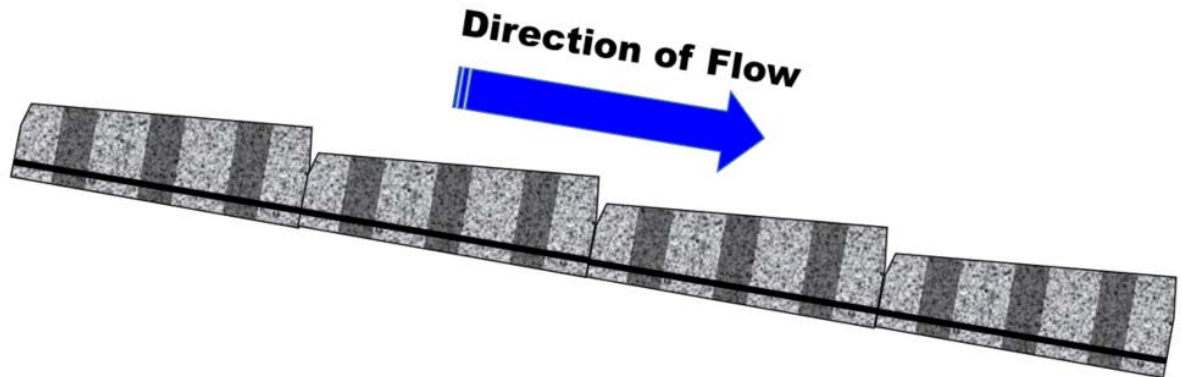


² The dome has a higher roughness than a flat block. This reduces velocity and increases shear, which makes the blocks more stable in a low velocity application. While dome blocks are not typically used in a spillway, dome blocks can be used where flow conditions are such that the factor of safety requirements (discussed later in this document) are met.

³ Note the ½-inch difference between the blocks. These blocks must be installed in a shingled type arrangement with the taper in the downstream direction (flow left to right in photo).

- (7) Untapered ACBs remain a useful structural element for dams and spillways. However, it is important to take into consideration the projection height. This document addresses this condition as well. Untapered blocks are particularly applicable in situations where flow is turbulent, or flow direction is not consistently unidirectional. This may occur where a spillway terminates into a low gradient or flat area below a dam. In this situation, the currents may be multidirectional or swirling under design flow conditions. To account for this, a designer may choose to transition from tapered to untapered block near the lower end of a spillway. Where the crest of the spillway also serves as a maintenance road, the designer may also choose to use untapered block.

Figure 4: Tapered ACB Installation Schematic⁴ (N.T.S.)

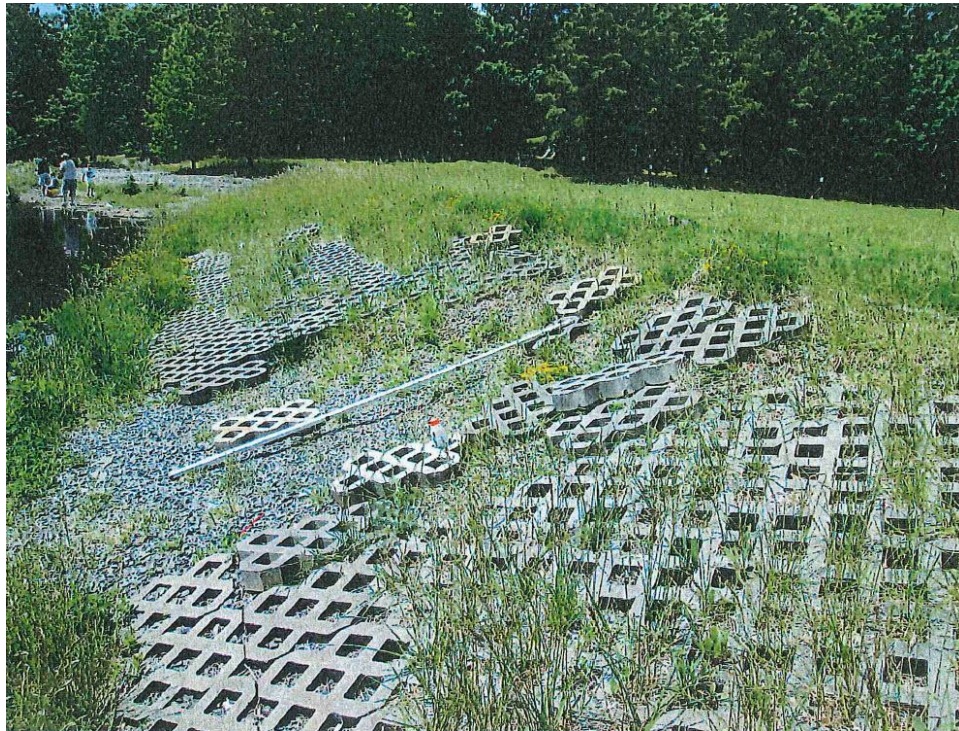


C. Connections

- (1) Cabled systems of ACBs are individual blocks connected by cables into a mat. The cable may consist of polyester cable, galvanized steel, or stainless steel. The individual blocks may be assembled into the cabled mat systems: either offsite or following hand placement. The system should be continuous with cables aligned parallel to the flow.
- (2) The use of cables restricts the differential movement and projection height between blocks and provides added protection to the system should an individual block become damaged. If significant damage occurs and the ACB installation begins to fail, cables can retard the unraveling of the installation. The cables are a design redundancy that reduces the potential of a large-scale failure of the ACB system that could lead to a spillway breach during a catastrophic event. However, since the cables do not limit small movement in the block, they are not included in the design computations for hydraulic stability.
- (3) Other significant benefits of using cables include ease of installation of preassembled block mats. Finally, in some areas, blocks may be subject to vandalism and theft. The use of cables reduces this problem by making unauthorized removal of blocks more difficult. Figure 5 shows an example of theft of ACB units from an uncabled channel project. The protection currently provided by the ACB units in this installation is obviously less than what it was designed to provide.

⁴ The block shapes are exaggerated to make an important point in this figure. This point is that the blocks work as a system with the downstream end of one block being above the upstream end of the next block and that the system is designed to have a specific direction of flow.

Figure 5: Example of Block Theft From an Uncabled ACB Installation



- (4) The most commonly used connections are either polyester cable or steel cable. If the cables will function as more than an installation tool, the selection of the cables must also consider specific environmental conditions of the site. Figure 6 provides guidance for selecting cable.

Figure 6: Table of Cable Choices for Varying Environmental Conditions

Environment	Recommended Cables	Recommended Fittings	Comments
Dry (Typical Spillway Application)	Galvanized	Aluminum	Typically galvanized or polyester are most economical cable choices.
	Stainless Steel	Copper or Tin-Plated Copper	
	Polyester	Aluminum	
Continuously Immersed (Fresh Water)	Galvanized	Aluminum	Polyester is typically given preference in this environment for economic reasons.
	Stainless Steel	Copper or Tin-Plated Copper	
	Polyester	Aluminum	
Salt or Brackish Water (Intermittent or Continual Immersion)	Polyester	Aluminum, Copper or Tin-Plated Copper	Stainless is typically a requirement of many DOTs and USACE.
	Stainless Steel	Copper or Tin-Plated Copper	

- (5) Figure 7 provides typical properties of steel cable. Steel cable is either stainless steel aircraft cable of type 302, 304, or 316 or galvanized steel aircraft cable as shown in figure 8.

Figure 7: Table of Typical Steel Cable Properties

Diameter	Construction	Breaking Strength
1/8 in	1x19 ⁵	2100 lbs
5/32 in	1x19	3300 lbs
3/16 in	1x19	4700 lbs

Figure 8: Steel Cables



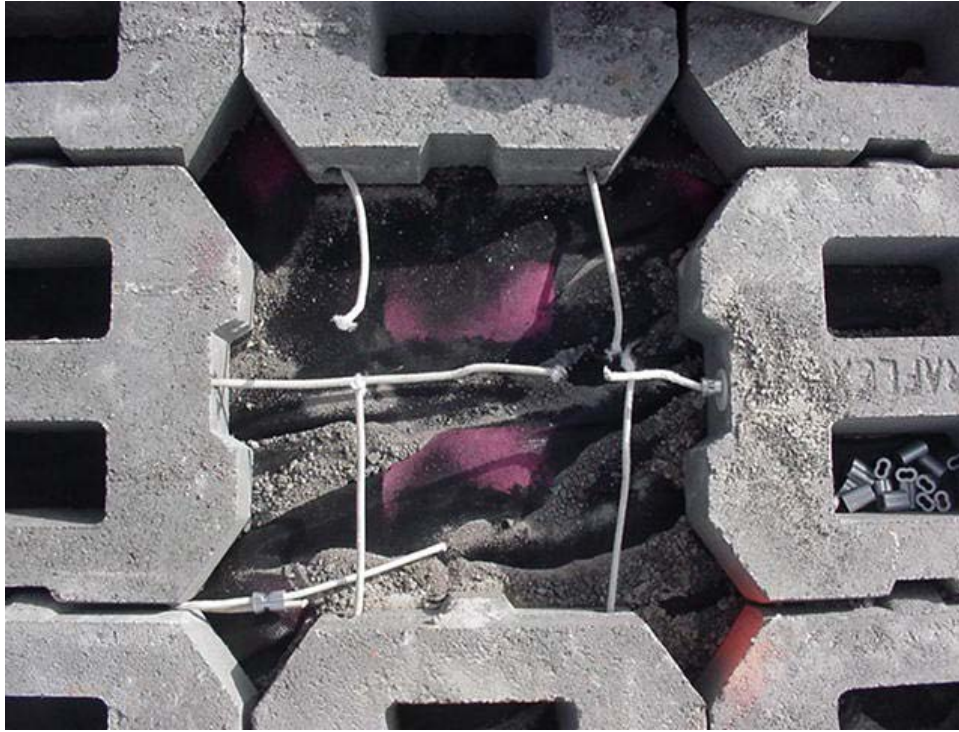
- (6) Figure 9 provides typical properties of polyester cable. Figure 10 shows an example of polyester cable which is typically characterized by high tenacity, low elongation, and continuous fibers. The cable outer jacket or cover protects the interior core of parallel fibers. The weight of the interior parallel fiber core is 65 to 70 percent of the total cable weight. The polyester cables are generally less expensive than steel cables. As described earlier in this document, block stability should be calculated without consideration of connecting cables.

Figure 9: Table of Polyester Cable Properties

Cable Diameter	Average Strength	Weight, lbs/100 ft	
		Minimum	Maximum
1/4 in	3700 lbs	2.47	2.74
5/16 in	7000 lbs	3.99	4.42
3/8 in	10000 lbs	4.75	5.26
1/2 in	15000 lbs	8.93	9.90

⁵ Configuration is one group of 19 wires. Selected for abrasion resistance and low stretch. Used in push- pull controls

Figure 10: Polyester Cables (Block Removed as Part of Project-Specific Aspect of Installation; Cables Should be Continuous in Final Installation)



- (7) In lieu of cables, some installations have adhered the blocks directly to an underlying geotextile or geogrid. This approach simplifies installation. However, as will be discussed later in this document (see section 628.5405), such an approach is generally not advisable.

628.5402 Basic Concepts of ACB Armored Spillway Design

A. Design Approach

- (1) The design and installation for stability of ACBs is critically important for public safety since an improperly designed and installed ACB system can result in sudden and catastrophic failure of a dam. Failure of a portion of a block lining can concentrate flows and create turbulence. This will significantly increase adverse stresses to the underlying material. A seemingly small disruption of the armored surface may compromise the stability of the entire spillway.
- (2) In addition, there are not readily applied equations or models that allow a designer to predict the rate or extent of the progressive damage resulting from such a disruption. Once failure has initiated it may proceed at a rapid rate and in an unpredictable pattern potentially threatening the integrity of the dam.
- (3) Failure of part of an ACB-lined spillway can be very expensive to repair. The loss or significant movement of a few blocks may necessitate the replacement of an entire section of ACBs.
- (4) For these reasons, an ACB lining must be treated as a *structural element* of a dam spillway. ACB lining is not sacrificial erosion protection. An ACB-lined auxiliary spillway must be stable under design storm conditions.

B. Hydrologic Design Criteria

- (1) The primary hydrologic loading condition relevant to the design of ACB armored auxiliary spillways for NRCS dams as defined in TR 210-60 (2005) is the **integrity hydrograph** (or freeboard hydrograph). An ACB armored auxiliary spillway must safely pass this integrity hydrograph event without overtopping the dam and without damaging the ACB armored spillway.
- (2) TR 210-60 also describes a lesser loading condition—the **stability hydrograph** (or auxiliary spillway hydrograph) that applies to an earthen spillway. The routing of this hydrograph through the dam should not cause erosional surface damage to the auxiliary spillway. Repair or significant maintenance should not be required after a stability hydrograph passes through the auxiliary spillway. The designer must check this lesser loading condition for vegetated or earthen auxiliary spillways. However, the designer does not need to check this condition for ACB armored auxiliary spillways or for structural spillways. Descriptions of the three basic types of auxiliary spillway linings and the associated hydrologic analysis requirements is as follows:
 - (i) **Vegetated or Earthen Spillways.**—Most NRCS dams have vegetated or earthen auxiliary spillways because these auxiliary spillway types are less expensive than structural spillways. Although no erosion is permissible during the lesser stability hydrograph, minor erosion is acceptable during the larger, more infrequent integrity hydrograph. Any anticipated erosion during the integrity hydrograph must not breach the level crest (control section) of the auxiliary spillway and cause the loss of flood storage in the reservoir pool. The designer must conduct an analysis sufficient to determine that any damage that the auxiliary spillway could experience during the integrity hydrograph event will not cause the dam to breach.
 - (ii) **Structural Spillways.**—A structural lining may increase erosion resistance of the auxiliary spillway where the stability hydrograph could result in damage to the spillway or where the integrity hydrograph could result in a potential breach. This structural lining, or structural spillway, can be roller-compacted concrete or structural concrete. A structural spillway must pass the integrity flood without damage to the spillway or embankment. Since the integrity hydrograph is larger than the stability hydrograph, the stability hydrograph is not a flood of concern for a structural spillway.⁶
 - (iii) **Armored Spillways.**—In lieu of a structural spillway, a surface armoring can increase the erosion resistance of an auxiliary spillway. This type of spillway lining is generally less expensive than a structural spillway lining but more expensive than a vegetative spillway lining. An armored spillway depends on the underlying soil of the spillway for support. Different armor types have been used. When ACBs are the surface armor, the auxiliary spillway is an **ACB armored spillway**. The design criteria for an armored spillway are as follows:
 - Since damage to an armored auxiliary spillway is not allowable during either the lesser stability hydrograph or the greater integrity (freeboard) hydrograph, a stability hydrograph analysis is redundant for an armored auxiliary spillway. Therefore, the designer does not need to analysis the auxiliary spillway performance with the stability hydrograph.
 - The maximum allowable activation frequency of an armored spillway is the same as an earthen or vegetated auxiliary spillway (defined in TR 210-60) because the armoring likewise depends on support from the underlying soil.
 - Like the requirement for a structural auxiliary spillway, an ACB armored auxiliary spillway must pass the TR 210-60 integrity (freeboard) hydrograph without damage to the structural components of the spillway. It is allowable for some erosion

⁶ Since a structural spillway is not susceptible to surface erosion or surface instability, the stability hydrograph is of no concern for sizing and design of the auxiliary spillway.

(damage) to occur downstream of the armored portion of the spillway, however, the armored portion of the spillway should not be damaged. This design requirement also applies to a structural concrete or roller compacted concrete structural spillway.

- The downstream terminus of an armored spillway (armored with ACBs or other approaches) is vulnerable to downstream channel head cut erosion. The designer should protect the downstream edge of the armor from channel erosion undermining and damaging the structure. It is also important to protect the side edges and upstream edges from undermining and damage during the design hydrograph.
- (3) Figure 11 provides a summary of stability and integrity hydrographs. Structural and vegetative spillways are also included for comparison of the design requirements of ACB armored spillways. Further details and specifics are available in TR 210-60.

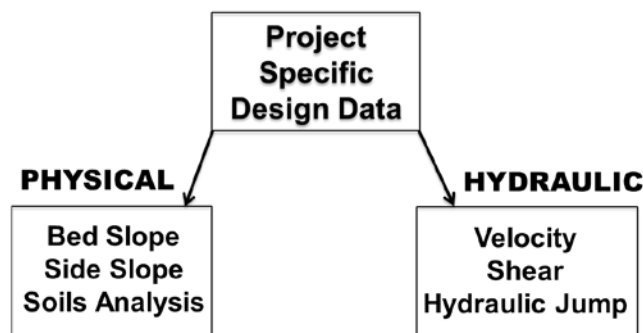
Figure 11: Comparison of Stability Hydrograph and Integrity Hydrograph

	Stability Hydrograph (auxiliary spillway hydrograph)	Integrity Hydrograph (integrity freeboard hydrograph)
Magnitude of Peak Flow	Smaller than integrity hydrograph	Larger than stability hydrograph
Top of dam	No overtopping during passage of stability hydrograph plus wave action	No overtopping during passage of integrity hydrograph
Earthen or Vegetated Auxiliary Spillway	No surface damage during passage of stability hydrograph	Minor surface damage is allowed during passage of integrity hydrograph, but this damage must not breach the level crest of the auxiliary spillway.
Structural Auxiliary Spillway	NA	No surface damage during passage of integrity hydrograph
Armored Auxiliary Spillway (including ACB armored spillway)	NA	No surface damage during passage of integrity hydrograph

C. Project-Specific ACB Design Parameters

- (1) The design parameters for an ACB system must be determined for every project. Figure 12 graphically presents these parameters.

Figure 12: Project Design Parameters Used in ACB Design Process

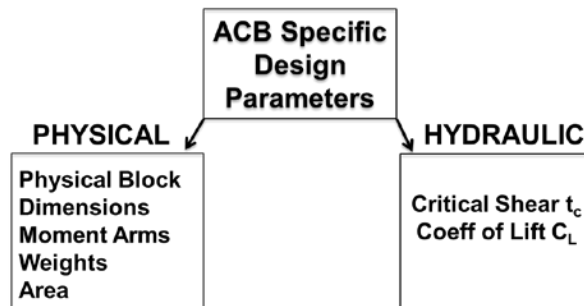


- (2) The physical project site parameters are determined from design or site-specific surveys. The hydraulic parameters can be determined using such tools as HEC-RAS, SITES, or WinDAM.

D. ACB Specific Design Parameters

- (1) Every type of ACB from various manufacturers possesses unique physical and hydraulic design parameters. These parameters are associated with each ACB style, type, and category. The parameters can be broken into physical and hydraulic parameters (fig. 13).

Figure 13: ACB-Specific Design Parameters Used in ACB Design Process



- (2) The manufacturer will provide the physical parameters of a specific ACB system, such as the specific weight, thickness, dimensions, etc., for each block. The block weight can vary with the aggregate used in the concrete and mix proportioning. If the blocks installed on a project are significantly lighter than the designed block, the designer must determine the factor of safety using the actual weight of the block that is used on the site.
- (3) The ACB hydraulic parameters are more complex and can only be determined through physical testing in a hydraulic flume. Hydraulic conditions calculated at specific ACB system thresholds are the basis of both the critical shear stress and the coefficient of lift values. These are *threshold of performance* parameters. Full-scale flume testing is required to calculate these values. The parameters are determined for each block type based upon full-scale flume testing. Figure 14 provides photographs of these types of flume tests. ASTM 7277 describes the necessary testing procedures and ASTM 7276 describes the data analysis methodology necessary to set the hydraulic design parameters for a given ACB system. The next section discusses this procedure in more detail.
- (4) It is important to consider how the ACB units are tested. For example, figure 14 shows a test where the flow is uniform. Therefore, the threshold parameters calculated for the ACBs shown in figure 14 would apply to situations where the flow is fairly straight and uniform.

Figure 14: Flume Test for ACB at CSU Showing Placed ACBs (left) and Testing (right)



- (5) Generally, turbulent conditions are not tested. Therefore, the designer should avoid using ACB units where the flow is severely turbulent and significantly nonuniform. Designers should also avoid conditions that include structures or obstacles can impede flow, create local turbulence, or create flow anomalies. If an ACB lining is to be used where there is an expected hydraulic jump (for example in a stilling basin), specific evaluation, which may include further testing, is necessary.
- (6) The surface area and shape of the block is specific to each ACB type. Different type blocks generally require their own specific flume tests. The block parameters used in the calculations must be for the same type of block specified for the project. However, the designer can account for variations in block weight and thickness in the equations used to assess stability. While hydraulic parameters are sensitive to weight, the design equations can assess block performance if the weight or thickness of the utilized block varies from the one analyzed in the lab testing.
- (7) It should be noted that other structural lining products can be used to provide an armored spillway. Some of these have a similar appearance to ACBs as described herein. The fact that other products are not specifically included in this document does not preclude the appropriateness of other techniques. Also, other techniques will likely become available in the future. However, any product used to provide for a structural spillway armoring should undergo similar state-of-practice (ASTM) testing and evaluation as described in this document.

628.5403 Hydraulic Design of Armored Spillways Using ACBs

A. ASTM 7276 Standard

- (1) ASTM D 7276 ACB Test Data Analysis Standard utilizes the Step Forewater Methodology. By using this approach, different practitioners can analyze the same data set and produce similar results. A summary of the highlights is as follows:
 - (i) A measured water surface profile is statistically fit to the optimum Manning's n value.
 - (ii) Plot the energy grade line (EGL) as an actual curved line rather than the assumed linear function used by the Federal Highway Administration (FHWA) analysis methodology (described in 210-NEH-654-TS14L).
 - (iii) Velocity and shear values are calculated at any position in the flume using the profiles determined in the previous step.
- (2) This methodology of analyzing the data is the only one accepted for determining hydraulic design parameters for ACB systems.

B. Setting the Project Factor of Safety

- (1) The factor of safety (FOS) is the ratio of the force that a system can withstand to the expected applied force. The FOS is a calculated value that is specific to the project conditions. The FOS equation is below:

$$Factor\ of\ Safety_{Calculated} (FOS_c) = \frac{Stabilizing\ Forces}{Destabilizing\ Forces}$$

- (2) The designer must select a target factor of safety for the project. This value is the **project factor of safety (FOS_p)**. A project factor of safety must be greater than one in engineering projects to account for unexpected loads, misuse, emergencies, as well as uncertainty. As illustrated in the equation below, the FOS_c must be equal or larger than FOS_p in an adequately designed project.

$$FOS_c \geq FOS_p$$

- (3) Factors of safety are important for analysis of any system. For the stream systems addressed by 210-NEH-654-TS14L, the recommended project factor of safety is between 1.5 and 2.0. FHWA HEC 23 (1997) recommends a minimum of FOS_P that is equal to 1.5 for situations where there are not significant uncertainties either in the project hydraulic conditions or in the installation. Where there is uncertainty in the analysis, the designer should select a higher factor of safety for the project. In addition, in situations where there is a loss of life expected because of a breach, an increased factor of safety target for the project is prudent.
- (4) A minimum factor of safety of NRCS dams, regardless of hazard class is 2.0. The value of 2.0 is used as FOS_P regardless of hazard class because low-hazard-potential dams require smaller design storms than high-hazard-potential dams. This 2.0 is a minimum value, and its use assumes that the designer has a high degree of confidence in the hydrologic and hydraulic models as well as the ACB analysis. It is expected that most dams⁷ designed, rehabilitated, or repaired under NRCS programs will have required sufficient analysis to provide designers with such confidence.
- (5) Situations with more uncertainty require higher factors of safety. In some situations, a designer or planner may want to account for specific sources of additional uncertainty and risk. Guidance in a variety of sources (Scholl et al. 2010; FHWA Design Guide 8 HEC 23 v2, 2009; HCFCD 2002; TEK 11-12 2002) indicate that for high risk, overtopping spillways, the recommended factor of safety should be much higher than 1. These documents provide the following equation and methodology for estimating a project factor of safety (FOS_P) where there is not sufficient confidence in the analysis to justify the use of 2.0 as a FOS_P .

$$FOS_P = SF_P \times X_C \times X_M$$

Where—

- FOS_P is the project factor of safety.
- SF_B is the base safety factor depending on project type⁸ (see fig. 15).
- X_u is the multiplier based on consequence of failure⁹ (see fig. 16).
- X_m is the multiplier based on model uncertainty¹⁰ (see fig. 17).

Figure 15: Base Safety Factor Based on Project Type

Application	SF_B
Channel bed or bank	1.2 to 1.4
Bridge pier or abutment	1.5 to 1.7
Spillway	1.8 to 2.0

Figure 16: Consequence of Failure Multiplier

Consequence of failure	X_C
Low	1.0 to 1.2
Medium	1.3 to 1.5
High	1.6 to 1.8
Extreme or Loss of Life	1.9 to 2.0

⁷ In some river bank or grade protection projects, a designer can justify a lower FOS_P .

⁸ Accounts for complexity of flow.

⁹ Consequence of failure relative to the cost of the ACB system.

¹⁰ Higher values used where there is uncertainty in the hydrologic and hydraulic modeling approach such as when a simple model is applied to a complex system.

Figure 17: Multiplier Based on Model Uncertainty

Hydraulic Model	X_M
Deterministic (e.g. HECRAS)	1.0 to 1.3
Empirical or Stochastic (e.g. Rational method, normal depth calculations)	1.4 to 1.7
Estimates	1.8 to 2.0

- (7) This approach may result in a very high FOS_P . A design may not be economically feasible. In such a situation, the designer should seek to reduce the uncertainty by revisiting the hydraulic and hydrologic analysis. Further analysis may justify the use of the smaller FOS_P of 2.0 as previously discussed.
- (8) Example Calculation – Selecting a Project Factor of Safety for a Dam With Known Parameters
- Given: Design for dam spillway with ACB protection. The dam is classified as high hazard potential but is well maintained and the sparsely populated areas that may be subject to inundation are located a mile below the dam. The designer has high confidence in the deterministic hydrologic and hydraulic models used to estimate the parameters used in the analysis.
 - Find: Appropriate project factor of safety.
 - Solution: Utilizing the discussion presented in the section above, a FOS_P of 2.0 is appropriate.
 - The designer would need to be able to document why he or she has sufficient confidence in the design parameters to justify the use 2.0 as a FOS_P . The next example illustrates how uncertainty in the parameters may result in a higher project factor of safety being necessary.
- (9) Example Calculation – Selecting a Project Factor of Safety for a Dam With Uncertainty in Parameters
- Given: Design for high-hazard-potential dam spillway with ACB protection. Several residences are immediately below the dam and may be flooded several feet deep during a breach. The hydrology calculations use the rational method. The design hydraulic calculations use a normal depth assumption.
 - Find: Appropriate project factor of safety.
 - Solution
 - Since the project is a dam, the SF_B selected is 1.9 (see fig. 15).
 - Since there is a potential for a loss of life, the selected X_c is 2.0 (see fig. 16).
 - Based upon methods used, the X_m selected is 1.5 (see fig. 17).

$$FOS_P = SF_B \times X_c \times X_m = 1.9 \times 2.0 \times 1.5 = \underline{5.7}$$

- (iv) This example illustrates the point that uncertainty in analysis as well as high consequences of failure will require a higher factor of safety. However, as described later in this document, a small increase in block size can result in a significant increase in factor of safety.

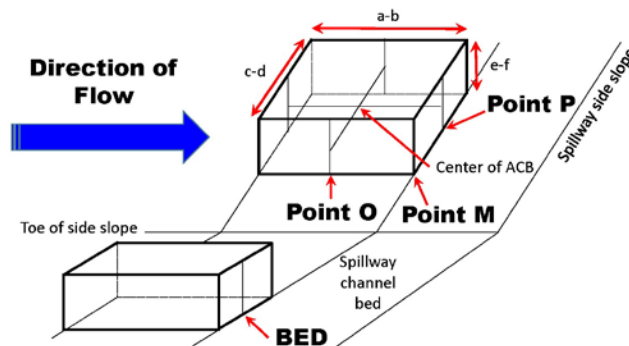
C. Calculating the ACB Factor of Safety

- The calculated factor of safety (FOS_C) is a representation of the stabilizing forces acting on the ACB system divided by the destabilizing forces acting on the system. It requires ACB specific and project specific inputs.
- The approach presented in 210-NEH-654-TS14L is appropriate for low velocity (<10 fps) systems such as found in streams and rivers. However, this 210-NEH-654-TS14L approach does not accurately capture the higher velocity forces present in spillways nor does it

consider the beneficial stabilization functions of the tapered block. The CSU methodology does consider these conditions. Therefore, designers should use the CSU methodology for most ACB-lined auxiliary spillways on NRCS dams.

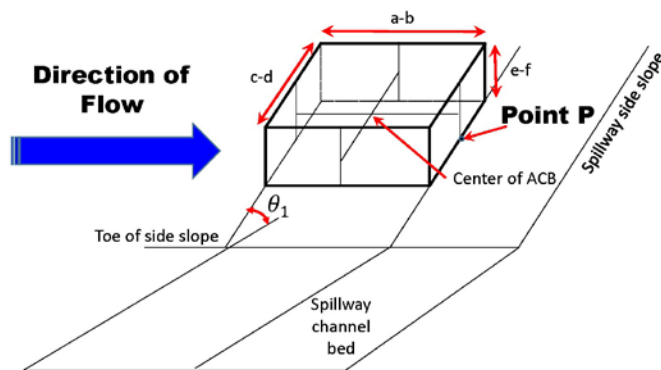
- (3) The CSU design approach is based upon the PhD dissertation of Dr. Amanda Cox (Cox 2010) and described in Cox, Thornton, and Apt (2014). This CSU approach calculates a factor of safety by using a moment stability analysis coupled with the computation of hydrodynamic forces including both boundary shear stress and flow velocity. The CSU analysis approach examines the safety factor (SF) for three possible rotations of the ACB on the channel slope and one rotation for the channel bed under uniform flow conditions. The lowest SF is the controlling value for the system. Therefore, the designer should select the lowest SF for the FOS_C for the project. The block configuration for this full analysis is illustrated in figure 18.

Figure 18: View of Block With Four Identified Pivot Points



- (4) Examination of the CSU analysis shows that, for the spillway conditions and block sizes that are the subject of this guidance,¹¹ the rotation point about the block edge in the downstream direction on the bank of the spillway will always result in the lowest SF. This allows the CSU approach to be simplified to a single SF equation. Figure 19 illustrates the block analysis configuration. A summary of the **Simplified CSU Methodology** is below:
- Determine orientation of the block and shape of the proposed spillway.
 - Determine the block specific parameters based on laboratory testing.
 - Calculate the hydraulic forces on spillway channel for design conditions
 - Calculate lift and drag forces on the block.
 - Calculate safety factor for the rotation of an individual ACB around the pivot point identified as P. This is the FOS_C for the project.

Figure 19: View of Block With Identified Pivot Point P



¹¹ This assessment assumes a spillway side slopes of 1.5H:1V or flatter. Steeper side slopes may require a more-detailed analysis as presented in the full CSU approach.

(5) **Calculation of Lift and Drag Forces.**—Lift and drag forces are calculated following the same basic approach.

(i) The drag force is the product of the average boundary shear force of the flow and the surface area of the block face that is parallel to the flow. The calculation is shown below:

$$F_D = \tau_o A_B$$

Where—

- F_D is drag force (lbs).
- τ_o is boundary shear stress (lbs/ft²).
 $\tau_o = \gamma Y S_f$ (or calculated with the momentum equation).
 γ is unit weight of water (62.4 lb/ft³).
 Y is depth of flow measured perpendicular to channel (ft).
 S_f is friction slope (ft/ft).
- A_B is block area parallel to direction of flow (ft²).

(ii) Calculate lift force by the following equation:

$$F_L = \frac{1}{2} C_L \rho A_B V^2$$

Where—

- F_L is the lift force (lb).
- C_L is lift coefficient.
- ρ is mass density of water (slugs/ft³).
- A_B is block surface area parallel to direction of flow (ft²).
- V is flow velocity (ft/s).

(iii) The value for C_L (lift coefficient) must be determined from full scale flume testing and the resulting analysis according to ASTM D 7276 and ASTM D 7277 standards. It is specific to the surface area, physical dimensions, and shape of the block. This important value is typically provided by the ACB manufacturer.

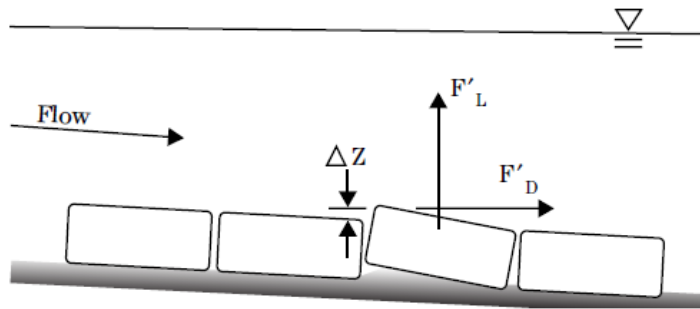
(iv) Calculate the additional lift and drag forces caused by a protruding block (fig. 20) using the equation below. It is important to note that these forces would be zero for tapered block applications since the projected height of a tapered block is zero.

$$F_D' = F_L' = 0.5 \Delta Z b \rho V^2$$

Where—

- F_D' additional drag force caused by block protrusion (lbs).
- F_L' additional lift force caused by block protrusion (lbs).
- ΔZ height of block protrusion (ft).
- b is block width normal to flow direction (ft).
- ρ is mass density of water (1.94 slugs/ft³).
- V is flow velocity (ft/s).

Figure 20: Forces on an ACB That is Protruding Into the Flow (210-NEH-654-TS14L)



- (v) The force that fast flowing water can exert upon a protruding block can be considerable. As demonstrated in the above equation, the force is a function of the square of the velocity. As a result, untapered blocks may need to be very large to provide for the design factor of safety. The minimum protrusion for untapered block should be set at $\frac{1}{2}$ inch.
- (vi) Since the flows in a spillway are in one direction, tapered blocks (fig. 3, fig. 4) are nearly industry standard for structural spillways. Due to the orientation of a tapered block with the flow, the tapered arrangement has an inverse protrusion with the upstream block; therefore, set the ΔZ at zero in the above calculations.
- (6) **Safety Factor Equation for Rotation About Block Edge Point (Pivot Point) P.**— The critical SF is calculated around point P (fig. 21). The equation for this SF is provided below. Note that this formula conservatively ignores interblock restraints, such as cables.

$$SF_P = \frac{l_3 W_{SY}}{l_2 W_{SX} + l_1 (F_D + F'_D) + l_3 (F_L + F'_L)}$$

Where—

- W_{SX} = submerged unit weight of block parallel to the side slope plane in the X direction ($W_{SX} = W_S \sin \theta_0$).
- W_{SY} = submerged unit weight of block normal to the side slope plane in the Y direction ($W_{SY} = W_S \cos \theta_0 \cos \theta_2$).

W_S = block submerged weight (lbs)

$$W_S = W_b((S_C - 1)/S_C)$$

W_b = weight of block (in air)

S_C = specific gravity of the concrete block

θ_0 = bed-slope angle (radians)

θ_1 = the vertical side-slope angle (radians)

θ_2 = angle between the bed-slope and the side slope from a cross section normal to the bed-slope plane (radians)

$$\theta_2 = \arctan(\tan \theta_1 \cos \theta_0)$$

- l_i = corresponding moment arms¹² (specific to ACB type).

¹² The direction of the flow across the surface of the block and the block shape defines the moment arms. The moment arms are defined by the manufacturer and are specific to the block dimension and shape. In most cases—

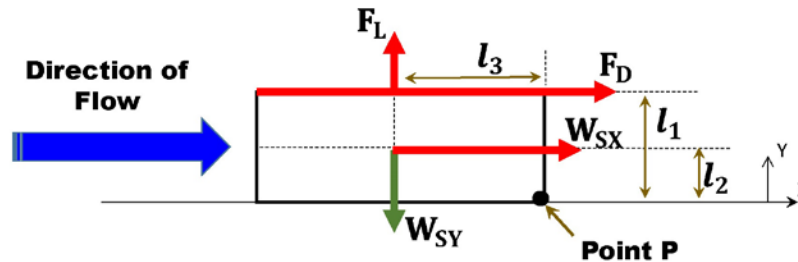
- l_1 is approximately equal to e-f.
- l_2 is approximately equal to $\frac{1}{2} l_1$.
- l_3 is approximately equal to $\frac{1}{2}$ a-b.

l_1 = block height and moment arm for the drag force component along the path of motion.

l_2 = moment arm for submerged weight force component parallel to the side-slope plane.

l_3 = moment arm for the lift force submerged weight force component normal to the side-slope plane.

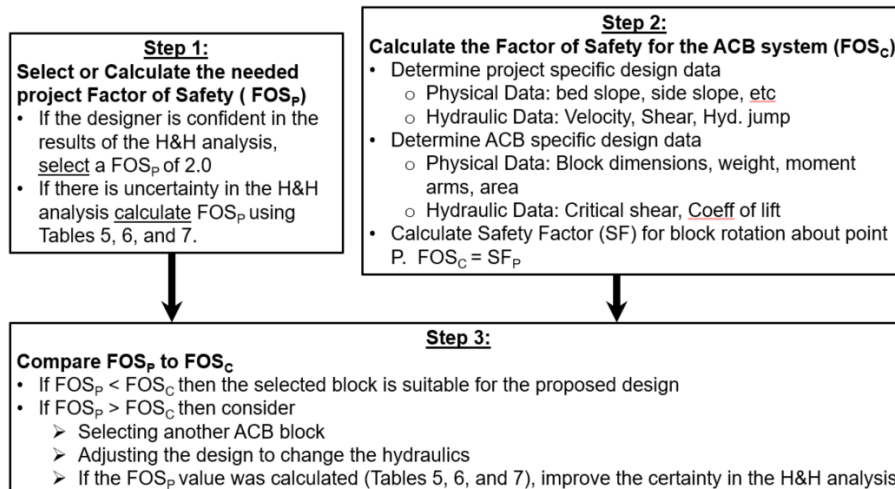
Figure 21: Free Body Diagram for Rotation of Block About Point P



D. Hydraulic Design Assessment of a Selected ACB System

- (1) Hydraulic assessment of a selected ACB system involves comparing the required or project factor of safety (FOS_P) with the calculated factor of safety (FOS_C). The basic process is similar to any engineering assessment.
 - (i) Step 1: Select or calculate required project FOS_P for site conditions.
 - (ii) Step 2: Using the simplified CSU methodology, calculate the FOS_C for the selected project block system. Use ACB and project specific inputs.
 - (iii) Step 3: Compare FOS_P required with FOS_C for selected system.
- (2) Figure 22 illustrates this approach. The following example calculations¹³ follow the described approach.

Figure 22: Graphical Representation of Design Process



However, this is not always the case since block surfaces can be shaped such that the moment arms are different from the dimensions. The designer must ensure that the values used in the determination of the lift coefficient (C_L) are used in the calculations.

¹³ The use of manufacturer specific data and example details is not meant as an endorsement of any product. Several acceptable products are available. The specific data is used to provide realism to the examples and to reiterate the importance of using model specific data from the particular block type.

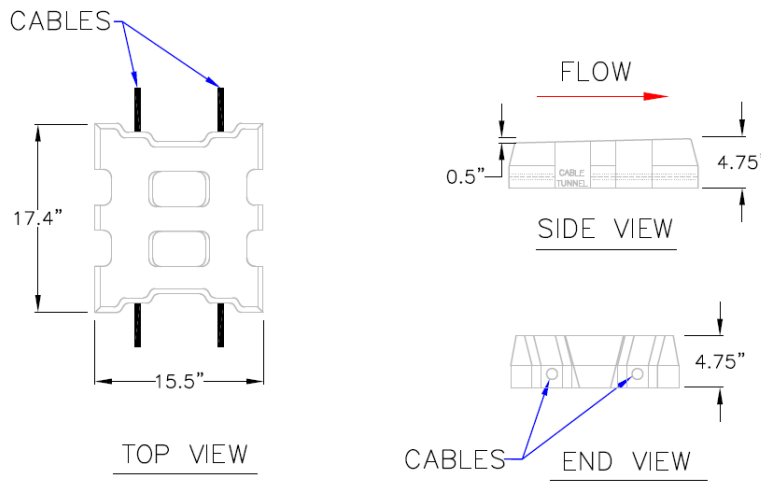
(3) Example Calculation – Design calculation for uncertain parameters:

(i) Given: Auxiliary spillway channel with the following hydraulic and project specific conditions:

- Several vacation homes are below the dam and may be inundated.
- The hydrology calculations use the rational method.
- The design hydraulic calculations use a normal depth assumption.
- Bed Slope (S_b) = 0.01 ft/ft
- Side Slope (S_{SD}) = 3H:1V
- Hydraulic jump in structural section below channel.
- Velocity (V) = 11 fps
- Boundary Shear Stress (τ_0) = 6 lb/ft²

(ii) Find: Assess design of ACB armoring with a 4¾ inch tapered block (fig. 23) using the simplified CSU methodology.

Figure 23: Hypothetical 4¾-inch ACB



- Block-Specific Data¹⁴ for the Selected 4¾-inch Tapered ACB
Nominal Dimensions: L = 17.4 in, W = 15.5 in, H = 4.75 in
Gross Area (A_B) = 1.77 sq ft
Min. Weight = 58 lbs
Open Area = 20%
Coefficient of Lift (C_L) = 0.0077 (determined from full scale flume testing)
 l_1 = 0.396 ft
 l_2 = 0.198 ft
 l_3 = 0.725 ft
 W_b = 65
 S_C = 2.2
 A_B = 1.343 ft²
 ΔZ = 0 (tapered block)

(iii) Calculations

- Step 1: Calculate required FOS_p for site conditions

¹⁴ The provided block information in this example is unique to the block chosen. For an actual design, such data will be developed for the specific block using an appropriate method or modeling exercise.

- Since the design parameters are based upon approximate methods, a higher FOS is needed than the minimum 2.0.

$$SF_B = 1.9$$

$$X_c = 1.7 \text{ (no loss of life is assumed for temporary vacation homes)}$$

$$X_m = 1.5$$

$$FOS_P = SF_B \times X_c \times X_m = 1.9 \times 1.7 \times 1.5 = \underline{4.8}$$

- At this point, the designer could decide if he or she wanted to reevaluate the H&H analysis or proceed with this target FOS_P

- Step 2: Calculate FOS of selected block system

- Bed-Slope Angle

$$\theta_0 = \text{ATAN}(S_b) = \text{ATAN}(0.01) = 0.0100$$

- Side-Slope Angle

$$\theta_1 = \text{ATAN}(1/S_s) = \text{ATAN}(1/3) = 0.322$$

- Side-Slope Angle Normal to the Bed Slope

$$\theta_2 = \text{ATAN}(\text{TAN}\theta_1 \times \text{COS}\theta_0) = 0.322$$

- Submerged Weight of Block

$$W_s = W_b((S_c - 1)/S_c) = 65((2.2 - 1)/2.2) = 35.4545 \text{ lbs}$$

- Submerged Unit Weight of Block Parallel to the Side Slope Plane in the X Direction

$$W_{sx} = W_s \sin \theta_0 = 35.4545 \sin(0.01) = 0.3545$$

- Submerged Unit Weight of Block normal to the side slope Plane in the Y Direction

$$W_{sy} = W_s \cos \theta_0 \cos \theta_2 = 35.4545 \cos(0.01) \cos(0.322) = 33.63$$

- Drag Force

$$F_D = \tau_0 \times A_B = 6 \times 1.343 = 8.058 \text{ lbs}$$

Additional drag force due to block protruding above adjacent block

$$F'_D = 0.5 \times \Delta Z \times b \times p_{\text{water}} \times V^2 = 0 \text{ (because this is a tapered block and thus no protrusion, } \Delta Z = 0)$$

- Lift Force

$$F_L = 0.5 \times C_L \times p \times A_B \times V^2 = 0.5 \times 0.0077 \times 1.94 \times 1.343 \times 11^2 = 1.213 \text{ lbs}$$

Additional lift force due to block protruding above adjacent blocks

$$F'_L = 0.5 \times \Delta Z \times b \times p \times V^2 = 0 \text{ (because this is a tapered block and thus no protrusion, } \Delta Z = 0)$$

- Factor of Safety for Rotation About Point P

$$\begin{aligned} SF_P &= \frac{l_3 W_{sy}}{l_2 W_{sx} + l_1 (F_D + F'_D) + l_3 (F_L + F'_L)} \\ &= \frac{0.725 \times 33.63}{0.198 \times 0.3545 + 0.396(8.058 + 0) + 0.725(1.213 + 0)} \\ &= 5.89 \end{aligned}$$

$$FOS_C = SF_P = \underline{5.89}$$

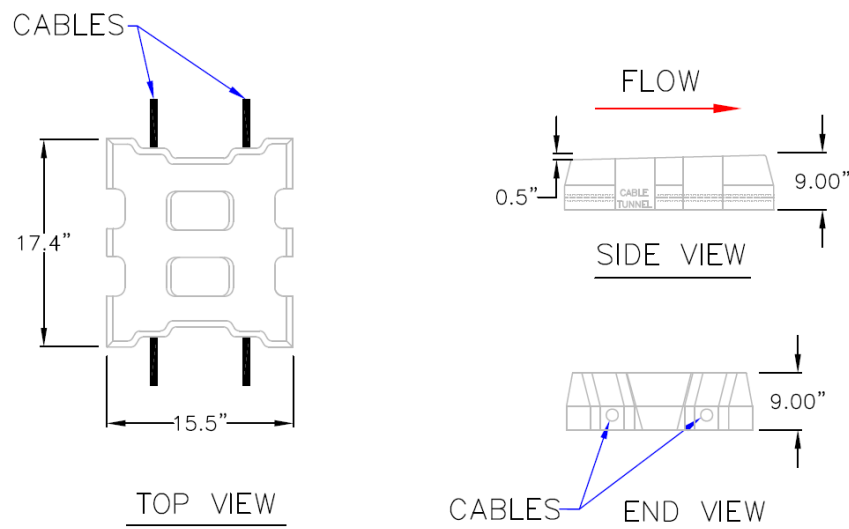
- Step 3: Compare FOS required with FOS for selected block system

Since the FOS_C of 5.89 above the FOS_P of 4.8, the design is appropriate. However, with more certainty in the calculations, it may be appropriate to select a lower FOS and therefore a smaller block.

(4) Example Calculation – Design calculation for known parameters:

- (i) Given: Auxiliary spillway channel with the following hydraulic and project-specific conditions:
- High-hazard-potential dam
 - Homes immediately below dam subject to inundation
 - Hydrology and hydraulics calculations based on deterministic models
 - Bed Slope (S_b) = 0.2 ft/ft
 - Side Slope (S_s) = 3H:1V
 - Hydraulic jump in structural section below channel
 - Velocity (V) = 25 fps
 - Boundary Shear Stress (τ_0) = 10 lb/ft²
- (ii) Find: Assess design of ACB armoring with a 9-inch tapered block (fig. 24) using the simplified CSU methodology.

Figure 24: Hypothetical 9-inch ACB



Block-Specific Data¹⁵ for the Selected 4¾-inch Tapered ACB

- Nominal Dimensions: L = 17.4 in, W = 15.5 in, H = 9 in
 - Gross Area = 1.77 sq ft
 - Min. Weight = 110 lb
 - Open Area = 20%
 - $C_L = 0.01244$ (determined from full scale flume testing)
 - $l_1 = 0.750$ ft
 - $l_2 = 0.375$ ft
 - $l_3 = 0.725$ ft
 - $W_b = 132$ lb
 - $S_c = 2.2$
 - $A_B = 1.343$ ft²
 - $\Delta Z = 0$
- (iii) Calculations
- Step 1: Select required FOS for site conditions

¹⁵ The provided block information in this example is unique to the block chosen. For an actual design, such data will be developed for the specific block using an appropriate method or modeling exercise.

Since the designer has good hydrologic and hydraulic analysis and can document the justification for having a high degree of confidence in the design parameters, he or she can choose: $FOS_p = 2.0$

- Step 2: Calculate FOS of selected block system
 - Bed-Slope Angle
 $\theta_0 = \text{ATAN}(S_b) = \text{ATAN}(0.2) = 0.197$
 - Side-Slope Angle
 $\theta_1 = \text{ATAN}(1/S_s) = \text{ATAN}(1/3) = 0.322$
 - Side-Slope Angle Normal to the Bed Slope
 $\theta_2 = \text{ATAN}(\text{TAN}\theta_1 \times \text{COS}\theta_0) = 0.316$
 - Submerged Weight of Block
 $W_s = W_b((S_c - 1)/S_c) = 132((2.2 - 1)/2.2) = 72 \text{ lbs}$
 - Submerged Unit Weight of Block Parallel to the Side Slope Plane in the X Direction
 $W_{sx} = W_s \sin \theta_0 = 72 \sin(0.197) = 14.09$
 - Submerged Unit Weight of Block Normal to the Side Slope Plane in the Y Direction
 $W_{sy} = W_s \cos \theta_0 \cos \theta_2 = 72 \cos(0.197) \cos(0.316) = 67.11$
 - Drag Force
 $F_D = \tau_0 \times A_B = 10 \times 1.343 = 13.43 \text{ lbs}$
- Additional drag force due to block protruding above adjacent block
 $F_D' = 0.5 \times \Delta Z \times b \times p_{\text{water}} \times V^2 = 0$ (because this is a tapered block and thus no protrusion, $\Delta Z = 0$)
- Lift Force
 $F_L = 0.5 \times C_L \times p_{\text{water}} \times A_B \times V^2 = 0.5 \times 0.01244 \times 1.94 \times 1.343 \times 25^2 = 10.128 \text{ lbs}$
- Additional lift force due to block protruding above adjacent blocks
 $F_L' = 0.5 \times \Delta Z \times b \times p \times V^2 = 0$ (because this is a tapered block and thus no protrusion, $\Delta Z = 0$)
- Factor of Safety for Rotation About Point P

$$SF_P = \frac{l_3 W_{sy}}{l_2 W_{sx} + l_1 (F_D + F_D') + l_3 (F_L + F_L')} = \frac{0.725 \times 67.11}{0.375 \times 14.09 + 0.75(13.43 + 0) + 0.725(10.128 + 0)} = 2.14$$

$$FOS_C = SF_P = 2.14$$

- Step 3: Compare FOS required with FOS for selected system
 - The smallest safety factor is 2.14 (SF_P). Therefore $FOS_C = 2.14$
 - Since this is above the FOS_p of 2.0, the design is appropriate.

E. Hydraulic Jumps and Stilling Basins

- (1) Where flows rapidly transition from high velocity to a lower velocity, a hydraulic jump can occur. When a hydraulic jump occurs, kinetic energy converts to potential energy. Energy is lost to turbulent transition and expended on the channel boundary through a rapid increase of flow height (the hydraulic jump). Designers may initiate a hydraulic jump at the lower end of an auxiliary spillway to slow the water and confine the turbulence to a stilling basin.
- (2) As described earlier in this report, the hydraulic conditions for the ACB application must be consistent with the hydraulic testing used to determine the block parameters. Since ACB

systems are typically flume tested under uniform flow conditions, ACBs are not readily applied in rapidly varying flow conditions such as occur with hydraulic jumps in stilling basins. Many designers chose to transition an ACB armor to a structural measure that can accommodate the hydraulic forces (e.g. a structural concrete stilling basin) before the expected hydraulic jump is initiated. Such a structure has accepted criteria that provides the designer with confidence in its ability to withstand the hydraulic forces of the turbulence.

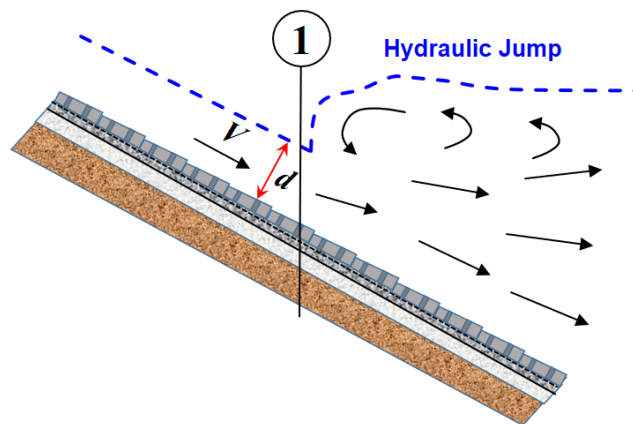
- (3) However, recent research has shown that ACBs can be stable and are applicable in some stilling basin applications where hydraulic jumps occur (Thornton and Nadeau 2018). Analysis has been conducted where the performance is indexed to the specific energy (E_s) of the flow before the jump. This equation is provided below and illustrated in figure 25.

$$E_s = \frac{V^2}{2g} + d$$

Where—

- E_s = specific energy.
- V = velocity (ft/s).
- G = gravitational constant (32.2 ft/sec²).
- d = depth (ft).

Figure 25: Schematic of Hydraulic Jump Over ACB System (the specific energy (E_s) is calculated before initiation of the jump at section 1) (N.T.S.)



- (4) This E_s is defined as the threshold of hydraulic jump stability for a given system. The project parameters pertaining to design conditions of velocity and depth of flow at the design velocity need to be determined and the specific energy of the design conditions calculated. This specific energy for the project design conditions is compared to the ACB system threshold stability E_s value determined by flume testing. If the project specific energy is below the threshold specific energy for the ACB system, then there would be adequate hydraulic jump stability. If the project specific energy is above the ACB systems threshold specific energy, this would indicate there is not adequate hydraulic jump stability and either a structural stilling basin would be required, or the hydraulics of the proposed structure would need to be changed so that the system could withstand the potential hydraulic jump predicted.
- (5) The ACB system threshold stability E_s value is based upon a specific block and an associated subgrade. The system threshold stability E_s value must be determined by full scale flume testing. The deployment of the block on a spillway must be at a channel and side slope no steeper than the flume test.

- (6) Full scale flume testing and evaluation has shown that a specific 4.75-inch tapered block can be stable to a system threshold stability E_s value of 5 feet.¹⁶ A three-dimensional confined drainage layer (fig. 26) can increase this limit to 18 ft (Nadeau et al 2018). It is important to note that these measurements are specific to the block type and conditions under which the block was tested in the flume. While thicker and heavier blocks should perform better underneath a hydraulic jump than thinner and lighter blocks, information sufficient for extrapolating the results of these test evaluations to larger blocks is not available at time of this document publication. In short, if there is supercritical flow and there is an expectation of a hydraulic jump on the ACB surface, the system threshold stability must be determined for the specific block type for specific conditions.
- (7) Using ACBs as part of a stilling basin may provide important cost savings over the use of structural concrete. However, until additional guidance is available for determining ACB performance under hydraulic jump conditions, designs should approach the use of ACBs in stilling basins with caution.

Figure 26: Three Dimensionally Confined Drainage Layer Used to Increase Stability of ACB Units Under Hydraulic Jump Conditions



F. High Velocities

- (1) Designers should expect high velocities in spillways. While ACBs can withstand great stresses, if there is a problem, a high-velocity situation can result in significant damage to the spillway. Where two mats abut in high-velocity applications, designers should avoid the use of half blocks.¹⁷ Instead of half blocks, designers should use full-sized blocks. The mats should be laced and drawn together. This eliminates the linear flow paths between the mats.¹⁸ If the computed velocities are higher than 25 fps, the designer should confirm with the manufacturer that all the assumptions used in the project design have been validated by the flume testing.
- (2) Cavitation has the potential to result in rapid failure to structural spillways that are experiencing very high velocity flows. This situation is often a concern with concrete slab

¹⁶ This testing also showed threshold stability E_s value of up to 8 feet for a standard ACB installation. However, a more detailed evaluation of the project risks, validity and accuracy of the hydraulic model used to develop the project design parameters was recommended.

¹⁷ Half blocks are utilized to keep mats rectangular for installation.

¹⁸ Typical installation of rectangular mats allows for a ½-inch gap between the mats and this could create a long linear flow path where moving water could cause issues.

- type armoring. The possible effect that cavitation may have on ACBs is not clear. While the inherent roughness and venting ability of the ACB units can reduce cavitation from occurring and thus provide some protection from damage induced by cavitation, it may not be sufficient. Some limited test results on 4-inch block with velocities up to 35 fps have shown no damage. However, until further research is available, designers should approach with extreme caution situations where high velocities with the potential of cavitation are expected.
- (3) Finally, the designer must conduct a hydraulic analysis to assess the potential for flow run-up and super elevation in the spillway. The area of coverage should also include necessary freeboard height on the sides of the spillway.

628.5404 Geotechnical Design Considerations for ACB-Armored Spillway Design

A. Subgrade

- (1) The underlying spillway subsurface supports the ACB units, so it must be globally stable under both dry and saturated conditions. Place the ACB system on undisturbed in-situ soils or properly compacted fill. The subgrade should provide a firm, uniform foundation for the ACBs and other components of the system. Avoid conditions where differential settlement can occur. Consideration of long-term differential settlement might require remediation of the subgrade to a greater depth than what auxiliary spillway construction typically requires.
- (2) The individual blocks of the system can conform to small, gradual changes in the subgrade while connected due to the geometric interlock or other system components (such as cables). Grade the subgrade to a smooth surface to avoid the corresponding ACB surface expression of abrupt changes that could affect hydraulic conditions. A smooth surface will ensure intimate contact between the prepared subgrade surface (including filter, geosynthetic materials, and bedding if needed) and the overlaying ACB units or mats. However, the use of small aggregate to “level up” the subgrade prior to placement of the ACB units should be avoided since high flows can wash out the material and leave gaps. The subgrade material must also be free draining or controlled with underdrain systems.

B. Filter Design

- (1) Install a properly designed filter system on the soil subgrade to permit free drainage of any seepage exiting the subgrade while preventing the loss of subgrade soil particles. The filter can consist of a geotextile, a graded granular filter, or a combination of both. If only granular filters are used, multiple layers may be required to provide filter compatibility between the relatively fine-grained subgrade soil and the overlying coarse-grained drainage layer.¹⁹ Designers frequently use geotextiles to minimize the number of layers in the filter system.
- (2) Geotextiles may be woven or nonwoven and be composed of multifilament yarns or monofilament yarns. However, do not use woven slit film (monofilament or multifilament) geotextiles as a filter beneath ACBs since these tightly woven materials can be prone to clogging. Nonwoven geotextiles are the most appropriate for use below ACBs and should be needle-punched and not heat-bonded or resin-bonded. The permeability of heat-bonded and resin-bonded nonwoven geotextiles is generally too low to provide adequate flow capacity to dissipate hydrostatic pressure. Therefore, heat-bonded or resin-bonded non-woven geotextiles are not acceptable.
- (3) The design of the filter system depends on the characteristics of the subgrade soil. Geotextiles can be prone to clogging if placed against soils with low- to nonplastic silty fines (Plasticity Index (PI) < 7), such as silty sands (SM, SP-SM), silty gravels (GM, GP-GM), and silts (ML). These highly mobile fines can accumulate on the face of the geotextile, resulting

¹⁹ Most test conditions include a geotextile below the ACB.

in clogging. If such soils are present, placement of a granular filter layer between the subgrade and the geotextile to perform the filtering function is necessary for the subgrade soil. In this case, the geotextile should be filter-compatible with the overlying granular filter material. Use a similar filter system with dispersive soils and internally unstable soils (broadly graded or gap-graded soils). For soils without mobile fines, place the geotextile directly on the subgrade soil, as illustrated in figure 27. These soils include clays and cohesive silts ($PI \geq 7$) and granular soils that are either clean (< 5 percent fines) or contain plastic fines ($PI \geq 7$).

Figure 27: Installation of an ACB Lining Using Untapered Blocks Appropriate for a Subgrade Without Mobile Fines



- (4) Design both granular filters and geotextile filters to be filter-compatible with the subgrade soils. In both cases, the designer must know the gradation of the subgrade soil. The design of granular filters should be performed according to 210-NEH-633-C, “Gradation Design of Sand and Gravel Filters”. AASHTO M288, Standard Specification for Geotextile Specification for Highway Applications provides a simple, widely used method for designing geotextile filters. This method is appropriate for installations where the geotextile is covered by a gravel drainage layer, which serves to buffer the geotextile from the dynamic flow conditions in the chute. Figure 28 gives the requirements for the apparent opening size (AOS) and permittivity of geotextile filters for the AASHTO M288 method.

Figure 28: Requirements for Apparent Opening Size and Permittivity (from AASHTO M288-06)

Property	Units	ASTM Standard	Percent of Base Soil Passing No. 200 Sieve		
			<15	15-50	>50
Apparent opening size ^{1/}	mm	D 4751	0.43	0.25	0.22 ^{3/}
Permittivity ^{2/}	s ⁻¹	D 4491	0.7	0.2	0.1

1/ - Maximum average roll values

2/ - Minimum average roll values

3/ - For cohesive soils with a plasticity index greater than seven, an apparent opening size of 0.30 mm may be used.

- (5) If the ACBs are placed directly on the geotextile,²⁰ then the geotextile should be designed for dynamic flow conditions. Published methods to design geotextile filters for dynamic flow conditions include—
- (i) FHWA (2008). *Geosynthetics Design and Construction Guidelines*, Pub. No. FHWA NHI-07-092
 - (ii) Luettich, S.M., Giroud, J.P., and Bachus, R.C. (1992). Geotextile Filter Design Guide, *Journal of Geotextiles and Geomembranes*, Vol. 11, No. 4-6, pp. 19-34. (reproduced in Koerner, R.M. (2012). *Designing with Geosynthetics*, 6th Edition)
- (6) Figure 29 provides survivability and endurance criteria for geotextiles. The property values in figure 29 reflect a class-II geotextile as specified in Material Specification 592 (210-NEH-642, “Specifications for Construction Contracts”). Class II is appropriate when a cushion layer of granular material is placed on the geotextile prior to placing large armor material on it. This condition exists for ACB chutes when a layer of drainage gravel is placed on the geotextile prior to placement of the ACBs. If ACBs are placed directly on the geotextile, then class-I properties should be specified, per Material Specification 592.

Figure 29: Survivability and Endurance Criteria for Geotextiles Under an ACB Chute (Assuming a Gravel Drainage Layer Over the Geotextile)

Property	Units	ASTM Standard	Woven Geotextiles ²¹	Nonwoven Geotextiles ⁸
Grab Tensile Strength	pounds	D 4632	180 min.	157 min.
Elongation at Failure	percent	D 4632	< 50	50 min.
Puncture Strength	pounds	D 4833	371 min.	309 min.
Trapezoidal Tear	pounds	D 4533	67 min.	56 min.
UV Stability (retained strength)	percent	D 4355	50 min.	50 min.

- (7) A design can use a simple geotextile filter system with certain soils as described above. However, **the preferred design approach for lining an auxiliary spillway with an ACB mat is to use a geotextile combined with a granular filter.** The advantage of this approach is that it provides a smooth surface on which to place the geotextile and thus facilitates the all-important intimate contact between the geotextile and its subgrade. Figure 30 illustrates a typical installation.

Figure 30. Typical Installation Featuring Geotextile Under the Drainage Stone and a Geogrid on Top of the Drainage Stone Followed by the ACBs

²⁰ ACBs placed directly on a geotextile are typically only untapered ACB systems. This design approach should be approached with caution, especially in high velocity spillway situations.

²¹ All values are minimum average roll values unless otherwise indicated.



(8) Example Calculation – Simple Geotextile Filter Design for ACB Spillways

Given—

Base Soil Definition: Clayey gravel (GC). Gradation as follows:

Sieve Size	Percent Passing
3 inch	100
1 inch	73
$\frac{3}{4}$ inch	66
$\frac{1}{2}$ inch	59
No. 4	47
No. 40	34
No. 60	31
No. 200	28
0.05 mm	26
0.02 mm	25
0.005 mm	18
0.002 mm	13

Design the geotextile to act as a filter for the base soil. Use AASHTO M288 Standard Specification for Geotextile Specification for Highway Applications Method:

- % fines = % passing No. 200 sieve = 28% for base soil
- In M288, for % fines from 15 to 50%,
- Max. Apparent Opening Size (AOS) = 0.25 mm; and
- Min. Permittivity = 0.2 s^{-1} (from fig. 28)
- Select geotextile to meet these requirements, as well as applicable survivability and endurance criteria. Refer to Geosynthetics Specifier's Guide (IFAI 2017) for potential candidate geotextiles.
- To minimize the risk of clogging, use a geotextile with an AOS as close to the maximum allowable value as possible. For woven geotextiles, use a percent open area (POA) of 10 percent if available (Giroud 2010), but no less than 4 percent.

(2) Example Calculation – Combination Granular/Geotextile Filter Design

(i) Design granular filter for base soil first. Use same soil as in the above example.

- (ii) To design a granular filter for this base soil, follow the step-by-step procedure in 210-NEH-633-26, “Gradation Design of Sand and Gravel Filters,”²² as below:

- Step 1 – Plot gradation of soil.

See plot of gradation on figure 31, labeled “Base Soil.”

- Step 2 – Regrade soil, if necessary.
 - Regrading on the no. 4 sieve is required if the soil contains gravel. The size limits of the gravel fraction are the no. 4 sieve and the 3-inch sieve.
 - Percent Gravel = (percentage passing 3-inch sieve) – (percentage passing no. 4 sieve) = 100% - 47% = 53%
 - Since the soil contains gravel, regrading on the No. 4 sieve is required.
- Step 3 – Prepare regraded curve.
 - Regrade on the no. 4 sieve.
 - Regrading Factor = 100 % / (percentage passing no. 4 sieve) = 100/47 = 2.13.
 - Therefore, multiply each original percentage passing value by 2.13 to obtain the following regraded curve:

Sieve Size	Percent Passing	
	Original	Regraded
3 inch	100	---
1 inch	73	---
¾ inch	66	---
½ inch	59	---
No. 4	47	100
No. 40	34	72
No. 60	31	66
No. 200	28	60
0.05 mm	26	55
0.02 mm	25	53
0.005 mm	18	38
0.002 mm	13	28

- Figure 31 shows the regraded gradation curve, labeled “Base Soil (regraded on #4).”

- Step 4 – Determine base soil category.
 - The percentage passing the No. 200 sieve for the regraded curve = 60%.
 - Therefore, from table 26-1, this soil is in category 2 (percentage fines from 40 to 85%).
- Step 5 – Determine maximum D_{15} of the filter.
 - From table 26-2, for a category-2 soil—
 - Max. $D_{15\text{-filter}} = 0.7 \text{ mm}$
 - Plot this value on figure 31.
- Step 6 – Determine minimum D_{15} of the filter.
 - From table 26-3—
 - Min. $D_{15\text{-filter}} = 4 * d_{15\text{-base soil}}$, but not less than 0.1 mm
 - $d_{15\text{-base soil}} = 0.003 \text{ mm}$
 - Min. $D_{15\text{-filter}} = 4 * (0.003 \text{ mm}) = 0.012 \text{ mm} < 0.1 \text{ mm}$

²² Example is illustrated in detail in example 26-3 of NRCS 210-NEH-633-26. Table numbers referenced in this example are from 210-NEH-633-26.

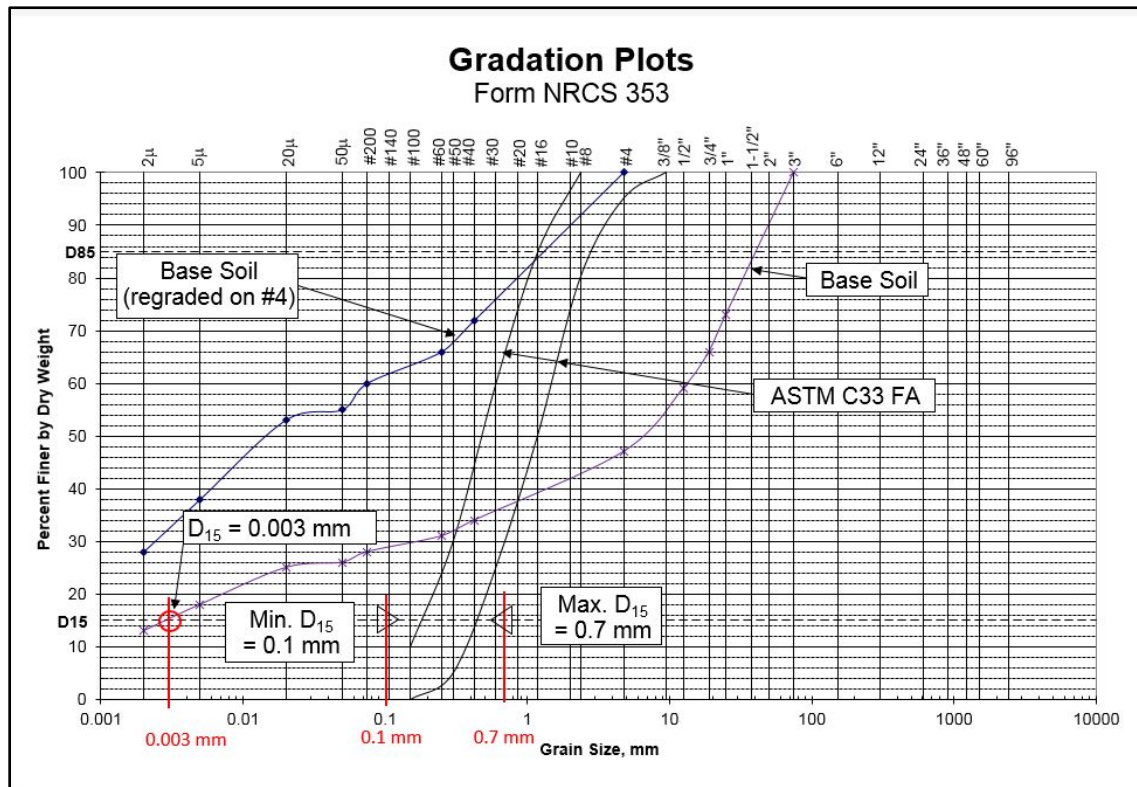
- So, min. $D_{15\text{-filter}} = 0.1 \text{ mm}$
- Plot this value on figure 31.
- Step 7-12 – See example 26-3 of 210-NEH-633-26 for remainder of filter design.
- ASTM C33 Fine Aggregate is an acceptable filter for this base soil. Its gradation limits are:

Sieve Size	Percent Passing	
	Minimum	Maximum
3/8 inch	100	100
No. 4	95	100
No. 8	80	100
No. 16	50	85
No. 30	25	60
No. 50	5	30
No. 100	0	10

- Figure 31 shows these plotted limits, labeled “ASTM C33 FA.” Now design the geotextile to act as a filter for the granular filter material, using the fine limit of the C33 FA envelope.
- Use AASHTO M288 Method:
 - Percent fines = 0% for granular filter
 - In M288, for percentage fines < 15%,
 - Max. AOS = 0.43 mm; and
 - Min. Permittivity = 0.7 s^{-1} (from fig. 28)
- Select geotextile to meet these requirements, as well as applicable survivability and endurance criteria. Refer to Geosynthetics Specifier’s Guide (IFAI 2017²³) for potential candidate geotextiles.

Figure 31: Grain Size Distribution Curve for a Combination Granular/Geotextile Filter Design

²³ Or latest version

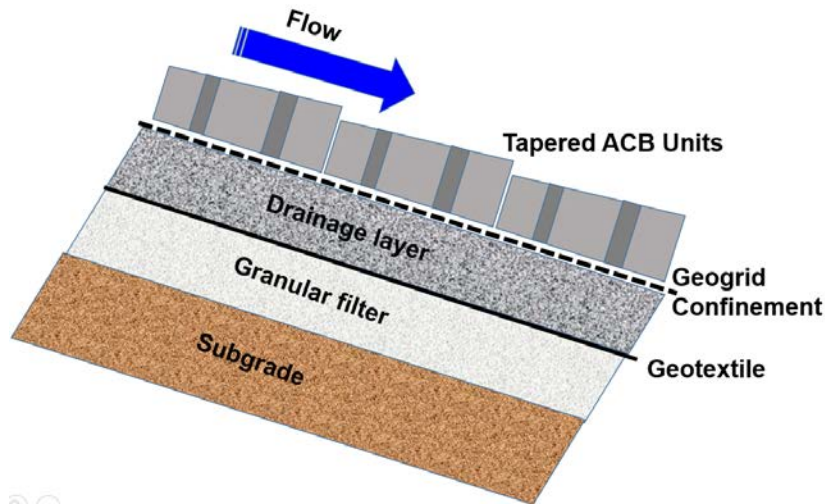


C. Drainage Layer Design Issues

- (1) Typical tapered ACB systems include a gravel drainage layer directly under the ACBs to prevent uplift pressures from developing under the ACBs during flow in the spillway. The drainage layer also acts as ballast to hold the geotextile in intimate contact with the subgrade. The full-scale flume test report will note this requirement for each tapered ACB system. If the testing incorporates a gravel drainage layer, then a drainage layer must also be included in the field installation. A design will often include a layer of geogrid²⁴ (sometimes referred to as a microgrid) between the gravel layer and the ACBs to prevent the loss of gravel particles through the openings in the ACBs or the through ACB joints (see fig. 32). Since one of the main function of this material is to retain the drainfill, selecting the appropriate geogrid is an important design decision. Figure 33 shows an ACB installation with a geogrid.

Figure 32: Schematic of a Tapered ACB System in Profile With Combined Granular/Geotextile Filter (N.T.S.)

²⁴ The term "geogrid" typically applies to materials with apertures greater than 1/4 inch that is designed to have apertures large enough to let particles protrude through them and develop interlock for strength as a reinforcement element. Under ACBs, the geogrid acts as a particle retention element to retain the drainage layer material. Since the openings can be smaller than 1/4 inch, it is sometimes referred to as a "microgrid."



- (2) A typical drainage layer is clean AASHTO #57 stone, per ASTM C33. Other sizes are acceptable, and the selection should be based on local availability of material and in consideration of the opening size of the geogrid. The layer thickness is typically 4 to 6 inches. The installed drainage layer thickness should correspond with the tested layer thickness. For the hydraulic stability of the blocks, thinner-than-tested layers are typically not acceptable and should be carefully considered by the design engineer with consultation involving the testing laboratory.

Figure 33: Typical ACB Installation (green material in photograph is the geogrid confinement)



- (3) The designer should also consider the implications of increasing the thickness of the drainage layer that was tested. A thicker drainage layer does not necessarily improve ACB stability. Generally, increasing the thickness of the drainage material layers decreases the physical stability of the ACB installation and should be avoided unless full scale testing has shown movement of the ACBs not to be an issue with the given drainage layer thickness tested. The designer can use a drainage layer that is thicker than tested but the appropriate threshold velocity and shear values may differ from those contained in the test report.
- (4) While water is flowing across the ACBs, the drainage layer is a saturated zone of low-velocity, high-pressure flow. However, the flow above the ACBs is a zone of high-velocity,

- low-pressure flow. The high-pressure zone in the drainage layer provides lift or buoyancy to the ACBs. The mass of the concrete blocks resists this lift.
- (5) By definition, the system has failed when the ACBs lose intimate contact with the subgrade. This failure can occur when the high-pressure lift in the subgrade exceeds the sum of the mass of the ACBs and the low pressure in the high velocity flow above the surface. This lifts the ACBs and erosion of the coarse-grained drainage layer material can begin.²⁵
 - (6) Therefore, in most situations,²⁶ do not place a geotextile between the drainage layer and ACBs. A geotextile is acceptable underneath the coarse-grained drainage layer, as discussed above. Any geosynthetic product placed on top of the drainage layer must allow water and air to migrate easily between the drainage layer and ACBs without allowing drainage layer particles to migrate into the ACB interstitial joints or openings. The size of the openings in the geogrid should be no larger than the D_{50} (or median) size of the drainage layer gravel. If the openings in the ACBs are small enough to meet this requirement, then a geogrid is not required. Designers should also consult manufacturer's recommendations.
 - (7) A geotextile should not be used directly under the ACBs (i.e., with no gravel drainage layer), because the geotextile can be pulled away from its subgrade by turbulence and reversals in flow where it is exposed at the base of holes in the ACBs. This loss of intimate contact between the geotextile and its subgrade can lead to the formation of slurry in the resulting void space and cause clogging of the geotextile. Furthermore, the fluttering action of the geotextile under dynamic flow conditions could lead to abrasion damage of the geotextile. For these reasons, the use of a drainage layer on top of the geotextile is necessary.
 - (8) In summary, the drainage layer and confining geogrid serve the following beneficial purposes:
 - (i) Provides confinement pressure on geotextile to prevent loss of intimate contact between the geotextile and its subgrade during flow.
 - (ii) Provides a smooth grade for installation of the ACBs.
 - (iii) During flow events, provides a way to vent high pore pressure in the drainage layer up through the ACB joints to the surface flow.
 - (iv) Prevents the loss of drainage layer particles through openings in the ACBs.
 - (v) After a flow event, drains water from the ACB surface.
 - (9) Drainage Case Study Example
 - (i) The following case study illustrates the importance of adequately addressing drainage and providing a filtered outlet. This example is from a wave protection installation²⁷ using ACBs. However, a similar failure mode could occur on an armored spillway if an unfiltered outlet is present. In fact, the length of a spillway as well as the duration of flows would make this a more critical situation.
 - (ii) The ACBs are on the front slope of a dam for wave protection. The blocks are placed on the 3H:1V slope with 14 feet vertical distance from the lower limit to the upper limit of the ACB system. A sand filter, covered by a nonwoven geotextile, is under the ACBs. Figure 34 shows the top of the ACBs during construction.

²⁵ This phenomenon has been observed in flume tests when geotextile was placed on top of the drainage layer and below the ACBs. The ACBs clearly failed because the pressure buildup in the drainage layer was not adequately vented through the geotextile. The ACBs were lifted and ultimately failed.

²⁶ Due to the high differential in pressure in spillway and dam overtopping applications, a geotextile should not be used between the ACBs and the drainage layer for high and significant hazard potential structures.

²⁷ This example of wave protection is provided in this chapter because it has photographs that dramatically illustrate the importance of adequately addressing drainage and providing a filtered outlet. The focus of the example is on the drainage issues. It should also be noted that a spillway application would also require a cutoff (or turn down) at the entrance control section.

Figure 34: Top of ACB Installation During Dam Construction (photograph perspective is looking from top to blocks at right)



- (iii) There is no controlled outlet. Water entering the installation through rainfall, wave action or upstream of the structure could flow through the entire sand layer. Figure 35 shows a schematic of this installation. As water flowed through the filter layer, it was able to mobilize sand. As the water carried the soil through the unfiltered outlet, the action initiated an infinite slope failure below the blocks. Figures 36 and 37 show the failure.

Figure 35: ACB Wave Protection on NRCS Dam (N.T.S.)

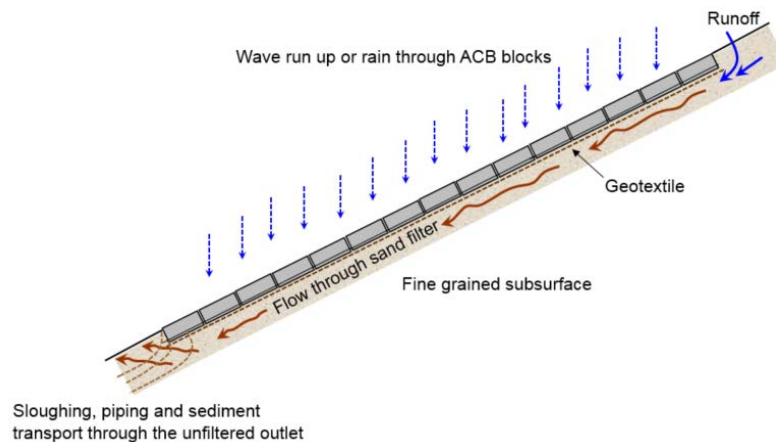
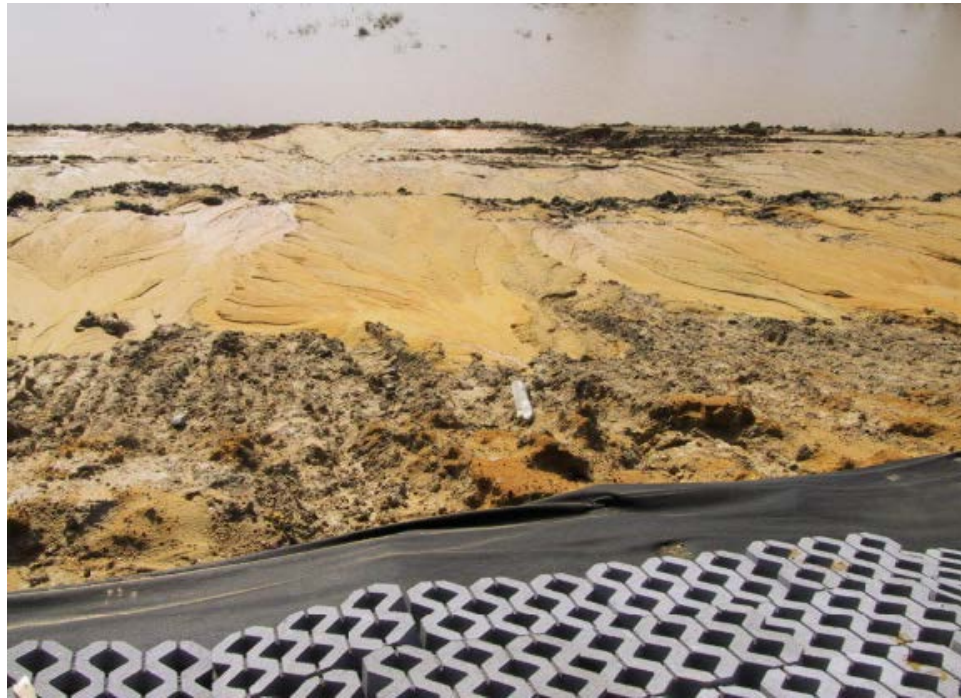


Figure 36: Soil Eroded From Under the Blocks Results in Failure of ACBs (photo perspective is looking downslope)

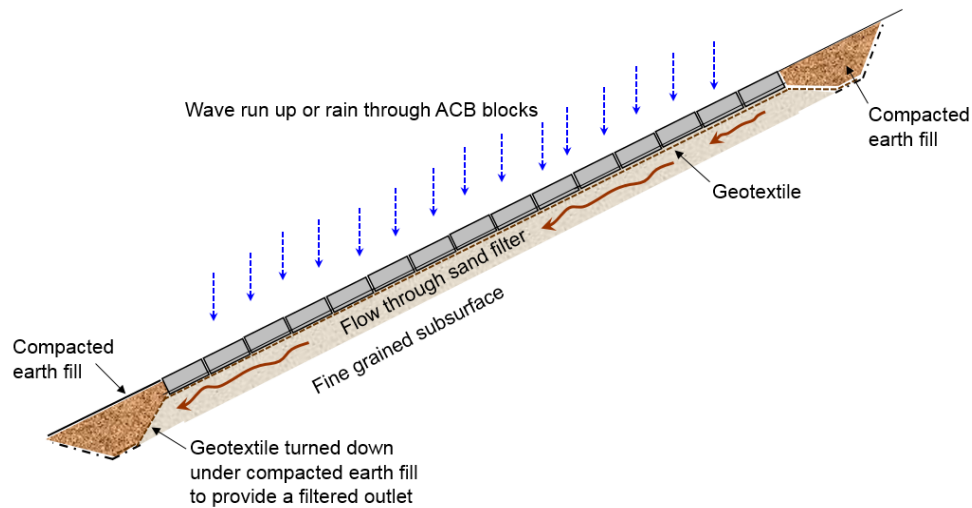


Figure 37: Eroded Soil From Under Geotextile Deposited Further Down the Slope (photo perspective is looking downslope)



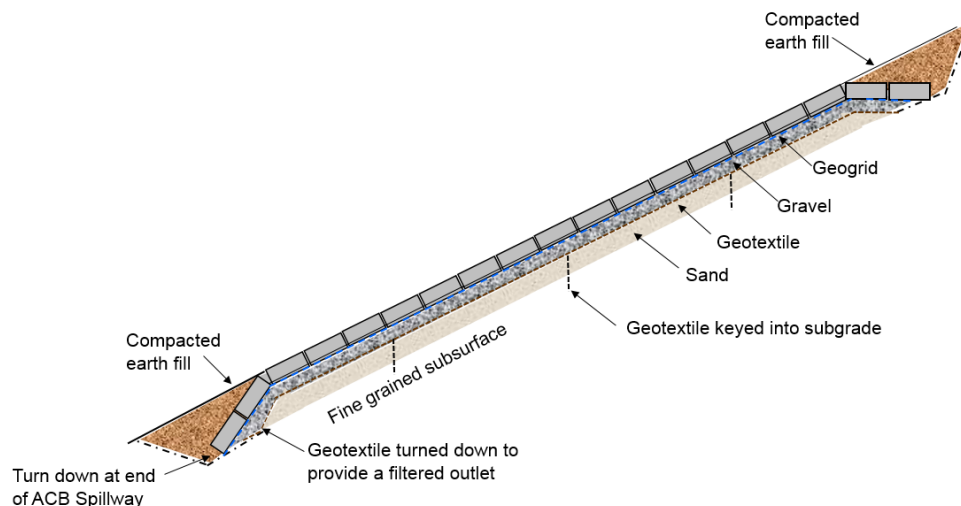
- (iv) This failure dramatically illustrates the importance of controlling drainage and avoiding an unfiltered outlet. A protected outlet for the sand filter may have prevented this failure. Figure 38 shows an example approach to protecting the outlet. In this figure, the design calls for the geotextile to be under a compacted earth fill to protect the filter outlet.

Figure 38: Simplified Schematic of ACB Installation With Filtered Outlet (N.T.S.)



- (v) A suitable outlet for the drain under an ACB-lined spillway is very important. Stresses are inherently higher on spillways and the consequences of structural failure can be sudden and catastrophic. Figure 39 shows a schematic of an ACB armored spillway. Note that while the spillway filter and drainage layer is more involved, the filtered outlet is essentially the same approach as for the wave protection above. Also, note that this example includes a series of cutoff walls (geotextile imbedded through the filter layer into the subgrade—approximately 18 to 24 inches, typically) installed across the slope to allow the water to pond and slowly drain rather than flow under the ACB system. Flowing water would not carry mobilized particles very far before stopping at the cutoffs.

Figure 39: Simplified Schematic of ACB Installation for a Spillway With Combined Granular/Geotextile Filter²⁸ and Filtered Outlet (N.T.S.)



²⁸ The geotextile is placed such that the upstream geotextile overlaps the downstream geotextile in a shingle-type arrangement.

D. Geologic Issues

The design process must include an evaluation of the subsurface soils and bedrock.²⁹ Conditions may exist that impact foundation preparation or the extent of coverage needed. Dispersive, collapsible, highly expansive (even bentonite), highly erosive, gypsiferous, and other potentially problematic soils may require additional treatment or removal during foundation preparation. Groundwater depths and lateral extent can affect the drain design and constructability. Evaluate the soils and bedrock prone to head cut development to determine the integrity of the underlying foundation as this could have a bearing on termination of the ACB coverage. Designers should consider avoiding areas prone to potential hazard conditions such as karst, sinkhole development, or areas with ongoing downstream channel degradation.

628.5405 Additional Design Considerations for ACB Armored Spillway Design

A. Climatic Issues

- (1) Weather varies across the Nation. Designers must consider the implications of heavy rains, significant snowfall, icing, drought, or extreme weather changes. These can vary by region as well as by site area. The designers must take into effect the potential impacts that such events could have on design performance.
- (2) A variety of cold climate issues should be addressed during planning and design. Frost heave can affect the foundation of the ACBs causing changes in subgrade soil strength, compacted density, and resulting in uneven surfaces. If not considered in the design, the effects of frost heave can compromise the integrity of the system making it more vulnerable to serious damage. Knowing frost depths can help reduce the potential for developing uneven surfaces.
- (3) In addition, specifications for ACB systems must include a requirement for freeze-thaw durability testing. It is important to specify the associated ASTM tests, minimum freeze-thaw cycles, as well as the corresponding weight loss criterion for a pass-fail determination.

B. Turbulence and Flow Direction

- (1) The hydraulic conditions for the ACB application should be consistent with the hydraulic testing used to determine the block parameters. Since the flume testing is straight and uniform flow, the application should be the same. Therefore, ACBs are generally not suited for highly turbulent conditions. Avoid converging flows, sharp changes in flow direction, and abrupt changes in velocity. Avoid objects in the spillway, such as trees, rock outcrops, and utility poles. While such objects are usually not permitted in most NRCS dam spillways, the designer should confirm that this is the case.
- (2) A tapered ACB installation is flow-direction specific. The downstream end of one block must be above the upstream end of the next block. This arrangement is suitable to most spillways where the flow is in one direction. However, at the spillway outlet, there may be situations where there is a potential for multidirectional flow or swirling currents. In such a situation, the designer may consider transitioning to untapered block or structural concrete.

C. Drift and Debris

- (1) Large debris can affect the lining of open-channel spillways. Large boulders can crack or dislodge ACBs. Trees or other debris can wedge in a channel and create turbulence, which

²⁹ Per the 210-NEM-531-A-531.7, "Requirements for Detailed Geologic Investigation," the design engineer must work with the geologist to plan the investigation.

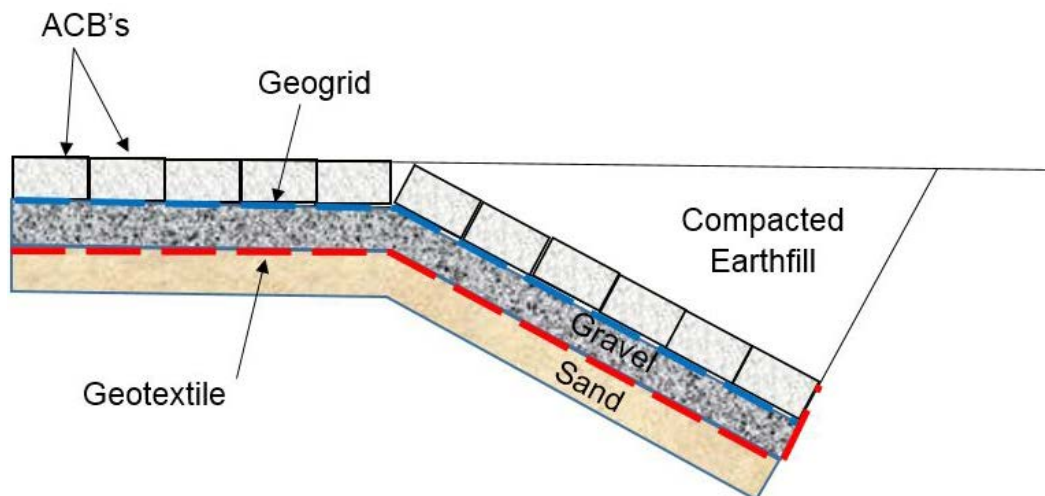
may concentrate flows. However, at time of the publication of this document, there have not been examples of natural debris causing damage to ACB armor.³⁰

- (2) Nevertheless, designers should evaluate the potential for large debris affecting a proposed ACB armored spillway installation. In addition, the O&M plan should require inspection of the spillway if a significant flood event has passed debris through an ACB armored spillway. Prompt repair of any damage is necessary to maintain the integrity of the system.

D. Edges and Ends

- (1) Measures to prevent flow paths developing under an ACB installation are important. The edges of an ACB installation must be finished to prevent flowing water under the ACB mat. This can be done by securing the edges of an ACB system as a turndown into a termination trench as illustrated in figure 40. Install termination trenches on the upstream and downstream ends of the system as well as along the sides parallel to the flow direction. Figure 41 provides a photograph of such an installation. Another approach is to utilize a cutoff wall as shown in figure 42. The weep holes shown in this figure prevent pressure buildup by draining any and all water behind the wall.

Figure 40. Turndown at End of ACB Chute (N.T.S.)



- (2) Inadequate design or improper execution of termination trenches is a common problem in ACB armored spillways. Inadequate or omitted block turndown or backfilling the trench with inappropriate material may lead to undercutting of the installation and ultimately the unraveling and failure of an otherwise well-designed system. Many ACB manufacturers call for the use of nonerodible backfill in termination trenches. Typically, the nonerodible backfill is concrete. However, any material that can withstand the anticipated hydraulic forces is acceptable.³¹

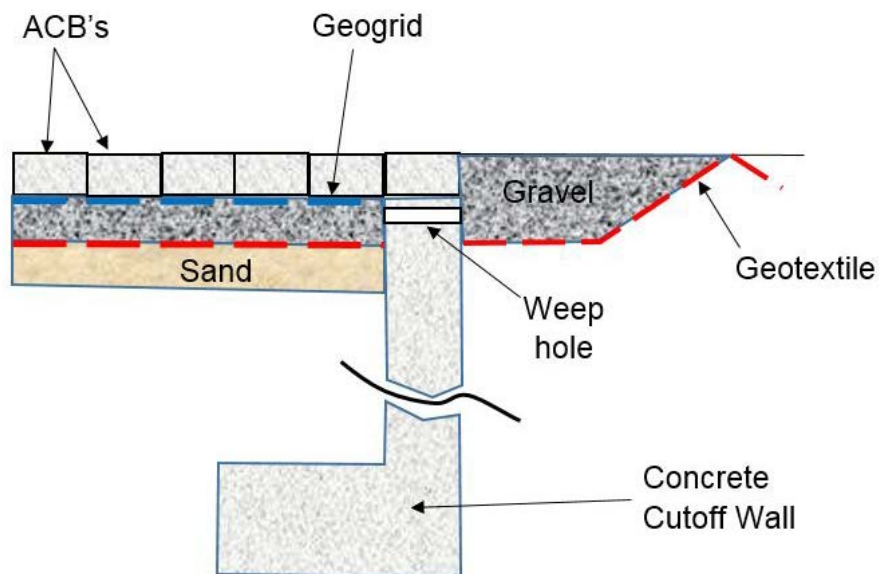
³⁰ The only example known to the authors of damage from material flowing through an ACB spillway was a unique occurrence where large concrete barriers were dislodged during a flood and rolled down an ACB spillway. Damage occurred but it is noted that this debris was larger and heavier than typical for NRCS-type dams.

³¹ Some States require that termination trenches are filled with concrete.

Figure 41: Cutoff Trench Installation



Figure 42. Termination of ACBs at Concrete Cutoff Wall (N.T.S.)



- (3) In either the turndown example or the concrete cutoff wall example, it is critical that the area is not undermined. In the downstream end of the spillway, the depth of the turndown or the depth of the wall must take into consideration the potential depth of scour.

E. Transitions

- (1) As noted earlier, install ACBs where flow is generally uniform. Avoid structures or obstacles that may impede flow. Tapered ACBs should generally not be used where significant flow turbulence is expected. As described earlier in this document, additional analysis is needed if a hydraulic jump is expected such as in a stilling basin.

- (2) Transitions of an ACB armor to such measures as a stilling basin or around infrastructure like manholes must include appropriate measures to ensure attachment of the mat to the ending structure as well as to prevent a preferential flow path under the mat. The transitions must prevent uncontrolled water flowing under the ACB mat. The designer should consult with manufacturers because the appropriate transitions may be block specific.

F. Vegetation

- (1) Vegetation can be used to mitigate the negative viewscape of ACB installations. Generally, the open cells are filled with soil up to the surface of the block and then planted with grass. Figure 43 shows an example of this approach. Preliminary research has shown that vegetation within the cells can increase the performance of an ACB armor. In one case, the allowable velocity increased 50 percent. However, the research available at time of the publication of this guidance is insufficient to accurately predict an increased factor of safety provided by vegetation.
- (2) A design can also use a shallow layer of sacrificial topsoil over the ACB surface. This soil layer covers the open areas as well as the entire ACB surface and provides an uninterrupted grass cover. This soil overlay should be shallow (less than 2 inches³²). Approach thicker layers with caution. During spillway flow, a thick layer of soil on the ACB structure may erode in a non-uniform manner resulting in deep rills and channels. Concentrated flows on the blocks places additional stress on elements of the structure beyond design values. If flow occurs over the ACB armored spillway, this shallow layer of soil will likely erode. To restore the original design aesthetic, replace and revegetate the eroded shallow soil layer.

Figure 43: Soil Added to an ACB Channel Lining



- (3) Top soiling and vegetating over an ACB mat may clog the drainage layer. Clogging of the drainage layer will affect the hydraulic performance of the structure. A vegetated mat can limit relief of water flowing out of the drainage layer near the toe, which can produce uplift in the block. In addition, migration of fines from the topsoil over time may compromise the

³² In some climates, this may be insufficient to allow for grass establishment.

drainage layer. Therefore, any design that utilizes soil placement over the ACB units should demonstrate that the soil would not clog the drainage layer nor impede drainage.

- (4) Do not allow woody vegetation, such as trees and bushes, to grow in the ACB spillway. The presence of woody vegetation can disrupt the flow, causing concentration of water and turbulence. In addition, roots from woody plants can lift the blocks and promote erosion under the cells. Lifting the blocks can also increase the overturning moments. As a result, woody shrubs³³ and trees can lead to failure of the system and must be avoided in ACB-lined spillways. The O&M documentation should require immediate removal of this type of growth.

G. Vehicle Use

- (1) Parking, stream ford crossings, and secondary road installations can use ACB-type units. The loadings from trucks or other heavy machinery can affect the contact between the block and the subgrade. This may not be an issue for a secondary road or parking-type facility. However, as described earlier in this document, spillways are subject to significant hydraulic forces and this contact is critical for ACB performance. Loss of adequate contact can lead to failure of the installation.
- (2) Generally, an ACB armored spillway should not be subject to regular vehicle traffic. However, maintenance may necessitate occasional vehicle traffic over an ACB armored spillway. If this is necessary, analysis must assure that the subgrade will not deform under the vehicle loads. In addition, only allow rubber-tracked vehicles onto bare ACB surfaces.

628.5406 Construction Issues for ACB-Armored Spillways

A. The following is a compilation of commonly encountered installation issues for ACB systems. NRCS Construction Specification 65, Articulating Concrete Block System (CS-65), found in 210-NEH-642, provides additional guidance.

B. Clearing

Remove all vegetation. Remove remaining roots from trees and brush to a depth of 1 foot (0.3 meters) below the subgrade surface. Rake and remove loose roots and twigs, turf clods, stones larger than ½-inch (13 mm) diameter, and other debris from the final surface. Correct rills and gullies. Place the ACB system on undisturbed native soils, or acceptably placed and compacted fill. Do not place the ACBs on surfaces that contain mud, frost, or organic soils.

C. Grading

Maintain the subgrade in a smooth condition between installation of the geotextile and the blocks. Windrows, stones, clods of cohesive soil, and irregularities must be raked smooth. Correct ruts, rills, and gullies resulting from traffic, precipitation runoff, groundwater seepage, etc. prior to installation of blocks. The grading tolerance must be within 2 inches (50 mm) from the prescribed elevations, with no abrupt variations that would cause unacceptable projections of individual blocks.

D. Geotextile

- (1) NRCS Construction Specification 65 and section 6.2 of the ASTM D6884 Standard provides guidance pertaining to geotextile installation. The basic premise of installing the geotextile is as follows:
 - (i) Ensure proper overlap in the proper direction pertaining to the flow of water
 - (ii) Use sewn seams

³³ Bunch grasses can also result in unacceptable root growth that may lift blocks.

- (iii) Ensure the fabric lays flat on the subgrade with minimal wrinkles (none is best)
- (iv) Ensure there are no rips, tears or holes in the installed fabric
- (v) Secure the fabric with pins or as described in the project specifications
- (2) The designer must also consider the rigors of installation (equipment, etc.) the geotextile may face when selecting the appropriate geotextile. The ability of the fabric to survive the installation process intact is critical to the functioning of the ACB system. As an example, the difference in cost between a 6-ounce, nonwoven and a 12-ounce nonwoven is minimal to obtain the added puncture resistance offered by the 12-ounce fabric. This is especially important when crushed stone is on top of the specified fabric.
- (3) The assembly of some ACB mattresses includes the geotextile attached to the bottom of the mattress such as seen in figure 44. However, transport often can damage this geotextile. It is for this reason that NRCS CS-65 requires the geotextile be supplied separate from and not affixed to the blocks or mattresses.

Figure 44: Installation of an ACB Lining With Geotextile Attached – *Not Recommended*



E. Drainage Layer Placement

If a crushed-stone drainage layer is required, the designer must specify the stone gradation (e.g., AASHTO #57) and minimum thickness requirements based on the full-scale flume test setup for a particular ACB system. The drainage layer is on top of the properly installed geotextile. The stone drainage layer is extended into the anchor trenches (see fig. 45) as well. Place aggregate drainage layers to the specified thickness and grade to create a smooth and uniform surface. Uniformity of thickness and attaining the minimum thickness specified are crucial for the ACB system to perform as designed. Typically, the stone is compacted with vibratory equipment.

F. Geogrid Placement

Place the geogrid on top of the stone drainage layer to help keep the stone confined under the ACB system and not allow it to wash out during a flow event through the open areas of the blocks. The aperture of the geogrid typically ranges from 0.08 by 0.08 inches to 0.5 by 0.5 inches. Overlap the geogrid per specifications. Typical overlaps of the fabric are 6 to 12 inches.

G. Block Placement

- (1) The installation of the ACB units can commence once the subgrade, geotextile, and stone drainage layer (if applicable) have been properly prepared and installed. The ACB units can be hand placed, hand placed with cables then inserted, or placed as mats depending on the system and its use of cables.
- (2) Most NRCS spillway armoring applications are installed using cabled mats (fig. 45). The use of mats of ACB units can reduce manual labor requirements and quickly cover large areas. The cables facilitate installation and handling of the mats. Typically, all sides are cabled together so that the system is continuous. While the cables are stout, they do not prevent movement of the blocks. Therefore, as noted earlier, the cables do not increase the factor of safety.
- (3) Designers should confirm block layout drawings with the block manufacturer(s) before final bid. ACBs are unique and special accommodations may be necessary. Manufacturer input before bidding may reduce change orders during construction. The contractor should also submit an ACB work plan for review and approval.
- (4) Install ACB systems as they were tested:
 - (i) If a geosynthetic or gravel layer was included in the flume test, it must be part of the field installation.
 - (ii) If anchors were included in the flume test, they must also be included in the field installation.
- (5) Projection height can significantly affect the stability of an ACB installation. If untapered blocks are used, do not exceed the design projection height during installation. The projection height is set to 0.5 inches or more depending on specific project details. If tapered blocks are used, the FOS equation described in this report do not account for any of the destabilizing forces from a projection. Therefore, install tapered blocks with the proper orientation to flow direction as shown in figure 4 (narrow edge upstream). If tapered blocks are inadvertently installed backwards (narrow edge downstream), the design is compromised. As a result, it is very important that the installer and construction inspection personnel understand the proper orientation for tapered block.

Figure 45: ACB Installation, NRCS-North Dakota



H. Key Trenches

- (1) Turn down ACB systems on the perimeter to prevent any surface flows from getting under the installation. Turning down the block mat and backfilling with nonerodible material (i.e., grout or concrete) works well as long as the depth of burial is greater than the predicted scour depth at the edges of the system. Typically, bury a minimum of two rows or columns of the ACB panels into an anchor trench (3-foot minimum), even when predicted scour is minimal.

Make sure to build the key trench as designed, to ensure that the manufacturer's recommendations for stability are followed.

- (2) Edge treatments of the ACB installation should preclude flowing water under the ACB system at the edges of the mats to prevent erosion of the subgrade drainage material. On long slopes, water entering the openings in the blocks can flood the filter or drainage layer under the ACBs. This can then mobilize filter or drain fill material. A series of shallow cutoff walls installed across the slope will guard against this type of failure and limit the movement of the material.

I. Panel Joint Treatments

- (1) Nonerrodible material is required to backfill the key trenches at the top and toe of slope as well as on the flanks. The material that can be used for these applications include—
 - (i) Nonshrink Grout (4000 psi typical).
 - (ii) Concrete (4000 psi typical).
 - (iii) Riprap (appropriately sized by the engineer of record to withstand the specific project hydraulic conditions).
- (2) When placing ACB systems in mats, there will be voids created in the following areas:
 - (i) End-to-end placement of mats up and down a slope.
 - (ii) Side-to-Side incidental gaps. All ACB mats should be placed snug to one other side-to-side, however if gaps greater than 2 inches result these need to be grouted (fig. 46).
 - (iii) Intersection of angle mats.
 - (iv) Against abutments and protrusions like manhole covers.
- (3) Grout is the preferred material for these voids since it does not contain large aggregate that can bind and result in incomplete filling of voids.

Figure 46: Grouted Mats Abutting During ACB installation, NRCS-ND



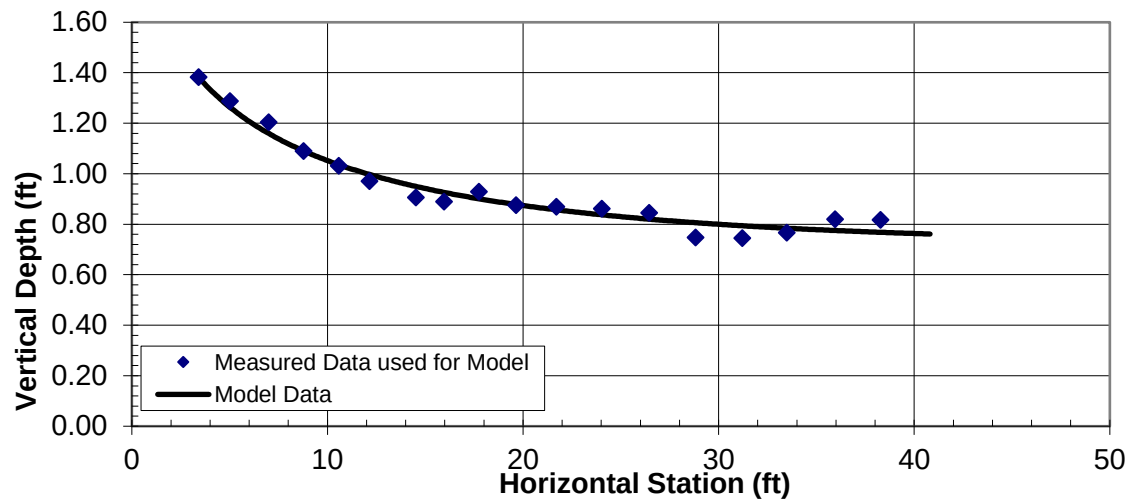
628.5407 Approval of ACB Designs

The use of ACB armoring systems is an important tool for safe and cost-effective dam design and rehabilitation work. However, the designer must ensure that proper ACB designs are attained using ACB-specific test and design data. To ensure proper design, the following information, at a minimum, should be prepared and documented as part of the design report:

- (1) Project-specific design data.

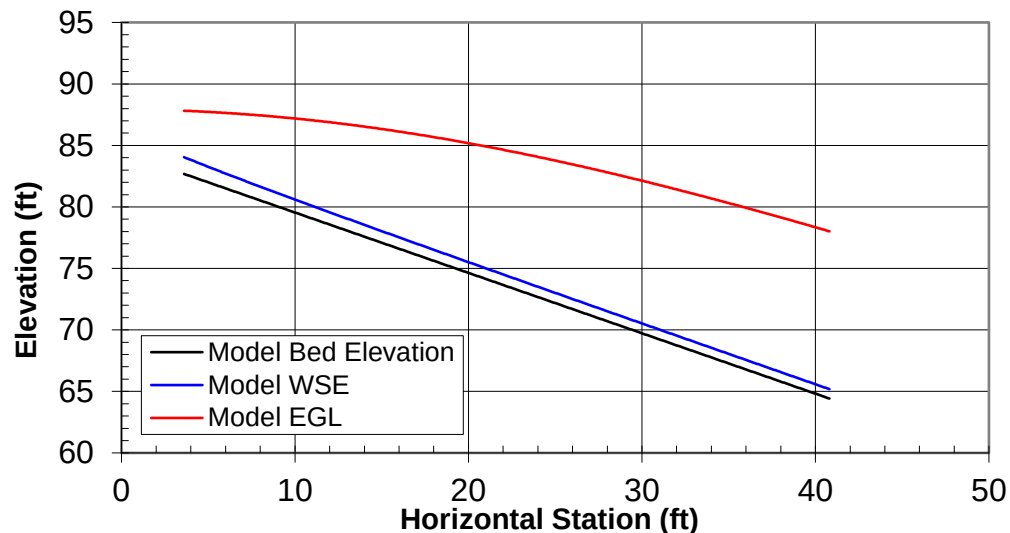
- (2) Selected project factor of safety and supporting justification.
- (3) Physical characteristics of the ACBs.
- (4) Full-scale flume test generated data for the selected ACB system related to velocity and shear.
 - (i) Manufacturer test report consistent with ASTM 7277.
 - (ii) Data analysis and results report consistent with ASTM 7276. This should include a plot of the measured water surface elevation points with the ASTM D7276 water surface curve fit to the plot. Figure 47 shows an example of this flow depth calibration.

Figure 47: Example Measured Water Surface Elevation Points With the ASTM D7276 Water Surface Curve Fit to the Plot



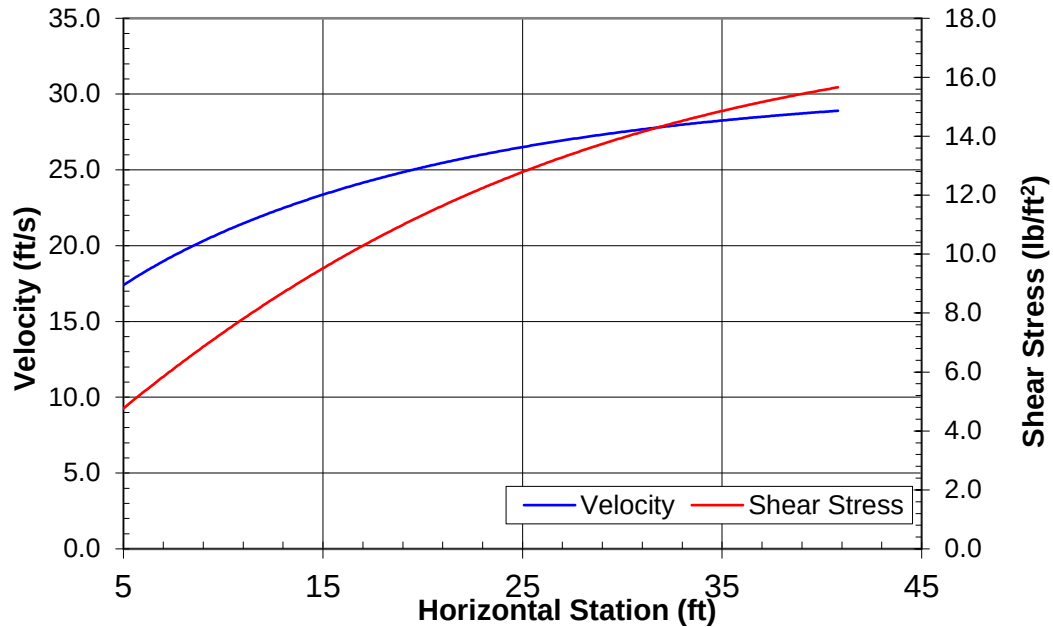
- (5) A plot showing bed slope, water surface and energy grade line. Figure 48 shows an example of this plot.

Figure 48: Example Water Surface and Energy Grade Line



- (6) Plot of shear stress and velocity versus embankment station. Figure 49 shows an example of this plot.

Figure 49: Example Shear Stress and Velocity Versus Embankment Station



- (7) Location from the above figure (fig. 49) used for critical values. Maximum values of shear stress and velocity were determined for a control volume immediately upstream of the beginning of flow aeration.
- (8) Calculated threshold velocity, threshold shear, and corresponding coefficient of lift (C_L).
- (9) The calculation of the predicted factor of safety using the simplified CSU methodology.
- (10) Design of appropriate filter system (geotextile, graded granular filter or combination of both). Base the analysis and design of the filter system on the identified characteristics of the subgrade.
- (11) Design of appropriate drainage layer if the underlying material is not free draining.
- (12) Assessment of hydraulic jump stability if applicable. Information to include specifics of full-scale flume testing for determination of ACB system threshold of stability (E_s).

628.5408 Installation Details

A. Inspection and approval is required at each stage of an ACB installation. This includes—

- (1) Subgrade preparation.
- (2) Geotextile and granular filter placement.
- (3) ACB placement.
- (4) Transitions and terminations.

B. Construction Specification 65, Articulating Concrete Block System, specifies installation details that conform with and add to the requirements in ASTM D6884, Standard Practice for Installation of Articulating Concrete Block (ACB) Systems. Total adherence to the construction specification is critical to the performance of the ACB system.

628.5409 Maintenance

A. Inspect the ACB armored spillway at the same schedule as the dam based upon the approved O&M plan. Inspect an ACB system after significant spillway flow. Identify and address any cracked

or broken blocks. Voids beneath the ACB surface are a concern. If there is any observed change in the ACB surface, check the for subsurface voids and promptly repair the system. Figure 50 shows an ACB installation where surface settlement was observed. These blocks bridge a significant void in missing stone infill. The structure was at risk until it was effectively repaired.

Figure 50: Depression Observed in ACB Surface



B. Inspect the transitions at both the upstream and downstream ends of the ACB system. Maintain the transitions to match the surface of the block system and avoid any protruding blocks.

C. Finally, maintain any design vegetation as indicated on the plans. Do not allow woody plants, trees, or shrubs to grow within the blocks. If there has been any evidence of significant brush growth, then further investigation is necessary to assure that the blocks have remained in contact with the subgrade and that roots have not caused voids to form.

628.5410 References

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- B. ASTM D 7276-08. Standard Guide of Analysis and Interpretation of Test Data for Articulating Concrete Block (ACB) Systems in Open Channel Flow
- C. AASHTO M288-06. Standard Specification for Geotextile Specification for Highway Applications.
- D. ASTM C33/C33M-16e1. Standard Specification for Concrete Aggregates.
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- S. NRCS 210-NEH-642, "Specifications for Construction Contracts"
- T. NRCS 210-NEH-633-26, "Gradation Design of Sand and Gravel Filters"
- U. NRCS 210-NEH-654," Stream Restoration Design Handbook"
- V. NRCS Conservation Practice Standard 402 (CPS 402), Dam
- W. Thornton, Christopher and Nadeau, Jim (2018). "Determination of Hydraulic Jump Stability for Articulating Concrete Block (ACB) Systems in Open Channel Flow." Paper in development