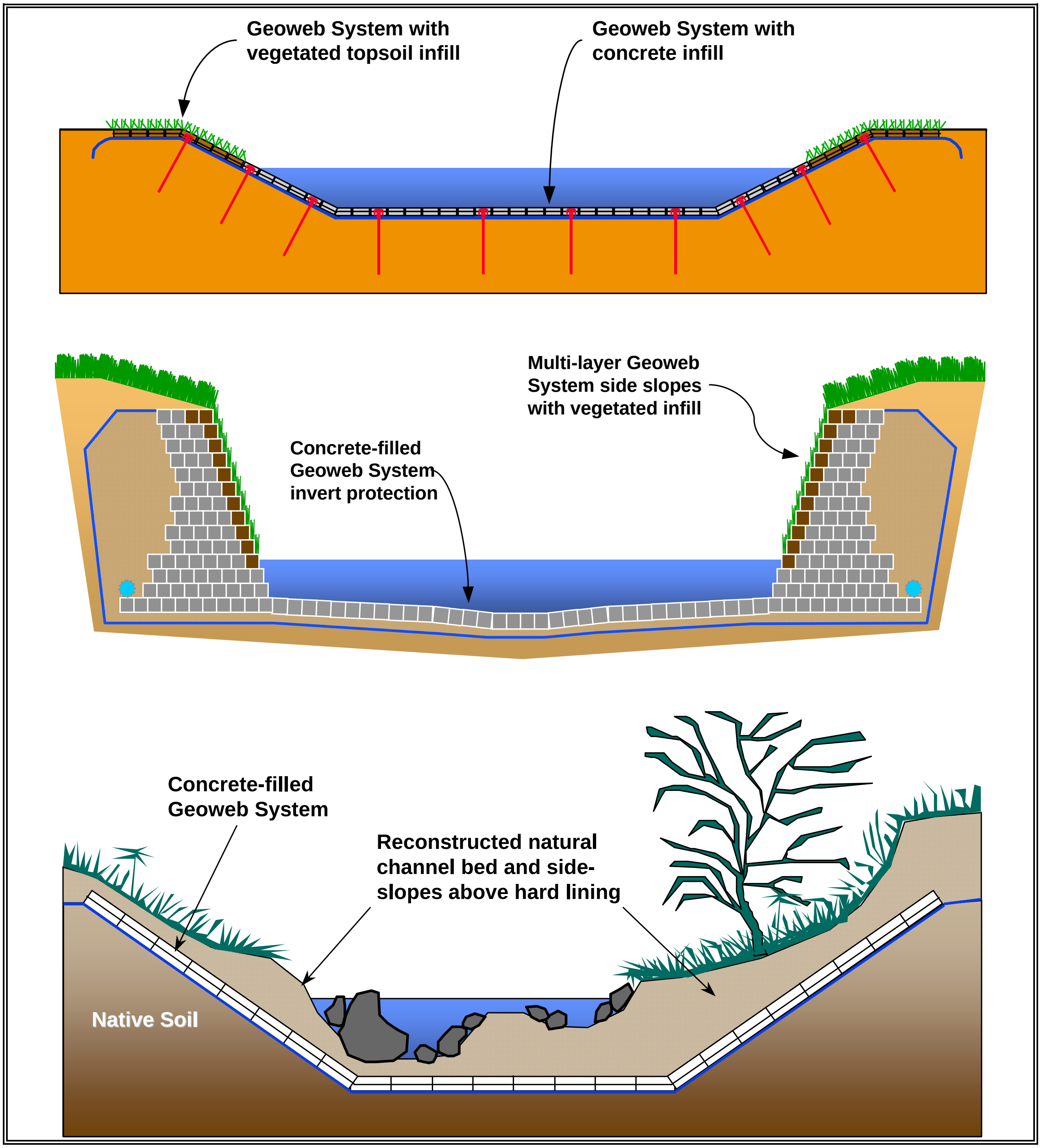
PRESTO

GEOSYSTEMS

GEOWEB®

CHANNEL PROTECTION SYSTEM
TECHNICAL OVERVIEW



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Introduction

Geoweb® Cellular Confinement Systems provide a wide variety of flexible stabilization and erosion control treatments for open channels and hydraulic structures. The structural performance and durability of conventional protection materials such as concrete, gravel, riprap and vegetation can be significantly improved by confining the materials within the cells of Geoweb systems.

The design of protective linings requires a clear definition of the maximum anticipated flow conditions and the associated hydraulic stresses to which the protection will be subjected. Consideration must be given to subgrade drainage requirements and the potential for long-term or seasonal deformations of the structure as a whole. Other factors include the surface roughness, i.e. the hydraulic efficiency of the lining system, and the ease with which future maintenance and sediment cleaning operations could be carried out. The protective system must also have compatibility with local environmental, ecological and aesthetic requirements. A technical overview of the design and construction of a range of open channel and energy dissipation structures that incorporate Geoweb protection systems is presented herein.

Channel Systems in General

The protection of channels and open-channel structures takes many forms and can include a range of natural and man-made materials. Broad categories of protection include:

Natural or vegetated linings (e.g. grass or reinforced grass)

Hard flexible armoring (e.g. rip-rap, gabions, pre-cast blocks, Geoweb protection system)

Rigid armoring (e.g. poured in-place reinforced concrete)

Combinations of protection materials are commonly applied within a channel system to account for variations in hydraulic conditions, aesthetic requirements, environmental factors, and cost constraints.

Selection of appropriate lining systems can be greatly influenced by the type and function of a particular channel structure in that the potential for extreme discharge events and associated hydraulic stresses may preclude the use of certain protective systems. The main classes of channel structure can be summarized as follows:

Natural drainage channels

Natural drainage channels are formed by the erosive effects of concentrated storm-water runoff, as the flow gravitates to lower elevations. The horizontal alignment and bed slopes of natural channels are often irregular, due to variations in topography and the erosion resistance of surface soils. Major storm runoff events can impose extremely damaging hydraulic stresses throughout the channel. Urban development within the channels' catchment area may significantly increase the severity of storm discharges in comparison to historical levels. Special measures and restrictions may be imposed to protect existing plant and aquatic animal habitats.

Man-made channels

Man-made channels, whether for drainage, irrigation, power generation or navigation, are generally more consistent in terms of alignment and cross-section. Predictions of maximum design flows can often be made with greater confidence thereby reducing the risk of under-design of protective works.

Hydraulic structures

Hydraulic structures are incorporated into many open-channel systems at inlets, outlets, constrictions, and severe changes in grade. In most situations, the primary function of these structures is related to the controlled dissipation of hydraulic energy. This is generally achieved by the transformation of potential energy (hydraulic head) to kinetic energy (velocity head), and the ultimate dissipation of the kinetic energy through frictional losses, turbulence and the generation of heat.

Consequently, hydraulic structures, such as spillways and drop-structures, are especially prone to severe erosion and hydrodynamic stresses and generally require more substantial forms of surface protection than those associated with channel linings. The Geoweb system may be appropriate for many of these problems.

General Design Considerations

It is important to clearly determine the function of the channel or open-channel structure at the outset of the protection design process. Local topography, native soils, groundwater conditions and the geometry of associated structures should also be examined, since these may impose special constraints on the design and construction of the protection works.

Determining the nature and severity of the hydraulic conditions that can occur at each section of a protective system is of primary importance. In many applications, it is not economically feasible to protect a channel or structure to a level that would accommodate the worst potential storm discharge event. Therefore, it is important to determine the standard to which full protection is expected, and the possible consequences of an event which significantly exceeds the design standard.

1) Protective Lining Systems

The key performance characteristics of protection materials for channels and structures include:

A) Surface Roughness

Surface roughness, defined most commonly as Manning's roughness coefficient "n", is a function of the lining type and surface finish of the material. In the case of relatively flat, grassed waterways, a Retardance coefficient "n" is used to relate the physical characteristics of the particular grass to the hydraulic loading parameter, VR (m^2/sec or ft^2/sec).

B) Erosion Resistance and Durability

Erosion resistance and durability of the protective lining, under both long and short-duration hydraulic loading, can be quantified as a limiting mean flow velocity (V) or a critical boundary shear stress. The maximum duration of design flow events is of importance when vegetative protection is involved.

C) System Stability

System stability can relate to the resistance of the lining, as a whole, to:

- translational displacement under severe boundary shear stress or extreme side-slope geometry and its ability to resist hydrostatic uplift (generally associated with severe changes in bed slope),
- hydrodynamic impingement, and
- hydraulic jumps.

A variety of supplemental anchors to enhance the sliding and uplift resistance of the lining can be incorporated where conditions demand.

D) System Flexibility

System flexibility ensures that the lining system can conform to localized deformations of the subgrade soils and bedding materials that may occur following construction or that may result from seasonal factors. Insufficient flexibility can result in the development of voids below the lining, the uncontrolled displacement of bedding materials, and ultimately, the catastrophic undermining of the protection system. Conversely, excessive flexibility can reduce the system's resistance to potential uplift forces referred to above. Therefore, optimum system flexibility for each installation should account for the specific subsoil and hydraulic conditions involved.

E) System Permeability

System permeability should be sufficient to allow the free drainage of adjacent subsoils and bedding materials. The need for drainage may result from the presence of a high ground-water table or the development of a rapid drawdown condition in the channel. Dissipation of potential hydrostatic uplift forces may be achieved by (1) drainage through the lining surface, (2) the provision of a separate collection and pressure relief system or, (3) a combination of both methods. All drainage systems should incorporate suitable soil filter components, such as an encapsulating geotextile, to prevent loss of subsoil particles or bedding materials due to soil piping.

F) Ease of Maintenance

Effective maintenance of a lining system often depends on the ability to access the invert of the channel with wheeled equipment and to mechanically remove any accumulated sediment or debris without damage to the protection system.

2) Geoweb System Components

General

The primary components of a typical Geoweb Channel Protection installation are illustrated in Figure 1. Specifications for each component type are based on anticipated hydraulic conditions channel geometry available infill materials and subgrade soil types. Details of standard Geoweb system components are summarized below with guidelines for their selection.

Additionally, but not illustrated, a turf reinforcement mat (TRM) over the Geoweb sections is used in vegetated lining systems.

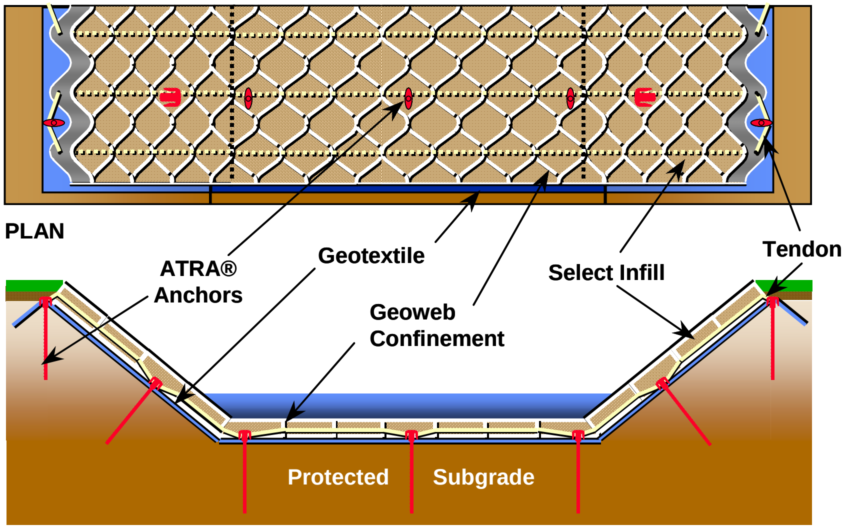
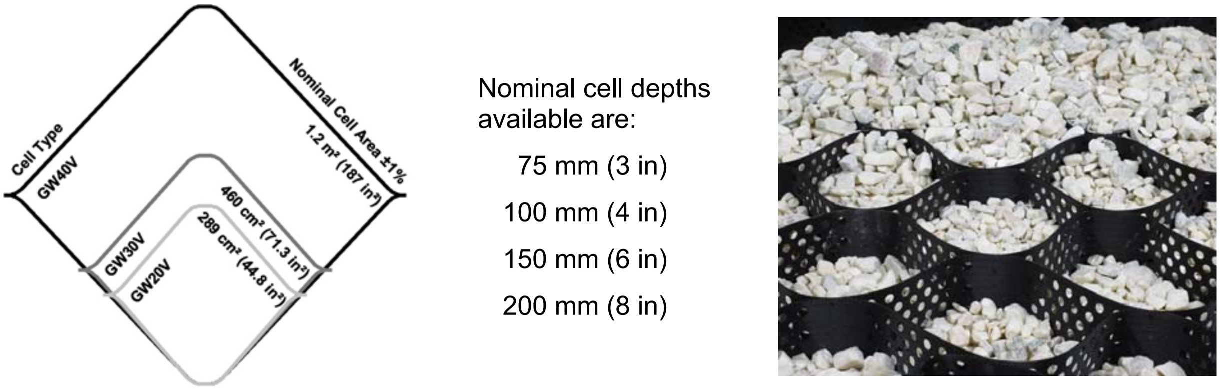


Figure 1 Geoweb Channel Protection - System Components

Geoweb Cell Sizes and Depths

Optimum cell size and depth is discussed below in sections covering Infill Selection.



Nominal cell depths available are:

75 mm (3 in)
100 mm (4 in)
150 mm (6 in)
200 mm (8 in)

Figure 2 Geoweb Cell Dimensions

Geotextile Underlayer

A non-woven needle-punched geotextile underlayer is recommended as a soil filter and drainage medium in channel lining installations. The edges of the geotextile should be dug into the subgrade at the perimeter of the protection area to prevent uncontrolled flow beneath the lining system. Conventional geotextile selection criteria, that accounts for specific subgrade soil types and ground water conditions, should be applied. Refer to *AASHTO-AGC-ARBTA Task Force 25 Specifications for Geotextiles* for examples.

Integral Polymeric Tendons

The range of standard tendons that can be incorporated into Geoweb channel protection systems are shown in Table 1.

In addition to providing a connection element for ground anchors and crest anchorage of steep side-slopes, integral tendons distribute the self-weight of loose infill materials that bear directly on the tendons. This anchorage method can be effectively employed when Geoweb protection is applied over geomembrane liners that cannot be penetrated with ground anchors.

Table 1 Typical Tendons

Reference Name	Minimum Break Strength
TP-31	3.11 kN (700 lbf)
TP-67	6.70 kN (1500 lbf)
TP-93	9.30 kN (2090 lbf)
TK-89	8.90 kN (2000 lbf)
TK-133	13.34 kN (3000 lbf)
TPP-44	4.40 kN (990 lbf)

Ground Anchors

Geoweb channel lining systems can incorporate a variety of ground anchors to accommodate specific channel geometry and hydraulic stresses.

Standard or "nominal" anchoring includes an array of ATRA® Anchors distributed at predetermined spacing along selected integral tendons. This arrangement ensures that anchor resistance is distributed effectively throughout the protective lining. Typical "nominal" anchor density is 1 anchor / m^2 (1 anchor / 10 ft²).

Special high capacity anchors can also be incorporated as an array in situations where high uplift forces and extreme geometry are involved. "Duckbill®" and "Helical" anchors are generally recommended in such situations.

Surface Treatments

A range of surface treatments can be applied to select infill materials to increase their erosion resistance or, in some instances, increase the effective roughness. Specific examples are detailed below.

3) Guidelines for Geoweb Infill Selection

A) Vegetated Topsoil Infill

General

Highly stable grass-linings can be developed in channels and swales using the Geoweb system in situations where high-velocity / shear, intermittent flows occur. The integrity of non-reinforced vegetated linings can be compromised if flows persist for extended periods. Soil particles are progressively removed from the root zone, creating rills and gullies that ultimately destroy the protection. However, with the Geoweb system and a turf reinforcement mat (TRM), stability of vegetation in channels with intermittent flow is dramatically increased.

Benefits of Cellular Confinement

- The Geoweb cells, when infilled with topsoil, form an effective container extending throughout the topsoil liner. A TRM cover over the Geoweb cells forms an effective lid to the container preventing rill and gully development, and mass movement of the topsoil when high flows and soil saturation occur.
- A predetermined depth of topsoil and the developing vegetative root mass is contained and protected within the individual Geoweb cells protected by the TRM. Roots readily penetrate through the non-woven geotextile underlayer into the subsoil, anchoring the entire lining system.
- The Geoweb system also allows roots to grow through and intertwine with the perforated cell walls creating additional reinforcement of the root zone.
- Confinement and anchorage of the root structure increases the limiting shear resistance of the protection and permissible duration of flow events.

Design Guidelines

- The vegetated topsoil-infilled Geoweb system is recommended in intermittent flow situations where rip-rap or concrete lining is undesirable and environmentally sensitive solutions are desirable. Peak flows must be intermittent and of relatively short duration (< 24 hours). The peak velocity is 10 m/sec (33 ft/sec) and peak shear stress is 860 N (18 lbf/ft²) can be sustained for short periods when the vegetated cover is well established.
- A turf reinforcement mat (TRM), either completely synthetic or synthetic with a bio-degradable component, must be applied to protect exposed topsoil and seed and to promote rapid establishment of vegetation. The TRM should be installed in accordance with their manufacturer's guidelines.
- For better overall performance, the perforated Geoweb system with a lightweight [150 - 200 g/m^2 (4 - 6 oz/yd²)], needle-punched, non-woven geotextile underlayer is recommended.

Cell Size Selection

- The recommended cell depth for vegetated Geoweb channel linings is:
  - 75 mm (3 in) when subsoils will support root development and side slope angles are <26°.
  - 100 mm (4 in) when subsoil vegetation support is questionable and side slope angles are >26°.
  - greater cell depths and irrigation may be required in arid regions.
- GW30V Geoweb cell size with a TRM is recommended for vegetated channel linings.

System Installation

- Over-filling or placement of large clumps of soil in the cells should be avoided. Ensure that all cells are completely filled after lightly tamping (compacting) the infill. Over compaction of infill may retard development of vegetation.
- Seeding and installation of the TRM should proceed immediately after the placement of topsoil infill.

B) Aggregate Infill

General

The stability of aggregates is related directly to the size, gradation, shape and density of the particles. Displacement of the smallest unconfined particles within a layer of aggregate channel protection due to moderate tractive forces can be expected. In low-flow conditions, replenishment of smaller particles will many times occur. However, the stability of the larger components will remain when properly selected. Contact your Presto Geosystems distributor for proper aggregate selection.

Benefits of Cellular Confinement

- Confinement of aggregate within Geoweb cells to form hard channel protection provides additional resistance to aggregate movement. The limiting hydraulic stresses relate to the particle sizes that are exposed at the surface of the individual infilled cells rather than the finer aggregate particles that are confined at depth within the cell walls. The cell walls limit flow through the aggregate layer and thereby prevent the development of localized flow-channels within the protective layer.
- In the event that flow conditions produce tractive forces at or slightly above the limiting values for the exposed aggregate, partial cell emptying can occur. The effect of such emptying causes an increase in the stability of the system as a whole due to the projection of the cell walls into the stream flow. (Reference 7)
- The erosion resistance of an aggregate-filled Geoweb lining can be increased without losing the inherent flexibility of the system by applying a concrete surface grout.

Design Guidelines

- Limiting recommended hydraulic conditions for a range of aggregate types have been determined through testing at Colorado State University – Hydraulics Laboratory. Contact Presto for design recommendations.
- When concrete grouts are applied to the surface of aggregate infills to increase erosion resistance, a minimum grout-penetration depth of 50 mm (2 in) is recommended.
- A non-woven, 200 - 240 g/m^2 (6 - 8 oz/yd^2), geotextile underlayer is recommended to prevent loss of fine-grained subsoil particles. The pore opening size of the geotextile should not exceed the D_{85} of the protected subsoil.

Cell Size Selection

Choice of Geoweb cell size is directly related to the maximum particle size of the aggregate infill:

Table 2 Maximum Recommended Aggregate Size

Geoweb Cell Depth	75 mm (3 in)	100 mm (4 in)	150 mm (6 in)	200 mm (8 in)
GW20V Cell	38 mm (1.5 in)	50 mm (2 in)	75 mm (3 in)	75 mm (3.5 in)
GW30V Cell	75 mm (3 in)	100 mm (4 in)	100 mm (4 in)	100 mm (4 in)
GW40V Cell	75 mm (3 in)	100 mm (4 in)	150 mm (6 in)	150 mm (7 in)

System Anchorage

Nominal surface anchorage for an aggregate-filled Geoweb lining includes continuous tendons running across the channel at 800 mm (32 in) centers with 500 mm (20 in) ATRA® Anchors spaced at 1 m (3 ft) intervals along each tendon.

Supplemental anchorage on steep side slopes can be determined through static analysis methods available from Presto Geosystems.

If ATRA® Anchors cannot be used, tendon spacing should be reduced to 400 mm (16 in) to increase the superimposed weight of aggregate infill bearing directly on the tendon system.

System Installation

- Infilling operations should avoid end dumping or dropping small aggregate [<75 mm (3 in)] from heights greater than 1000 mm (3 ft) and large aggregate [>75 mm (3 in)] from heights greater than 500 mm (20 in). Ensure that cells are not over-filled.
- Aggregate can be compacted into the Geoweb cells using a plate tamper or the back of a smooth bucket on the placement equipment.

C) Geoweb Protection with Concrete Infill

General

Poured concrete can provide hard, durable protection for channels and hydraulic structures that are exposed to severe hydrodynamic stresses. Conventional reinforced concrete protective linings are essentially rigid and must include distinct construction / expansion joints to perform effectively. A stable select granular base is often required to minimize the possibility of void formation below the armoring. Uncontrolled movement of the base materials can result in structural cracking and in extreme cases, uplift and displacement of the lining. The potential for damage is increased if long-term or seasonal subgrade deformations occur. These factors can greatly increase installed costs of conventional linings.

Benefits of Cellular Confinement

- Infilling the Geoweb cells with ready-mixed concrete produces a durable, erosion-resistant lining system of uniform thickness that retains flexibility and the ability to conform to potential subgrade movement. Special compacted granular bedding layers, necessary with conventional poured concrete slabs, can be omitted. The Geoweb system acts primarily as a lightweight, flexible form that can readily adapt to a wide range of channel geometry.
- Normal drying shrinkage of the concrete infill gives the entire lining surface an ability to drain ground water from the subgrade. The uniformly distributed shrinkage also enhances the system's ability to articulate in case of subgrade deformation.

- The quality, surface finish and thickness of the concrete can be selected to meet specific design needs. A non-woven geotextile underlayer, combined, if necessary, with custom outlet ports, ensures effective subgrade drainage and subsoil filter protection.
- A mechanical bond is maintained between the concrete infill and the interior of each cell by the unique wall surface of the Geoweb system. The wall can either be textured perforated or textured non-perforated. The amplitude of the texture is greater than potential concrete shrinkage, thereby locking the concrete infill into the individual cells of the system. The 10 mm ($^3/_8$ in) diameter perforations allow cross-cell flow of concrete, providing superior locking of the concrete infill into the individual cells of the system.
- High installation rates can be expected. Concrete can be placed by pumps, boom-mounted skips or direct discharge from ready-mix trucks.

Design Guidelines

- Concrete infill is recommended for channels that may be exposed to high flow velocities, turbulence or hydrodynamic impingement. Concrete quality, in terms of compressive strength, aggregate/cement ratio, water/cement ratio and air entrainment, should be selected in accordance with normal engineering practice relative to site conditions.
- Lean-mix and gap-graded concrete can be used as low-cost infills where hydraulic stresses and weathering conditions are moderate.
- Various surface finishes, trowel, broom or rake, meeting specific aesthetic or surface friction requirements are possible. Aggregates or gravel can also be embedded into the surface of wet concrete infill to produce a variety of textures, colors, and surface finishes.
- Evaluation of subsoil permeability and the potential for rapid draw down is especially important when determining the type of geotextile or geocomposite underlayer.

Cell Size Selection

- GW30V Geoweb cell, with a cell area of 460 cm² (71.3 in²), is generally recommended on slopes steeper than 18.5° (3H:1V), unless the concrete infill has a very low slump.
- Cell depth selection is normally based on the potential tractive and uplift forces to which the protective lining could be exposed. In addition to increasing the unit weight of the system, greater cell depth significantly increases the flexural stiffness and uplift resistance of the system.
- The concrete-infilled, 75 mm (3 in) depth, GW30V Geoweb system was tested at Colorado State University – Hydraulics Laboratory according to ASTM WK7072 and sustained flows up to 10.8 m/sec (35.5 ft/sec) and shear stresses up to 980 N (20.5 lbf/m²) without signs of distress. The concrete had a rough broom finish.

Surface Anchorage

- Special slope anchorage requirements can be determined on the basis of detailed hydraulic analyses. See Design Procedures below.

System Installation

- Concrete infilling should generally proceed from the top of side slopes to the toe. Over-filling of cells is not recommended.

4) *Function and Geometry*

Listed below are specific functional and dimensional criteria that influence the selection and design of protective lining systems.

A) Design for Maximum Hydraulic Efficiency

The hydraulic efficiency of a channel section can be expressed as a discharge per unit cross-sectional area "q" for a given bed slope. Efficiency increases as the lining roughness "n" decreases, and the hydraulic radius "R" (Area / Wetted Perimeter), increases. Hence, the most efficient open channels would have a relatively smooth lining and be semicircular in section. In practice, efficient sections are those which approximate a semicircle (see Figure 3). Hydraulic efficiency is associated with high flow velocities; therefore, the chosen lining must be capable of resisting the relatively high stresses that normally result.

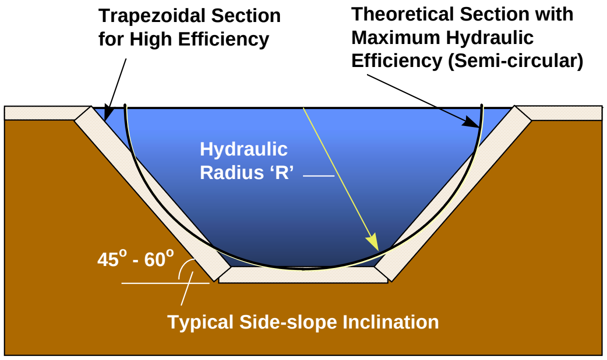


Figure 3 Section Requirements for High Hydraulic Efficiency

B) Design for Minimum Channel Width

Restrictions on overall channel width are common, particularly in urban areas. This problem can be compounded by the increased storm run-off that is generally associated with urban development. Such channel sections normally incorporate near vertical side walls and a protected invert. See Figure 4. The invert can have either a shallow V-section or a low-flow channel to handle dry-weather flows and minimize deposition of sediment.

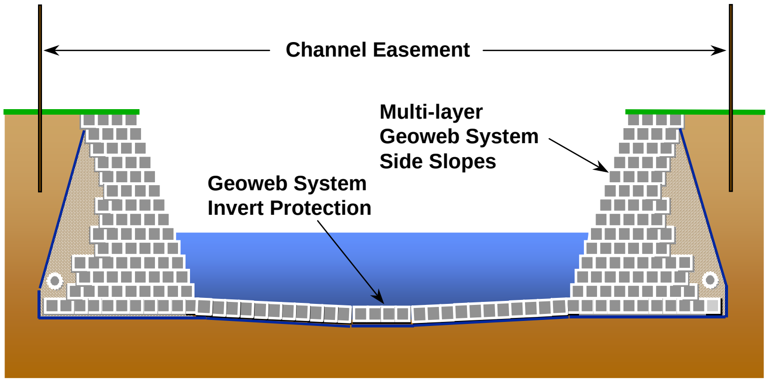


Figure 4 Composite Section where Space Restrictions Apply

C) Design to Limit Flow Velocity

Certain types of channel lining materials, particularly small riprap, gravel, and vegetation, have relatively limited resistance to severe flow conditions. Performance limitations are off-set by the low cost of the materials and, in some instances, their aesthetic appeal. There are two standard methods of achieving this goal:

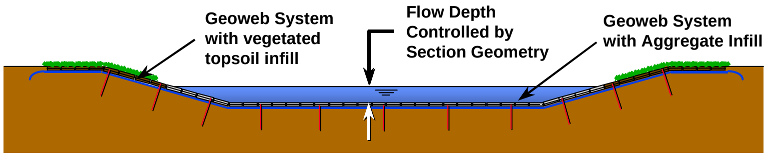


Figure 5 Reduction of Flow Velocity with Wide Section

1. Provide a wide, shallow channel section thereby reducing hydraulic efficiency, flow velocity and associated boundary stresses as depicted in Figure 5.
2. Reduce the general bed slope with a series of armored drop structures as depicted in Figure 6. Shear stresses in the channel sections between the drops are minimized due to the flatter bed slope.

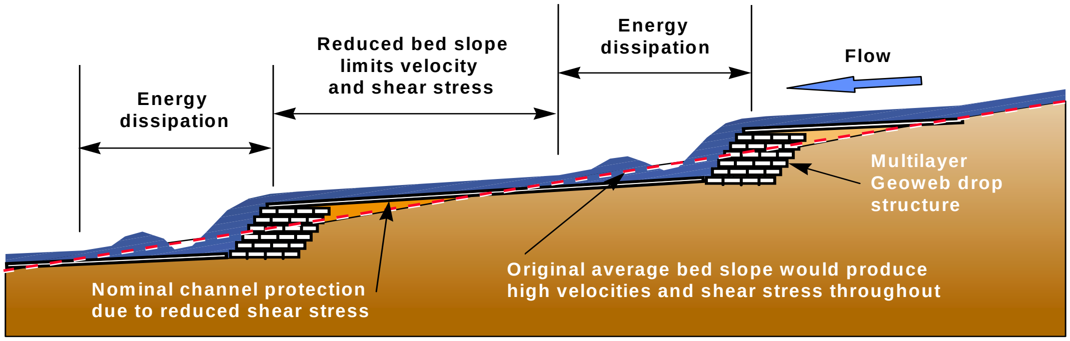


Figure 6 Reduction of General Bed Slope with Multi-layer Drop Structures

D) *Maximized Revegetation*

Well-established vegetation can provide effective and ecologically acceptable protection of open-channels. Under extreme flow conditions however, soil loss from the root-zone of the vegetation can compromise the protection. This problem can be eliminated by the development of the vegetation within the cells of the Geoweb system on both the invert and side-slopes of a channel cross-section as depicted in Figure 7. In addition, the installation of multi-layered Geoweb side-walls provides a steepened stable soil mass that can support full vegetated cover in situations where channel capacity must be maximized.

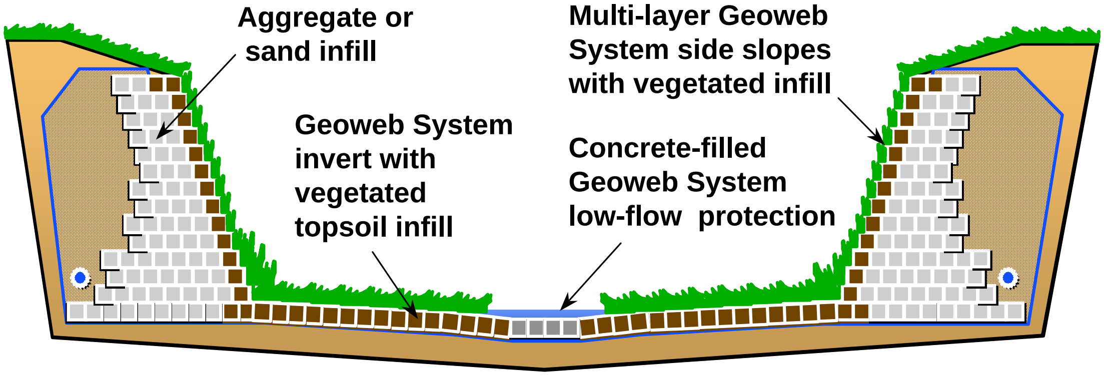


Figure 7 Vegetated Composite Geoweb Channel Protection System

E) Design for Energy Dissipation

The Geoweb lining system can be applied in a variety of configurations that provide efficient dissipation of energy. They include drop structures, spillways and stilling basins, stepped chutes, and the application of high-retardance infills. See Figure 8 and Figure 9.

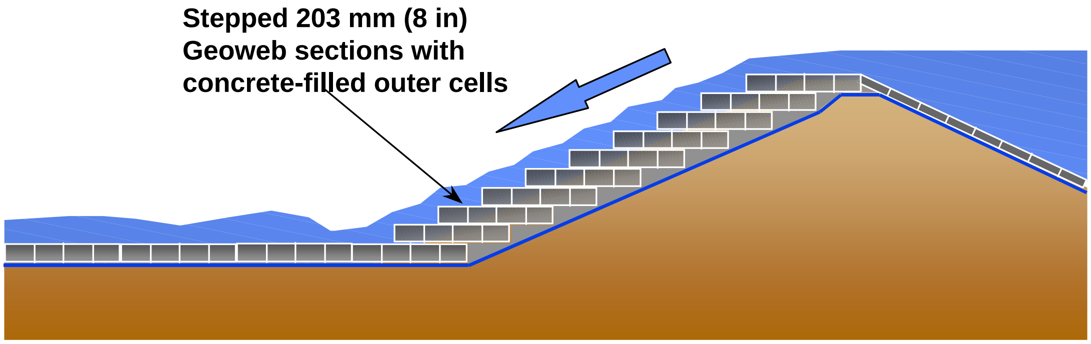


Figure 8 Energy Dissipation with Stepped Geoweb System Spillway

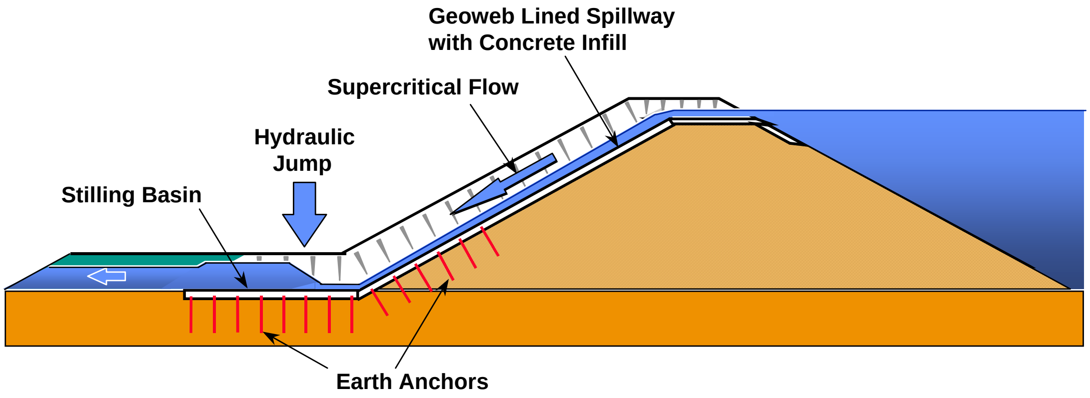


Figure 9 Typical Geoweb System Spillway and Stilling Basin

Concrete filled Geoweb linings can be adapted in a number of ways to meet the requirements associated with spillway and stilling basin protection. Flow conditions within the spillway channel are determined by application of the Bernoulli equation with appropriate allowances for frictional losses that reflect the use of either a sooth trapezoidal Geoweb lining or a stepped multi layer configuration. The resistance of the lining to the imposed shear stresses is then checked to determine whether supplemental system anchorage is necessary.

Based on the Froude number and application of the Momentum equation, the location and size of potential hydraulic jumps that can occur within the stilling basin and lower spillway channel are established. Out of balance uplift forces resulting from development of predicted jumps can be resisted with an array of ground anchors attached to integral tendons running through the Geoweb lining. Anchor spacing, typically between 600 - 900 mm (24 - 36 in), is a function of the thickness and flexural stiffness of the lining. Minimum anchor capacity, including a reasonable factor of safety, can then be determined.

F) Concealed Protection of Fish Habitat

Elimination of conventional ‘hard’ protection in streams that provide a habitat for fish is a requirement in some storm-water management jurisdictions. A natural eroding channel with meandering low-flow and plunge pools is preferred. Unfortunately, in the event of extreme flow conditions, this approach can expose the channel and adjacent structures to severe undermining and damage.

A unique approach in such situations is the installation of a buried Geoweb lining system with concrete infill, at predetermined depths below the bed and side-slopes of the channel as illustrated in Figure 10.

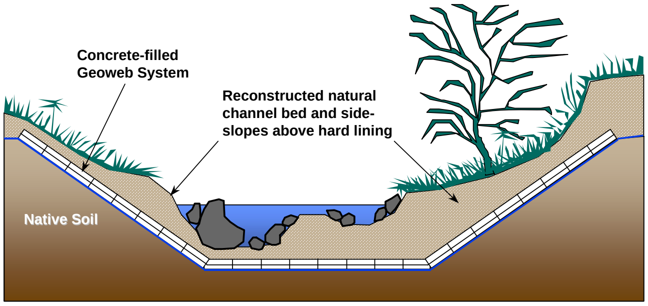


Figure 10 Concealed Protection of Natural Channel

Design Procedures

1) Channel Capacity and Flow Velocity

The **Manning formula** provides the most widely used method of quantifying the flow conditions in open channels. The formula describes the relationship between the *geometry* of a channel section, the lining *roughness*, the bed *slope* and the average *flow velocity* at various *depths of flow*. See Figure 11. The equation is as follows:

$$v = \frac{R^{2/3}\, s^{1/2}}{n} \text{ (SI units) or,}$$

$$v = \frac{1.486\, R^{2/3}\, s^{1/2}}{n} \text{ (Imperial units)}$$

where:

v = average velocity [m/sec (ft/sec)]
n = roughness coefficient
R = hydraulic radius = A/P [m (ft)]
A = cross-sectional area of flow [m² (ft²)]
P = Wetted perimeter [m (ft)]
s = bed slope [m/m (ft/ft)]

The discharge, Q, [m^3/sec (ft^3/sec)] is determined by:

$$Q = A\, v$$

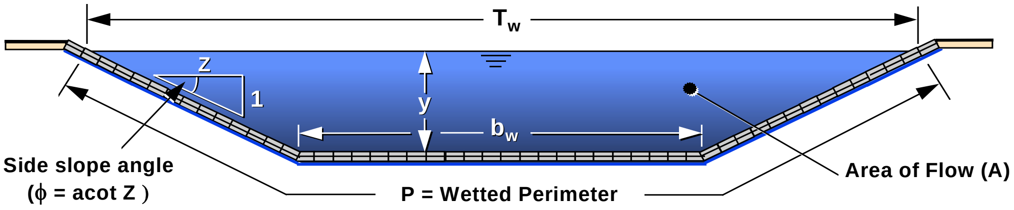


Figure 11 Typical Trapezoidal Channel Geometry

It is possible to determine, by trial and error, combinations of the above variables that satisfy the equations and describe the flow conditions for a given discharge. For steady flow conditions, i.e. constant discharge, the continuity principle can be expressed as follows:

$$Q_1 = A_1 v_1 = A_2 v_2 = Q_2$$

(Subscripts 1 and 2 denote sections 1 and 2 in Figure 12)

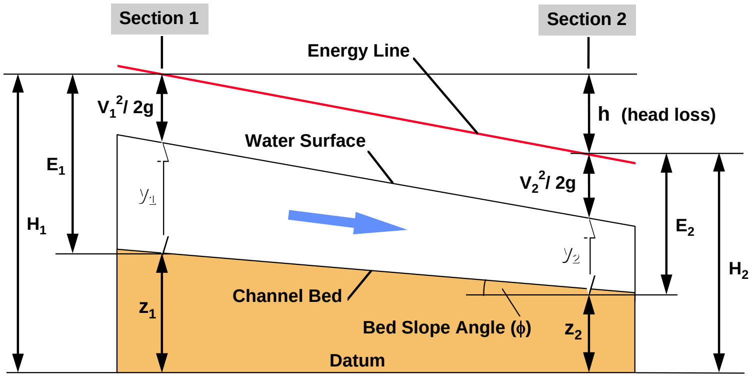


Figure 12 Open Channel Flow – Definitions

2) *Roughness Coefficients*

A) Vegetated Linings

The Manning ‘n’ roughness coefficients of grassed channel linings depend on the type, density and length of the ‘sward’ or above ground components of the vegetation. Unlike ‘hard’ lining materials, the ‘n’ values of grasses vary significantly according to the intensity of flow within the channel. As the depth and velocity of flow increases, the grass is deflected in the direction of flow until, at extremely high hydraulic loading, the grass is laid almost flat against the subgrade. Hence, the ‘n’ value, or, ‘degree of retardance’ decreases as channel discharge increases. The retardance characteristics of various grass types have been determined experimentally under a range of flow intensities that can be quantified as the product of velocity V, and hydraulic radius R. These are shown in Figure 13. Determining the flow conditions in grass-lined channels must be through an iterative calculation process since the values of V, R and ‘n’ are interdependent.

Retardance Classification	Grass Length mm
A - Very High	600 +
B - High	250 - 600
C - Moderate	150 - 250
D - Low	50 - 150
E - Very Low	<50

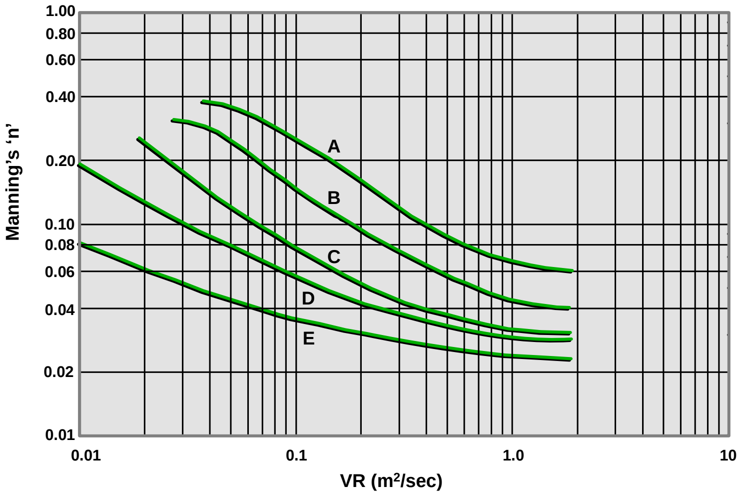


Figure 13 Retardance Categories for Grass-Lined Channels

B) Aggregate Linings

The Manning roughness coefficients of aggregate linings are governed primarily by the size, shape and gradation of the particles. Typical ranges are shown in Figure 14. The 'n' value of aggregate linings can be estimated by application of the following equation:

$$n = 0.0152\, D_{50}^{1/6}$$

where: D_{50} = Stone size (mm)

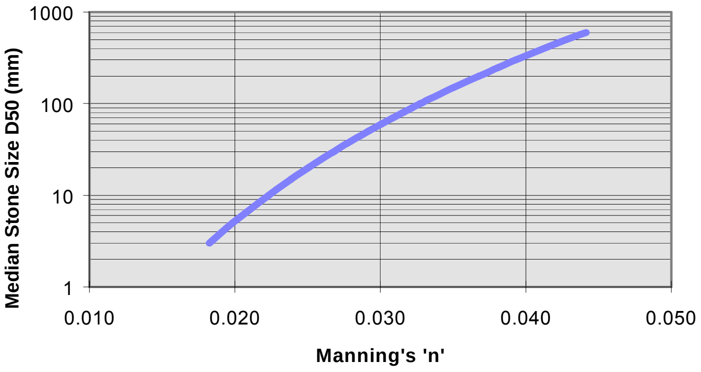


Figure 14 Relationship between Median Stone Size and 'n'

C) Concrete Linings

The roughness coefficients of uniform poured concrete channel linings generally fall within a narrow range of values depending on the applied surface finish. Common finishes will produce 'n' values of 0.012 - 0.022, (see Table 3). Irregular surface geometry or the partial embedment of coarse aggregate particles can be applied to the concrete lining if higher 'n' values are required.

Table 3 Typical Roughness Coefficients for Concrete-filled Geoweb Linings

Surface Finish of Concrete-Filled Geoweb Lining	Typical Range of Manning 'n' Values
Smooth Steel Trowel	0.012 - 0.014
Wooden Float	0.013 - 0.015
Broomed	0.016 - 0.018
Raked	0.020 - 0.022
Partially Embedded Gravel or Rock	0.022 - 0.030
Stepped Multi-layer	0.030 - 0.040

D) Composite Linings

Certain channel sections may employ more than one lining type or finish and are referred to as composite sections. The composite or effective Manning 'n' value for such sections can be calculated as follows:

$$n_c = \left[\frac{\sum_{1}^{i} P_i\, n_i^{3/2}}{P} \right]^{2/3}$$

where:
nc = Composite Manning roughness coefficient
ni = Manning roughness coefficient for lining material in each section
P = Wetted perimeter (m)

3) *Freeboard and Height of Protection*

The required freeboard and the height of a protective lining above the maximum design water level within a channel relates to the size and capacity of the structure. Recommended minimum values are given in Figure 15.

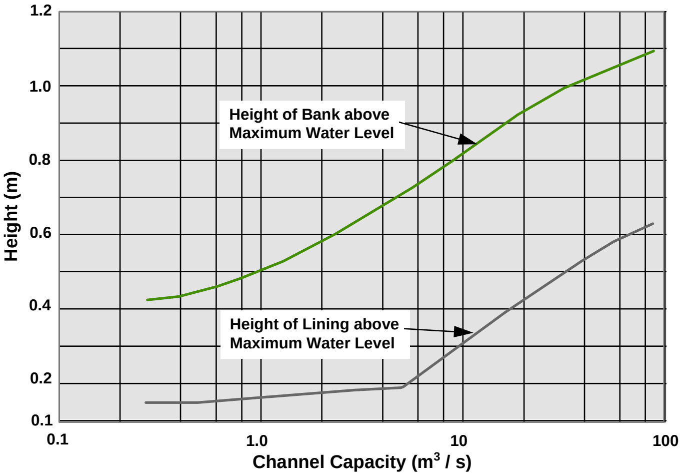


Figure 15 Recommended Freeboard and Lining Height above Water Level

4) *Subcritical and Supercritical Flow*

Subcritical flow conditions exist in channels that have mild bed slopes. Conversely, *supercritical* flows occur in channel sections with steep bed slopes. The Froude number, F_r, determines the nature of the flow and is determined through:

$$F_r = \frac{Q}{A\sqrt{g\,y}}$$

where:
Fr = Froude number
y = depth of flow
Subcritical flow conditions exist when Fr < 1
Supercritical flow conditions exist when Fr > 1

Supercritical flows associated with energy dissipation structures such as spillways and drop structures occur at the downstream outlet as the discharge descends from a higher elevation to a lower elevation. The process involves the transformation of potential energy (hydraulic head) to kinetic energy (velocity head) resulting in the generation of high flow velocities at the structure. The Froude number quantifies the process for design purposes.

Hydraulic jumps occur at the transition from supercritical to subcritical flow for example at the downstream end of a spillway chute. The form and size of a jump and hence the amount of energy that is dissipated in the jump are related to the Froude number of the upstream supercritical flow.

5) *Bernoulli Energy Equation*

The energy at any section in a channel can be expressed as:

$$H = \frac{\alpha V^2}{2g} + y\cos\phi + z$$

where:
H = Total energy head above datum (m)
ϕ = Channel bed slope (degrees)
V = Flow velocity (m/sec)
z = Elevation of invert above datum (m)
g = Gravitational acceleration (m/sec²)
α = Energy coefficient (degree of turbulence - range 1.0 - 1.36)
y = Flow depth (m)

The Bernoulli equation provides a method to determine change in flow depth and velocity between specific sections of a channel once allowances for head or energy losses have been considered. Head losses 'h' can result from boundary friction transitions hydraulic jumps and bends. Hence:

$$h = \left(y_1 + \frac{V_1^2}{2g}\right) - \left(y_2 + \frac{V_2^2}{2g}\right) + \left(z_1 - z_2\right)$$

Frictional losses h_f that occur within a specific reach of a channel can be estimated by applying a derivation of the Manning equation to the velocity head component to give:

$$h_f = \frac{19.6\,n^2\,L}{R^{4/3}} \cdot \frac{V^2}{2g}$$

where:
hf = Head loss due to friction (m)
V = Flow velocity (m/sec)
n = Manning roughness coefficient
g = Gravitational acceleration (m/sec²)
L = Length of channel reach (m)

Application of this equation to a typical spillway is shown in Figure 16.

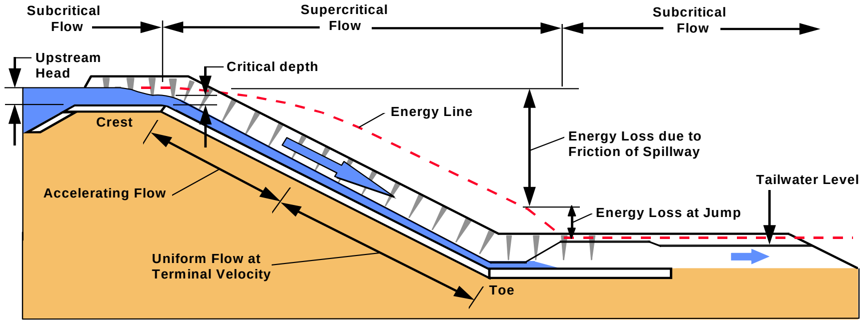


Figure 16 Flow Characteristics of Spillways

6) Momentum Equation

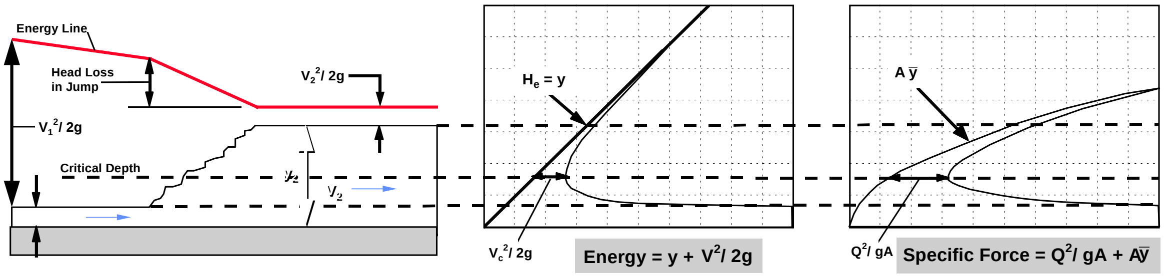
The momentum equation is derived from Newton's Second Law whereby F = M a (Force = Mass x Acceleration). Forces that act on a body of water include pressure, gravity and friction. The specific force, F_s, at a given channel section is defined as follows:

$$F_s = \frac{Q^2\,\beta}{g\,A} + \beta'\,\bar{y}\,\cos\phi\;A$$

where:
F_s = Specific force (N)
A = Flow area (m²)
β = Momentum correction factor
Q = Flow rate (m³/s)
β' = Pressure correction factor
ϕ = Channel slope (degrees)
$\bar{y}$ = Distance from water surface to centroid of flow area (m)

The first term is momentum flow per unit weight of water and the second term is pressure force per unit weight of water. The equation can be used to determine water depths before and after an hydraulic jump. A simplified form of the equation, where β = β' = 1 and the channel bed is horizontal, cosϕ = 1, is as follows:

$$F_{s1} = \frac{Q^2}{g A_1} + \bar{y}_1 A_1 = F_{s2} = \frac{Q^2}{g A_2} + \bar{y}_2 A_2$$



a) Jump Profile b) Energy Head Diagram c) Specific Force Diagram

Figure 17 Energy and Force Profiles of Hydraulic Jump

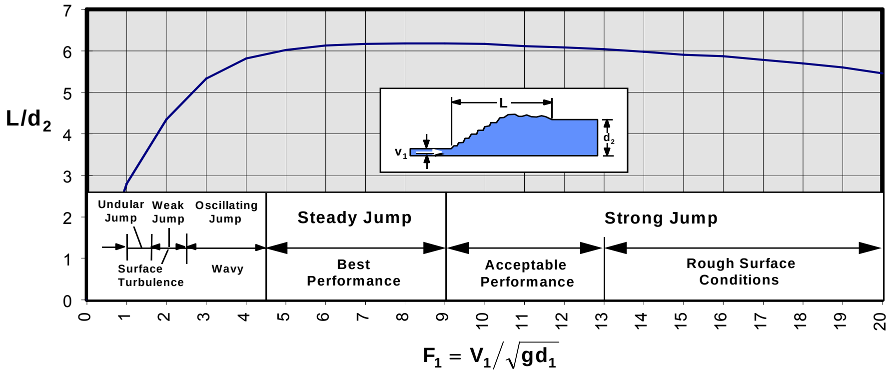


Figure 18 Relationship of Jump Length and Froude Number

Subscripts 1 and 2 denote sections 1 and 2 respectively. Hence, if Q and y_1 (supercritical flow depth) are known, then y_2 (subcritical flow depth) can be found. The equation is generally applied in situations where rapidly varying flow conditions exist. The energy equation will provide similar results if acceleration forces are not excessive.

7) Tractive Forces

Hydrodynamic forces, commonly referred to as *tractive*, *drag* or *shear* forces, are imposed on the protective lining of the bed and side slopes of open channels due to the flow. When the protection is relatively smooth and uniform, the tractive force is related to the hydraulic roughness or lining skin friction. The magnitude of the tractive force is also influenced by the shape and alignment of the channel. The distribution of forces within a typical trapezoidal channel is shown in Figure 19.

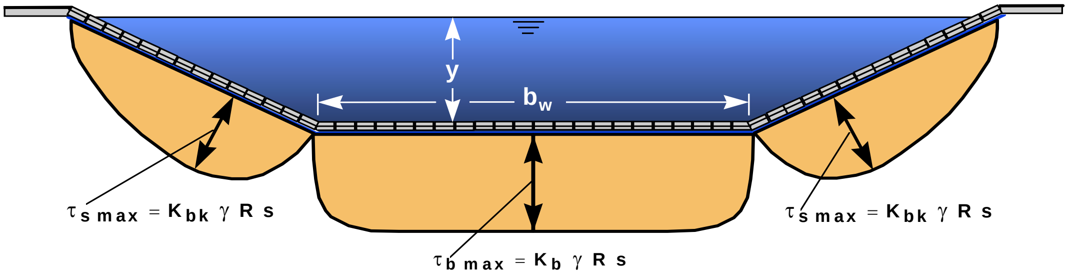


Figure 19 Tractive Force Distribution - Trapezoidal Channel

Maximum tractive forces can be calculated as follows:

$$\tau_{b\,max} = K_b\ \gamma\ R\ s$$

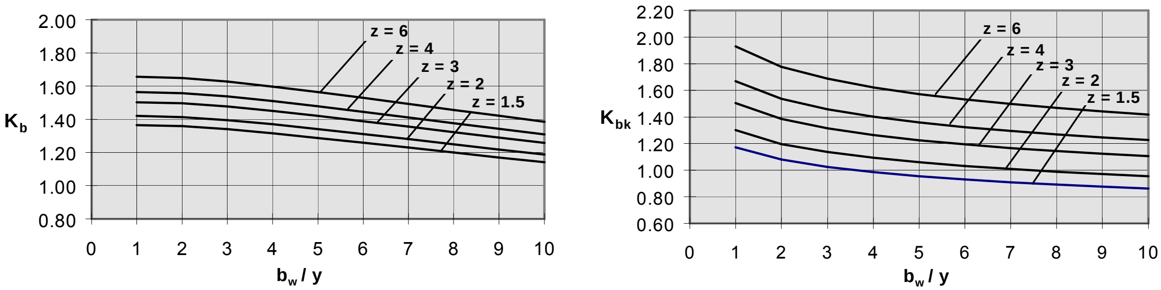
where:

$\tau_{b\,max}$ = Maximum tractive bed force (kg/m²)
s = Bed slope (m/m)
γ R s = Average tractive force along bed (kg/m²)
Kb = Tractive force bed coefficient
γ = Specific force / unit weight of water (kg/m³)
R = Hydraulic radius (m)

$$\tau_{s\,max} = K_{bk}\ \gamma\ R\ s$$

where:

$\tau_{s\,max}$ = Maximum tractive bank force (kg/m²)
Kbk = Tractive force bank coefficient



a) Maximum Bed Boundary Shear $K_b = \frac{\tau_b}{\gamma R s}$

b) Maximum Bank Boundary Shear $K_{bk} = \frac{\tau_s}{\gamma R s}$

Figure 20 Bed and Side Slope Force Coefficients for Trapezoidal Channels

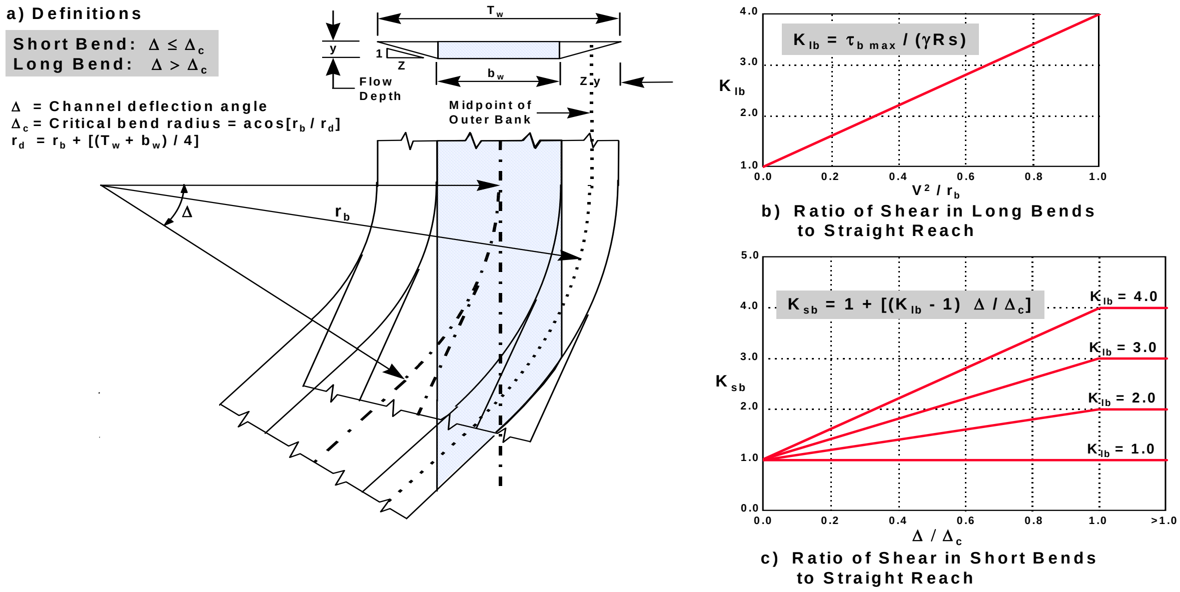
Tractive forces also increase on the outside of bends due to centrifugal forces. These additional forces can be related to the tractive forces imposed on the bed of the channel by application of a suitable bend coefficient K_{bd}.

$$\tau_{bend\,max} = K_{bd}\ \tau_{b\,max}$$

where:

τ bend max = Maximum tractive bend force (kg/m²)
Kbd = Bend force coefficient
τ b max = Maximum tractive bed force (kg/m²)

The bend coefficient depends on whether the bend is classified as ‘long’ or ‘short’. The relationship between bend geometry and force coefficients, (K_{lb} or K_{sb}), is given in Figure 21.



b) Ratio of Shear in Long Bends to Straight Reach

c) Ratio of Shear in Short Bends to Straight Reach

Figure 21 Determination of Bend Length and Bend Shear Ratios

Projections or irregularities in the lining can produce severe localized turbulence and significant additional drag and uplift forces. Special ground anchorage may be required in such situations. The possibility of large debris accumulating in the channel should also be assessed in this context.

Permissible tractive forces for various lining materials and soil types have been established from extensive studies and research. The critical shear resistance of non-cohesive materials on the bed of a channel can be empirically related to the size and density of the individual particles. The stability of materials on the side slopes of channels also depends on the angle of repose of the lining material and the side slope inclination.

The critical shear stress, at which incipient movement of particles on the channel bed will occur, can be determined approximately as follows:

$$\tau_{cd} = 0.0642\, D_{50}$$

where:

τ cb = Critical shear stress of particles on channel bed (kg/m²)

D50 = Median particle size

The critical shear stress of particles on the channel side slopes can be determined as follows:

$$\tau_{cs} = K_{sb}\, \tau_{cb}$$

where:

τ_{cs} = Critical side slope shear stress (kg/m²)

Ksb = $\sqrt{1 - \sin^2 \phi_s / \sin^2 \theta}$

ϕs = Side slope angle (degrees)

θ = Angle of repose of material (degrees)

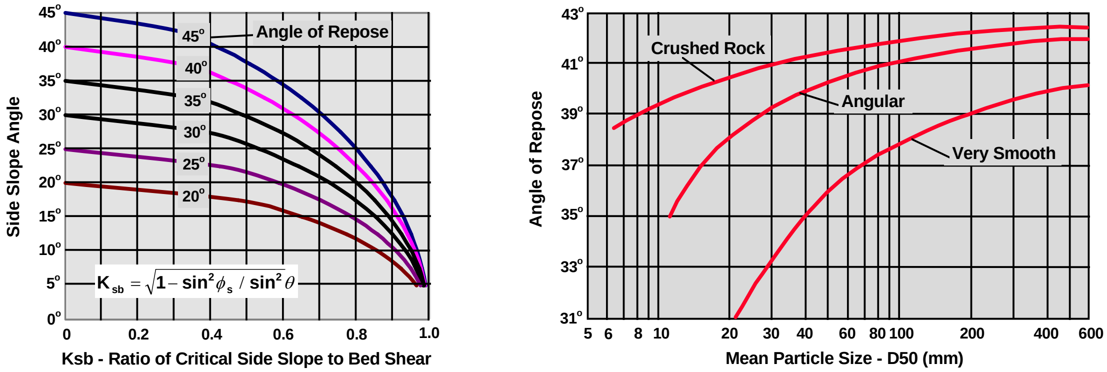


Figure 22 Design Parameters for Unconfined Aggregate Protection

8) *Stability of Geoweb Lining Systems*

A) Vegetated Infill

The overall stability of vegetated Geoweb lining systems with a turf reinforcement mat (TRM) covering, as with all vegetated protection, depends greatly on the quality, density and maturity of the vegetation and its root system. The key function, as discussed previously in 3) *Guidelines for Geoweb Infill Selection*, of the Geoweb system in such applications is the containment and protection of the root zone in order to prevent movement of the saturated soil mass. This capability is particularly important when persistent concentrated flows occur.

The limiting hydraulic stress that a vegetated lining can sustain has been studied by a number of researchers, including Colorado State University (CSU) – Hydraulics Laboratory. Sustainability is a function of the survivability of the grass blade under flow conditions, the health of the root system, the interaction of the root system with the Geoweb cell wall, the characteristics of the saturated soil, and the quality of the covering TRM. From CSU hydraulic studies on the Geoweb / TRM system, a peak velocity of 10 m/sec (33 ft/sec) and a peak shear stress of 860 N (18 lbf/ft²) is attainable without system degradation.

B) Aggregate Infill

Full-scale flume testing of Geoweb lining systems with granular infills was conducted at the Canada Centre for Inland Waters (CCIW), Burlington, Ontario in 1987 and at Colorado State University – Hydraulics Laboratory. The research included the determination of critical flows, slopes, and aggregate D_{50} relative to cell size and depth of aggregate loss within the Geoweb cell. The test results provide a rational basis for the design of aggregate-filled Geoweb linings by relating the variables to aggregate stability. Contact your Presto representative for design recommendations.

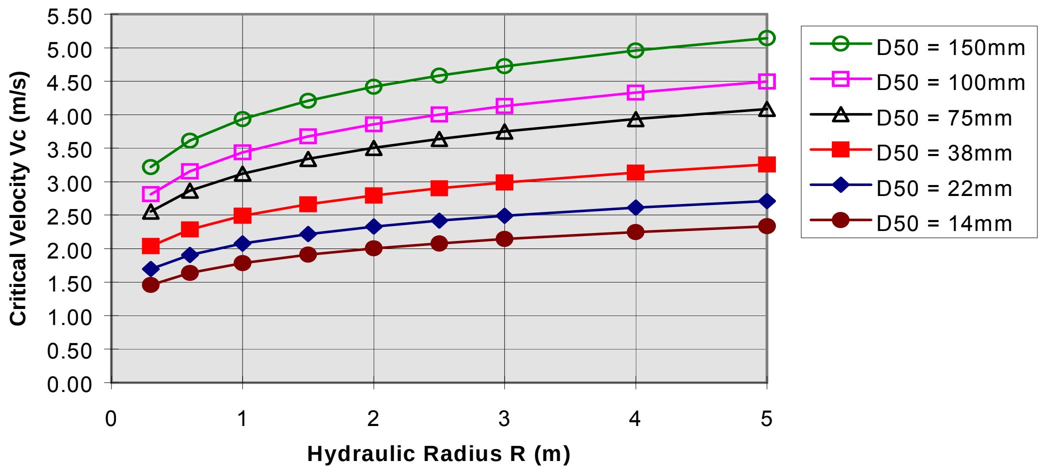


Figure 23 Relationship between Critical Velocity, R and D_{50} with Cells Full (Based on GW20V Cell Geoweb Sections)

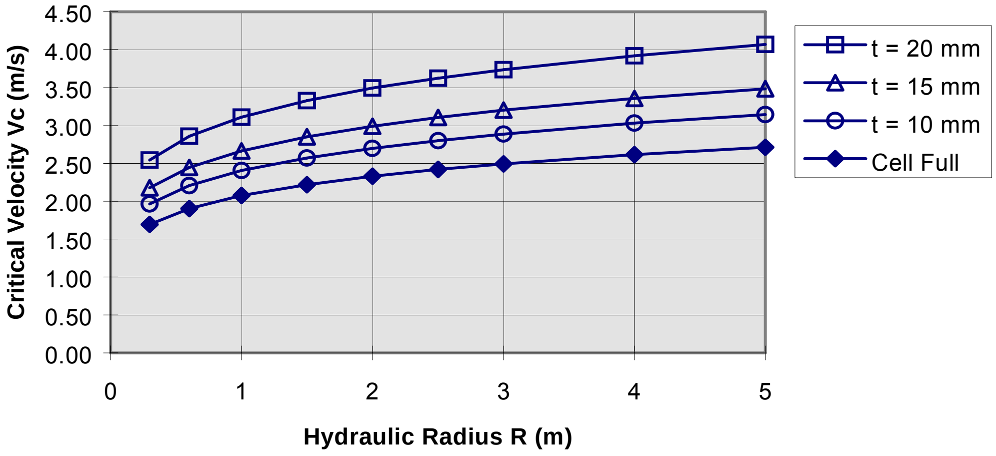


Figure 24 Influence of Cell Emptying on Critical Velocity (D_{50} = 22 mm) (Based on GW20V Cell Geoweb Sections)

Tractive forces which exceed those reflected in Figure 23 cause progressive emptying of the cells. As this process develops, the frictional resistance and shear resistance of the system increase. Hence, a partially emptied lining exhibits significantly higher stability than a Geoweb lining that is aggregate filled. This phenomenon can be quantified in terms of the ratio t/λ, where t = the depth of scour and λ = the length of individual cells in the direction of flow [225 mm (8.8 in) for GW20V Geoweb cell]. Typical performance curves for partially emptied Geoweb cells are shown in Figure 24.

Contact your Presto representative for changes related to aggregate recommendations.

C) Concrete infill

Concrete channel linings, whether in the form of rigid poured slabs or assemblies of individual precast units, can generally withstand high hydraulic stresses that result from uniform or gradually varied flows.

Concrete linings are often the preferred method of protection when severe bed slopes create supercritical flow conditions.

The rough-broom-finish, concrete-infilled, 75 mm (3 in) depth, GW30V Geoweb system was tested at Colorado State University – Hydraulics Laboratory according to ASTM WK7072 and sustained flows up to 10.8 m/sec (35.5 ft/sec) and shear stresses up to 980 N (20.5 lbf/m²) without signs of distress due to its 100% face-to-face contact and a superficial mass of 177 kg/m^2 (36 lb/ft^2).

Also, considerable testing has been carried out on various block systems to establish the limiting flow velocities in relation to block weight and system flexibility. The findings of a number of such tests have been published in CIRIA Report 116 (Reference 4) together with recommended maximum flow velocities as follows:

1) Blocks with face to face contact length less than 75%
   Maximum design velocity - 6 m/sec (20 ft/sec)
2) Blocks with face to face contact length greater than 75%
   Maximum design velocity - 8 m/sec (26 ft/sec)

A minimum superficial mass of 135 kg/m^2 (28 lb/ft^2) is also required.

Available Tools & Services

Presto and Presto's authorized distributors and representatives offer assistance to anyone interested in evaluating, designing, building or purchasing a **Geoweb Channel Protection System.** You may access these services by calling 800-548-3424 or 920-738-1707. In addition to working directly with you, the following design and construction resources are available for your use with the **Geoweb Channel Protection System**.

Design	Material and CSI-format Specifications, System Components Guideline, Request for Project Evaluation, AutoCAD® Drawings, SPECMaker® Specification Development Tool, Technical Resources Library CD, videos
Construction	Installation Guidelines, Anchor Spacing Guidelines, SPECMaker® Specification Development Tool, Technical Resources Library CD, videos

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