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Riprap Alternatives: Application and Opportunities

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COVER PHOTO

Cover photo shows the use of interlocking concrete tri-lock blocks as an alternative to riprap bridge abutment armoring.

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1. EXECUTIVE SUMMARY

Sourcing rock riprap in northern British Columbia has become an increasing challenge in recent years and even when suitable rock is located near a project it is often cost prohibitive to develop it. Discussions with B.C. Ministry of Forests Lands and Natural Resource Operations (FLNRO) have indicated that over the last few years the cost to supply and install riprap has increased from approximately $30/m^3 to $75/m^3 (not including blasting). As a result, FLNRO has requested FPInnovations to review potential riprap alternatives that could be used for forestry applications.

FPInnovations conducted a literature review, held multiple meetings and conference calls with suppliers of riprap alternatives, and worked with one supplier to conduct a theoretical design using riprap alternatives. Through this work it was found that there are several viable rock riprap alternatives that can be used in the forest industry and are currently available on the market. The most significant cost savings were found for products that would replace smaller class riprap (i.e., 35 kg-class). However, marginal savings were found for larger class riprap in situations where the closest riprap source was a substantial distance from the project (e.g., more than 100 km).

Riprap alternatives that were found to be most applicable for the forest industry include rolled erosion control products (RECP), geocells, and precast concrete products (PCCP). RECP considered in this report include turf reinforcement mats (TRM) and high-performance TRM. Erosion control blankets (ECB) are also included as another type of RECP; however, they are a temporary measure used to establish vegetation on site, with long-term flow resistance being derived from vegetation type and coverage. Geocells also can be used as a riprap alternative in some circumstances; however, careful consideration must be given to the site and hydraulic conditions before selecting this type of product. PCCP discussed in the report include tri-lock concrete blocks, articulating concrete block mattresses (ACBM), and three-dimensional concrete units. PCCP appear to have the most promise for replacing large class riprap because they are more durable than RECP or geocells. For example, PCCP are able to withstand impacts from floating large woody debris, vehicles or ice.

When considering use of a riprap alternative it is important to involve qualified professionals who are experienced with these types of revetment systems. Standardized testing for riprap alternatives does not reflect real-world environmental conditions or installation techniques. Testing for these products typically consists of a flume where flows are uniform and the discharge rates are monitored and controlled. Ensuring products are used in a manner intended by the manufacturer and installed according to manufacture specifications is critical to the success of the revetment. Furthermore, some standardized testing facilities are limited in the amount of discharge they can subject riprap alternatives too. It was found that, in some instances, the products did not reach a failure criteria and that design values for shear stress and water velocity were extrapolated from test data.

2. DISCLAIMER

This report is intended to provide a general overview of products currently on the market that can be used as alternatives to riprap in a forest industry setting. This report does not recommend specific products, manufacturers or suppliers; however, presents information obtained from various literature sources and meetings. FPInnovations did not conduct field evaluations of any products described in this report. This report cannot replace professional judgement, and aspects of this report do not apply in all circumstances. When considering use of riprap alternatives it is important to consult professionals with experience and training in their design and installation. In addition, given that products and techniques outlined in this report will be new, even for experienced contractors, owners and field staff; a robust quality management program (QMP) must be implemented to ensure successful installation and long-term performance. As such, a QMP must allow for an adequate number of professional field inspections to ensure installation meets the standards set by design documents.

All budgetary pricing contained in this report, including product and installation costs, vary greatly by supplier, product, region, installation and design assumptions. Further, unforeseen site conditions can increase costs. All budget pricing contained herein was considered during the first quarter of 2016.

3. INTRODUCTION

In northern B.C., rock riprap has become increasingly difficult to source and develop for resource road projects. Reasons for this include a scarcity of suitable rock and a lack of local qualified blasters. Even when blasters are available, and rock is located with in close proximity to a construction site, the cost of mobilization to the northern part of the province is prohibitive. Within recent years this has led to increased resource road and bridge project costs, with some projects being modified or cancelled. As a result, the B.C. Ministry of Forests Lands and Natural Resource Operations (FLNRO) requested FPInnovations to provide a review of alternatives to riprap that are currently available , and assess their suitability for resource road and bridge applications (i.e., revetments, bridge piers, bridge abutments and bank stabilization). Additionally, FLNRO requested FPInnovations to review the testing methodology these alternatives undergo, and whether the testing criteria are applicable to typical forest industry conditions.

4. OVERVIEW

This report investigates current products available on the market that can be used as alternatives to traditional rock riprap, and discuss their suitability in the resource industry. Additionally, the report reviews testing methodologies used by manufacturers to better understand how manufacturer specifications relate to real-world conditions. This report does not provide detailed design methodologies for riprap or riprap alternatives; however, it does provide reference to design manuals and technical reports where further information can be found. Finally, a conceptual review of using riprap alternatives for a bridge replacement project in northern B.C. provides cost implications and benefits of using these products.

5. BACKGROUND

Riprap is the term used to define large, angular blocks of rock typically used on a streambank, shoreline or slope to armor against erosion and scour of underlying soils. Largely due to B.C. geology, riprap has been the most commonly used material for bank protection. It is durable, there is substantial industry experience installing it and, historically, it has been readily available. Additionally riprap structures, as a whole, are flexible and rarely fail even when minor structural shifting occurs or individual rocks are eroded. Furthermore, they are easily constructed and repaired in the event of damage (MOE, 2000). Riprap also provides protection against water action, and when used at a pier location provides armoring against scour which can undermine pier bents, leading to costly repairs or bridge failure. In some instances riprap can provide a buffer against large debris striking bridge piers and abutments; however, this is a secondary function.

Historically, in British Columbia, riprap sources were abundant and developing quarries in close proximity to resource road and bridge projects was common practice. Further, there was an abundance of skilled and experienced blasters in the province available to blast quarries in remote locations. However, in recent years FLNRO has identified that in the northern part of B.C. sources of riprap are becoming less abundant, and even when a quarry site is identified mobilizing blasters to site is cost prohibitive, as they often have to travel from the southern portion of the province.

While riprap has been the most common armoring method in the past, technological advances in geosynthetics, concrete, and biological alternatives are reducing the need for rock to protect against stream, shore and slope erosion. Riprap alternatives include three main types:

1) stand-alone biological solutions (e.g., hydroseeding, live stakes, live fascines, brush matting, live siltation, branch packing, reed clumps, and fibre rolls).

2) combinations of biological armoring and geosynthetics (e.g., turf reinforcing mats, synthetic wattles, and vegetated geogrids).

3) manufactured concrete, steel, and petroleum systems (e.g., rock-filled geocells, rock-filled gabions, concrete lock blocks or interlocking blocks, articulating concrete block mattresses, and A-jacks®[1]).

Alternatives to riprap come with various specifications and guidelines; however, determining how these specifications relate to resource road and stream crossing applications has been a challenge. The testing methodology for many of the riprap alternatives (i.e., geosynthetics and articulating concrete block mattresses) are conducted under uniform flow conditions. When considering bridge abutments or stream channel reinforcement, flow conditions are often non-uniform. The lack of manufacturers' specification regarding the use of these riprap alternatives under lab conditions has resulted in design engineers being hesitant to use them. Understanding how standardized testing relates to real-world conditions, and finding examples where alternatives have been used will provide insight into how they can be incorporated by design engineers. Another challenge is that design specifications for living systems are missing or only now under development because these riprap alternatives are naturally

[1] A-jacks® are precast concrete armor units made of two symmetrical interlocking halves. Each half consists of a central core with three identical legs that radiate outward at 90-degree spacing (Nilex, 2016).

variable. Shallow soil mantle reinforcement is achievable with living systems; however, reinforcement of deeper layers is not well understood.

6. RIPRAP (HARD ARMOR)

Purpose

Conventionally, riprap or hard armor is a layer of large angular rock blocks placed at bridge abutments, bridge piers, stream banks, steep slopes, culvert inlets and outlets and as lining in conveyance channels (ditches) to prevent damage caused by scour, erosion and sloughing (Brown and Clyde, 1989). Riprap revetments protect against this damage through a combination of rock weight, size gradation, durability and thickness (MOE, 2000). Furthermore, riprap must be used at bridge abutments and piers to prevent the scour and erosive action of shifting or constricted stream channels caused by disturbance to the natural banks following bridge and road construction (FLNRO, 1999). Decisions regarding riprap use are dependent on the stream channel characteristics and design flood event; or in the case of steep slopes, the slope gradient, length and soil type. For streams, riprap dissipates energy of the flowing water thereby reducing its ability to erode the soils beneath. On steep slopes, riprap is often placed on the bottom third of the slope to prevent rotational type slope failures. Typically, riprap is placed on a geosynthetic or granular filter layer which distributes the weight of the riprap evenly over the area, while allowing for separation of fine soil particles, relief of hydrostatic pressures and uniform settlement of the riprap blanket.

Riprap also serves the purpose of protecting against impacts and mechanical forces. This is particularly true in B.C. where heavy rains and spring runoff regularly occur. Another consideration in B.C. is ice and the potential for large ice flows to damage elements of infrastructure and redirect streamflow. In cold northern climates the freeze and thaw action in-between riprap may dislodge individual rocks and compromise revetment integrity. Additionally, freeze and thaw can break down rock size over time. Ensuring riprap is sized appropriately can mitigate potential damage caused by large debris and ice.

Design Considerations

When designing with riprap several factors must be considered, such as, 'is the structure to be armored?', the stream characteristics, and source of riprap material. Designing a riprap revetment for a permanent structure bridge abutment on a high-flow stream with significant flood events is different than designing for a temporary bridge on an ephemeral creek that may see flows only half of the year. Just as important, knowing what rock sources are available can influence the design process.

Rock size selection is one of the most important considerations when designing a riprap revetment or armor blanket. Determining the rock size requires designers to have a thorough understanding of the stream characteristics, as well as what is being protected. First designers must consider the design discharge, flow type, section geometry, capacity of the stream to carry debris and extent of required protection (Brown and Clyde, 1989). When this is understood decisions can be made regarding rock size and gradation, riprap revetment thickness, filter layer design, end and top treatment of the revetment, bank slope and vertical extents of the revetment, toe treatment and scour protection and which construction methods best suit the site (MOE Water Management Branch, 2000). FLNRO's Bridge Design and Construction Manual (1999) provides further information regarding riprap design considerations and concepts, as well as allowable riprap size and mass classes based on the estimated maximum stream velocities (Table 1). In the case of FLNRO bridge projects, the minimum required thickness for riprap armoring is 1.75 times the nominal D_{50} size. The nominal D_{50} size is based on a rock particle mixture where no more than 50 percent by mass is smaller than the median size[2].

Table 1. Riprap size and mass classes recommended for various stormflow velocities (FLNRO, 1999)

Nominal (D_{50}) riprap size class (mm)	Riprap mass class (kg)	Maximum stormflow velocity (m/s)
200	10	2.5
300	35	3.0
450	125	3.6
600	280	4.2
800	700	4.8
1000	1300	5.3
1300	2800	6.0

Failure Methods

Several common failure modes have been identified for riprap which includes particle erosion, translational slides, modified slumps and slumps (Brown and Clyde, 1989). To combat these failure modes adequate rock sizing, weight, gradation, durability and revetment blanket thickness is required (MOE, 2000). As discussed, one benefit of riprap is that minor failures in the revetment blanket are easily repaired and often times do not compromise the structural integrity of the revetment. However, if design considerations for the site are inadequate, for example inadequate rock size based on the estimated design discharge, than failure of the revetment is likely.

Particle erosion is a common riprap revetment failure mode. Typically, this is caused when the resistive forces of the revetment are exceeded by the hydrologic forces. Rocks are dislodged from the revetment and often deposited in the channel bed adjacent to the revetment. If rocks are allowed to deposit adjacent to the revetment and build up, this can cause additional particle displacement as the flows are deflected and turbulent. While there are many causes of particle erosion, several common causes are; inadequate stone size; individual stones removed by impact or abrasion; bank slope exceeds angle of repose and gradation is too uniform (Brown and Clyde, 1989).

Translational slides are another common failure mode of riprap revetments and are commonly initiated when the toe of the revetment is undermined. Undermining can be caused by particle erosion, channel thalwag migration or impacts from debris and ice. Translational slides are characterized by a separation

[2] D_{50} of 200 mm means that no more than 50 percent of the rock particles, by mass, are smaller than 200 mm as measured along the rocks intermediate axis (FLNRO, 1999).

in the revetment blanket that forms a fault line running parallel to the channel direction. The separated riprap on the lower portion of the slope will migrate down the slope and may result in bulging at the bottom of the slope. Some identified causes of translational failures are; overly steep bank side slope; excess hydrostatic pressures under the revetment; undermining of revetment toe caused by erosion or some other method (Brown and Clyde, 1989).

Modified slump failures are characterized as a mass movement of material along an internal failure surface. This type of failure is similar to a translational failure, however, the geometry of the damaged riprap resembles early stages of failure caused by particle erosion. Additionally, the causes of modified slump type failures are more subtle and may include the riprap resting very near it’s angle of repose; as a result any imbalance or movement of individual rocks creates instability in adjacent rocks or the revetment. Another potential cause is when material that is critical to the support of the upslope riprap becomes dislodged by settlement of the submerged riprap, impact, abrasion or particle erosion (Brown and Clyde, 1989).

Slump failures are a rotational-gravitational movement of the riprap along a concave upward curved failure plane. These failures are related to underlying base material that supports the revetment. Excess pore pressures are the typical cause, and result in the shearing and displacement of materials along a slip surface. Known causes of slump failures are; heterogeneous base material with layers of impermeable material that act as a fault line when subject to pore pressure; and, overly steep side slopes where the force of gravity exceeds the inertial force of the riprap and base material along the friction plane (Brown and Clyde, 1989).

Another failure mode often overlooked for riprap revetments is nuisance or persistent flows beneath geosynthetic layers. Riprap revetments are often designed for a specific design discharge event such as the 100-year storm event, or Q_{100}. When these storm events occur and there is a “catastrophic failure” of the revetment it is often attributed solely to the storm event. Ian Corne with Nilex Civil Environmental Group based out of Burnaby B.C. has been working with various revetment systems for over 13 years, and believes nuisance or persistent sub-surface flows beneath revetment geosynthetic mats is the underlying cause of many catastrophic failures. Sub-surface flows erode soils beneath the geosynthetic and eventually lead to erosion gullies or large voids beneath the revetment. High tensile strength geosynthetic is able to span these voids under static conditions, maintaining the appearance that the revetment is in good condition. However, under storm conditions the added weight and violence of high water velocity causes the geosynthetic to burst. This can result in riprap being dislodged from the revetment similar to particle erosion failures described above. While additional research is needed to confirm whether nuisance or persistent subsurface flow is a major contributor to riprap revetment failures, taking this into consideration when designing with riprap will increase the durability of the structure (Corne, 2016).

Issues with Sourcing Riprap in British Columbia

The two major challenges to developing riprap in northern British Columbia come from regional scarcity of suitable rock and a lack of certified blasters. These challenges also provide significant motivation for finding suitable applications for riprap alternatives. British Columbia is a vast province, covering almost one million square kilometers. As such, the geology of B.C. is highly variable, with some areas having abundant riprap sources while others have virtually none. There are five distinct physiographic regions in B.C.: The Coast mountains and islands, the Interior plateau, the Columbia mountains and southern Rockies, the northern and central plateaus and mountains, and the Great Plains (Valentine *et al*, 1978). The geology of each region is unique, and the effects of glaciation and erosion have played a critical role in the abundance of riprap sources. Regions west of the Rocky Mountains tend to have abundant exposed bedrock which can be developed into riprap, while areas east of the Rocky Mountains tend to have deep deposits of glacial drift overlying bedrock. Additionally, exposed bedrock east of the Rocky Mountains tends to be sandstone and shale which is not ideal for riprap due to its lack of durability (Catto, 1991).

In the southern portion of B.C. there are many drilling and blasting companies capable of developing riprap quarries. The majority of companies are based in Kamloops with some in the Columbia/Kootenay and Vancouver Island regions. These blasting companies are often busy working for other industries such as oil and gas or mining, and when they are able to schedule work in the north the cost of mobilization is often high. Further, according to sources within FLNRO, the cost of supply and install of riprap (not including blasting) has more than doubled in recent years. The high cost of mobilization, coupled with the increased cost of supply and install has led to some FLNRO projects being delayed or re-designed.

7. RIPRAP ALTERNATIVES

There is an identified need within the forest industry to find appropriate riprap alternatives that are able to withstand the challenges of remote construction sites, limited monitoring, and unpredictable environmental conditions. Riprap alternatives are not widely used in the forest industry, however, some products are being used for civil applications.

Typical civil construction applications for riprap alternatives include conveyance structures where rock riprap would be used such as ditch lines, storm water collection ponds, ephemeral or intermittent stream banks and parking lot or construction run-off. In general, these types of conveyance structures are adjacent to residential, commercial or industrial areas where resources and expertise are abundant during installation. Additionally, structures located near these areas can be easily monitored following construction, and have any identified issues quickly remedied. Forestry applications for riprap alternatives face different challenges than their civil counterparts, as construction is often in remote locations where stream flows may be perennial with periods of extreme flows, ice build-up, and transportation of large woody debris. Further, unpredictable environmental conditions can exceed design assumptions, and remote locations make regular monitoring of structures a challenge.

There are several manufactured concrete, steel, and petroleum system options available on the market which include Rolled Erosion Control Products (RECP), geosynthetic cellular confinement systems (geocells), and Pre-cast Concrete Products (PCCP). RECP are typically made of either geosynthetic or natural fibre materials to create an erosion-resistant barrier that can promote natural vegetation and be used in a number of conveyance or slope stabilizing applications. PCCP, such as articulating concrete block (ACBM) mattress systems and A-jacks®, can be used in a similar manner as traditional riprap. All riprap alternatives have benefits and drawbacks, and it should be noted that although manufacturer specifications may be available, a professional with experience designing these types of revetment systems should be consulted.

Rolled Erosion Control Products

RECP encompass a range of products that can be used for short and long term armoring applications. The American Society for Testing and Materials ASTM describes RECP as "*a temporary degradable or long-term non-degradable material manufactured or fabricated into rolls designed to reduce soil erosion and assist in the growth, establishment and protection of vegetation".* A discussion with various suppliers of RECP and a review of various manufacturer specifications indicates the potential to use RECP as a riprap alternative in a variety of forestry applications. However, RECP may not be a suitable replacement for riprap in large streams where significant flows carry large debris or ice which can damage the RECP revetment. In fact, conversations with colleagues in the U.S.D.A. Forest Service have indicated the RECP should only be used as a riprap alternative for low gradient / low turbulence systems.

The two types of RECP's applicable for use in the Forest Industry are Erosion Control Blankets (ECB) and Turf Reinforcement Mats (TRM). ECB and TRM are similar in that they are both a rolled blanket system that provides immediate protection against shear stress and erosion, while promoting the growth of vegetation through the blanket. The establishment of vegetation results in a stable root mat which increases the shear strength capacity of the system, reduces water turbidity and stabilizes slopes. The main differences are that ECB are a temporary measure used to promote establishment of vegetation, and typically incorporate natural fibres such as straw and coconut matting into the matrix. ECB are typically well suited for conveyances with shallow slopes and intermittent flow conditions such as ditch lines, ephemeral stream channels, or unstable slopes. They can also be placed over top of a seeded surface. ECB's are not meant for use in turbulent flow conditions or where high design discharges are expected. ECB typically exhibit flow and shear stress resistance strengths similar to fully vegetated structures (Table 2). It should be noted that ECB typically address surficial slope erosion issues, and that ECB final design values for flow and shear stress resistance in a vegetated state are ultimately dependant on the vegetation type and coverage that develops on the site.

Table 2. Typical ECB flow and shear stress resistance values (vegetated state) derived from averages of several similar products available on the market

ECB type based on service life	Flow (m/s)	Shear stress resistance (Pa)
Short Term (<6 Months)	1.8	80
Medium Term (< 2 Years)	2.5	105
Long Term (< 3 Years)	3.4	130

TRM utilize a three-dimensional structure and are intended for long-term bank protection against scour and erosion, while promoting vegetation establishment through the geosynthetic mat. The three-dimensional structure of TRM's promotes vegetation growth by allowing germination beneath the blanket while protecting the seeds from erosion or becoming food for birds and small mammals. Once in place, TRM's have an immediate benefit in protecting the bank from scour and erosion and are able to resist modest flows and shear stress prior to vegetation establishment. As vegetation grows up through the three-dimensional matrix it bonds the mat to the ground surface, further increasing the

TRM's ability to resist intense storm flows and shear stress (Table 3). In situations where a TRM might be unable to properly protect against design flood events, the stream bank is extremely steep or bank soils are prone to instability a high-performance TRM can be used. High performance TRM's are made of durable geosynthetics and incorporate specialized anchor systems to further increase their ability to reduce erosion and scour (Figure 1).

Table 3. Typical TRM flow and shear stress resistance values derived from averages of several similar products available on the market

TRM category based on installed bank gradient and anticipated water flow t	Maximum Flows (m/s)		Maximum Shear (Pa)	
Table text	Unvegetated	Vegetated	Unvegetated	Vegetated
≤ 1:1 Slope Moderate to High Overland Flows	2.7	4.9	96	383
≥ 1:1 Slope Moderate to High flows	2.9	4.6	120	383
≥ 1:1 Slope High Flows	3.2	6	144	478
≥ 1:1 Slope Extreme High Flows	3.8	7.6	156	576
High-Performance TRMs	4.6	7.6	285	742

The ability of RECP's to resist erosion and scour while promoting vegetation growth make them suitable for forestry applications. Promotion of vegetation enhances the environmental value of the site and can potentially create habitat for fish and small animals. In addition vegetation will capture and retain sediments, acting as a filter for reducing water turbidity and promoting deposition of any eroded materials. Field studies have shown that utilizing TRM's doubles the flow velocities vegetated banks can withstand (Theisen and Carroll, 1990). Considering RECP's ability to resist erosion and scour, while promoting vegetation growth, potential forest industry applications may include stream bank stabilization or remediation, bridge abutments on low-gradient / low-flow streams, culvert inlets and outlets, road decommissioning, slope stabilization and ditch lines. For applications in streams, it should be noted that RECP's are not able to resist mechanical impacts such as logs or large branches floating down stream. Once damaged, erosion and scour may occur beneath the RECP further propagating the damage and causing the RECP to separate from the subgrade altogether. With this in mind a professional assessment of the use of RECP's should include the potential for damage by impact or ice.

Figure 1. Example of a HPTRM and cable anchor system (Propex, 2013).

Engineering Properties and Standardized Testing

RECP manufactures submit their products to a range of standard and proprietary test methods in order to provide quantifiable measure of their physical properties and engineering capabilities. The property that directly relates to use as a riprap alternative is the RECP's ability to resist flow and shear stresses. Tables 2 and 3 provide an overview of capabilities for several categories of ECB's and TRM's available on the market, however, these values are averages of several similar products and not appropriate for design purposes.

The standard test method used for characterizing RECP performance is ASTM Internationals' D6460 *standard test for determination of rolled erosion control products performance in protecting earthen channels from stormwater-induced erosion*. The objective of this test is to determine the relationship between shear stress and soil loss, determine the relationship between velocity and soil loss and determine hydraulic conditions of failure in the test channel. To accomplish this, a test channel is prepared with a rectangular cross-section that has the RECP installed in it. Water is delivered to the channel through a regulated water delivery system that can be monitored to ensure consistent flow rates. Water flow from the delivery system is parallel to the flume slope through the test channel which allows evaluation of soil loss based on a known flow rate. A minimum of three tests are performed for the RECP, with failure criteria for unvegetated tests being 12.7mm of soil loss or catastrophic failure and vegetated tests being 12.7mm soil loss, catastrophic failure or enough erosion to allow continuous flow of water beneath the RECP (ASTM 6460, 2012).

Another consideration for using RECPs on stream banks or hillslopes is their ability to protect against rainfall induced erosion. ASTM Internationals' D6459 Standard Test Method for Determination of Rolled Erosion Control Products Performance in Protecting Hillslopes from Rainfall-Induced Erosion evaluates this. However, as with installation of any RECP, installation techniques, and site conditions vary greatly from laboratory test environments. This test method utilizes a full-scale test procedure to simulate conditions typically found on construction sites prior to vegetation establishment and provides for a comparative evaluation between bare soil and those covered by an RECP. This is an important consideration in forest operations as introducing sediments to ditches or streams can have negative impacts on the aquatic environment. The test evaluates RECP ability to reduce soil loss and sediment concentrations during simulated storm events and the ability to protect water quality. Bare soil plots are compared to those with RECP installed over top by collecting runoff water and quantifying the amount of sediment in the samples. The test can also be applied to RECP's with vegetation established on them which can then be used to determine effective vegetation coverage for various rainfall intensities (ASTM 6459, 2015).

Design Considerations

Due-diligence should be exercised when considering the use of RECP's. Standard testing methods, such as the ASTM 6460, do not reflect typical field installation techniques, site conditions or turbulent flows (AASHTO-NTPEP, 2011). Furthermore, these testing methods evaluate sheet flow parallel to a slope, while typical installation on a stream channel or adjacent to a bridge abutment would have flows perpendicular to the slope. Therefore engaging a design engineer with experience using RECP's is required. Additionally, a site evaluation is required to determine the appropriateness of using certain types of RECP's. As a general rule, RECP's should only be used as a stand-alone alternative to riprap on streams with low gradients, minimal turbulent flows and low potential for transporting large woody debris, branches or ice. Furthermore, the ability to monitor the RECP revetment should also be considered.

A thorough discussion of using RECP's for conveyance systems can be found in the National Highway Associations Hydraulic Engineering Circular No. 15 (HEC-15) The HEC-15 provides a comprehensive overview of design considerations for the use of RECP's in roadside channels (Table 4).

Table 4. HEC-15 Design Considerations for using RECP's for conveyance systems (Kilgore and Cotton, 2005)

Open channel flow	Shear stress	Design parameters
• Type of flow • Normal flow depth • Resistance to flow	• Equilibrium concepts • Applied shear stress • Permissible shear stress	• Design discharge frequency • Channel cross section geometry • Channel slope • Freeboard

Additional consideration should be given to using RECP's as part of a larger system. For example, RECP's can be used to protect portions of an embankment or stream channel that only experiences flows during extreme discharge events. On the lower portions of the slope riprap or concrete riprap alternatives could be used. In this way, the embankment can be completely protected, while saving the cost of placing riprap over the entire slope. Additionally, the RECP will allow vegetation to establish which adds to the aesthetics of the revetment, increases capacity for shear stress and flow resistance and can act as a filter to keep road sediments out of the stream.

As discussed above, manufacturer specifications and standardized testing for maximum permissible flow rates and shear are typically derived from flow conditions parallel to the test slope. As a result, specialized edge treatment, anchor pattern layout or seam fastening may be critical to the long-term durability of the system to ensure that stream flows cannot lift up the edges. Layout and density of anchor rods and staples is a significant consideration (for example Figure 2). Field staff experienced with the installation of RECP believe that when RECP systems fail it is often a result of contractors not adhering to anchor rod or staple layout and density. Supervision during the installation of an RECP system, therefore, should be performed by personnel experienced with their use, and periodic field inspections by the designer should be carried out as part of a quality management program to ensure a successful installation and long-term system performance. The extra time spent at the front end of the project will reduce the potential for costly re-work, maintenance or repairs to improperly installed RECP systems.

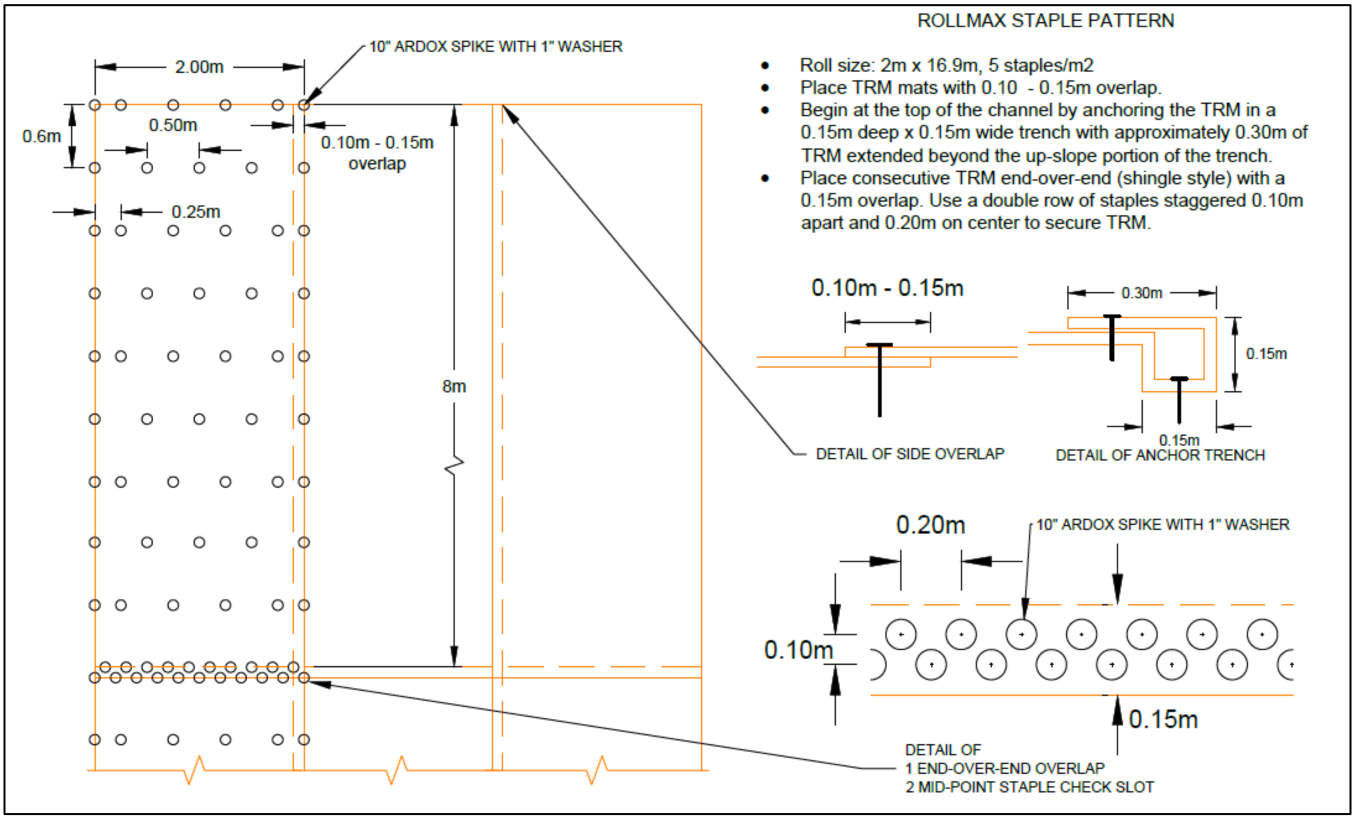


Figure 2. Example TRM staple pattern (Nilex, 2014).

Geosynthetic Cellular Confinement Systems

Geosynthetic cellular confinement systems (geocells) were originally developed in the late 1970's by the U.S. Army Corps of Engineers for building stabilized roads expediently out of sand. Since then a host of applications has been found for this technology such as stabilizing steep embankments, streambank protection and armoring ditch lines. Geocells are comprised of a matrix of three-dimensional cells arranged into an expandable mattress that is anchored to a surface and infilled with material (Figure 3). Discussions with Jarrod Penny, from Layfield Group Construction, indicates that a geocell product they supply, GeoWeb®[3], can be used to protect stream banks, channels, and ditch lines from erosion caused by extreme storm discharge events. For forestry applications, GeoWeb® would be used as part of a system, overlaid with a TRM to ensure materials remained confined within the cells. This would provide additional protection from erosion and scour while allowing vegetation to grow on the slope. Site preparation would include installation of a separation layer beneath the geocell, such as a non-woven geotextile.

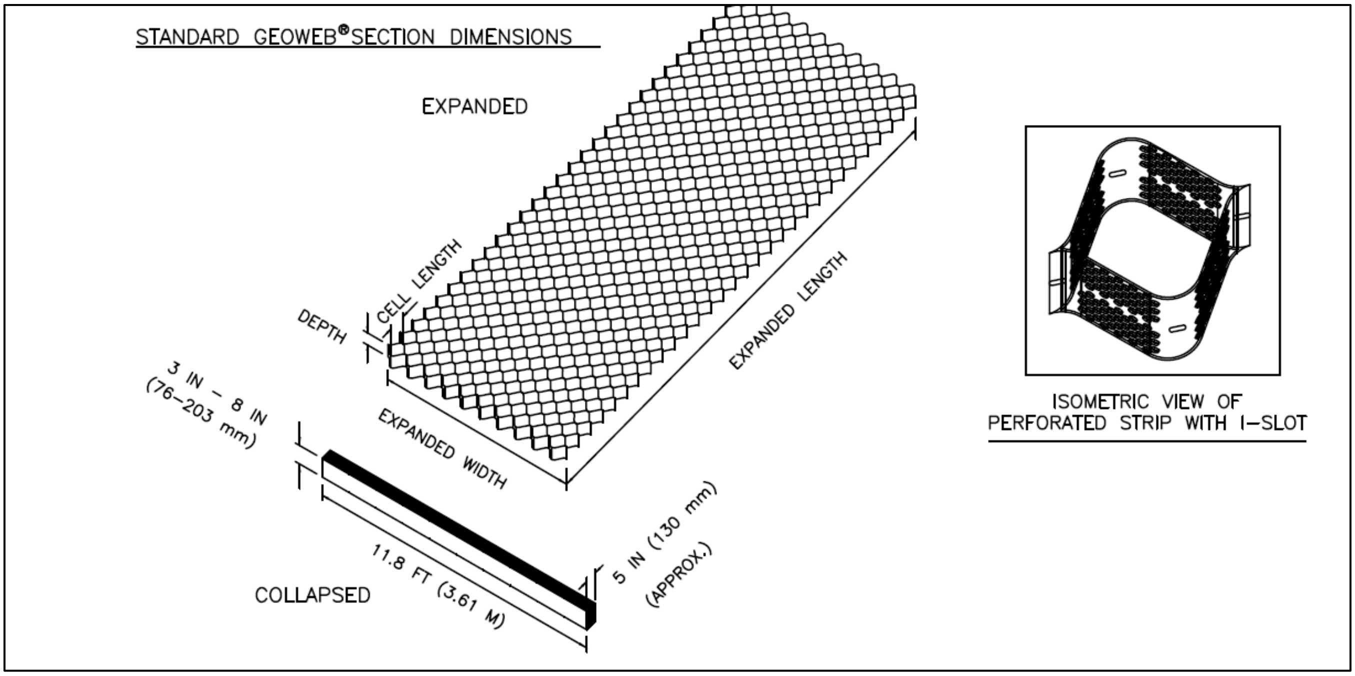


Figure 3. Standard GeoWeb section (Presto, 2013).

Engineering Properties and Standardized Testing

Between April 2005 and August 2006, Presto Geosystems tested GeoWeb® as part of a composite system with a TRM overlay in a flume system at Colorado State University Steep-gradient Overtopping Facility (CSU SGOF) at the Hydraulics Laboratory of the Engineering Research Center (ERCD). The objective of the test was to determine thresholds for shear stresses and flow rates in order to quantify

[3] GeoWeb® is a three dimensional cellular confinement system that can be infilled with a variety of coarse granular material, topsoil, or concrete. The three-dimensional structure holds the upper soil layer in place on slopes and prevents erosion and scour. Additional information can be found at: https://www.layfieldgroup.com/Geosynthetics/Erosion-and-Sediment-Control-Products/Geoweb-Slope-and-Channel-Protection.aspx

the hydraulic forces the system could handle. The test used GW30V, 150 mm deep, GeoWeb® and North American Green C350 composite turf reinforcement matting. This integrated system was established in a planter test box with the GeoWeb® installed to manufacturers specifications then infilled with soil, the TRM was installed overtop and seeded with Kentucky bluegrass. Vegetation was allowed to establish over a 14 day period allowing root integration throughout the system. For the test, the planter box was put in a flume at a slope of 2:1 (horizontal to vertical). Water was pumped into the flume at a uniform flow rate parallel to the slope. Six tests were performed on the composite geocell / TRM system; however, due to facility constraints system failure of 13 mm soil loss was not achieved. The maximum discharge flows achieved during testing ranged from 0.4 m^3/s to 3.1 m^3/s. Maximum shear stresses achieved during testing ranged from 550 Pa to 760 Pa (Presto, 2007).

Another cellular confinement system available on the market is Geo Products' EnviroGrid® geosynthetic cellular confinement system. Similar to other geosynthetic cellular confinement systems it has a three-dimensional structure and can be used to protect and stabilize steep slopes and stream channel banks. In July of 2014, EnviroGrid® was tested at the TRI Environmental Research Laboratories in Texas as per the ASTM 6460 methodology. For the ASTM 6460 standard test an RECP system is considered to have failed once 13 mm depth of soil loss has occurred. However, for geocells it is believed this would provide overly conservative permissible flow and shear values because geocells provide containment throughout the topsoil layer, with common cell depths ranging from 75 mm to 150 mm. As such, the testing methodology was amended to consider 25 mm and 38 mm of soil loss from the system. EnviroGrid® was tested for maximum permissible flow and shear for five conditions; infilled with 50 mm-size rock, infilled with 100 mm-size rock, infilled with soil and seeded with Bermuda grass allowing six weeks to establish cover, infilled with soil and covered with Bermuda grass sod, and infilled with soil and seeded with Bermuda grass allowing six weeks to establish cover plus a TRM overlay. Results of the testing can be found below (Table 5).

Table 5. EnviroGrid® flume test results for limiting flow and shear values at 13 mm, 25 mm, and 38 mm soil loss (Geo Products, 2014)

Infill Material	Limit Velocity (m/s)			Limit Shear (Pa)		
Soil loss	13 mm	25 mm	38 mm	13 mm	25 mm	38 mm
EnviroGrid® with 2" [50mm] Rock	2.1	11.2	14.6	158	254	345
EnviroGrid® with 4" [100mm] Rock	8.8	11.2	13	225	292	345
EnviroGrid® with 6-Week Bermuda Grass	12.6	16.9	20.2	316	412	488
EnviroGrid® with Bermuda Sod	16.5	25.4	27.6	383	517	622
EnviroGrid® with 6 Week Bermuda plus TRM	22	27.2	30.4	469	575	646

Design Considerations

When considering a geocell revetment as an alternative to riprap armoring it is important that they are used in appropriate locations. Furthermore, professionals with experience and training in the design and installation of geocells should be consulted. Geocells can be used as a method for making smaller rock sizes perform similar to large rock sizes as seem by the testing done with EnviroGrid®. They can also be used as part of a system with TRM's, as shown by the Colorado State University testing of GeoWeb®, to create a revetment that promotes vegetation growth. The advantage of using a geocell is that it can be infilled with materials that would typically be considered unsuitable as backfill. This is due to the geocells ability to confine material within the three-dimensional matrix. Examples of material that can be used for infilling geocells are sand, local pit run, poorly graded gravel aggregate; poorly graded crushed rock and concrete. As with any revetment system that is an alternative to traditional riprap, a qualified professional should be part of the design team to ensure the system is appropriate for the application.

Testing at the CSU SGOF showed that geocells can be successfully used as part of an integrated system with a TRM. Due to facility constraints at CSU SGOF, the maximum discharge rate that the GW30V GeoWeb® in an integrated system could be tested at was only 3.1m^3/s. As such, any subsequent design discharge claims would be extrapolations of this data. Design discharge flows for a Q_{100} event can be significantly higher than 3.1 m^3/s. In forestry applications it may be necessary to utilize a geocell with smaller cell dimensions to increase the stability of the system such as the GeoWeb® GW20V. Using a smaller cell size ensures adequate confinement of infill materials, especially on steep slopes. Cost of the GeoWeb® is based on product type and amount needed. Additionally, when using GeoWeb®, it is recommended that a non-woven geotextile is placed as a separator between the geocells and the subsoils. The typical cost for Layfield's LP6 non-woven geotextile is $1.00/$m^2$. Budgetary pricing for GeoWeb® can be found in Table 6.

Table 6. Budgetary pricing of GeoWeb®

	Unit Cost ($/$m^2$)			
Product	GW20V4 (100 mm cell depth)	GW20V6 (150 mm cell depth)	GW30V4 (100 mm cell depth)	GW30V6 (150 mm cell depth)
	$14.50/$m^2$	$20.50/$m^2$	$12.00/$m^2$	$18.00/$m^2$

As with most riprap alternatives, impacts by large woody debris or ice can compromise the integrity of the system. In the event a section of the geocell revetment is damaged, the underlying separation layer of non-woven geotextile will be exposed but would continue to provide erosion protection under moderate flow conditions, however, during extreme flows complete failure of the revetment may occur. Washing away of infill material beneath the TRM under normal environmental conditions is also a concern with these systems, especially where highly erosive subsoils exist. In some instances, the TRM placed over the geocell may hide erosion of geocell infill; over time the loss of material may form an erosion gully that is spanned by the TRM but not visible. This can lead to a catastrophic failure of the system during a storm event, similar to that discussed for riprap. As such monitoring and periodic inspections should be taken into consideration when deciding whether to use these systems.

Pre-cast Concrete Products

Several pre-cast concrete products (PCCP) are available in western Canada that can be used in a similar manner as rock riprap, providing a more durable and damage resistant revetment than the RECP's discussed above. Tri-lock concrete blocks, articulating concrete block mats (ACBM) (Figure 4), and A-jacks® (Figure 5) can be readily transported to remote locations, and can be used as an alternative to large classes of riprap.

A tri-lock revetment is a system of triangular interlocking concrete blocks made of two components, a 'lock block' and a 'key block' (report cover photo). Each component is keyed into the other allowing the blocks to articulate and conform to curves in the subgrade. When interlocked the blocks are still able to slide vertically past each other which allows for partial settlement of the underlying formation without loss of system integrity. Table 7 presents physical data for the two sizes of tri-lock concrete blocks. The 100 mm (4") thick blocks can accommodate stormflows that, according to FLNRO (1999), would require 35 to 700 kg-class riprap. The 150 mm (6") thick blocks can accommodate stormflows that, according to FLNRO (1999), would require 700 to 2800 kg-class riprap. Typically underlain with a woven geotextile, tri-lock blocks are manually placed to create a revetment. The edges of the revetment should be buried below scour depth to prevent undercutting. The revetment can be further stabilized by promoting vegetation of the site (e.g., adding grass sod into the voids between the blocks and by adding wattles or willow whips along the upper edges of the revetment). A combination of block thicknesses could be used to increase roughness to slow stream flow for fish (e.g., when creating the streambed portion of an armored ford)(Sambo, 2000). Tri-lock blocks cost between $38 and $45 per square metre and, to this, the underlying woven geotextile costs would add about $1 per square metre (transportation and installation costs are in addition to this).

Table 7. Properties of Tri-lock Concrete Blocks

Block thickness (mm)	Coverage per pair of blocks (1 key and 1 lock block) (m^2)	Mass of pair of tri-lock blocks (1 key and 1 lock block) (kg)	Maximum stormflow velocity (m/s)
100	0.19	31	3 – 4.9
150	0.19	44	4.9 - 6

ACBM are a matrix of interconnected concrete blocks that can articulate independently of each other. Blocks can be either closed or open celled depending on the application, and are connected by geometric interlocking, cables, ropes or geotextiles (Figure 6). ACBM are commonly manufactured into 2.7 m by 6.2 m (8 feet by 20 feet) mattresses that require, at minimum, a 30 ton-class excavator to lift into place. A-jacks® are a six-legged pre-cast concrete structure with the legs radiating outwards. They can be arranged in various configurations, and are light weight enough that they can be placed by hand in difficult to access sites.

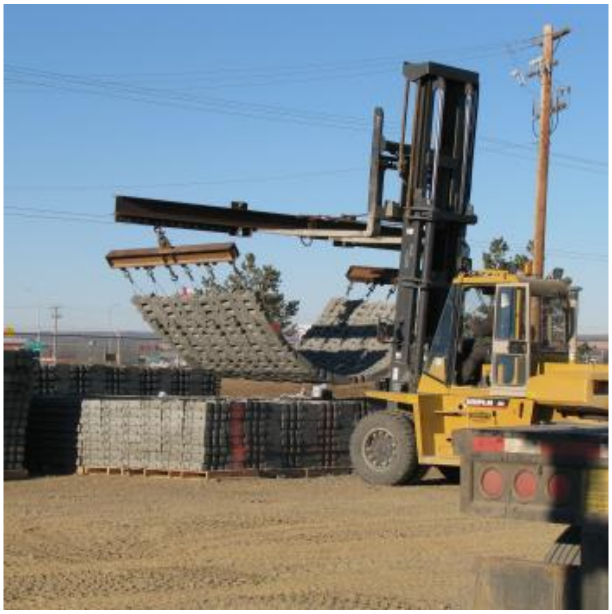


Figure 4. ACBM being stacked for transport (Nilex[a], 2016).

Figure 5. A-jacks® being installed on a stream bank (Nilex[b], 2016).

There are several articulated concrete block revetment systems available on the markets that can be used as an alternative to riprap armor revetments. ACBM differ in several ways, and selection of an ACBM will depend on site specific design criteria. ACBM come with either open or closed cells. Open cell ACBM's are lighter than closed cells, with approximately 20% open space in the mat. The open cell ACBM can be infilled with vegetation. Closed celled ACBM's are heavier, and therefore, provide a more durable revetment than open celled ACBM's. Additionally, closed celled ACBM's are less likely to be damaged during high flows by large woody debris as there are no openings for debris to get caught. The second differentiating point for ACBM's is how they are connected. Connection type can be geometric interlocking, cables, ropes, geotextile, geogrids or a combination of these (ASTM-7277, 2008). In general, ACBM mats cost between $40 and $50 per square metre, however, with transportation and installation costs can be expected closer to $225 per square metre.

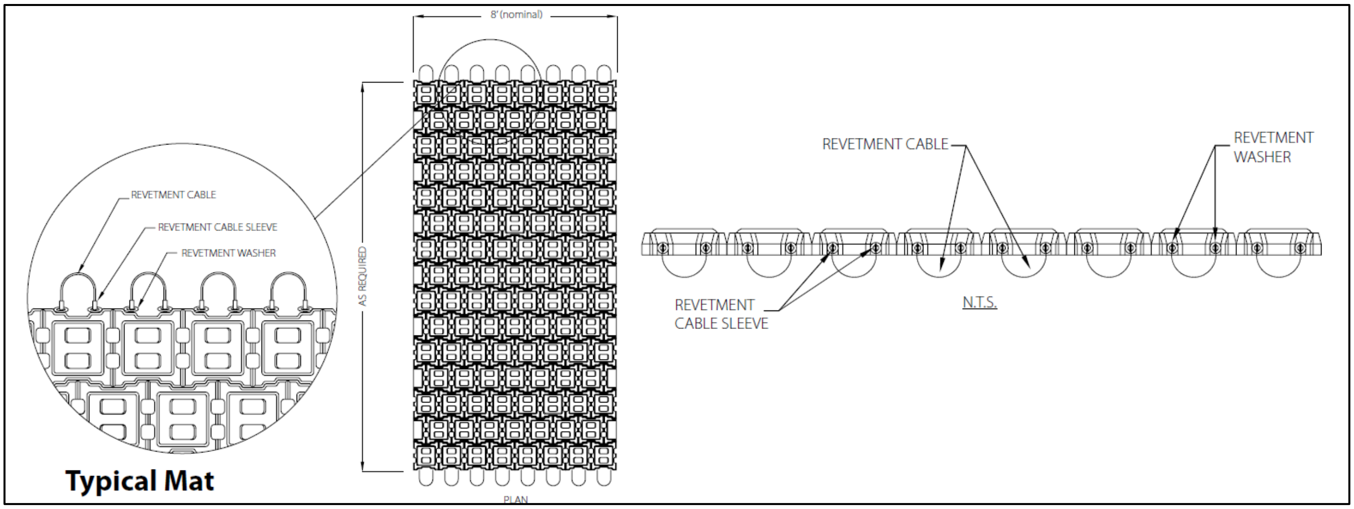


Figure 6. Standard drawing of an ArmorFlex® ACBM revetment mat (Contech, 2012).

Installation of ACBM's requires proper site preparation and attention given to anchoring. Installation begins with subgrade preparation and installation of a free draining layer to a depth equal to the depth of the ACBM. Inclusion of the drainage layer is site and product specific, and the design for inclusion of a well graded filter layer and/or nonwoven geotextile is to be assessed on a project-by-project basis. For the free draining layer, a local pit run aggregate can be used; however, it will require an evaluation to ensure the gradation will act as an adequate filter layer. Excavation of a toe trench is then required that will allow a minimum of two blocks to be buried below the predicted scour depth of the channel. An anchoring trench at the top of the embankment may also be necessary depending on site conditions, and should allow a minimum of two blocks to be buried. A geotextile should then be placed over the slope, including in the trenches. Once this has been completed the ACBM mat can be laid on the slope and secured using helix, duckbill or platypus type anchors (Figure 7).

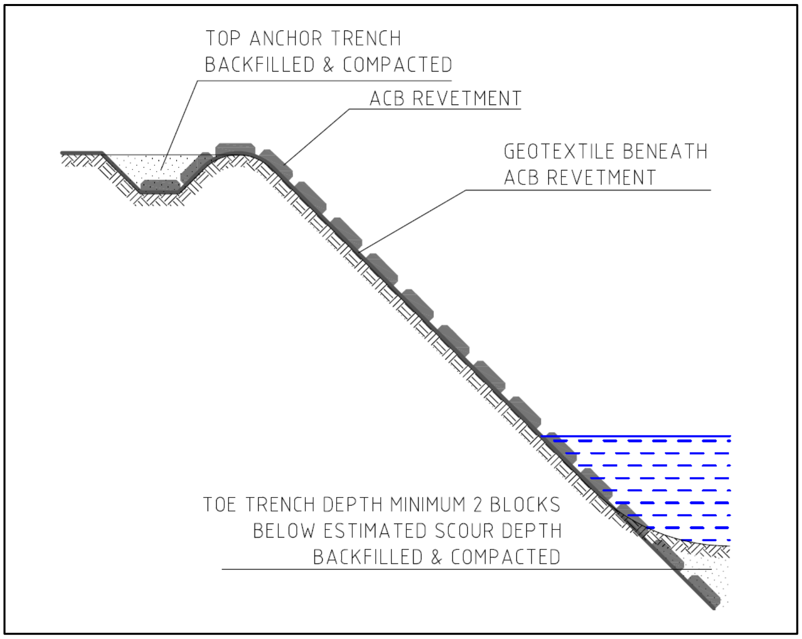
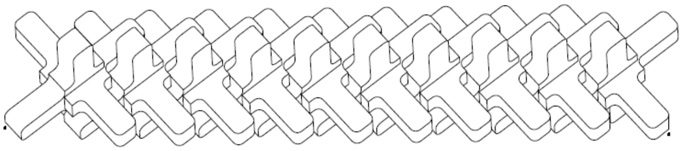


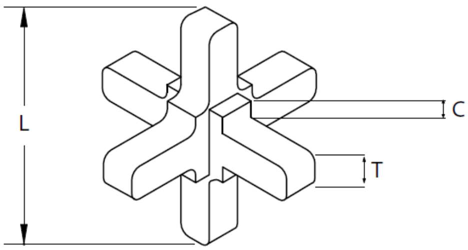
Figure 7. Typical ACBM revetment installation along stream bank.

A-jacks® are a three-dimensional concrete armoring system that can be placed individually or as a unit (Figure 8). A-jacks® are six-legged units which are durable under a range of environmental conditions, and have been used to successfully armor bridge piers and abutments, river banks and culvert outlets. The interlocking design allows for a flexible revetment system with approximately 40% void space. Laboratory tests have shown A-jacks® to dissipate the energy of high-flow water and prevent scour and erosion at bridge abutments and piers (Ayres, 1999). Furthermore, the A-jacks® allow fine particles suspended in the water column to settle out and infill the voids which strengthens the cohesion of the unit matrix and provides additional scour protection (Nilex[c], 2016).

When assembled A-jacks® weigh approximately 35 kg, have a total length of 0.6 m, height of 0.4 m and fit together at approximately three units per lineal metre (Figure 8). They can be installed individually or as a preassembled unit. Similar to other bank protection measures, subgrade preparation is important. First, the stream bank should be contoured and prepared by excavating a toe trench below the stream channel bottom, with a depth equal to the height of one A-jack®. A geosynthetic should then be placed in the toe trench and draped over the bank to be protected. Typically, the non-woven geotextile specified for use will depend on the filtration characteristics of the site and the amount of required resilience to anticipated construction damage. Once the toe trench is prepared and the geosynthetic is in place, A-jacks® can start being installed either individually or as pre-assembled modules. Pre-assembly is recommended as the required modules can be assembled in a staging area free of hazards or challenges and then cable tied and lifted into place with an excavator. A-jacks® are stacked as required until the design elevation is achieved. Excavated material from the toe trench can be dumped back through the A-jacks® to infill any voids. Installation around bridge abutments and piers will require additional design consideration, and may require individual placement of A-jacks® (Nilex[c], 2016). Typical cost of an A-jacks® piece is $25, with a cost of $250/m when stacked two courses high; two on the base with one on top.



A-Jacks Placement Profile



A-Jacks Unit

A-Jacks Unit Specification

A-JACKS	L(IN)	T(IN)/H(IN)	C(IN)	VOL(FT^3)	WT (LBS)
AJ-24	24	4	1.84	0.56	78

Figure 8. A-jacks® standard specifications (Contech, 2012).

Engineering Properties and Standardized Testing

ACBM mats and concrete armoring units undergo stringent quality control during the manufacturing process to ensure the final product meets ASTM and CSA standards for precast concrete products. Testing allows for real-time evaluation of the concrete mix design and ensures quality control of raw materials used. Standard tests include temperature, air content, density and yield and compressive strength. Additional tests can be performed on the finished product as required or requested by the design engineer (NPCA, 2013).

Testing for ACBM mat resistance to flow and shear stress forces is similar to testing for RECP's, and uses a flume system with a controlled discharge and water monitoring system. The ASTM standard for ACBM mats is the ASTM D7277-08 Standard Test Method for Performance Testing of Articulating Concrete Block Revetment Systems for Hydraulic Stability in Open Channel Flow. In addition, there are two companion standard test documents that establish how test results should be interpreted (ASTM D7276-08) and how the ACBM revetment system should be installed (ASTM D6884-03). The ASTM D7277-08 test consists of a continuous four hour flow over the ACBM at a uniform discharge. The test is repeated at higher flow rates until the ACBM revetment shows deformation, soil loss or a loss of contact with the soil subgrade. Determination of a failure can be somewhat subjective, as it may be difficult to observe minor deformations or soil loss during the four hour continuous flow period. However, if upon completion of the test any of the following conditions are present than it can be assumed that the threshold has been reached.

- Vertical displacement or loss of a block (or group of blocks)
- Loss of soil beneath the geotextile, resulting in voids
- Liquefaction and mass slumping/sliding of the subsoil

At this time there is no standard testing method for A-jacks® concrete armoring units. However, model and full scale laboratory tests conducted by the manufacturer Armortec Inc. at the Colorado State

University’s (CSU) Engineering Research Center have documented their hydraulic characteristics and performance capabilities under a variety of conditions. Model and full scale tests were conducted to show A-jacks® ability to protect stream bank channels from toe erosion, stabilize slopes and protect bridge abutments and piers from scour. The study evaluated 150 mm scale models, and the full-size 0.4 m high A-jacks® under flume conditions. A-jacks® were evaluated individually, and in a variety of high-density interlocked configurations. It was found that the high-density interlocking configurations provided the most consistent stability performance. Results of these tests are the foundation of a design manual for A-jacks® created by Ayres Associates (1999) for Armortec Inc. Additionally; A-jacks® are an accepted pier scour countermeasure under the U.S Federal Highway Administration (FHWA) Guidelines.

Design Considerations

As with RECP’s standard testing methods for ACBM revetment systems does not reflect real world conditions or field installation techniques. Therefore, it is important to understand the limitation of ACBM revetment systems when considering their use as a riprap alternative. The FHWA Hydraulic Engineering Circular No. 23 (HEC-23) provides hydraulic design procedures for both ACBM bank revetment and bed armor systems along with ACBM systems to prevent scour at bridge piers. For these design procedures, the first step is determining a Factor of Safety (FS) which requires professional experience and judgement. Additional considerations include the effect protruding blocks will have on the system, longitudinal and vertical extents of the revetment and the filter requirements required beneath the revetment, either geotextile or coarse granular material filters are common. For design of pier scour protection measures, hydraulic uncertainties surrounding bridge piers warrant increasing the FS, and taking into consideration the layout details of the ACBM system so that it slopes away from the pier in all directions (Figure 9); filter requirements; how the ACBM will be sealed where it meets the bridge pier; and how the ACBM will be anchored in place (Lagasse *et al*, 2009 Vol. 2). Furthermore, for forest industry applications, the cost of transportation for the ACBM and equipment will need to be considered, as well as performance monitoring.

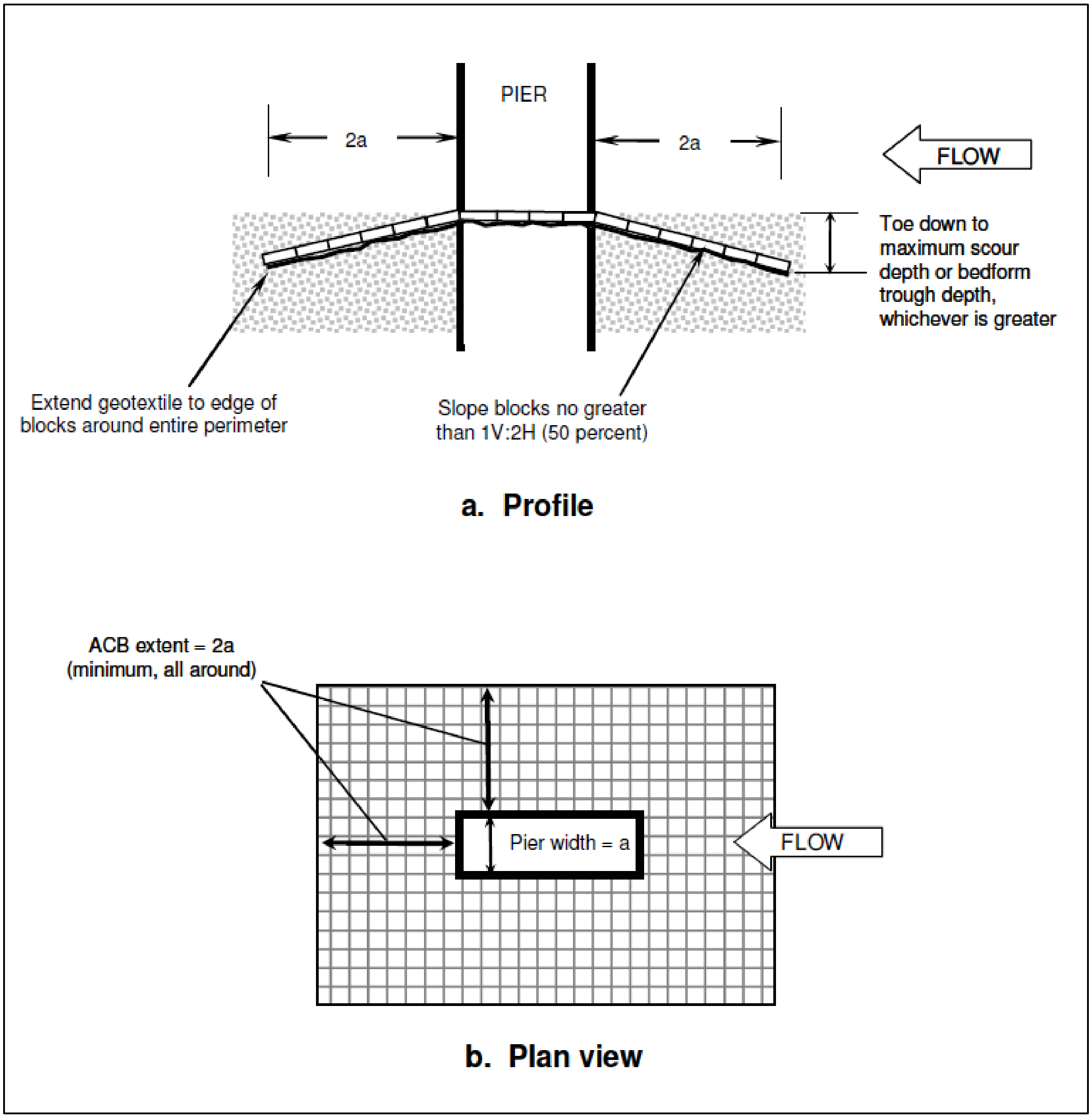


Figure 9. ACBM layout diagram for pier scour countermeasures (Lagasse *et al*, 2009 Vol. 2).

Concrete armor units, like A-jacks®, have been successfully used as a replacement for riprap in situations that require large rock sizes to resist extreme hydraulic forces. This includes shorelines, channels, streambanks and scour protection at bridges. Their consideration for use over the last century has grown considerably, and they have even been used by the U.S. Army Corps of Engineers for channel protection (Ayres Associates, 1999). Their primary advantage is that they typically have greater stability than riprap and can be interlocked to create complex shapes. This increased stability and interlocking capability allows them to be placed on steep slopes, in locations with challenging access and at bridge abutments and piers (Figure 10 and Figure 11). Furthermore, they are lighter than the riprap used for equivalent flow conditions (Lagasse *et al*, 2009 Vol. 1).

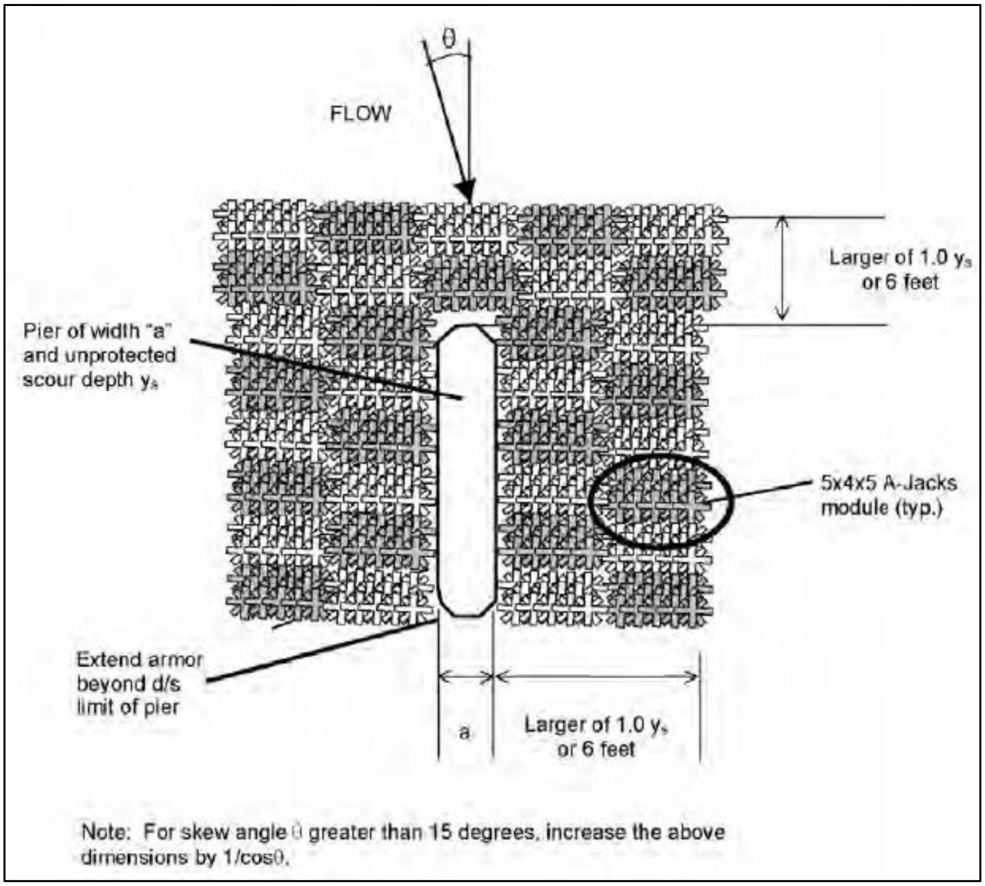


Figure 10. Plan view of A-jacks® modules used for pier scour protection (Lagasse *et al*, 2009 Vol. 2).

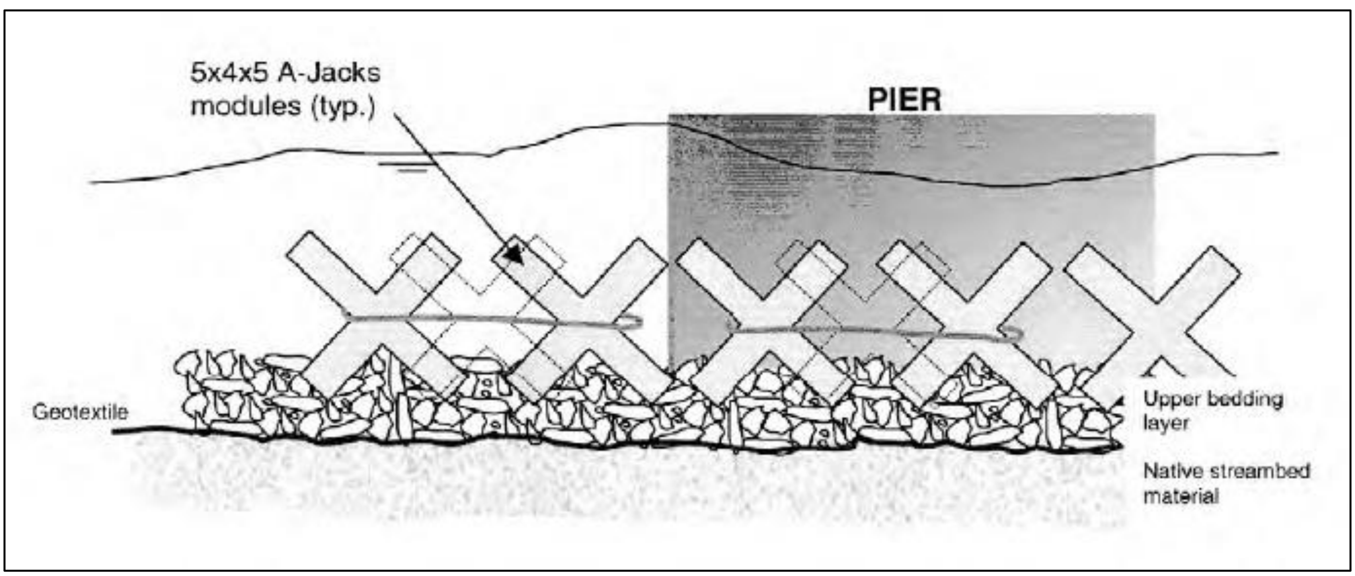


Figure 11. Detail of A-jacks® installed at a pier on a bedding layer of blast stone with geotextile (Lagasse *et al*, 2009 Vol. 2).

A design manual for A-jacks® was prepared by Ayres Associates from Fort Collins, Colorado, for the manufacturer Armortec, Inc. in August 1999. The design manual provides technical information and guidelines for the hydraulic design of stable open-channel conveyance structures and scour protection for piers using A-jacks®. Data for the manual was provided to Ayres Associates by Armortec and the Colorado State University's (CSU) Engineering Research Center. Technical information presented in this manual is based on laboratory tests conducted at CSU, and are extrapolations of scale models. Therefore, designers must use professional experience and judgement when considering the use of A-jacks® for armoring stream banks, bridge abutments and piers. Provided in the manual are scaled design shear stress and design velocities for the 0.6 m A-jacks®. These are given as 1820 Pa and 6.7 m/s, respectively, when installed on a 13% slope and A-jacks® are arranged in a high density interlocking pattern. It should be noted that these values represent a specific arrangement of A-jacks® under specific flow conditions; however, it does provide a good benchmark for designers. Similar to ACBM's, consideration must be given to the transportation and installation costs of A-jacks®, and it may be necessary to create a staging area where A-jacks® can be assembled and lashed together prior to lifting into place.

8. THEORETICAL DESIGN USING TURF REINFORCMENT MATS

A theoretical case study using TRM was performed for a recently completed FLNRO bridge replacement project located at approximately 4.4 km on the Lower Goat Road near McBride, B.C. This project was completed between April and June 2015, with the installation of a 100 foot-long span bridge over the Goat River. The bridge was designed for the Q_{100} storm event, with design discharge estimated at 189 m^3/s, and an estimated velocity of 4.8 m/s. The design called for approximately 55 m^3 of 35 kg-class riprap, and 360 m^3 of 700 kg-class rip rap to armor the upstream bridge approach (Appendix A). At the time of construction, riprap was not locally available and had to be transported by rail to a staging area 3 km from the bridge. Fortunately, CN Rail provided the transportation at no cost to FLNRO, as the bridge was of critical importance to CN Rail's operations in the area.

The purpose of the theoretical case study using TRM as riprap alternatives was to gain an understanding of how these technologies could be applied in a forestry setting, their cost, and the benefits (constraints) of using them. Working with Nilex Civil Environmental Group based out of Burnaby B.C., three TRM were considered for the Lower Goat Road project:

1. ArmorMax®[4] as an alternative to the 35 kg-class riprap
2. P550 Vmax[5] TRM as an alternative to the 35 kg-class riprap
3. ArmorFlex® as an alternative to 700 kg-class riprap

Four scenarios were evaluated using the three TRM: one scenario using ArmorMax®, one using P550 Vmax as an alternative to 35 kg-class riprap, and two scenarios using ArmorFlex® as an alternative to 700 kg-class riprap. Scenarios were based on an assumed haul distance for rock riprap and costs to

[4] ArmorMax® is a flexible anchor reinforced vegetation system consisting of three-dimensional high performance turf reinforcement mats and earth percussion anchors.

[5] P550 Vmax is a turf reinforcement mat that can be used on slopes ≥ 1:1 in extremely high flow channels. It consists of three UV stable extra heavy weight polypropylene nets with a 100% polypropylene fiber matrix in between.

quarry and process, and transport. For the scenarios comparing 35 kg-class riprap to TRM alternatives, it was assumed that a suitable riprap source was located within 20 km of the project site considering most projects have access to smaller class riprap within this distance. For the larger 700 kg-class riprap two haul distances were used, 100 km and 500 km. These distances were selected as it was unknown where the closest riprap source was located in proximity to the project, and it can be assumed that if CN Rail had not provided transport, the riprap would have been brought in by truck from significant distances. Additionally, having to transport larger class riprap 100 km or more in northern B.C. is a reasonable expectation, while transporting riprap 500 km would represent a worst-case scenario.

Scenario 1: Nilex ArmorMax® compared to 35 kg-class riprap

Assumptions for this scenario were as follows:

- 35 kg-class riprap hauled from a pit 20 km from project site
- 35 kg-class riprap placed in a 450 mm-thick blanket
- $70/m^3 – quarry and process, and install 35 kg-class riprap
- $30/m^2 – ArmorMax® system cost (includes anchors and delivery to site)
- $10/m^2 – Armormax® installation cost
- Costs of site prep and sub-excavation not considered

For this scenario, using the ArmorMax® System a total cost savings of $1,157 was found compared to 35 kg-class riprap produced and hauled from a pit 20 km from the project site (Figure 12). There is also an estimated 3.8 hours in time saved by using ArmorMax® compared to riprap. Additional benefits of using the HPTRM include reduced carbon emissions; vegetation growth on the slope, installation can be done by general labor saving on machinery wear and tear, and increased job site safety (Appendix B).

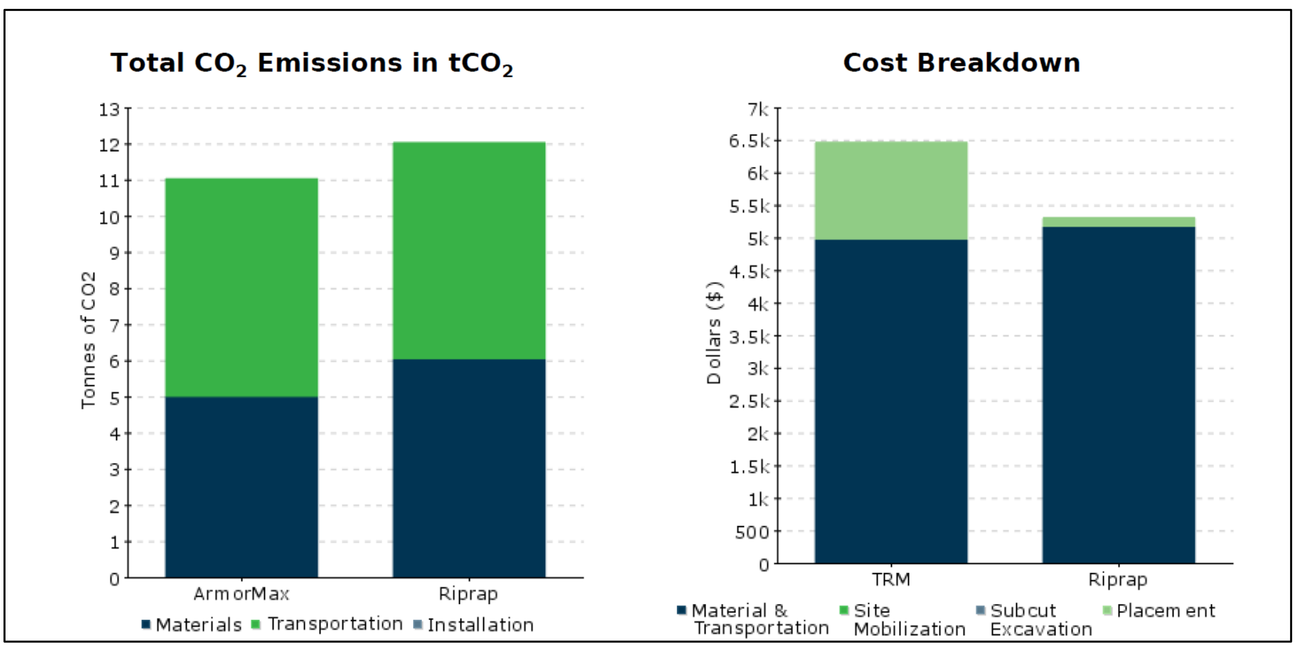


Figure 12. Carbon emission and cost comparison of Nilex's Armormax® vs. 35 kg-class riprap (Appendix B).

Scenario 2: P550 Vmax compared to 35 kg-class riprap

Assumptions for this scenario were as follows:

- 35 kg-class riprap hauled from a pit 20 km from project site
- 35 kg-class riprap placed in a 450 mm-thick blanket
- $70/m^3 – quarry and process, and install 35 kg-class riprap
- $10.50/m^2 –Vmax® system cost (includes anchors and delivery to site)
- $10/m^2 –Vmax® installation cost
- Costs of site prep and sub-excavation not considered

Results of this scenario were similar to Scenario 1, however, additional costs savings were found for using the P550 TRM of $2,000 when compared to 35 kg-class riprap hauled from 20 km (Figure 13). The majority of cost savings come from the lower unit price of the P550 Vmax, because this product is not as robust as the Vmax® system evaluated in Scenario 1. Additional benefits of using the P550 TRM include reduced carbon emissions, vegetation growth through the TRM (carbon sink), installation requires only general labor, no truck or machinery damage from the riprap and jobsite safety is increased (Appendix C).

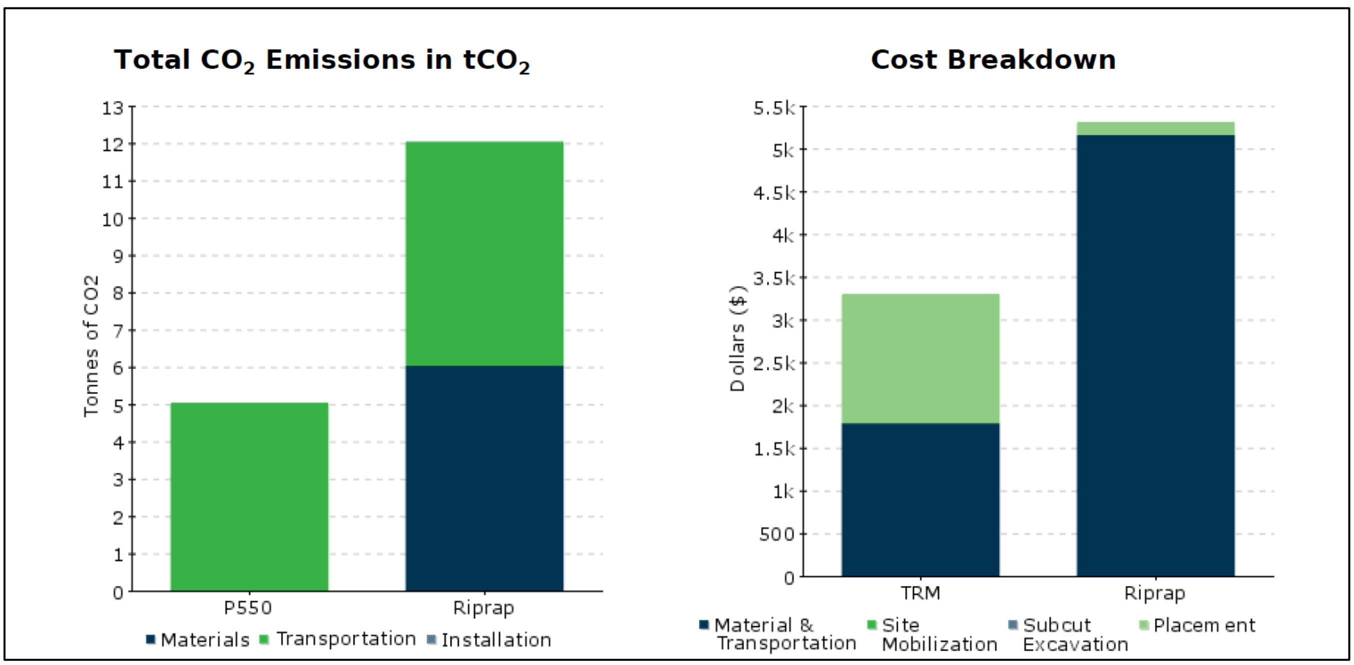


Figure 13. Carbon emission and cost comparison of Nilex's P550 Vmax TRM vs. 35 kg-class riprap (Appendix C).

Scenario 3: Class 75 ArmorFlex® ACBM compared to 700 kg-class riprap hauled 100 km

Assumptions for this scenario were as follows:

- 700 kg-class riprap hauled from a pit 100 km from project site
- 700 kg-class riprap placed in a 1400 mm-thick blanket
- $130/m^3 – quarry and process, and install 700 kg-class riprap
- $90/hour – transportation cost for 700 kg-class riprap (2 hour round trip)
- $225/m^2 – Class 75 ArmorFlex® ACBM revetment (includes delivery and install)
- Costs of site prep and sub-excavation not considered

For this scenario Nilex proposed the use of the Class 75 ArmorFlex® ACBM revetment system as an alternative to 700 kg-class riprap. When compared to riprap being hauled 100 km to site it was found that using ArmorFlex® would cost approximately $8,000 more than the riprap (Figure 14). While more costly than riprap for this scenario, there is value in the knowledge that ArmorFlex® can be used as an alternative to large class riprap for extremely high flow design discharge and velocity. Additionally, ArmorFlex® is more environmentally friendly than riprap, and shows significant reduction in carbon emissions for this scenario (Appendix D).

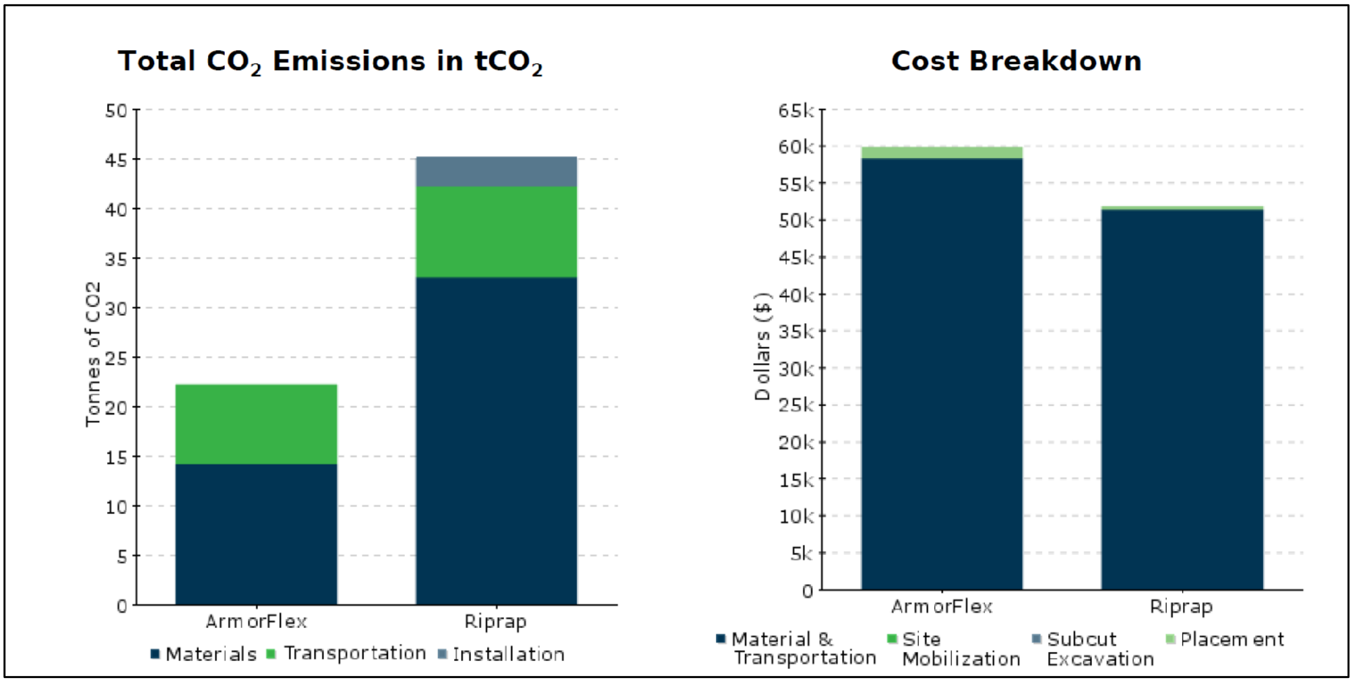


Figure 14. Carbon emission and cost comparison of Nilex's Class 75 ArmorFlex® vs. 700 kg-class riprap (Appendix D).

Scenario 4: Class 75 ArmorFlex® ACBM compared to 700 kg-class riprap hauled 500 km

Assumptions for this scenario were as follows:

- 700 kg-class riprap hauled from a pit 500 km from project site
- 700 kg-class riprap placed in a 1400 mm-thick blanket
- $130/m^3 – quarry and process, and install 700 kg-class riprap
- $90/hour – transportation cost for 700 kg-class riprap (10 hour round trip)
- $225/m^2 – Class 75 ArmorFlex® ACBM revetment (includes delivery and install)
- Costs of site prep and sub-excavation not considered

For this scenario Nilex proposed use of Class 75 ArmorFlex® ACBM revetment system as an alternative to 700 kg-class riprap. When compared to riprap being hauled 500 km to site it was found that using ArmorFlex® would save approximately $9,000 (Figure 15). Typically, riprap could be sourced closer to a project than this, however, in remote locations this type of distance could be a reality. While the scenario only shows marginal cost savings, it provides further support that an ACBM revetment system can be used in forest industry applications, even for significant design discharge and velocities. (Appendix E).

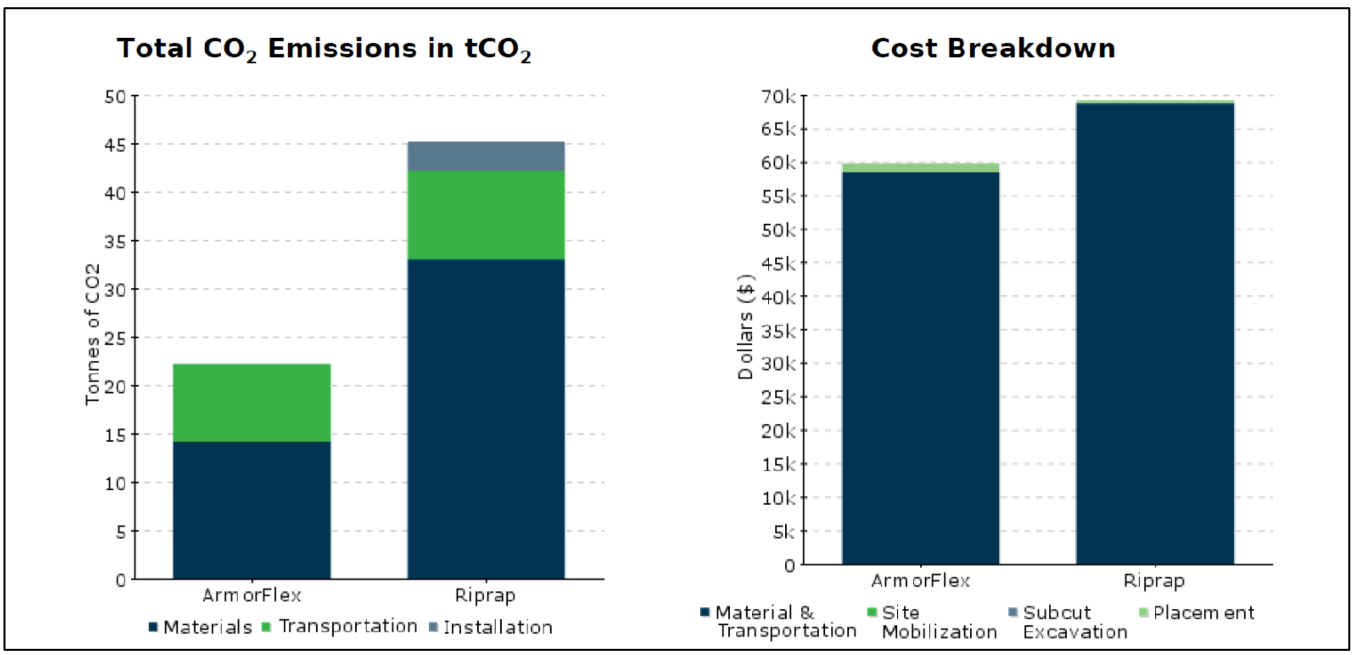


Figure 15. Carbon emission and cost comparison of Nilex's Class 75 ArmorFlex® vs. 700 kg-class riprap (Appendix E).

9. CONCLUSION

Finding economical alternatives to traditional rock riprap revetments is becoming increasingly necessary for the forest industry in northern B.C. Due to regional geology there is a lack of suitable rock to develop for riprap, and even when rock is available the cost of blasting, supply and installation can be significant. Fortunately, advances in geosynthetics and precast concrete armoring units have created riprap alternatives. Furthermore, these alternatives often provide added benefits such as promotion of vegetation growth through the revetment system, reduced carbon emissions and safer installation conditions for workers.

Products available that can be used as alternatives to riprap include rolled erosion control products (RECP), geocells, and precast concrete products (PCCP). RECP's and geocells should typically only be used for low-gradient/ low-turbulence systems. However when used as part of an integrated system, or when vegetation has been able to establish, they can be used for more significant revetment systems. Precast concrete products such as articulating concrete block (ACBM) mattresses and A-jacks® can be used as a replacement for rock riprap in most instances. Used as part of an integrated system with RECP's or as a stand-alone revetment PCCP's can replace large riprap classes. Additionally, they are easy to install, require less equipment time than riprap and produce less carbon emissions than typical riprap revetments. Costs for ACBM's and A-Jacks® are comparable to the cost of rock riprap, with the potential for further savings with reduced equipment time and no need for expensive blasting.

A theoretical design using riprap alternatives on a bridge crossing near McBride, B.C. showed that high-performance turf reinforcement mats (HPTRM) can be used as an economical solution when compared to small class riprap. For large class riprap, using an ACBM showed marginal cost savings when compared with transporting 700 kg-class riprap a significant distance (500 km), and a marginal increase in costs when transporting the riprap shorter distances (100 km). Regional evaluations of cost effectiveness can be made based on typical haul distance to suitable rock. This theoretical design also showed that riprap alternatives are a viable option for significant stream crossings with large Q_{100} estimated discharge flows (in this case, 189 m^3/s).

Based on a literature reviews, discussions with various riprap alternative suppliers and the theoretical design it appears there are many options for riprap alternative use in the forest industry. As with any revetment design, experienced qualified professionals are required to ensure that the system is designed and installed appropriately. Additionally, with alternatives to riprap professionals must be aware of the standardized testing methods used to develop engineering properties (design shear stresses and velocity resistance) for the product as often standardized testing methods are not representative of real-world installation techniques or conditions.

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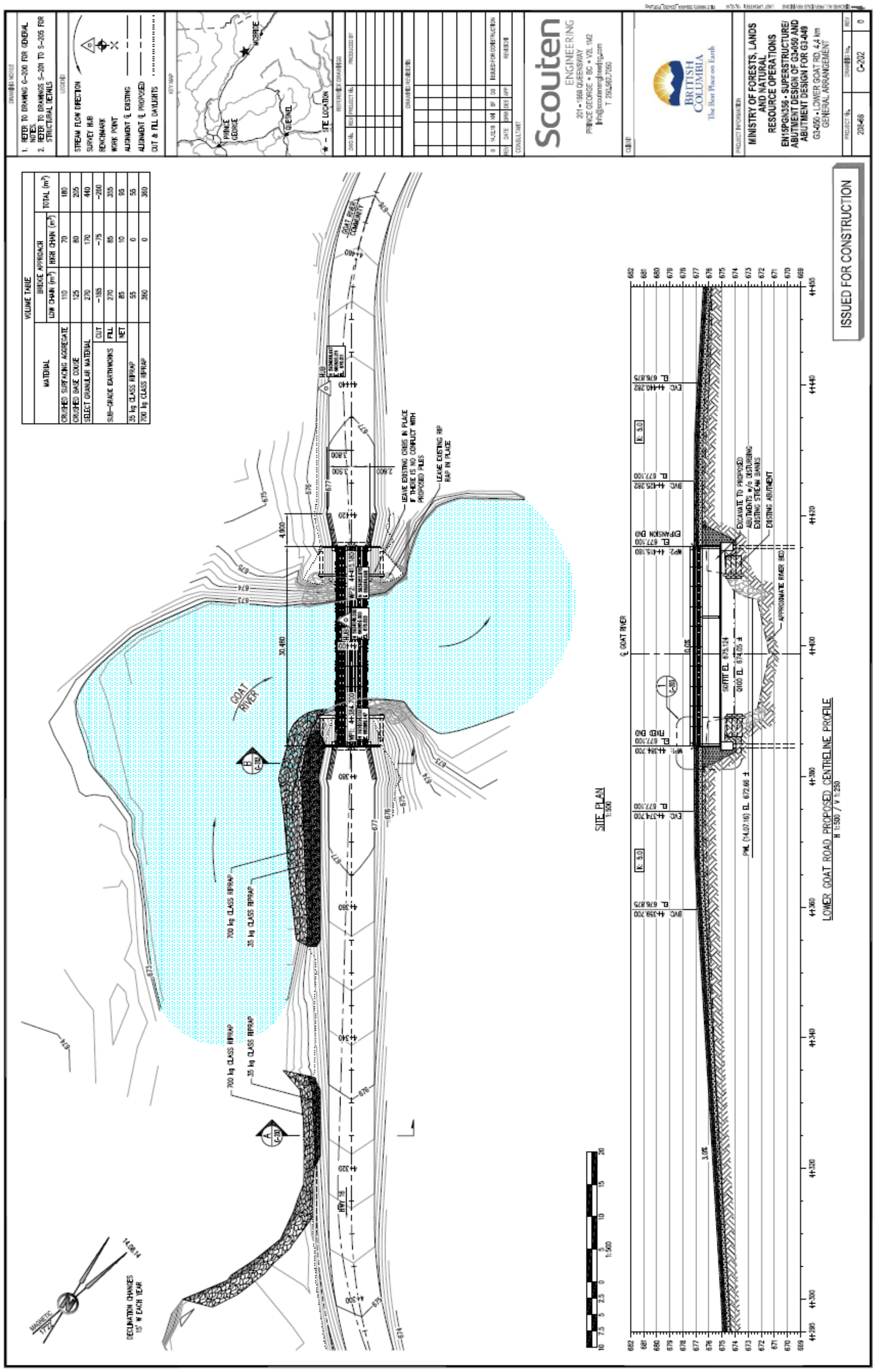
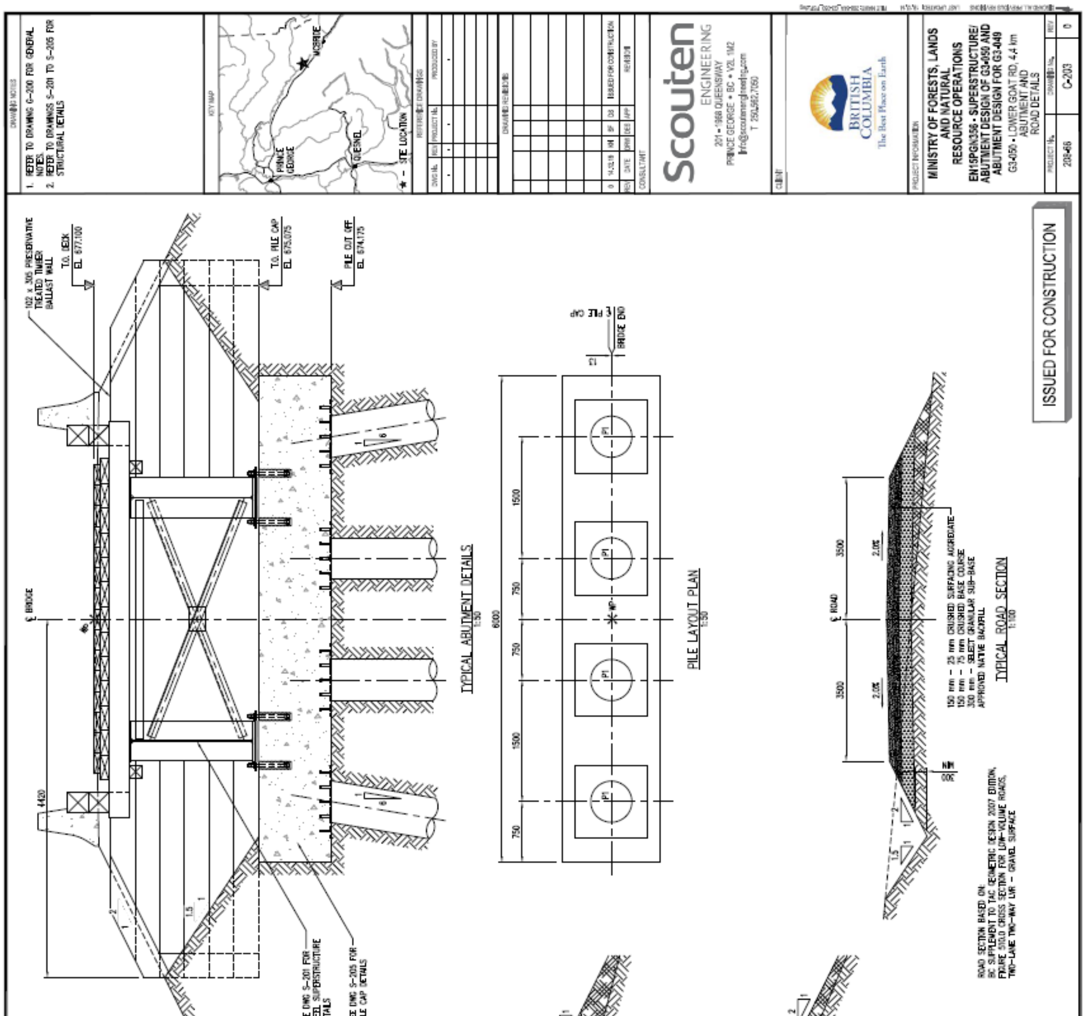
10. APPENDIX A – LOWER GOAT ROAD CROSSING AT 4.4 KM ISSUED FOR CONSTRUCTION DRAWINGS

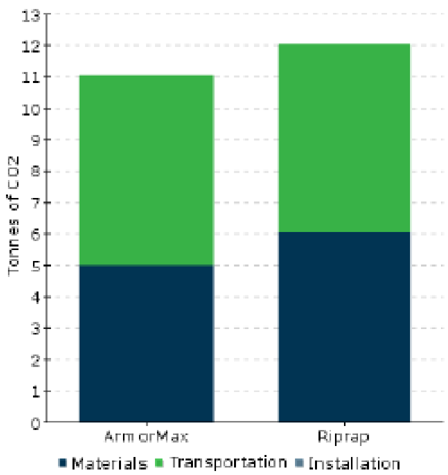



ISSUED FOR CONSTRUCTION
TYPICAL ABUTMENT DETAILS
PILE LAYOUT PLAN
TYPICAL ROAD SECTION
DETAIL 1
SECTION A
SECTION B
Scouten
ENGINEERING
BRITISH COLUMBIA
The Best Place on Earth
MINISTRY OF FORESTS, LANDS AND NATURAL RESOURCE OPERATIONS
C-203

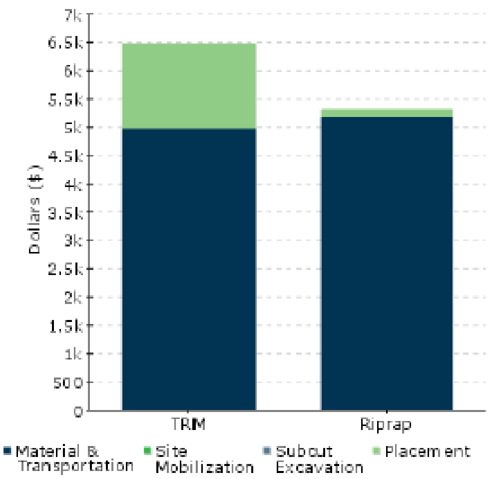
11. APPENDIX B – ARMORMAX® VS. 35 KG-CLASS RIPRAP

35kg Riprap vs. ArmorMax (20km haul - Goat River) **TRM vs. Riprap**

Total CO_2 Emissions in tCO_2



Cost Breakdown



Products	Transportation (tCO_2)	Material (tCO_2)	Installation (tCO_2)	Total Emissions (tCO_2)	Total % Saving of Carbon Emissions vs Riprap
ArmorMax	5.92	4.72		10.64	17%
Riprap	6.06	6.26	0.49	12.81	

	Riprap	TRM
Tonnes of CO_2 Saved		**2.2 tCO_2**
Dump Trucks Saved off the road		**5**

Costs

	Riprap	TRM
Total Material/ Transportation Cost	$5,143.00	$4,950.00
Total Mobilization Cost	$0.00	
Total Excavation Cost	$0.00	
Total Placement Cost	$150.00	$1,500.00
Total Cost	**$5,293.00**	**$6,450.00**
Cost Savings Over Riprap		$-1,157.00
Total Hours	6.2	2.4
Time Savings Over Riprap (Hours)		3.8

Disclaimer

The results in this document are for estimate purposes only to provide the client with a realization of potential savings on a project. This document is not intended to be a quote for materials or a guaranteed cost and material savings.

1. Inputs

Project Information	Input	Determining Area	Input
Nilex Warehouse	Edmonton	Length of Channel (m)	15
Project Title	35kg Riprap vs. ArmorMax	Bottom Width (m)	10
Project Location	20km haul - Goat River	Height of Channel (m)	0
		Left Slope (H:1)	0
Required Information	**Input**	Right Slope (H:1)	0
TRM Product List	ArmorMax	Total Area (m^2)*	150.00
Distance from Nilex Warehouse to Site (km)	580	Sub-cut Depth for Riprap*	0.45
Distance from Rock Source to Site (km)	20		
Riprap Class (mm)	300		
Sub-cut Depth for Riprap	0.45		

**Automatically calculated once the area of the channel is entered in. Nilex can capture this information in this spreadsheet.*

2. Material Costs

Material	Input Cost
Riprap - per m^3	70
TRM - per m^2 (actual product indicated above under TRM Product List)	30
ArmorFlex - per m^2 (if chosen)	
Geotextile - per m^2	1

3. Costs

RIPRAP COSTS

Item	Input Cost	Item	Input Cost
Truckload Quantity	15	Site Mobilization & Demobilization	0
Rock Delivery (round trip time)	1	Sub-cutting Excavate & Haul Rate	0
Rock Delivery Cost	0	Machine Rate	0
Number of Textile Rolls Required	1	Geotextile Install Cost	1
Geotextile Delivery Cost	0		

TRM Costs

Item	Input Cost	Item	Input Cost
Staples/Anchors - per m^2	6	Number of Rolls Required*	3
Staples/Box - per box	1000	Material Delivery - flat rate	0
Staple Price - per box	0	TRM Install Cost - per m^2	10

**Automatically calculated once the area of the channel is entered in Section 1. Nilex can capture this information in this spreadsheet.*

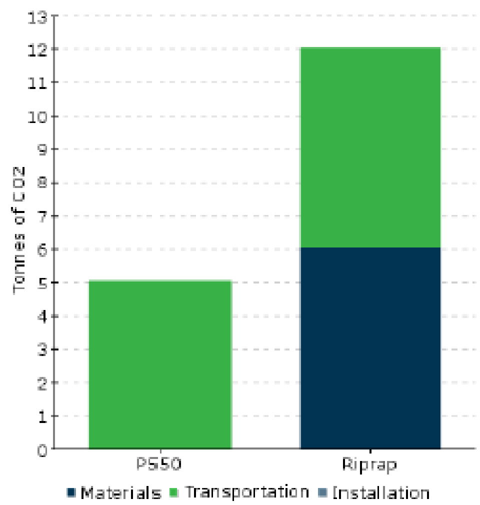
4. Production Rates

Item	Input Cost	Item	Input Cost
Sub Excavation Rate - m^3/hr	20	Riprap Placement Rate - m^3/hr	24
Excavator Fuel Rate - L/hr	22		
Riprap Machine & Fuel Rate - L/hr	22		
TRM Placement Rate - m^2/hr	68		

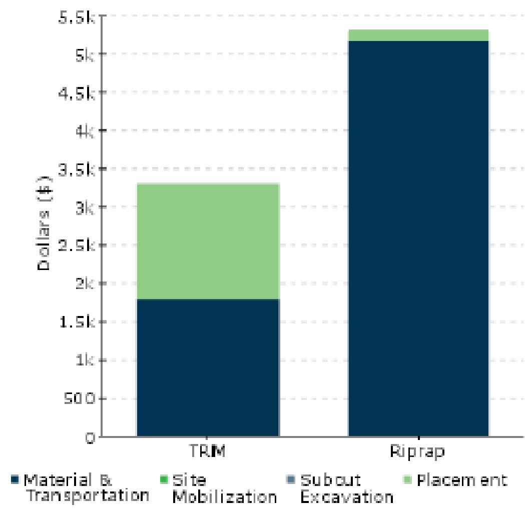
12. APPENDIX C – P550 TRM VS. 35 KG-CLASS RIPRAP

NILEX CIVIL ENVIRONMENTAL GROUP **35kg Riprap vs. P550** (20km haul - Goat River) **TRM vs. Riprap**

Total CO_2 Emissions in tCO_2



Cost Breakdown



Products	Transportation (tCO_2)	Material (tCO_2)	Installation (tCO_2)	Total Emissions (tCO_2)	Total % Saving of Carbon Emissions vs Riprap
P550	5.26	0.34		5.60	56%
Riprap	6.06	6.26	0.49	12.81	

	Riprap	TRM
Tonnes of CO_2 Saved		**7.2 tCO_2**
Dump Trucks Saved off the road		**5**

Costs

	Riprap	TRM
Total Material/ Transportation Cost	$5,143.00	$1,782.50
Total Mobilization Cost	$0.00	
Total Excavation Cost	$0.00	
Total Placement Cost	$150.00	$1,500.00
Total Cost	**$5,293.00**	**$3,282.50**
Cost Savings Over Riprap		$2,010.50
Total Hours	6.2	2.4
Time Savings Over Riprap (Hours)		3.8

Disclaimer

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1. Inputs

Project Information	Input	Determining Area	Input
Nilex Warehouse	Edmonton	Length of Channel (m)	15
Project Title	35kg Riprap vs. P550	Bottom Width (m)	10
Project Location	20km haul - Goat River	Height of Channel (m)	0
		Left Slope (H:1)	0
Required Information	**Input**	Right Slope (H:1)	0
TRM Product List	P550	Total Area (m^2)*	150.00
Distance from Nilex Warehouse to Site (km)	580	Sub-cut Depth for Riprap*	0.45
Distance from Rock Source to Site (km)	20		
Riprap Class (mm)	300		
Sub-cut Depth for Riprap	0.45		

**Automatically calculated once the area of the channel is entered in. Nilex can capture this information in this spreadsheet.*

2. Material Costs

Material	Input Cost
Riprap - per m^3	70
TRM - per m^2 (actual product indicated above under TRM Product List)	10.50
ArmorFlex - per m^2 (if chosen)	
Geotextile - per m^2	1

3. Costs

RIPRAP COSTS

Item	Input Cost	Item	Input Cost
Truckload Quantity	15	Site Mobilization & Demobilization	0
Rock Delivery (round trip time)	1	Sub-cutting Excavate & Haul Rate	0
Rock Delivery Cost	0	Machine Rate	0
Number of Textile Rolls Required	1	Geotextile Install Cost	1
Geotextile Delivery Cost	0		

TRM Costs

Item	Input Cost	Item	Input Cost
Staples/Anchors - per m^2	6	Number of Rolls Required*	5
Staples/Box - per box	1000	Material Delivery - flat rate	0
Staple Price - per box	50	TRM Install Cost - per m^2	10

**Automatically calculated once the area of the channel is entered in Section 1. Nilex can capture this information in this spreadsheet.*

4. Production Rates

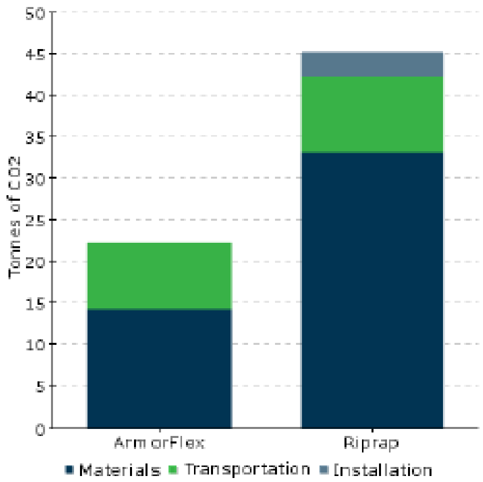
Item	Input Cost	Item	Input Cost
Sub Excavation Rate - m^3/hr	20	Riprap Placement Rate - m^3/hr	24
Excavator Fuel Rate - L/hr	22		
Riprap Machine & Fuel Rate - L/hr	22		
TRM Placement Rate - m^2/hr	68		

13. APPENDIX D – CLASS 75 ARMORFLEX® VS. 700 KG-CLASS RIPRAP HAULED 100 KM TO SITE

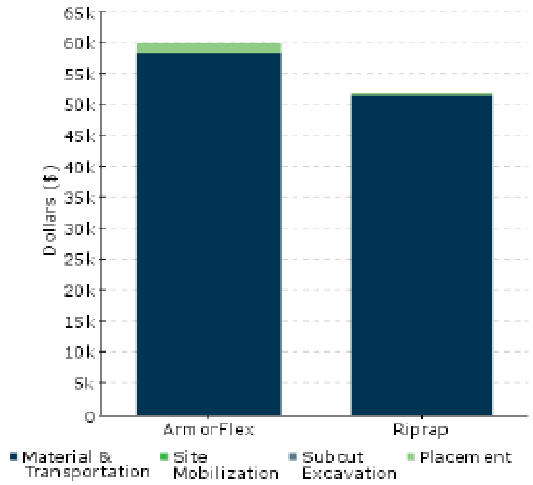
700kg Riprap vs. Class 75 Armorflex (100km haul - Goat River)

ArmorFlex vs. Riprap

Total CO_2 Emissions in tCO_2



Cost Breakdown



Products	Transportation (tCO_2)	Material (tCO_2)	Installation (tCO_2)	Total Emissions (tCO_2)	Total % Saving of Carbon Emissions vs Riprap
ArmorFlex	7.63	14.26	0.47	22.36	50%
Riprap	9.28	32.91	2.58	44.77	

	Riprap	ArmorFlex
Tonnes of CO_2 Saved		**22 tCO_2**
Dump Trucks Saved off the road		**22**

Costs

	Riprap	ArmorFlex
Total Material/ Transportation Cost	$51,344.95	$58,243.00
Total Mobilization Cost	$0.00	0.00
Total Excavation Cost	$0.00	$0.00
Total Placement Cost	$257.00	$1,337.00
Total Cost	**$51,601.95**	**$59,580.00**
Cost Savings Over Riprap		$-7,978.05
Total Hours	32.9	6.0
Time Savings Over Riprap (Hours)		26.8

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1. Inputs

Project Information	Input	Determining Area	Input
Nilex Warehouse	Edmonton	Length of Channel (m)	25.7
Project Title	700kg Riprap vs. Class 75 Armorflex	Bottom Width (m)	10
Project Location	100km haul - Goat River	Height of Channel (m)	0
		Left Slope (H:1)	0
Required Information	**Input**	Right Slope (H:1)	0
ArmorFlex Product List	75	Total Area (m^2)*	257.00
Distance from Nilex Warehouse to Site (km)	580	Sub-cut Depth for Riprap*	1.4
Distance from Rock Source to Site (km)	100	Sub-cut Depth for Armorflex*	0.19
Riprap Class (mm)	800		
Sub-cut Depth for Riprap	1.4		

**Automatically calculated once the area of the channel is entered in. Nilex can capture this information in this spreadsheet.*

2. Material Costs

Material	Input Cost
Riprap - per m^3	130
TRM - per m^2 (actual product indicated above under TRM Product List)	0
ArmorFlex - per m^2 (if chosen)	225
Geotextile - per m^2	1

3. Costs

RIPRAP COSTS

Item	Input Cost	Item	Input Cost
Truckload Quantity	15	Site Mobilization & Demobilization	0
Rock Delivery (round trip time)	2	Sub-cutting Excavate & Haul Rate	0
Rock Delivery Cost	90	Machine Rate	0
Number of Textile Rolls Required	1	Geotextile Install Cost	1
Geotextile Delivery Cost	0		

ArmorFlex Costs

Item	Input Cost	Item	Input Cost
Material Delivery - flat rate	0	Sub-cutting Excavate & Haul Rate - per m^3	0
Number of Mats Required*	18	Mobilization & De-mobilization - flat rate	0
Number of Textile Rolls Required*	1	Machine Rate - per hour	300
Geotextile Delivery Cost - flat rate	0	Geotextile Install Cost - per m^2	1

**Automatically calculated once the area of the channel is entered in Section 1. Nilex can capture this information in this spreadsheet.*

4. Production Rates

Item	Input Cost	Item	Input Cost
Sub Excavation Rate - m^3/hr	20	Riprap Placement Rate - m^3/hr	24
Excavator Fuel Rate - L/hr	22	ArmorFlex Machine & Fuel Rate - L/hr	22
Riprap Machine & Fuel Rate - L/hr	22	ArmorFlex Placement Rate - Mats/hr	5

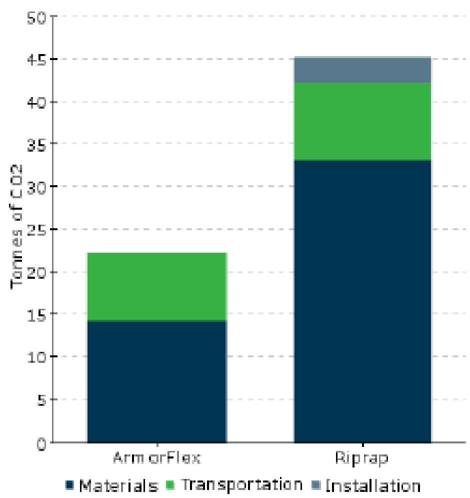
14. APPENDIX E – CLASS 75 ARMORFLEX® VS. 700 KG-CLASS RIPRAP HAULED 500 KM TO SITE

NILEX CIVIL ENVIRONMENTAL GROUP

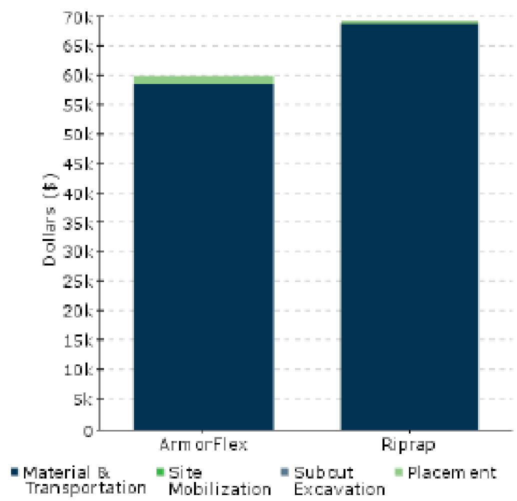
700kg Riprap vs. Class 75 Armorflex (500km haul - Goat River)

ArmorFlex vs. Riprap

Total CO_2 Emissions in tCO_2



Cost Breakdown



Products	Transportation (tCO_2)	Material (tCO_2)	Installation (tCO_2)	Total Emissions (tCO_2)	Total % Saving of Carbon Emissions vs Riprap
ArmorFlex	7.63	14.26	0.47	22.36	50%
Riprap	9.28	32.91	2.58	44.77	

	Riprap	ArmorFlex
Tonnes of CO_2 Saved		**22 tCO_2**
Dump Trucks Saved off the road		**22**

Costs

	Riprap	ArmorFlex
Total Material/ Transportation Cost	$68,624.95	$58,243.00
Total Mobilization Cost	$0.00	0.00
Total Excavation Cost	$0.00	$0.00
Total Placement Cost	$257.00	$1,337.00
Total Cost	**$68,881.95**	**$59,580.00**
Cost Savings Over Riprap		$9,301.95
Total Hours	32.9	6.0
Time Savings Over Riprap (Hours)		26.8

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1. Inputs

Project Information	Input	Determining Area	Input
Nilex Warehouse	Edmonton	Length of Channel (m)	25.7
Project Title	700kg Riprap vs. Class 75 Armorflex	Bottom Width (m)	10
Project Location	500km haul - Goat River	Height of Channel (m)	0
		Left Slope (H:1)	0
Required Information	**Input**	Right Slope (H:1)	0
ArmorFlex Product List	75	Total Area (m^2)*	257.00
Distance from Nilex Warehouse to Site (km)	580	Sub-cut Depth for Riprap*	1.4
Distance from Rock Source to Site (km)	100	Sub-cut Depth for Armorflex*	0.19
Riprap Class (mm)	800		
Sub-cut Depth for Riprap	1.4		

**Automatically calculated once the area of the channel is entered in. Nilex can capture this information in this spreadsheet.*

2. Material Costs

Material	Input Cost
Riprap - per m^3	130
TRM - per m^2 (actual product indicated above under TRM Product List)	0
ArmorFlex - per m^2 (if chosen)	225
Geotextile - per m^2	1

3. Costs

RIPRAP COSTS

Item	Input Cost	Item	Input Cost
Truckload Quantity	15	Site Mobilization & Demobilization	0
Rock Delivery (round trip time)	10	Sub-cutting Excavate & Haul Rate	0
Rock Delivery Cost	90	Machine Rate	0
Number of Textile Rolls Required	1	Geotextile Install Cost	1
Geotextile Delivery Cost	0		

ArmorFlex Costs

Item	Input Cost	Item	Input Cost
Material Delivery - flat rate	0	Sub-cutting Excavate & Haul Rate - per m^3	0
Number of Mats Required*	18	Mobilization & De-mobilization - flat rate	0
Number of Textile Rolls Required*	1	Machine Rate - per hour	300
Geotextile Delivery Cost - flat rate	0	Geotextile Install Cost - per m^2	1

**Automatically calculated once the area of the channel is entered in Section 1. Nilex can capture this information in this spreadsheet.*

4. Production Rates

Item	Input Cost	Item	Input Cost
Sub Excavation Rate - m^3/hr	20	Riprap Placement Rate - m^3/hr	24
Excavator Fuel Rate - L/hr	22	ArmorFlex Machine & Fuel Rate - L/hr	22
Riprap Machine & Fuel Rate - L/hr	22	ArmorFlex Placement Rate - Mats/hr	5

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