Engineered Earth Armouring Solutions: An Alternative to Rock Riprap

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Engineers are tasked to provide solutions for infrastructure challenges in the most efficient manner possible. One must balance standard practice with innovation to constantly improve effectiveness and efficiency. Rock riprap is an accepted traditional solution for erosion control and surficial slope stabilization, but there are other alternatives.

Engineered Earth Armouring Solutions™ (EEAS) are environmentally friendly and economical erosion control and surficial slope stability solutions designed to provide significant hydraulic performance improvements over rock riprap. An EEAS consists of a High Performance Turf Reinforcement Mat (HPTRM) in combination with Engineered Earth Anchors™, and is designed to meet a project's hydraulic, geotechnical, design life, environmental and economic needs.

When designing erosion control and surficial slope stabilization measures for your project, it is important to remember that there are other alternatives to traditional solutions like riprap. The EEAS has a number of additional benefits such as proven hydraulic performance, improved pollutant removal and carbon footprint, and reduced installation and maintenance cost. The performance of EEAS has been tested and approved by the U.S. Army Corp of Engineers (USACE) with millions of square metres of successful installations. The EEAS is designed to resist hydraulic stresses and offers a more durable, environmentally friendly, and economical alternative to traditional rock riprap solutions.

1. INTRODUCTION

Engineers are tasked to provide solutions for infrastructure challenges in the most efficient manner possible. One must balance standard practice with innovation to constantly improve effectiveness and efficiency. Rock riprap is an accepted traditional solution for erosion control and surficial slope stabilization, but there are other alternatives.

Engineered Earth Armoring Solutions™ (EEAS) are economical erosion control and surficial slope stability solutions designed to provide significant improvements in hydraulic performance, environmental benefits, and geotechnical stability when compared to rock riprap. An EEAS consists of a High Performance Turf Reinforcement Mat (HPTRM) in combination with Engineered Earth Anchors™ and is designed to meet a project's hydraulic, geotechnical, design life, environmental and economic needs.

This paper presents the features and benefits of an EEAS in erosion control and surficial slope stability applications and will include the following:

- A durability and economic comparison against rock riprap.
- A hydraulic performance comparison against rock riprap.
- The environmental benefits of using a green solution for erosion control.
- A geotechnical performance comparison against rock riprap.

2. ECONOMIC CONSIDERATIONS

The economic benefit of an EEAS is dependent on balance between durability, required maintenance, and total installed cost. If a material is not durable enough to last for the required design life then excessive maintenance or installation of additional material may be needed.

2.1. Durability

The durability of an erosion control solution is dependent upon various project-specific environmental properties. It is paramount that the solution used to armor critical infrastructure such as levees, spillways and canals possess the required durability to provide adequate performance. Degradation in performance can come from Non-Hydraulic stresses such as environmental stresses or mechanical damage or from material degradation caused by chemical, solar, or thermal exposure.

The U.S. Nuclear Regulatory Commission (NRC) states in their report on the Design of Erosion Protection for Long-Term Stabilization that the durability and weathering characteristics of rock riprap should be evaluated in the design methodology. Critical areas, such as channels are susceptible to weathering from freeze/thaw and wet/dry cycles. The NRC also states that the rock riprap should be tested and scored based on the results and type of rock as shown in Figure 1. If the scoring criteria for rock quality is not met then the rock is either rejected or the size is increased in order to account for the potential weathering.

Laboratory Test	Weighting Factor			Score										
	Lime-stone	Sand-stone	Igneous	10	9	8	7	6	5	4	3	2	1	0
					Good			Fair			Poor			
Sp. Gravity	12	6	9	2.75	2.70	2.65	2.60	2.55	2.50	2.45	2.40	2.35	2.40	2.25
Absorption, %	13	5	2	.10	.30	.50	.67	.83	1.0	1.5	2.0	2.5	3.0	3.5
Sodium Sulfate, %	4	3	11	1.0	3.0	5.0	6.7	8.3	10.0	12.5	15.0	20.0	25.0	30.0
L/A Abrasion (100 revs). %	1	8	1	1.0	3.0	5.0	6.7	8.3	10.0	12.5	15.0	20.0	25.0	30.0
Schmidt Hammer	11	13	3	70	65	60	54	47	40	32	24	16	8	0

1. Scores were derived from Tables 6.2, 6.5, and 6.7 of NUREG/CR-2642 - "Long-Term Survivability of Riprap for Armoring Uranium Mill Tailings and Covers: A Literature Review," 1982.

2. Weighting Factors are derived from Table 7 of "Petrographic Investigations of Rock Durability and Comparisons of Various Test Procedures," by G. W. DuPuy, Engineering Geology, July 1965. Weighing factors are based on inverse of ranking of test methods for each rock type. Other tests may be used; weighting factors for these tests may be derived using Table 7, by counting upward from the bottom of the table.

3. Test methods should be standardized, if a standard test is available and should be those used in NUREG/CR-2642, so that proper correlations can be made.

Figure 1 NRC Scoring criteria for determining rock quality

In order to obtain the rock riprap quality the individual laboratory test results are compared to Figure 1 to determine each score, from 0 to 10. The scores are then weighted based on the rock type and the totals are compared to the maximum possible weighted score to determine the rock riprap quality as a percentage. For critical areas, a total score of 80-100 results in no required oversizing, a total score of 65-80 results in required percentage increase in D_{50}, and a total score of less than 65 results in the rejection of the rock riprap.

In the same way that the quality of the rock affects the size of the riprap, the quality of the HPTRM affects the durability of the EEAS. HPTRMs are very stable materials, but their susceptibility to ultraviolet (UV) degradation is dependent upon the type, quality and amount of the UV inhibitor utilized during manufacturing. The durability and long-term performance of the HPTRM is tested per ASTM D-4355 to quantify the rate of degradation after an established amount of exposure. While other test methods only focus on the UV light, D-4355 utilizes a xenon arc in order to reproduce the entire spectrum of sunlight for a more representative test. HPTRMs, while intended to be vegetated, also are designed to be exposed to sunlight. Whether seed or turf is used, no project can be guaranteed to maintain 100% vegetative coverage during the entire design life. Therefore, HPTRM designs require increased durability, having the test duration per ASTM D-4355 of 3,000 and 6,000 hours. ASTM D-4355 has been used by permanent erosion control product manufacturers for more than 20 years to specify the durability of HPTRMs.

In addition to laboratory testing, field samples of HPTRMs must be evaluated to correlate results from ASTM D-4355 to real-world exposure for a better understanding of the material's design life. In 2015, samples of HPTRM were taken from an installation in Scottsdale, Arizona, to determine the retained tensile strength after 13 years of exposure (Figure 2). The results showed an average retained tensile strength of 80% when compared to independent third-party test results. Using retained tensile strength as well as independent and internal test results for UV resistance, we can begin to anticipate the functional longevity of the HPTRM in both the USA with annual solar radiation of 21.70 MJ/m^2-day and Australia with annual solar radiation of 22.68 MJ/m^2-day (Figure 3). When backed up with manufacturing quality-control programs, third-party test results, and more than 20 years of field performance, HPTRMs can offer a design life of more than 50 years.

Figure 2 Scottsdale, AZ Installation (2002 Left, 2015 Right)

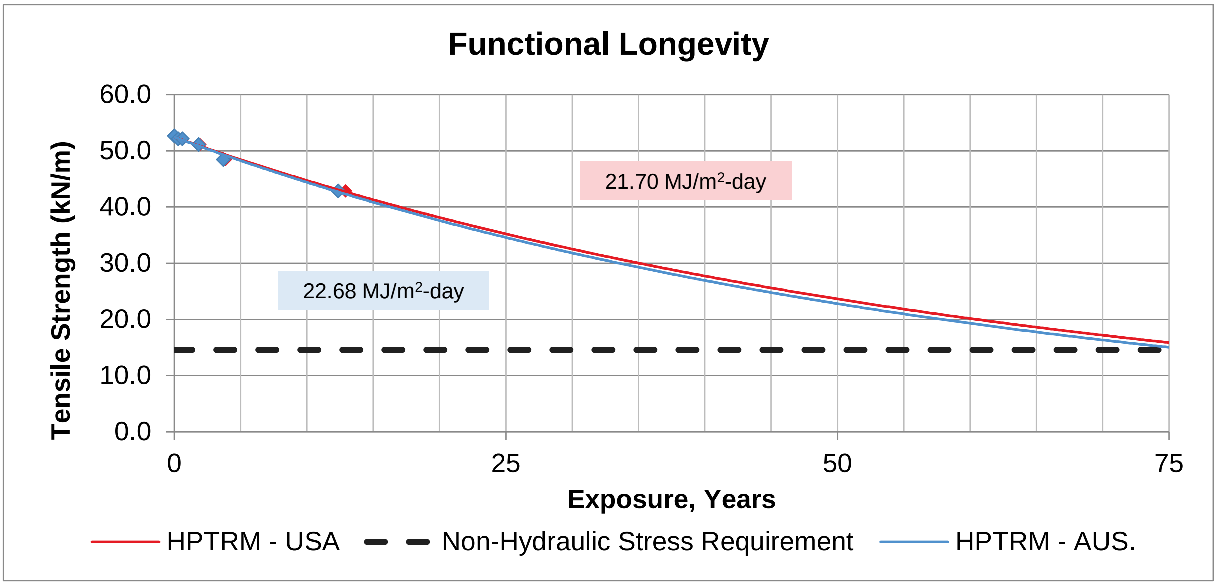


Figure 3 HPTRM Functional Longevity

The HPTRM shown in Figure 2 was installed in 2002 and after 13 years of performance had only around 40% vegetation established. While the vegetation establishment was great for the region, it shows that HPTRMS can often be exposed to solar radiation during the entirety of the project life.

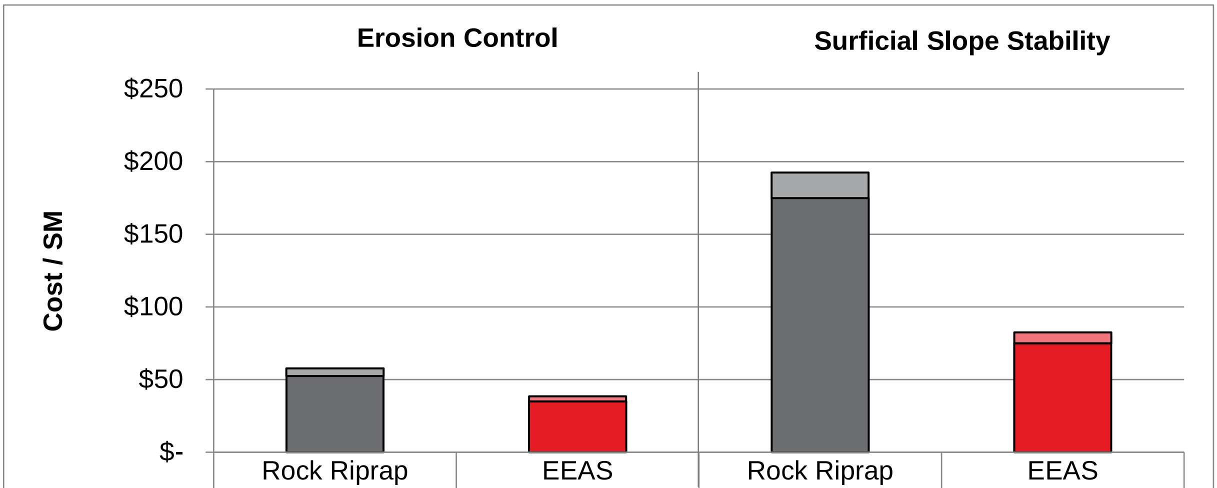
2.2. Maintenance

Because an EEAS and rock riprap can be in place for more than 50 years, isolated areas may require maintenance through time. For rock riprap, maintenance will consist of replacing mobilized rock as well as removal of vegetation. The maintenance of an EEAS involves the mowing and care of vegetation, if desired, and patching of any damaged areas. The New York Department of Environmental Conservation Standards and Specifications for Erosion and Sediment Control state that both rock riprap and grass channels require maintenance for long-term performance, and that their annual maintenance cost is approximately 10% of the initial installed cost. However, if the erosion control or surficial slope stability solution is not properly selected then general maintenance might not be sufficient.

2.3. Installation Cost

The total installed cost of an erosion control or surficial slope stability solution will vary regionally depending on availability of materials, labor rates, and size of project. On average in 2018, the installed cost of rock riprap is around $175 per cubic metre. Assuming a section thickness of 30 cm for erosion control, the installed cost of rock riprap is around $52 per square metre. For an erosion control application, the installed cost of an EEAS in 2018 is around $35 per square metre, showing an upfront cost savings of 33% (Figure 3). If larger rock is required based on hydraulic constraints then there could be an even larger upfront cost savings with the use of an EEAS.

Assuming a section thickness of 1 m for surficial slope stability, the installed cost of rock riprap is around $175 per square metre. For a surficial slope stability application, the installed cost of an EEAS in 2018 is around $75 per square metre, showing an upfront cost savings of 57% (Figure 4). If larger rock is required based on hydraulic constraints then there could be an even larger upfront cost savings with the use of an EEAS.



	Rock Riprap	EEAS	Rock Riprap	EEAS
Maintenance	$5.25	$3.50	$17.50	$7.50
Installation	$52.50	$35.00	$175.00	$75.00

Figure 4 Solution Cost Comparison

3. HYDRAULIC PERFORMANCE

Every year billions of cubic metres of sediment are dredged from waterways. In order to combat this, the Clean Water Act (CWA) requires that facilities and project sites implement measures to prevent pollutants, such as sediment, from entering the nearby waterways. When soil erodes, it is transported and deposited downstream. If not controlled, erosion will continue to cause pollution of our waterways. Therefore, when designing roadway embankments and channels it is critical to protect the slopes and banks from erosion to ensure long-term success of the project and surrounding areas. Analyses are required to determine the anticipated hydraulic stresses so an erosion control solution with adequate performance can be selected.

3.1. Shear Stress

Historically velocity was the main hydraulic factor in open-channel analyses. The Hydraulic Engineering Circular 15 (HEC-15) by the Federal Highway Administration (FHWA) recommends that hydraulic shear stress be used to determine erosion potential instead of velocity. Shear stress is the tractive force developed from the flow of water along a channel that looks to remove or dislodge soil particles. The maximum shear stress at the bottom of a channel per HEC-15 is shown in equation (1).

$$\tau_d = \gamma d S_0 \qquad (1)$$

τ_d = shear stress in channel at maximum depth, Pa
γ = specific weight of water, 9810 N/m^3
d = maximum depth of flow in channel, m

3.2. HPTRM Performance

The HPTRM component of an EEAS has been used for more than 20 years and is specially designed to exhibit very high erosion control capacity as well as demonstrate superior durability. HPTRMs act to protect and reinforce the subgrade soil below, reducing the overall soil loss from the site. The earth anchor component of the EEAS acts to permanently secure the HPTRM and improve both the hydraulic and geotechnical factors of safety. As some soils are more erodible than others, the onsite soil type will affect the overall performance of the selected erosion control solution. Because HPTRMs work to reinforce vegetation, the type of vegetation utilized also will affect the overall performance.

Erosion control materials are constantly tested and performance thresholds continuously defined through rigorous exposure to severe hydraulic forces in both real-world and laboratory scenarios (Figure 5). Hydraulic performance is measured as the resistance to shear stresses in controlled laboratory flow experiments as well as documented field performance. Full-scale tests on HPTRMs performed per American Society of Testing and Measurement (ASTM) D-6460 have shown significant resistance to shear stress in various vegetated and non-vegetated conditions (Table 1).

Table 1. HPTRM Full-Scale Test Results

Vegetation Condition	Soil Loss (cm)	Shear Stress (Pa)
Unvegetated HPTRM	< 1.3	130
Unvegetated HPTRM with Engineered Earth Anchors	< 1.3	170
30% Vegetated HPTRM	< 1.3	380
70% Vegetated HPTRM	< 1.3	575
90% Vegetated HPTRM	< 1.3	770

Figure 5 Full Scale Hydraulic Testing

The flume shown in Figure 5 shows the full scale hydraulic testing of an HPTRM at Colorado State University (CSU). CSU is one the leading research facilities on the hydraulic performance of erosion control solutions.

3.3. Rock Riprap Performance

Hard armoring solutions such as rock riprap are often utilized for erosion control and are accepted in the engineering community as standard practice. When designing with rock riprap, one must consider all the variables that affect the overall performance. HEC-15 states that the permissible hydraulic shear stress of rock riprap on the bottom of a channel is dependent upon the mean size of the rock, D_{50} as shown in equation (2).

$$\tau_p = F_*(\gamma_s - \gamma)D_{50} \tag{2}$$

τ_p = permissible shear stress, Pa
F_* = Shield's Parameter, typically 0.047 for Reynolds numbers less than $4x10^4$
γ_s = specific weight of the stone, N/m^3
D_{50} = mean rock riprap size, m

When rock riprap is placed on a slope, it can become unstable as the weight that typically holds it in place begins to drive failure. The erosion resistance of rock riprap therefore reduces as the slope gradient on which it is placed increases as shown in equation (3).

$$\tau_{p,s} = \tau_p \sqrt{1 - \left(\frac{\sin\theta}{\sin\phi}\right)^2} \tag{3}$$

$\tau_{p,s}$ = permissible shear stress on a slope, Pa
θ = angle of side slope
ϕ = rock riprap angle of repose

Although this reduction in performance of rock riprap can easily be visualized on channel side slopes, it's often forgotten when evaluating performance on channel bed slopes. The hydraulic performance of rock riprap based on rock size and slope angle, as compared to the hydraulic performance of an EEAS based on vegetation condition, can be seen in Figure 1. The rock riprap hydraulic performance assumes a Shield's Parameter of 0.047, a specific weight of 24 kN/m^3 and an angle of repose of 45 degrees.

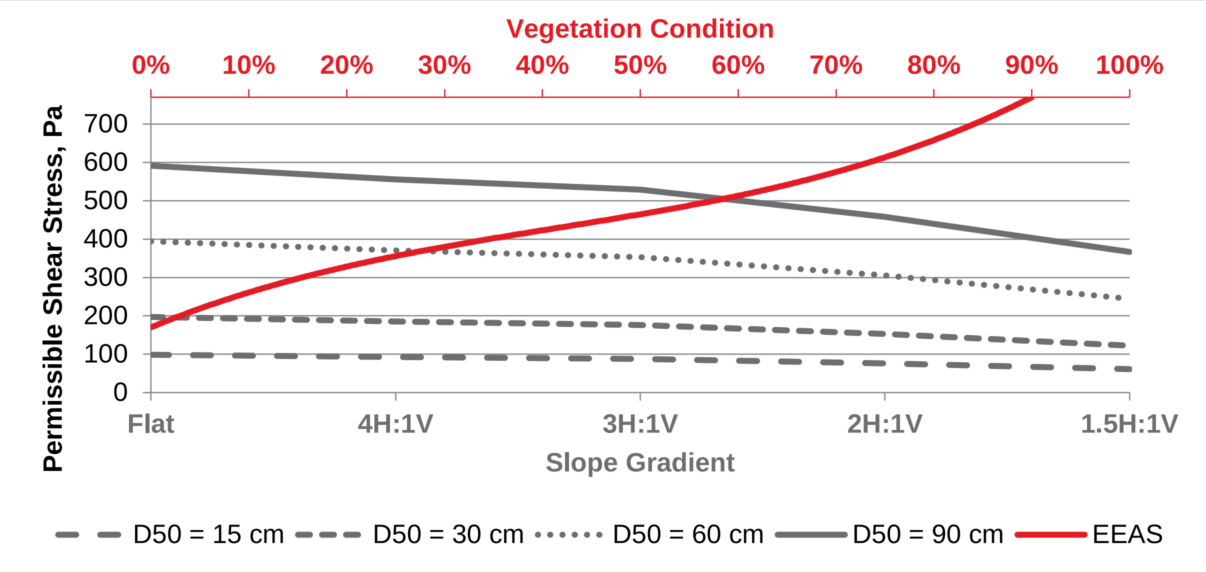


Figure 6 Hydraulic Performance

Rock riprap is commonly used because it can provide protection immediately upon installation. However, one must consider that the design methodology is based on the average stone size, and smaller sizes will be more susceptible to being dislodged. In addition, when larger stone sizes are used, smaller bedding stone will be required to provide consistent contact between the geotextile filter fabric and subgrade.

4. ENVIRONMENTAL CONSIDERATIONS

An EEAS provides significant environmental benefits when compared to traditional technologies such as rock riprap. Utilizing the HPTRM component of an EEAS provides an opportunity to remove pollutants from overland flow with the use of vegetation and can improve traffic and emissions by reducing the amount of trucks required for transportation of materials. Although often overlooked, these topics are important for the long-term success of slope stabilization projects.

4.1. Pollutant Removal

While rock riprap is an accepted traditional solution, the Environmental Protection Agency (EPA) states in “Storm Water Technology Fact Sheet - Turf Reinforcement Mats” that although “these permanent measures can withstand great hydraulic forces, they are costly, and they do not provide the pollutant removal capabilities of vegetative systems.” The EPA has established the use of vegetation as a best management practice (BMP). Vegetation acts to slow water velocities, increasing sedimentation and filtration of heavy metals (Table 2) as well as encouraging infiltration of water back into the groundwater table. HPTRMs also are set as standard BMPs by the EPA to allow for the use of vegetated solutions where the hydraulic limits of unreinforced vegetation have been reached. The EPA further states that HPTRMs “provide a cooler substrate than traditional hard armor techniques, reducing water temperature increases that could otherwise impact aquatic life.”

Table 2. Effectiveness of Design Swales - EPA Storm Water Technology Fact Sheet - Vegetated Swales

Pollutant	Median % Removal
Total Suspended Solids	81
Oxygen-Demanding Substances	67
Nitrate	38
Total Phosphorus	9
Hydrocarbons	62
Cadmium	42
Copper	51
Lead	67
Zinc	71

4.2. Traffic Reduction

In addition to the pollutant-removal capabilities of reinforced vegetation, shipping and installation of an EEAS requires significantly less transportation and use of heavy machinery. When considering the logistics of shipping the required quantity of material, a comparison can be made between one 20,000 square metre (SM) truckload of EEAS and the equivalent coverage amount of 6,000 cubic metres (CM) rock riprap (Table 3).

Table 3. Logistics Comparison

Description	Quantity Required	Trucks Required	Distance to Jobsite	Total Shipping Kilometres
Rock Riprap	6,000 CM [1]	400 [2]	50 km [3]	20,000
EEAS	20,000 SM	1	500 km [4]	500

1. Estimated based on 20,000 SM of coverage and a section thickness of 30 cm
2. Estimated based on single truckload volume of 15 CM
3. Estimated distance to local rock quarry
4. Distance estimated at 10 times the distance for rock riprap

There are several traffic costs per kilometre of vehicle traffic established by the FHWA: pavement wear ($0.019), congestion ($0.152), crash potential ($0.005) and noise pollution ($0.009). Continuing this comparison, the additional cost associated with the traffic created by the transportation of rock riprap and EEAS based on the estimated logistics comparison is $3,723 and $95, respectively. This shows more than 95% reduction in traffic cost when an EEAS is used in place of rock riprap.

4.3. Emissions Reduction

Once the quantity of trucks required for shipping of material is known, the cost associated with the health of transportation emissions can be estimated. The Federal Emergency Management Agency (FEMA) establishes the emissions output associated with transportation based on the amount of horse-power hours. When the amount of emissions generated is compared to the health cost of emissions established by the California Department of Transportation (Caltrans), the economic impact of emissions can be quantified.

Furthering the comparison, the transportation of rock riprap creates more than 36 tonnes of emissions, while the transportation of the EEAS is reduced to less than 1 tonne. This translates to an emissions cost of more than $17,000 for transporting the rock riprap and less than $500 for the EEAS. This again shows more than 95% reduction in emissions cost when an EEAS is used in place of rock riprap.

5. GEOTECHNICAL PERFORMANCE

The USACE defines a slough as “a shear failure in which a surficial portion of the embankment moves downslope”. While surficial slope failures are often considered maintenance problems, if not addressed they can become progressively larger and effect the safety of the total slope. Unfortunately, these failures are often incorrectly categorized as erosion issues and the prescribed solution is therefore ineffective. Figure 7 shows two slopes that have attempted to solve a geotechnical failure with an erosion control solution only and have seen continued failure as a result.

Figure 7 Surficial Slope Instability

In addition to the economic, hydraulic, and environmental benefits, an EEAS can be designed to provide geotechnical improvement to the slope’s surface. In this application, the earth anchors are designed to be installed through the HPTRM and past the existing or anticipated failure plane. The strength and durability of the HPTRM is critical in order to connect the earth anchors together into a passive system that resists movement. Figure 8 conceptually shows how the components of an EEAS can be used to stabilize an embankment against surficial sloughing. We then see this concept come to fruition on the project shown in Figure 9.

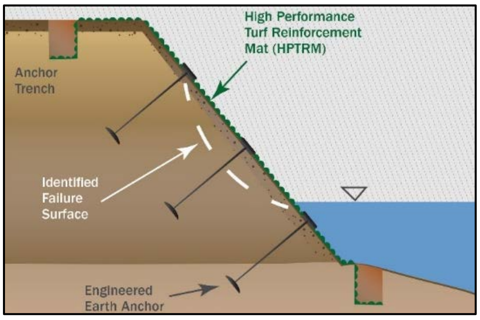


Figure 8 - EEAS for Surficial Slope Stability Concept

Figure 9 Surficial Slope Failure (Left) stabilized with EEAS (Right)

A slope stability analysis considering various slope geometries completed using GeoStudio's Slope/W slope stability software can show a side by side comparison. The analysis uses vertical slice limit equilibrium methods to determine slope stability following the Spencer method for the given geometry, soil, rock riprap, and earth anchoring parameters. The soil parameters for this example can be seen in Table 4.

Table 4. Slope Stability Soil Parameters

Soil Type	Strength Type	Unit Weight	Cohesion	Friction Angle
Embankment Soil	Mohr-Coulomb	17 kN/m³	0 kPa	28°
Rock Riprap	Mohr-Coulomb	21 kN/m³	0 kPa	42°

For this comparison, the slopes armored with an EEAS had a failure depth limited to 60 cm in order to isolate the surficial failure. Earth anchors were modeled using a 1.2 m horizontal spacing and 0.9 m vertical spacing with various pullout capacities. The geotechnical performance comparison for surficial slope stability can be seen in Figure 5.

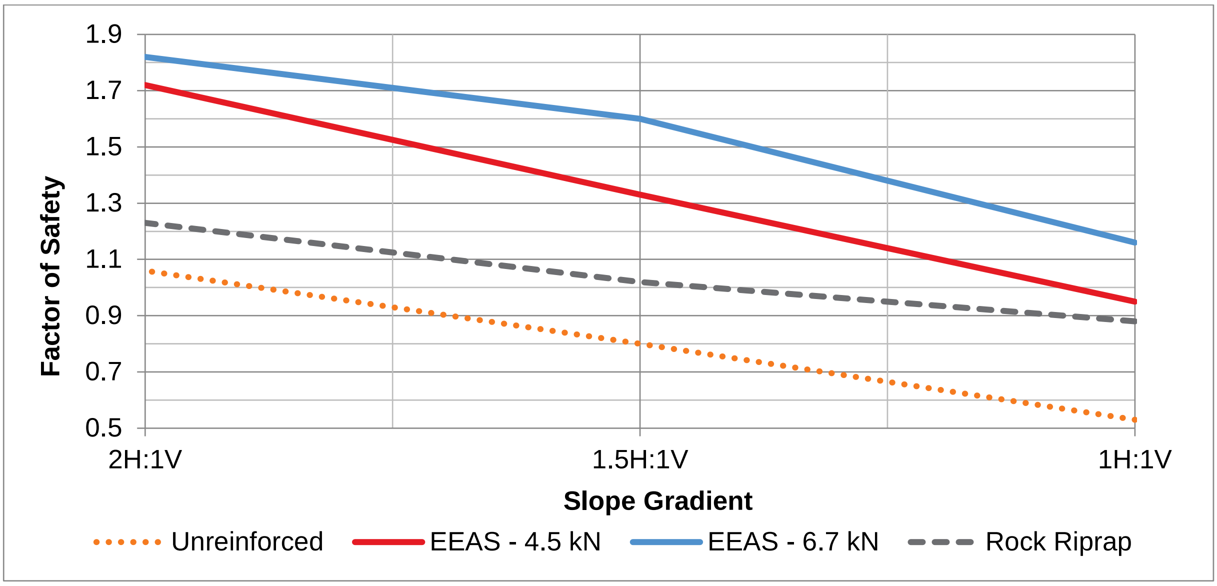


Figure 10 Geotechnical Comparison

The above geotechnical comparison does not consider the effect of groundwater and assumes a homogeneous soil layer. The inclusion of groundwater can affect the overall model by reducing soil strength, increasing the soil's unit weight, as well as adding a pore water pressure component to the stability calculations. When non-homogeneous soil layers exist within the slope, weaker layers can contribute to localized failures. If the proper information is collected for the slope in question, the variation in soil layers and the presence of groundwater can be accounted for within the analysis.

6. SUMMARY

When designing erosion control or surficial slope stability measures for your project, remember there are other alternatives to traditional solutions like riprap. The EEAS has a number of additional benefits such as proven hydraulic performance, improved pollutant removal, improved surficial stability, reduced carbon footprint, and lower installation and maintenance cost. The performance of EEAS has been tested and approved by the U.S. Army Corp of Engineers (USACE) with millions of square metres of successful installations. The EEAS is designed to resist hydraulic stresses and offers a more durable, environmentally friendly, and economical alternative to traditional rock riprap solutions.

To ensure the successful use of an EEAS on your project, the following criteria should be required:

- Full-scale hydraulic testing and a hydraulic analysis for project conditions
- A geotechnical stability analysis for project conditions
- A vegetation establishment plan for project conditions
- Third-party UV test results as well as proven field performance and durability

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