

# Sustainable Engineering Solution for Slope Stability with Anchor Reinforced Vegetation System (ARVS)

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## ABSTRACT

Sustainability and resiliency are becoming more important in project design, with emphasis being placed on the environmental impact. Slope stability solutions should be designed to provide a low environmental impact to achieve long-term performance and overall project success. During design, it is important to consider factors such as durability, economics and environmental impacts. The Anchor Reinforced Vegetation System (ARVS) is recognised as a sustainable armouring and slope stability solution proving both surficial stability and erosion control at the same time. An ARVS is a component system consisting of a High Performance Turf Reinforcement Mat (HPTRM) to provide erosion protection and surficial strength, coupled with Percussion Driven Earth Anchors (PDEAs) for resistance to shallow-plane instability. The system is designed to optimise rapid vegetation growth and keep soil in place, thereby resisting mobilisation of soil masses associated with sliding failures of slopes. Key physical and material properties of the component system include optimal ultraviolet resistance, flexibility, and tensile strength of the HPTRM, along with its ability to promote vegetation establishment through increased soil and moisture retention. PDEAs can be selected in various lengths and strengths and are composed of corrosion-resistant material to ensure longevity while maintaining ease of installation. Design methodology of the ARVS for reinforcement against relatively shallow translational sliding failures consists of an infinite slope method solution adapted for the inclusion of PDEAs. Procedures for utilising the ARVS for relatively deep-seated rotational sliding failures include the modelling of stability using conventional limit equilibrium methods. Components of the ARVS are integrated into the model using slope stability modelling software. Results include the potential for an engineered ARVS solution for specific cases of reinforcement for slope stability. The sustainability of the ARVS solution including environmental parameters such as carbon footprint, economical and engineering aspects is analysed and compared with traditional solutions. An example of the practical application of the design methodology is demonstrated.

*Keywords:* Slope stability, Reinforced vegetation, Sustainable, ARVS

## 1 INTRODUCTION

Slope movements occur in a wide range of material types (including rock, debris, and earth) and mobilisation modes (falls, topples, slides, spreads, and flows) (Varnes, 1978). Time and costs associated with the maintenance, repair, and reconstruction of failing slopes are financial burdens. Conventionally acceptable methods of slope repair such as substantial excavation and replacement often experience degradation and undesirable environmental impacts. Alternative sustainable methods for stabilisation of failing slopes are thus often demanded which can include passive, in situ remediation techniques that incorporate vegetation as a component of the stabilisation strategy. An Anchor Reinforced Vegetation System (ARVS) is such a method explored herein, consisting of a High Performance Turf Reinforcement Mat (HPTRM) capable of promoting robust vegetative growth, secured permanently by an engineered arrangement of Percussion Driven Earth Anchors (PDEAs) to provide slope surface stability (normally up to 3m deep). Of course, this system is not designed to solve global stability issues.

The design of an ARVS consists of identifying the mechanism of failure (or potential failure) of an earthen slope composed of geometric, soil, and hydrologic properties specific to a localised area. Evaluation of the failure (or potential failure) surface

location is critical to the reinforcement design of the system. Once the failure mechanism and failure surface are understood, deterministic computational evaluation methods can be used to predict slope instability and provide mitigation design alternatives. Facilitating the establishment of vegetation within the ARVS provides additional elements of strength to alleviate soil mass mobilisation over time.

This paper presents details of the ARVS, design procedure and installation for slope stability. The paper will focus primarily on failures associated with sliding soils present within the uppermost layers of a slope including regression/erosion/sloughing type failures on public infrastructure projects such as road and rail cuttings or embankments.

Almost all sliding of soil masses are because of the combination of increased shear stress acting on the soil, along with reduced shear strength of the soil itself. Identifying the sole reason of a sliding slope failure is nearly impossible, as multiple factors can cause the increased stress and reduced soil strength which leads to a significant soil mobilisation. As a result, it is reasonable to assume that eliminating all identified causes of increased stress and reduced strength is not necessary for stabilisation. Instead, a strategic implementation of reinforcement associated with improving one or two key failure mechanisms can be an effective mechanism (Sowers and Sowers, 1961).

While erosion is technically not a mode of slope failure, it can often be considered as a root cause and can end up with similar undesirable consequences. Rainfall and surface runoff can detach and transport soil particles, resulting in rilling and gullies forming along a slope face. These indentations can eventually alter (i.e. steepen) the slope geometry and the ability of the soil to support itself, leading to the propagation of a surface failure. Furthermore, active erosion on a slope will greatly limit the establishment and growth of vegetation, resulting in reduced resistance to shear stress, as vegetation affects the cover factor in allowable shear stress calculations (Coppin and Richards, 1990; Kilgore and Cotton, 2005). While prevention or control of erosion does not provide an engineered reinforcement solution for slope stability, it may greatly reduce the cost and impact of proposed methods to mitigate slope failure.

## 2 MODES OF FAILURE AND REINFORCEMENT

Sliding failures can generally be classified into one of two modes, translational failure or rotational failure. Translational failure is a sliding mass along a plane of failure parallel to the surface, of minimal depth (e.g., surficial slope instability) while rotational failure is deeper-seated sloughing of a larger soil mass, usually in a circular-shaped failure plane (Varnes, 1978). It is important to be able to differentiate between the two modes prior to selecting a representative model for analysis and design.

Translational failure is typically identified as a scenario where the length of the failure surface is at least 10 times greater than its depth (Miller, 2012). Typically, the plane of failure is underlain by a stronger soil or bedrock which makes the soil movement approximately parallel to the original slope surface. This representation can be modelled as an infinite slope, where conditions are idealised and there are no defined upper and lower boundaries within the failure plane. Simplifying the scenario into this model allows the designer to introduce a reinforcement system that bolsters the resisting forces and stabilises the slope against translational sliding (Gray and Leiser, 1982).

Rotational failure is normally when the length of the failure surface is typically 3 to 6 times greater than its depth (Miller, 2012).

Reinforcement against both modes of slope failure consists of reducing shear stresses as well as increasing the shear strength of the soil mass. The ARVS can be used as either a passive or active reinforcement system which makes this solution a unique solution. Resistance to instability can be provided passively through full development of PDEA capacity after slope movement begins, or PDEAs can be post-tensioned and locked at a specified design load to function as an active reinforcement system.

PDEAs are not only effective in resisting the shallow shear forces associated with both modes of failure,

but they also force the potential rotational failure arcs deeper into the ground, thus producing a curved failure path with greater normal stress along the lower half. This effectively increases the shear resistance of the soil mass due to higher normal stress, thus drawing on more of the friction component of the soil (as the cohesion component is independent of the normal stress).

## 3 ANCHOR REINFORCED VEGETATION SYSTEM (ARVS)

The ARVS is a multi-component system that includes a High Performance Turf Reinforcement Mat (HPTRM) installed on the slope surface, permanently secured using Percussion Driven Earth Anchors (PDEAs) in a designed pattern, driven to a designated distance below the surface of the slope (Figure 1). Each component of the ARVS has a unique purpose enabling the whole system to serve as an effective solution to provide slope stability against both translational and rotational sliding failures. The purpose of the ARVS as a slope reinforcement solution includes utilising the PDEAs as a system of active or passive reinforcement to provide resistance to driving forces, incorporating the HPTRM as a high-tensile strength geosynthetic (typically more than 40kN/m in both directions) with very high UV stabilisation for distributing load amongst the PDEAs and providing further resistance to movements, and providing a permanent layer for the establishment and reinforcement of vegetation through the three-dimensional matrix of the HPTRM, which will control surface erosion and assist in resisting shear forces.

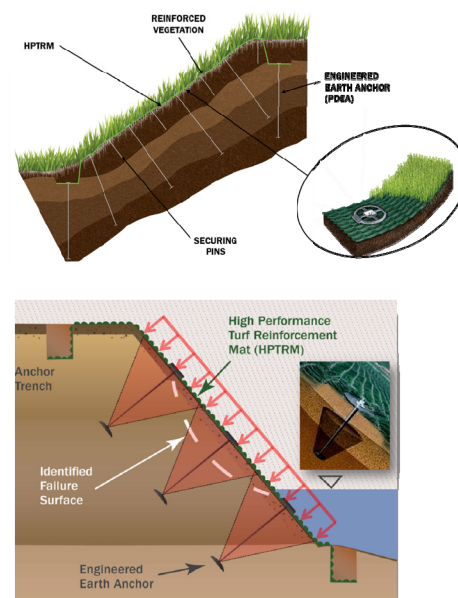


Figure 1. Anchored reinforced vegetation system (ARVS)

In addition, the ARVS serves to isolate the underlying soil from erosive forces by providing continuous coverage of the slope face. As the HPTRM is tensioned across the surface of the slope,

it has a compressive influence on the enclosed soil mass, thereby increasing stability against mobilisation. The tensioned geosynthetic also engages normal stress at the base of the failure surface, which increases stability of the soil mass. The PDEAs impart discrete loads at the slope face, and by penetrating through the failure surface provides friction, adhesion, bearing, bending resistance, and torsional resistance. The open weave of the HPTRM provides relief of pore water pressure build-up within the soil mass. Over time, the compressive HPTRM causes soil densification, thereby increasing internal friction angle and cohesion, providing greater stability. Finally, the HPTRM promotes vegetative growth (where applicable) and thereby provides extra benefits to slope stability (Koerner 1990; Hryciw and Haji-Ahmad, 1992).

Use of a synthetic HPTRM composed of a homogeneous, lofty, three-dimensional matrix of woven polypropylene fibres promotes the ability of the system to function as designed. A homogeneous dense woven HPTRM with the highest available tensile strength (minimum 40kN/m) should be used. Densifying the woven matrix promotes greater resiliency without sacrificing porosity of the geosynthetic to allow for relief of pore pressure from saturated soils within a slope mass (Figure 2) (Ghiassin et al., 1997). Hydraulic resistance to velocity and shear stresses (generated by flowing water), an optimal relationship between the overall thickness of the material and its flexibility, high strength and resiliency, and a high-degree of UV resistance (at least 90% retained tensile strength at an accelerated exposure simulation of 10,000 hours) are important parameters for the long-term performance and survivability of the ARVS.



Figure 2. Homogeneous dense woven HPTRM in an ARVS

PDEAs as part of an ARVS can come in a variety of sizes, lengths, and strengths, but typically consist of three major components. The first is a solid anchor head, typically manufactured as die-cast aluminium, and ranging in size and weight. The anchor head is connected freely to a tendon, which consists of either flexible wire rope or a rigid steel threaded bar. The length of the tendon is specified in the design, but typically requires embedment at least 600mm beyond the plane of failure. At the opposite end of the tendon is a bearing plate or cap, ranging in size from a 75mm diameter zinc-plated aluminium disc, to a 100mm x 150mm steel spreader plate (Figure 3).

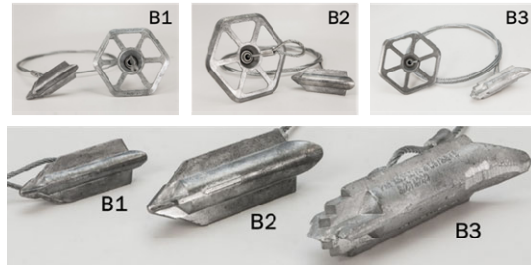


Figure 3. Percussion Driven Earth Anchors (PDEAs)

Understanding the mechanics behind installing the PDEA component will aid a quality installation of the whole system. The required tools are a percussion hammer, a ground rod driver, drive steel compatible with the PDEA, a setting tool, and wire cutters. The complete installation procedure and details should be followed which is out of the scope of this paper.

Strength of the PDEA is quantified by a value known as the “pull-out” resistance of the anchor, which is generally defined as the tension load causing one or more of the components to yield, or to physically remove the entire PDEA from the ground – whichever occurs first. Typically, the pull-out strength of the anchor is a function of soil characteristics, as removal of the PDEA from the ground normally occurs before components yield. Generally speaking, the pull-out strength of an anchor varies from 100-250kg for the smallest anchor (depending on soil characteristics), to approximately 2000kg for the largest (feasibly incorporated) anchor. In most cases, stability analysis and reinforcement design would be completed based on available geotechnical data, and subsequent tension loading and measurement would be performed on in situ soils of the slope to validate the design.

Establishment of quality vegetation can provide direct and substantial effects on the long-term stability of the ARVS-reinforced slope. Vegetation is critical to alleviating surface soil erosion, which can be a contributing factor to increased shear stress and decreased shear strength of a slope’s soil. Vegetation serves to impede erosion through various means. Interception of rainfall is provided by the shoots, or foliage of a plant, absorbing its volume and dissipating its energy imparted to the soil. Restraint is provided by the roots of the plant, providing a system to physically bind and confine particles of soil. Retardation of runoff is provided by the shoots (foliage) of the plant by providing an increase of roughness to the slope surface, thereby slowing the velocity of erosive water flow. Infiltration of runoff is assisted by plant systems, which provide physical and chemical attributes that maintain healthy soil capable of infiltrating more water. Finally, transpiration of near-surface groundwater is achieved through plants that absorb it, providing delays to saturation of the slope’s soils (Gray and Leiser, 1982). Selection of the appropriate geosynthetic material as part of the ARVS is critical to the performance of the system. Utilisation of an HPTRM with specific material and performance properties will increase the effectiveness of the ARVS with respect to erosion control, vegetation

establishment, tensioned load distribution and coverage, and functional longevity (Figure 4).



Figure 4. ARVS after installation (left) and after vegetation (right)

Although the erosion control and shallow plane mass-movement mitigation benefits of vegetation should always be incorporated where feasible, the HPTRM and PDEA array system in an unvegetated condition can still be an effective reinforcement solution in many cases (Figure 5). The UV resistance) of the HPTRM is very important in these conditions. A minimum of 90% UV resistance after 10,000 hours accelerated test is suggested for the HPTRM. In cases that soil type and chemicals may affect the durability of the PDEA, this needs to be considered in the design and PDEAs made of special material may need to be used. As a substitute for the erosion control benefits of vegetation, the use of a lightweight, non-woven geotextile below the HPTRM can provide a barrier to the migration of fine aggregate particles, while still providing the open area to act as a porous medium to facilitate evaporation and drainage.



Figure 5. HPTRM and PDEA for an unvegetated condition

#### 4 ARVS SOLUTION TO SHALLOW/SURFICIAL FAILURE (THE INFINITE SLOPE MODEL)

Where the failure mode is expected to be a relatively shallow, surficial failure, a basic infinite slope analysis is often appropriate. Available resistance to slope failure is dependent on the friction angle of the soil and the normal force  $N$ , which acts perpendicularly to the shear surface. However, additional frictional resistance can be realised by incorporating the anchor force to the equation, as illustrated in Figure 6, for non-saturated, cohesionless soils:

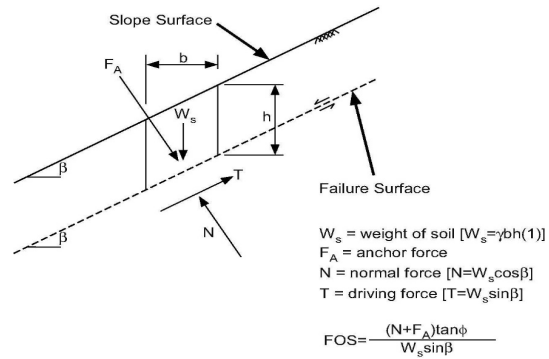


Figure 6. Infinite slope model calculation (Durham et al., 2012)

Where  $\gamma$  is soil unit weight,  $\phi$  is soil angle of internal friction,  $c$  is soil cohesion,  $\beta$  is slope angle,  $h$  is vertical height of soil mantle, and  $b$  is width of the analysed element. The factor of safety (FS) against sliding (ratio of resisting forces to driving forces) is calculated as:

Resisting Forces,  $R = (N + F_A) \tan \phi$   
 Driving Forces,  $D = T$

$$FS = R / D$$

If the anchors are not post-tensioned and locked-off at the specified design load, the soil friction angle should be based on residual strength, since the anchors will not fully develop their capacity until the slope has begun to move. It should be noted that the anchor force,  $F_A$ , could represent one anchor per square metre with a design capacity of 10kN, or five anchors per square metre, each with a design capacity of 2kN. The number of anchors per square metre is determined by the design engineer.

Similarly, for the case where the soil has cohesion and/or seepage forces present, the anchor force can be incorporated into the equations illustrated in Figure 7, below:

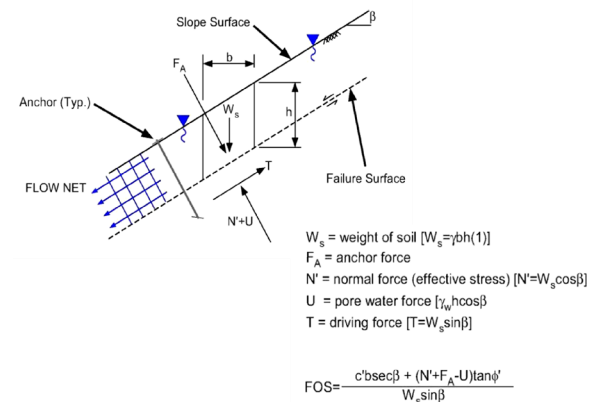


Figure 7. Infinite slope model calculation, with cohesion/seepage forces (Durham et al., 2012)

As for the case with cohesionless soil without seepage, if the anchors are not post-tensioned and locked-off at the specified design load the cohesion should be based on residual (fully softened) strength.

The anchor force ( $F_A$ ) is controlled by the pull-out resistance of the anchor, which is a function of the anchor head dimensions, anchor length, geotechnical soil properties, and in situ moisture conditions. Pull-out resistance should be verified in the field with in-situ testing. A FS value ranging from 1.2 to 1.5 is recommended, and selection should be based on the quantity and quality of field testing and engineering judgment, the type of project, relevant codes and standards, consequence of failure, design life, etc. The anchor force  $F_A$  is limited by the punching shear capacity of the bearing plate through the HPTRM, which is a function of the plate material, plate dimensions, and the plate's mechanical interaction with the HPTRM.

## 5 ARVS SOLUTION FOR DEEP-SEATED ROTATIONAL FAILURE (LIMIT EQUILIBRIUM ANALYSIS)

Many larger slopes have complex geometry anticipated deep-seated rotational failure modes that do not lend themselves to the simplified assumptions of an infinite slope analysis. In these instances, conventional limit equilibrium analysis may be used to evaluate the anchorage design. Commercially available computer programs such as Slope/W or SLIDE have been used with successfully in modelling and designing ARVS solutions. SLIDE for example utilises several different limit equilibrium methods (such as Bishop, Spencer, Morgenstern-Price, Janbu, among others) for comparison of critical slip surfaces with the lowest FS values. The program allows the user to employ a circular surface grid search to iterate to the critical slip circle in a rotational sliding failure (or potential failure). The software is also effective in analysing non-circular sliding failures (or potential failures) consistent with the infinite slope model for translational slope movement (block glide), and cases where earth materials are heterogeneous and/or anisotropic.

In utilising limit equilibrium analysis for ARVS design, HPTRM should be modelled as a reinforcement layer, more specifically as a geotextile (although it is not a geotextile) where the tensile strength of the material can be input into the support properties.

When modelling the HPTRM, the force application should be set to passive (a module allows the user to specify this value). This limits the HPTRM in developing a resisting force only after some slope movement has occurred. The strip coverage is typically set to 100 percent as there are generally no gaps between the layers of HPTRM.

When modelling the PDEAs, an "End-Anchored Support" option is typically chosen in the software. The force application for the PDEAs is generally set to active, since the anchors will exert a force upon the slope without any prior slope movement (where tensioned upon installation). If the anchors are not post-tensioned, then they should be treated as a passive force and modelled accordingly.

The example illustrated in Figure 8 below shows a proposed slope subject to stability analysis for failure

potential in a rotational sliding mode. In this scenario, a slope comprised of a non-homogeneous mixture of soil types was analysed for stability when altered to a steepness of 1H:1V. Both soil types identified in the slope had cohesion, but groundwater was not present and pore water pressure was not applicable. Using a trial-and-error method of reinforcement design, an ARVS was modelled using an HPTRM and PDEAs of sufficient anchor head, tendon, and bearing plate size to achieve a 9kN pull-out strength capacity (assumed, to be verified in the field through load testing). Spacing of the PDEAs was proposed on 0.9m centres in two directions. Based on these parameters, the SLIDE program completed a search for the radius of the critical slip surface and returned an FS of 1.3 from the Bishop Simplified Limit Equilibrium Method. To provide a more conservative design, the effects of established vegetation on increased shear strength of the soil mass are neglected. This is suggested to be considered as a design requirement in general for all projects as it may take time to establish vegetation and a failure could occur in the meantime.

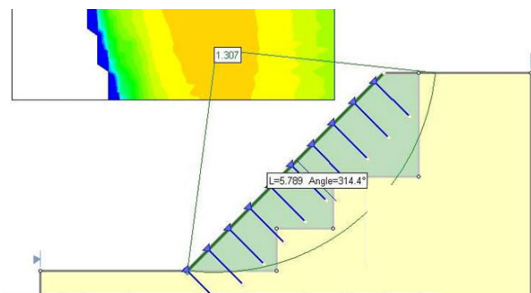


Figure 8. Example limit equilibrium analysis Modelled in SLIDE (Durham et al., 2012)

## 6 CONCLUSION

The Anchor Reinforced Vegetation System (ARVS) is a component system consisting of a High Performance Turf Reinforcement Mat (HPTRM) to provide erosion protection and surficial strength, coupled with Percussion Driven Earth Anchors (PDEAs) for resistance to shallow-plane instability. The system is designed to optimise rapid vegetation growth and keep soil in place, thereby resisting mobilisation of soil masses associated with sliding failures of slopes. In addition, the ARVS serves to isolate the underlying soil from erosive forces by providing continuous coverage of the slope face. The ARVS can be used as either a passive or active reinforcement system which makes this solution a unique solution. PDEAs are not only effective in resisting the shallow shear forces associated with both modes of failure, but they also force the potential rotational failure arcs deeper into the ground, thus producing a curved failure path with greater normal stress along the lower half.

Where the failure mode is expected to be a relatively shallow, surficial failure, a basic infinite slope analysis is often appropriate. Commercially available computer programs such as Slope/W or SLIDE have been used successfully in modelling and designing

ARVS solutions for deep-seated rotational failure analysis.

Key physical and material properties of the component system include optimal ultraviolet resistance, flexibility, and tensile strength of the HPTRM, along with its ability to promote vegetation establishment through increased soil and moisture retention.

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