Analyzing Different Methods to Model a Marine Mattress on a Partially Submerged Slope

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ABSTRACT

Earth and rock-filled gabions have valuable applications in engineered dams, walls, and foundations, as well as for erosion control and military force protection. A gabion mattress, also commonly known as a marine mattress, is a variation of the gabion that utilizes geosynthetic materials with a relatively small height compared to its much larger length and width dimensions. While gabion baskets and walls are typically used for slope stability, marine mattresses are primarily used to protect against erosion and wave action along slopes. While uplift stability and down-slope sliding are two concerns to be mitigated when incorporating a marine mattress into designs, the presence of a marine mattress on a slope affects the underlying slope's stability. Slope stability analyses are essential for design of sloped applications of marine mattresses, particularly on soft soils, and the ability to accurately set up analysis software to aid in geotechnical design is crucial in making sound engineering recommendations. While there is some information in the literature regarding slope stability regarding gabion boxes baskets and walls, as well as geosynthetics and revetment stone layers along slopes, there is limited information on modelling revetment stone filled geosynthetic gabion mattresses along a slope. In their recent 2021 software update, the limit equilibrium software used in performing the analysis introduced a reinforcement library to choose specific manufactured geosynthetic products. This consists of a limited selection of products from two manufacturers. While geogrids are not included, a marine mattress was not included in the updated version. In this study, the stability of a partially submerged marine mattress was analyzed in five potential ways including modelling as (1) a high-strength material, (2) an unreinforced layer of revetment stone, (3) a layer of revetment stone enveloped by a geosynthetic material, (4) a layer of revetment stone enveloped by a specific manufactured geo-grid, and (5) a surcharge load with the same unit weight as the revetment stone layer. The advantages and disadvantages of each modeling scenario are discussed, and factors of safety for global failure are compared.

INTRODUCTION

Marine mattresses are a type of gabion made of geosynthetic material, such as a geogrid, and filled with revetment type stone. These mattresses are typically placed along slopes to prevent erosion, as shown in Figure 1, and not normally used to strengthen slopes. Their overlaying on slopes can be expected to affect the strength and stability of that slope. Eltarabily et al. (2019) used the limit equilibrium software, GeoStudio Slope/W, to compare factors of safety in a canal before and after installing a marine mattress. Results showed that the canal lined with a marine mattress resulted in a lower factor of safety. In their study, a marine mattress was modelled as a surcharge load on a slope, neglecting any strength gained by the geosynthetic material that make up a marine mattress.

Figure 1. Typical Marine Mattress installed along a shoreline (Source: Hughes 2006).

Software is becoming increasingly sophisticated and prevalent in engineering design. Knowing a software's strengths and limitations, as well as abilities in modelling different scenarios is crucial in making appropriate design recommendations. However, when seeking to model a specific condition, modelling methodologies between different individuals has the potential to yield results that differ. This in turn may impact overall design recommendations that result from the analysis.

Significant research has been done in the analysis of geotextile mats, predominantly in scour protection and dike creation projects, where the matts are laid on level foundations (Guo 2016, Huang 2021, Li et al. 2020, Wang et al. 2020, Yan and Chu 2010). Borges and Cardoso (2002) used both finite element models and limit equilibrium methods, similar to those in this study, to analyze a set of geosynthetic-reinforced berms, finding agreement between the methods in terms of slip surface and factor of safety. There are limited standards and design equations for marine mattress on sloped surfaces. Brown (1979) developed equations that considered the effects of wave action on mattress stability, but these equations prescribed minimum thicknesses and not factors of safety. In addition, they only consider the slope, stone infill density, infill void space, and wave height, ignoring surface soil properties and global stability of the mattress-slope system. Hughes (2006) indicated that these equations were originally developed for gabions and cautions their application to marine mattresses without additional factors of safety considered. Tensar International Corporation (2020), a marine mattress manufacturer, provides a design guide utilizing the same equations as Brown (1979). Global Synthetics Pty Ltd. (2015), whose marine mattresses incorporate wire mesh instead of geosynthetic materials, provide design equations for determining mattress thickness for erosion protection roles; however, these equations, developed by Maynord (1995), consider rock infill movement within mattress to constitute failure rather than overall mattress movement, and so do not consider slope stability to be an important failure mode. They also recommend placing their mattresses on slopes no steeper than 1V:1.5H but provide no description of the likely failure modes or design equations at steeper slopes. The literature is limited in research that considers the effect of a marine mattresses on a slope using limit equilibrium analysis. Particularly lacking is the literature which methods may provide the most and least conservative results.

SOFTWARE AND METHODS

The software used in this sensitivity analysis was (hereafter referred to as “the software”). This annual software update was their first to introduce a manufacturer reinforcement library to choose specific geosynthetic products, consisting of a limited selection of products from only two manufacturers. This new feature allows for additional geosynthetic specification inputs that were not previously available in the previous user-defined geosynthetic window of the software. For this study, one of the preloaded geosynthetics was chosen - the Tensar® UX1400 geogrid. All specifications for this geogrid able to be input were input the user-defined geosynthetic parameters used in the user defined geosynthetic approaches 3A, 3B, and 3C, later discussed. Materials were chosen to be standard Mohr-Coloumb materials, requiring just a unit weight and friction angle for the cohesionless materials considered. The unit weight for the revetment stone modelled to fill the marine mattress was 113 pcf (17.83 kN/m^3), while an angle of internal friction of 32 degrees was used. This weight was also used for the revetment stone without a geosynthetic model, as well as for the high strength model, and surcharge load model. The bank slope material was a gravelly sand with a unit weight of 116.4 pcf (18.28 kN/m^3) and phi angle of 35 degrees. Suction strength for both materials was ignored for simplicity These properties are summarized in Table 1. Spencer analysis was the limit equilibrium method chosen. Horizontal-to-vertical slope ratios of 1:1, 2:1, 3:1, 4:1, and 5:1 were analyzed to observe relationships at these various angles. Examples of these slopes are shown in Figure 2. The entry slip surface ranged from the middle of the slope to the right end of the model, while the exit slip surface ranged from the middle of the slope to the left end of the model. The slip surfaces.

Table 1. Material properties considered.

Material Type	Unit weight, pcf	Unit weight, kN/m^3	Friction Angle, degrees
Marine Mattress	113.5	17.83	32
High Strength Mattress	113.5	17.83	/
Gravelly sand	116.4	18.28	35

MODELLING METHODOLOGIES CONSIDERED

The first approach models the marine mattress as just the revetment stone material that fills the mattress while ignoring the geosynthetic material that makes up the mattress. This allows a failure surface to be considered both around and through the mattress; however, it neglects any tensile strength and resistance to downslope movement from the geosynthetic.

The second approach models the mattress as a high strength material. This forces the analysis to only consider slip surfaces around, and not through, the mattress. While this takes into account not allowing the failure surface to pass through the rigid mattress, its overestimates the actual rigidity of the geosynthetic mattress.

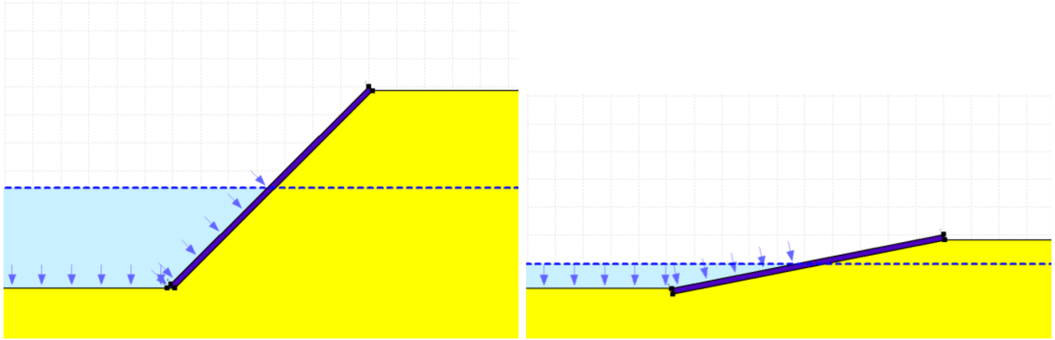

Figure 2. Steepest slope considered (1:1 slope) on the left and shallowest slope (5:1 slope) on the right.

The third approach uses a surcharge load with the same force as the unit weight of the revetment stone that fills the marine mattress. This takes into account the weight of the mattress but does not take into consideration the tensile strength of the geosynthetic, nor the friction angle of the revetment stone.

The fourth approach models the mattress as the revetment stone material enveloped in a geosynthetic reinforcement to allow the additional tensile strength of geosynthetic mattress to be considered. The few necessary input parameters for the geosynthetic reinforcement derived from the much larger standard specifications provided in the software for preloaded geogrids (i.e. Tensar® UX1400 geogrid). The direction a geosynthetic reinforcements is input in the software affects the results. It was desired to study the effect this has on marine mattress modeling; therefore, reinforcements were input with three configurations: (A) outer geogrid reinforcement placed counterclockwise, followed by the diaphragm material perpendicular to the slope, (B) outer geogrid placed clockwise, followed by the diaphragm material perpendicular to the slope, and (C) outer geogrid placed as set longitudinally parallel to the slope, followed by the diaphragm material.

The fifth approach models the marine mattress as reinforcement lines using the pre-loaded properties of the geogrid considered in this analysis. This preloaded reinforcement material contains inputs in addition to the normal geosynthetic tab, specifications that were not considered during the third approach. Similar to the prior approach, the geogrid reinforcement was drawn in the same three configurations: A, B, and C.

Each method takes the friction angle of the revetment material within the mattress and tensile strength of the geosynthetic that makes up the mattress marine into consideration at varying degrees. Additionally, comparing the standard user-defined geosynthetic reinforcement method with the new pre-loaded manufacturer geogrids built into the software was also a goal in having both methodologies considered.

A summary of each approach is shown below in Table 2.

RESULTS OF ANALYSIS

The results of this sensitivity analysis are shown below in Figure 3. From an angle of about 45 to 35 degrees, the high strength mattress model yields the highest factors of safety, while from

35 degrees to about 12 degrees the geosynthetic set model resulted in the highest factors of safety. The clockwise drawn user-defined geosythetic and clockwise manufactured geogrid models both resulted in the lowest factors of safety for all angles evaluated. Enveloping the revetment stone layer in geosynthetic reinforcement was intended to take the geosynthetic reinforcement into consideration; however, it was either a non-reinforced high strength material model or surcharge load that resulted in the highest factors of safety.

Table 2. The five approaches (and their variations) considered.

No GeoSynthetic	Surcharge Load	User Defined Geosynthetic	Preloaded Geosynthetic
1 – High Strength Mattress	3 – Surcharge Load Only	4A – Counterclockwise Geosynthetic around revetment stone	5A – Counterclockwise Geogrid around revetment stone
2 – Revetment Stone Only		4B – Clockwise Geosynthetic around revetment stone	5B – Clockwise Geogrid around revetment stone
		4C – Upward Geosynthetic around revetment stone	5C – Upward Geogrid around revetment stone

The results for the no reinforcement approach only slightly underperformed the parallel set and counterclockwise placement of the geosynthetics, as shown in Figure 3 above. The results from the geosynthetic and geogrid methods, using both upward and counterclockwise placement, were the same, as shown by the overlapping lines in Figure 4 below. On this figure, the clockwise drawn geosynthetic and geo-grid resulted in the same factors of safety that underperformed the counterclockwise and parallel slope models, suggesting further research is needed into the software's modeling methods for geosynthetic reinforcement, and its effects on design.

Considering the surcharge load, high strength mattress, and no reinforcement models show an inconsistent relationship that depends on the slope of the bank, as shown in Figure 5. For the steepest slope considered (1V:1H, 45 degree), the largest factor of safety was seen using the high strength mattress approach, with the surcharge load approach resulting in factors of safety similar to the no reinforcement approach. At gentler slopes, the surcharge approach resulted in higher factors of safety, with the high strength approach resulting in factors of safety similar to the no reinforcement approach.

COMPARISONS AND LIMITATIONS

A study by Eltarabily et al. (2019) compared the factors of safety in a canal with and without a marine mattress in order to quantify the changes seen after installing a marine mattress. In that study, a surcharge load was used to model a marine mattress, with an average difference in factor of safety between the canal with and without a mattress being about 0.1965. The research presented in Figure 3 above show that the surcharge load method to model a marine mattress can result in the highest factors of safety of all models considered, particularly at gentler slopes. At about a 45 degree angle, all methods result in a factor of safety no more than 0.5 different than all other values. At gentler slopes, the differences between methods can be over 1.5.

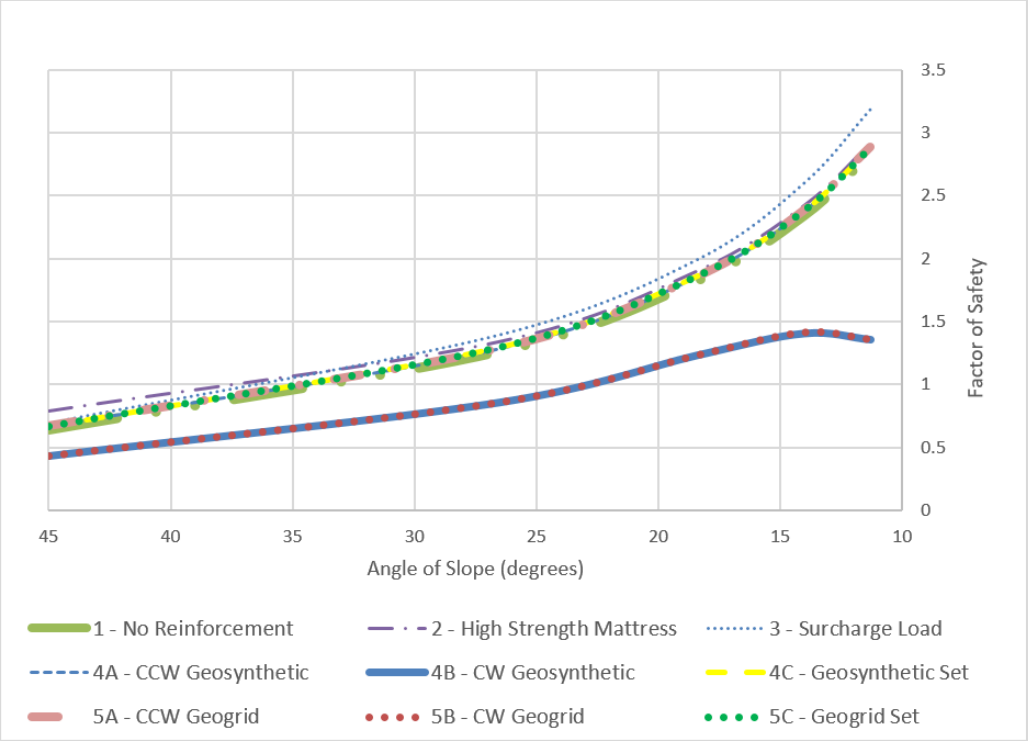

Figure 3. Results from all considered approaches.

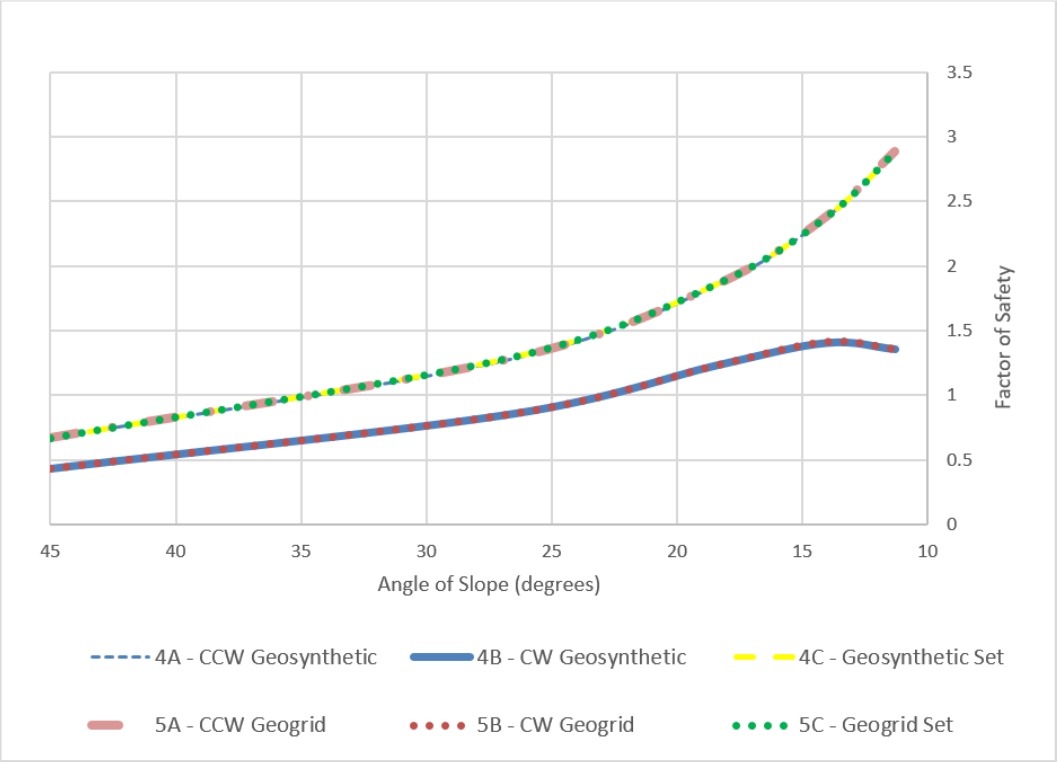

Figure 4. Results from all approaches utilizing geosynthetic reinforcements.

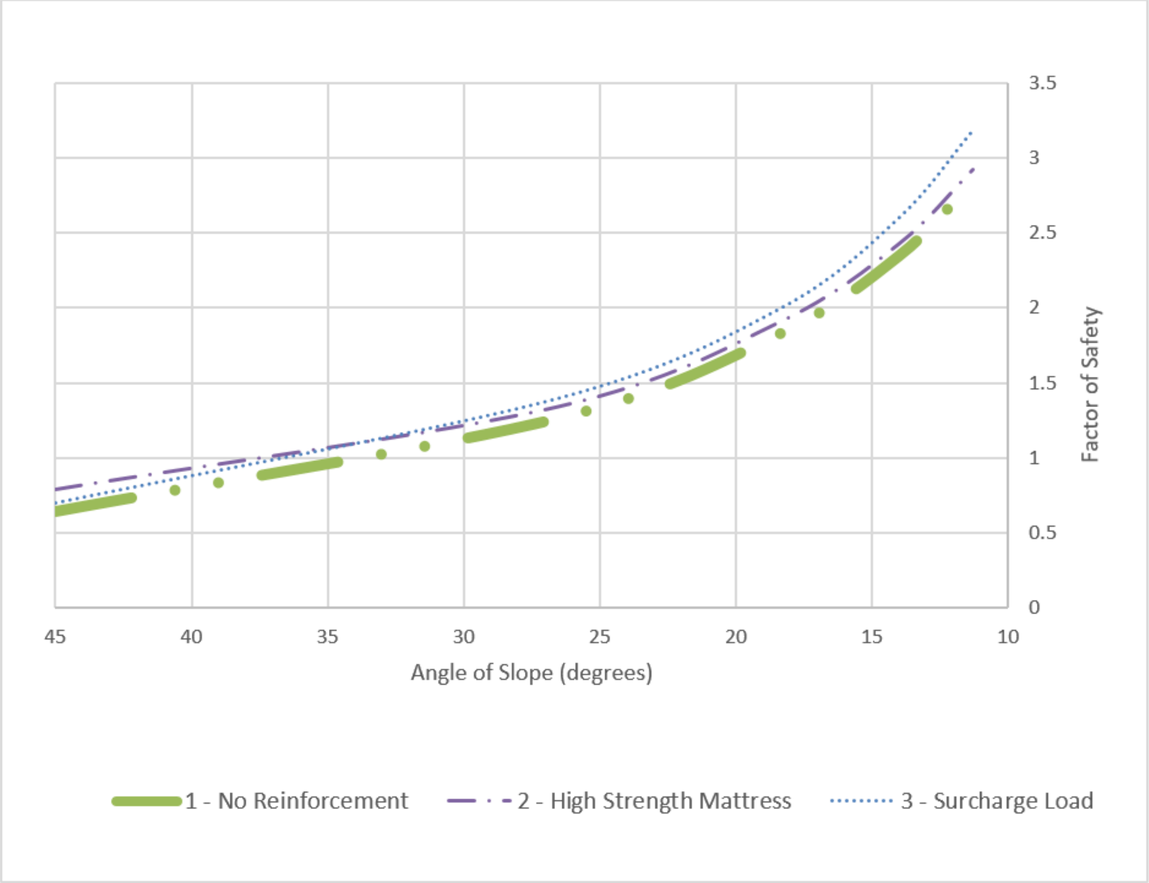

Figure 5. Results for surcharge load, high strength mattress, and no reinforcement approaches.

There are several limitations to this study. The decision to focus on a variety of modelling approaches necessitated the limiting of failure analysis to circular, global failures only. Future work should address modeling methodologies effects on local failures such as toe failures and top failures as well as non-circular failure planes. While sensitivity analysis was conducted and found no difference in modeling approach results with a weaker underlying soil, it was not tested whether different geotextile parameters would influence modeling approach results.

CONCLUSION

Slope stability modeling software may be used to analyze conditions that the software is not optimized for. In these cases, the methods selected to set up the model to analyze a particular condition can have a significant impact on the results and conclusions.

The Slope/W™ GeoStudio© 2020 version 10.2.1.19666 software is the first update to contain the option to select manufactured geogrids as a reinforcement option. This is in additional to being able to type in user defined specifications for geosynthetics. The manufactured reinforcement options contain additional product specifications; however, when borrowed and input into user-defined reinforcement which requires less specifications, the results are the same when all other variables are the same.

Both the manufactured geogrids and user-defined reinforcement models that were placed counter-clockwise resulted in factors of safety much lower than all other models at all other angles of slope for the canal. While models produce conservative values, more research is needed to see if the results are overly conservative.

When the angle of the canal slope was about 45 to 33 degrees, the high-strength material model resulted in the highest factors of safety. When the angle of the canal slope was about 33 to 12 degrees, the surcharge load model resulted in the highest factors of safety. The revetment stone material was enveloped in geosynthetic material for other models considered under the assumption that the model would consider the tensile strength; however, the two models which resulted in the highest factors of safety did not include the revetment stone material enveloped by a geosynthetic reinforcement.

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