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Automated Search for Optimal Cost of Geosynthetic-Reinforced Soil Walls under Climatic Conditions

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Abstract. This study presents a methodology for optimizing the design of geosynthetic-reinforced soil (GRS) structures by integrating numerical modeling and cost optimization under transient climatic conditions. A coupled 2D analysis was conducted using SEEP/W and SLOPE/W to evaluate the effects of climatic oscillations (comprising precipitation, evapotranspiration, temperature, and humidity) on the Factor of Safety (FoS) over a 1,096-day simulation period. The results indicated a strong correlation between precipitation cycles and FoS variation, with lower values occurring during wet periods and recovery observed during dry spells due to increased suction in the unsaturated soil. To improve the cost-effectiveness of the design, an optimization algorithm implemented in MATLAB was used to minimize reinforcement costs while ensuring structural safety. The optimization was performed at the time of minimum FoS using the fmincon function from the MATLAB toolbox, which applies the Sequential Quadratic Programming (SQP) algorithm. The procedure considered a 1 m extrusion of the GRS wall and the commercial availability of materials. The process yielded a 17% cost reduction compared to the initial design.

Keywords: Optimization, Reinforcement, Geosynthetic, Cost.

1 Introduction

Retaining structures are essential in large engineering works such as bridges, dams, and highways. One solution for their implementation is reinforced soil structures, which combine soil — which performs well under compression — with materials that provide tensile strength, and are recognized as more economical solutions according to Ehrlich and Becker [1]. Considering this, several types of reinforcement have been developed, and among the most recent are geosynthetics [2].

The stability analysis of a reinforced soil wall is typically performed using the global Factor of Safety (FoS), estimated by applying deterministic software such as GeoStudio, which enables the simulation of various solutions to assess how variations in each parameter affect stability results. Consequently, it is possible to optimize the structure to avoid overdesign, identifying the most efficient scenario to minimize material consumption and costs while adhering to safety standards.

Although such software offers great ease in analyzing these structures, it requires simulations with manual parameter insertion, which becomes time-consuming when testing multiple solutions. One way to streamline this process is by using programs capable of automatically inserting variables.

Thus, in this paper, GeoStudio 2025 is combined with MATLAB — a programming and numerical computing software widely used in engineering — to optimize a geosynthetic-reinforced soil wall under climatic effects. In addition, the Sequential Quadratic Programming (SQP) method is employed, which is a nonlinear optimization technique that solves constrained problems by linearizing the constraints at each iteration.

2 Problem Setting

2.1 Geosynthetic-Reinforced Soil Wall

For this paper, a hypothetical Geosynthetic-Reinforced Soil (GRS) wall was considered. The geometric parameters of the structure were defined according to the guidelines of the Federal Highway Administration [3]. The wall was reinforced with a nonwoven geotextile and featured a concrete facing. In the simulations, reinforcement layers were spaced at 0.5 m intervals and extended 4 m in length, resulting in a structure with 11 reinforcement layers. The reinforcements were installed with a 1% inclination, which was also applied to the top of the reinforced zone. The face of the wall was designed with an inclination of 1H:10V.

To ensure proper drainage, three drainage geocomposites were placed behind the concrete facing, spaced every 1.5 m, to facilitate water flow. Additionally, a vertical geocomposite drain was installed at the back of the GRS wall to prevent water accumulation in the reinforced zone. This vertical drain was positioned 0.5 m below the top of the wall to avoid direct water entry. A discharge pipe connected to the vertical drain was embedded in gravel and wrapped in the same nonwoven geotextile used for reinforcement. The section of the structure is shown in Figure 1.

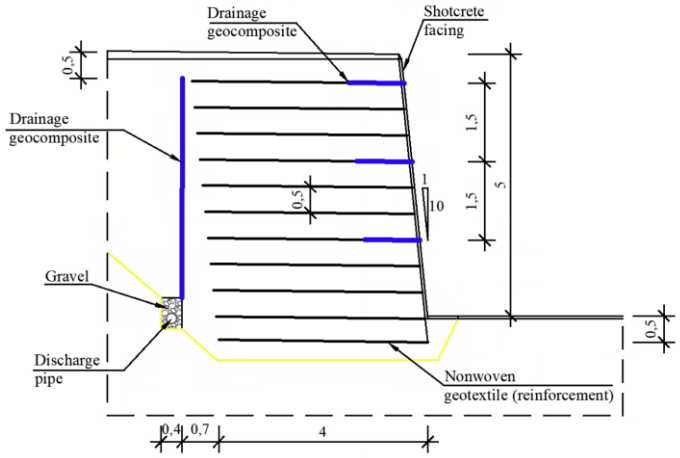


Figure 1. GRS wall section

2.2 Numerical model of a GRS Wall

The present study includes deterministic stability analyses of a Geosynthetic-Reinforced Soil (GRS) wall under climatic effects, performed using GeoStudio 2025.1.1. Slope stability was evaluated with the limit equilibrium method implemented in SLOPE/W, a module of the GeoStudio suite. This tool computes the FoS, defined as the ratio between the shear strength that the soil can mobilize and the shear stress acting on it. In other words, the FoS represents the extent to which shear strength can be reduced before the system reaches a state of limit equilibrium [4].

Climatic effects were incorporated using SEEP/W, which performs transient seepage analyses based on user-defined boundary conditions. Accurate modeling requires considering the hydraulic properties of both the soil and the geotextile. Therefore, water retention curves for both materials were adopted from previous laboratory studies [5, 6] and modeled using the van Genuchten (1980) and Durner (1994) equations (Figure 2). For infiltration modeling, an initial suction of 45 kPa was assumed for the reinforced soil, following Albino et al. [5].

The wall described in the previous section was modeled in GeoStudio using a two-dimensional geometry. Climatic parameters were applied in SEEP/W to simulate daily pore water pressure variations. For stability analysis, the Morgenstern–Price method was used in SLOPE/W. This mathematically rigorous method accounts for all interslice forces and satisfies both force and moment equilibrium conditions. The model stored pore water pressure distributions for each simulated day, enabling the FoS to be calculated for every time step.

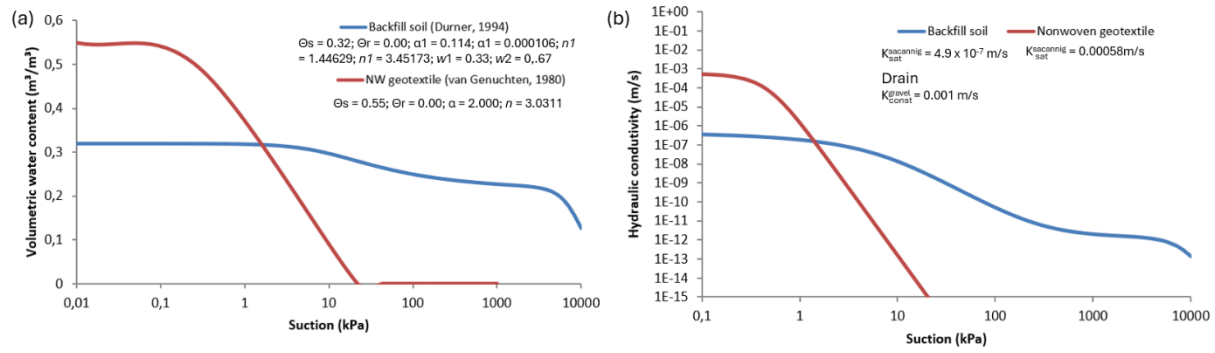


Figure 2. (a) Water retention curves, (b) Unsaturated hydraulic conductivity, adopted from Albino *et al.* (2020)

2.3 Meteorological data

For the climatic conditions, data from 2013 to 2015 for São Paulo City, Brazil, were considered. This period was selected because it closely represents the historical average precipitation recorded by IAG-USP between 1933 and 2017. These data were used to model infiltration and flow processes, accounting for the effects of rainfall, evapotranspiration, air humidity, and temperature. The objective was to determine the pore water pressure distribution in the structure at different time steps for the subsequent factor of safety analysis. The precipitation, evapotranspiration, temperature, and humidity data used in the simulations are presented in Figure 3.

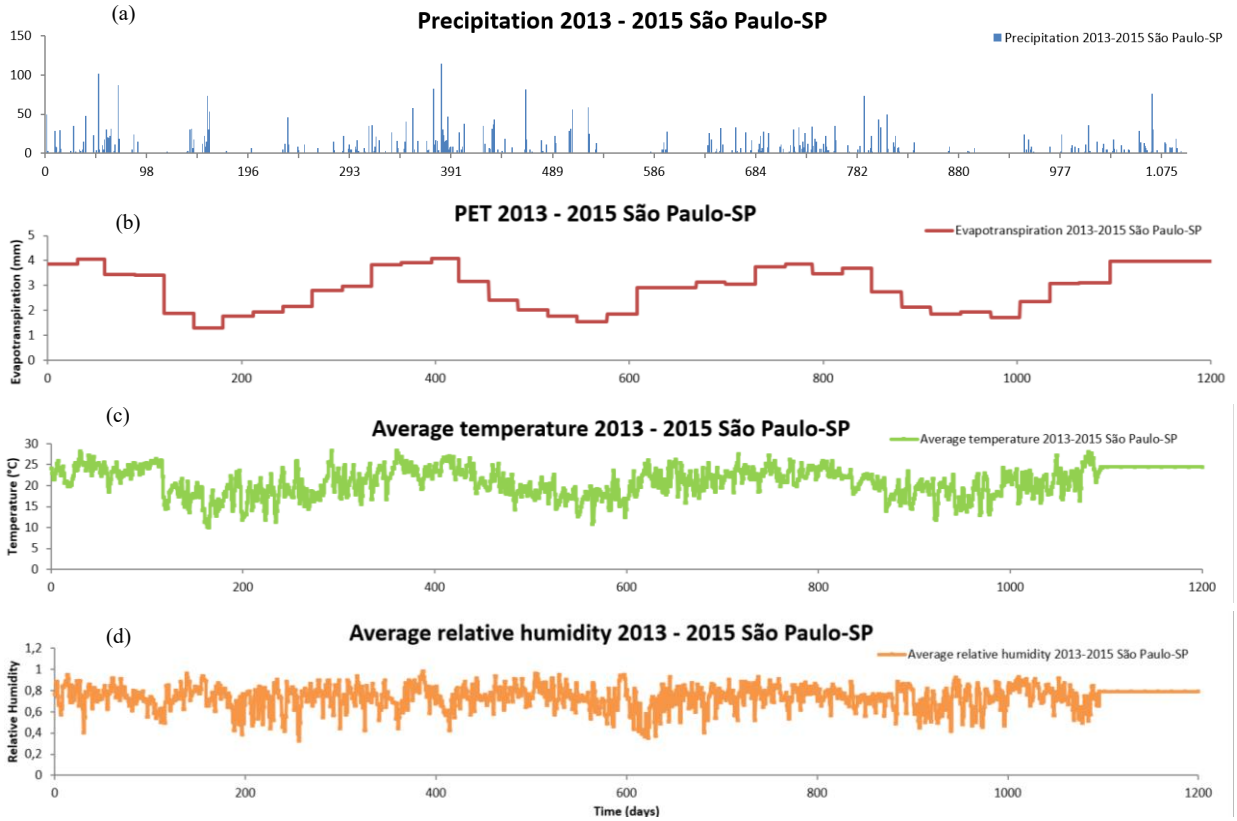


Figure 3. Meteorological data used in the analysis (a) precipitation, (b) evapotranspiration, (c) temperature, (d) relative humidity

2.4 Cost Data

For the cost optimization, it was necessary to obtain information about the prices practiced in the domestic market. To this end, a geosynthetic supplier was consulted, making it possible to determine a relationship between the increase in the material's tensile strength and its cost. To incorporate this information into the optimization process, the collected prices and corresponding tensile strengths were plotted in a graph, which revealed an approximately linear growth trend. Based on this, a mathematical function that best describes this behavior was derived and implemented into the optimization code. This allowed the cost associated with each solution to be calculated. The relationship obtained is shown in Figure 4.

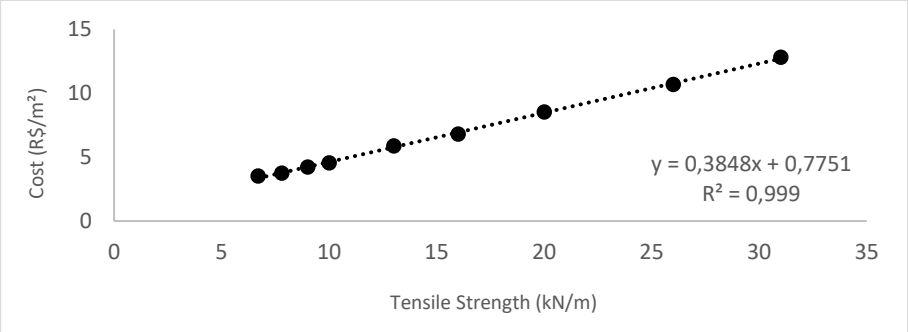


Figure 4. Cost Variation as a Function of Geosynthetic Strength

3 Methodology

3.1 Steps of Optimization

In this study, the data presented were used to develop an analysis capable of simulating the structure with user-defined parameters and identifying the optimal design point that ensures cost efficiency while maintaining the required safety of the construction. This section provides an overview of the implemented optimization procedure.

(1) **Determine the GRS wall geometry:** The geometry of the structure was defined based on literature recommendations for geosynthetic-reinforced soil walls. In this preliminary phase, AutoCAD was used to produce the initial technical drawings.

(2) **Model the geometry in GeoStudio 2025.1.1:** The previously defined geometry was recreated in GeoStudio using a 2D environment to allow numerical analysis.

(3) **Seepage analyses:** In this step, the climatic effects to be considered and the boundary conditions of the model were defined. These were applied in SEEP/W to perform transient flow simulations, which allowed the determination of pore water pressure distribution over time. Parameters such as the total simulation duration and the number of time steps were set. In this study, a period of 1,096 days was simulated using 4,384 time steps (4 steps per day).

(4) **Limit equilibrium analysis:** Using SLOPE/W, limit equilibrium analyses were carried out to calculate the FoS for each day of the simulation.

(5) **Select time step for optimization:** To minimize computational cost, the optimization phase was carried out using a single representative day, corresponding to the minimum FoS observed, thereby ensuring safety.

(6) **GeoStudio 2025 file:** A GeoStudio file (.gsz) was created for each selected day, containing only the slope stability analysis. This file is a compressed archive that includes, among other files, an XML file storing all definitions and model settings. This XML file is modified during optimization to update input parameters. In addition, CSV files generated by GeoStudio contain the calculated FoS values and are used for result extraction.

(7) **Integration between GeoStudio and MATLAB:** In the MATLAB environment, a function was developed to automate the modification of XML files based on selected input parameters and to execute

the simulation via GeoStudio. In this study, the variables considered were the cohesion, friction angle, and unit weight of both soils, as well as the tensile strength of the reinforcement, which was treated as an optimization variable.

(8) **Optimization routine:** A MATLAB routine was developed to define the values of the input variables used in the optimization. This routine utilizes the fmincon function from the MATLAB toolbox to test different tensile strength values, aiming to find the one that results in a Factor of Safety as close as possible to 1.5, which is the minimum required by design standards.

4 Results

4.1 Climatic Effects on Factor of Safety

Based on the initial simulation of the 1,096-day period using GeoStudio 2025, the variation in the Factor of Safety at each time step was observed. To evaluate the impact of climatic effects on slope stability, a static analysis was also performed for comparison purposes. The goal was to highlight the differences in results when climate-related variations are considered versus a steady-state condition. The FoS values obtained for the structure throughout the simulation are presented in Figure 5.

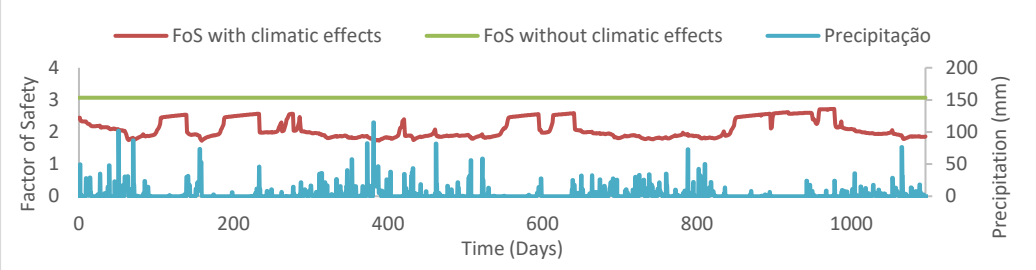


Figure 5. Variation of the FoS with and without climatic effects

The comparison revealed that the FoS is higher when climatic effects are not considered. It is also evident that the time-dependent analysis introduces significant variation in the FoS throughout the simulation period. During rainy periods, the Factor of Safety tends to decrease, while in dry periods it increases and stabilizes until the next wet season. This behavior can be explained by the role of suction in unsaturated soils. According to Marinho [7], suction in unsaturated soils can be defined as the isotropic pressure that pore water exerts to attract additional water. During drying processes, suction increases, which contributes to higher shear strength. Therefore, after periods of intense rainfall, the subsequent effect of evapotranspiration leads to an increase in suction, which in turn raises the Factor of Safety.

The analysis of FoS variation was also essential to identify the optimal point for optimization. By evaluating the results for each day of the simulation, it was possible to determine the day on which the FoS reached its minimum value. This day was considered the critical point of the analysis, and the optimization was carried out under its pore water pressure conditions to ensure safety. It is also important to note that the simulation considered the first three years of the GRS wall, so no prior stabilization of pore water conditions was performed before the simulations.

4.2 Stability analysis

After the 1,096-day simulation in SEEP/W, SLOPE/W was used to calculate the FoS for each day in order to identify the representative day for numerical analysis (the day of minimum FoS). Figure 6 presents the pore water pressure distribution and the corresponding Factor of Safety obtained from GeoStudio simulations for the first day, the last day, and the day with the minimum FoS, shown in Figures 6a, 6b, and 6c, respectively. These results, obtained directly from GeoStudio, served as a control to verify that the MATLAB program was correctly

returning the FoS based on the initial input parameters. This comparison confirmed that the implementation is functioning as intended and can be reliably used to evaluate different parameter combinations.

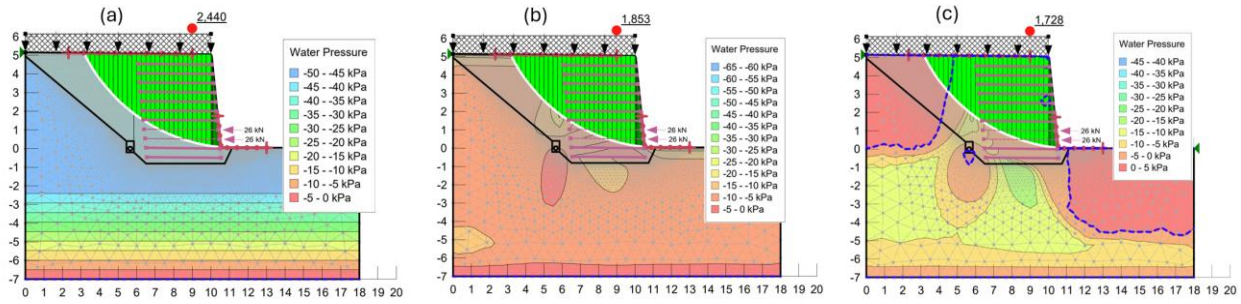


Figure 6. FoS and pore water pressure for (a) Initial day, (b) Last day, (c) Critical day

4.3 Cost optimization

For the cost optimization, the initial parameters were: cohesion (c') = 0, friction angle (ϕ) = 35°, unit weight (γ) = 20 kN/m³, and an initial tensile strength of 26 kN/m for the geosynthetic. Using the pore water pressure results from the critical day of the simulation, the initial Factor of Safety (FoS) was 1.728.

To calculate the final cost, the optimized cost in R$/m² was multiplied by 44 m, corresponding to the total length of the 11 reinforcement layers (each 4 m long). For simplification, a unit depth of 1 m perpendicular to the section was assumed (i.e., extrusion of the GRS wall).

The optimization algorithm starts with an initial guess for the tensile strength and performs simulations by testing values within defined minimum and maximum limits. A target FoS and a tolerance are specified as input parameters. The algorithm then iteratively searches for the tensile strength that meets the safety requirement at the lowest possible cost.

As outputs, the algorithm provides the optimized tensile strength, the corresponding Factor of Safety, and the final cost after optimization. These results are summarized in Table 1.

Additionally, a function was developed to generate plots illustrating the optimization process. These plots show the evolution of the FoS and associated cost at each iteration. Figure 7 presents these results. It can be observed that the optimization function tests both lower and higher values of tensile strength until convergence is achieved.

Table 1. Output of the optimization

Parameter	Optimum Value
Tensile Strength (kN/m)	19.4
FoS	1.5
Custo (R$)	362.65

Since the exact optimized tensile strength is not available in commercial catalogs, the closest higher value must be adopted in practice. In this case, 21 kN/m was selected. Table 2 compares the initial and optimized solutions. Despite the slight increase in tensile strength to match market availability, the optimization still resulted in a 17% cost reduction, demonstrating that the algorithm effectively minimized cost while maintaining structural safety.

Table 2. Output of the optimization

Parameter	Initial	Optimum	Economy
Tensile Strength (kN/m)	26	21	
FoS	1.728	1.569	17%
Custo (R$)	469.48	389.66	

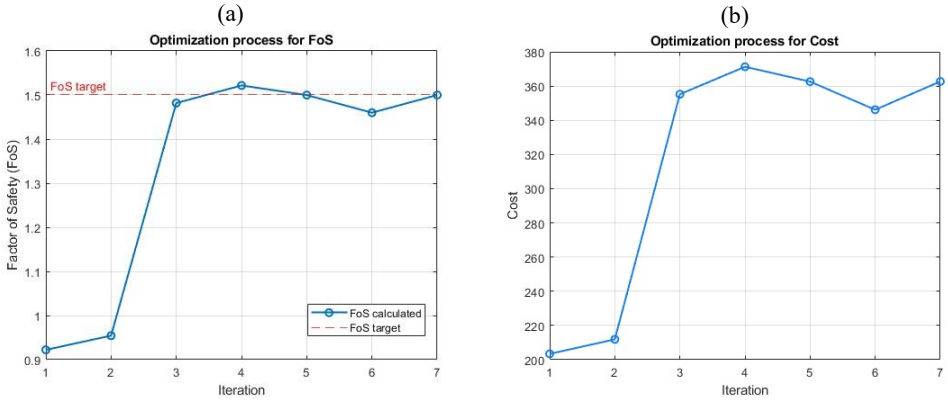


Figure 7. Output graph of the optimization (a) FoS optimization process, (b) Cost optimization process.

5 Conclusions

This study demonstrated that climatic effects significantly influence the variation of the Factor of Safety, generally leading to lower values during rainy periods. A clear relationship was observed between precipitation patterns and FoS variation: during wet periods, the FoS tends to decrease due to increased pore water pressure, while in dry periods, evapotranspiration promotes suction in the unsaturated soil, resulting in an increase in FoS. This behavior reinforces the importance of considering transient climatic conditions in geotechnical stability analyses.

Additionally, a cost and safety optimization algorithm were successfully implemented. The proposed methodology enabled the reduction of geosynthetic tensile strength while still meeting safety requirements. By integrating market-based material constraints and performance criteria, the optimization process achieved a cost reduction of approximately 17% compared to the initial design. These results highlight the potential of coupling numerical simulation tools with optimization techniques to enhance both the economic and technical performance of geotechnical structures.

The proposed methodology showed promising results, but it is important to note its limitations related to the constraints of the numerical software used, as its predefined settings may limit result generalization. Future work should extend the approach to other geometries, soil types, and climatic scenarios.

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