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Characterization of the Influence of Geometric and Mechanical Parameters on the Behavior of Reinforced Earth Structures Through Simulation

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ABSTRACT

The initial research described in [1] resulted from the combination of a powdery soil with reinforcement layers. When combined in this way, the soil and the reinforcement develop a certain amount of tensile strength due to friction forces [2]. The objective of this work is to characterize, through numerical simulation, the influence of geometric and mechanical parameters on the behavior of reinforced earth structures. To achieve this, a mechanical behavior model was developed using Python functions to better simulate the interactions between the soil and the reinforcements. However, geotechnical input parameters were adopted, such as the angles of internal friction of the backfill sand (20° and 35°) with its bulk densities(16 kN/m³ to22 kN/ m³) as well as for the supported soil and the foundation soil(25 ° and 18 kN/m³). The results showed that the longer the reinforcement bars, the greater the structure's resistance to sliding, and that the optimal value to ensure stability and safety is L = 0.7H. However, it should be noted that as the spacing between reinforcement bars S_V increases, the coefficient of friction f^* and the tensile forces T_m and T_p also increase.

Keywords: Characterization, reinforced soil, simulation, friction angle, tensile stress

1 INTRODUCTION

In reinforced earth structures, the reinforcement bars are subjected to significant tensile forces resulting from interaction with the backfill mass [3], [4], and [5]. The behavior of these structures varies depending on the characteristics of the soil and the reinforcement used [6]. Geotechnical properties of the soil, such as the angle of friction and unit weight, strongly influence stress distribution and adhesion at the soil-reinforcement interface.

The purpose of this section is to deepen the understanding of soil-reinforcement interaction mechanisms and to analyze the influence of geometric and mechanical parameters on the behavior of reinforced earth structures. To this end, parametric studies are conducted on a sample structure, taking into account parameters such as the length and spacing of the reinforcement, the configuration of the facing, and the properties of the backfill. To perform these complex analyses, we use numerical simulations developed using the Python programming language. Its use allows us to automate the calculation process, perform large-scale parametric analyses, and generate clear and accurate visualizations of the results. These tools thus enable us to evaluate the impact of various parameters on aspects such as the maximum tensile stress in the reinforcement, the tensile stress at the facing, and the resulting moments.

2. MATERIALS AND METHODS

INPUT PARAMETERS FOR THE ADOPTED MODEL

To illustrate the calculations in this study, a reinforced earth wall is analyzed over a 1-meter-long section with a mechanical height of 9 meters. The thickness of the facing is neglected in the calculations. The dimensions and mechanical properties of the model are based on reasonable assumptions for structures of this type, taking into account materials commonly used in reinforced earth construction [7].

Length of reinforcement (L): According to standard recommendations [6], [8] for this type of structure, the length of the reinforcement must be at least70% s of the wall height, i.e.,$L \geq 0{,}7Hm$ in accordance with the provided specifications. In this case, this corresponds to a reinforcement length of$6{,}3\ métres$.

Vertical spacing of reinforcements (Sv): The vertical spacing was calculated based on current standards [8], resulting in a spacing of 2 meters. This spacing complies with regulatory requirements to ensure a uniform distribution of forces along the height of the wall.

Backfill material: The backfill material used in this study is granular sand. The mechanical properties of this sand may vary depending on its degree of saturation and compaction. The variation in the internal friction angle of the sand in this study will range from$\emptyset = 20°$ to$\emptyset = 35°$, while its unit weight will vary from$\gamma_m = 16\ \mathrm{kN/m^3}$ to$\gamma_m = 22\ \mathrm{kN/\ m^3}$.

Supported Soil: The parameters considered in our study to characterize the soil to be supported are as follows:$\emptyset_b = 25\ °$ and$\gamma_b =$ 18 kN/m³

Foundation Soil: The parameters considered in our study to characterize the supporting soil are as follows:$\emptyset_f = 25\ °$ and$\gamma_f =$ 18 kN/m³

Applied Overload: In this study, the overload is considered within a range of $q = 500\ kN/m^2$ à $q = 1500\ kN/m^2$.

To simplify the analysis, the following assumptions were made:

The backfill is considered a homogeneous and isotropic material with elastoplastic behavior. This allows for a realistic representation of the interaction mechanisms between the soil and the reinforcement.

The reinforcements are assumed to be perfectly anchored in the soil, with full adhesion at the soil/reinforcement interface, thus ensuring efficient force transmission.

The surcharge applied to the top of the structure is uniformly distributed, simulating a constant load on the structure, which is typical in practical application scenarios.

These model choices and assumptions aim to accurately reflect the behavior of a reinforced earth retaining wall under representative loads, thereby enabling a thorough and relevant analysis.

INTRODUCTION TO THE PYTHON LANGUAGE AND PROGRAMMING PROCEDURE

For this parametric study, the Python programming language was chosen for modeling and analyzing reinforced earth structures. Python is an open-source language known for its ease of use and widespread adoption in the fields of engineering and science, particularly for scientific computing and data analysis. Its extensive ecosystem of libraries enables effective handling of complex modeling needs related to soil-reinforcement interactions.

To evaluate the influence of structural and mechanical parameters on the stability of reinforced earth structures, a Python code was de. This code models the variation of different parameters by tracking their influence on the characteristic aspects of the structure. Below, the details of the main lines of the code are presented section by section to clarify its operation [9], [10], [11].

INFLUENCE OF REINFORCEMENT LENGTH L

The length of the reinforcements L is a key parameter in the design of reinforced earth structures, directly influencing the stability and strength of the entire structure. For this analysis, certain parameters were kept constant and are listed in Table 1.

Table 1: Values of parameters kept constant for this analysis

Constant parameters	**Values**
Bulk density of the backfill material	$\gamma_m = 16\ \mathrm{kN/m^3}$
Overload on the fill	$q = 100\ \mathrm{kN/m^2}$
Angle of internal friction of the supported soil	$\emptyset_b = 25°$
Angle of friction of the backfill material	$\emptyset_m = 20°$
Vertical spacing between reinforcements	$S_V = 2\ \mathrm{m}$
Depending on the length of the reinforcing bars:	$L = 0{,}4H$
	$L = 0{,}6H$
	$L = 0{,}7H$

$S_V = 2\ \mathrm{m}$: Vertical spacing between reinforcements, calculated using the formula given by the equation

However, the length of the reinforcing bars L was varied (Figures 1–5) across three specific values (Table 1) to observe its effects on the results [9].

Figures 1 through 5 examine the impact of different reinforcement lengths on the friction coefficient f^*, the tensile forces (T_m and T_p) as a function of the relative height variation ($s = \frac{z_0}{H}$), and the safety factor against sliding as a function of the earth thrust force.

INFLUENCE OF VERTICAL REINFORCEMENT SPACING S_v

The vertical spacing of the reinforcements S_V refers to the distance between two adjacent reinforcements in a reinforced earth structure. For this analysis, several parameters were kept constant, and their values are listed in Table 2.

Table 2: Values of parameters kept constant for this analysis

Constant parameters	**Values**
Bulk density of the backfill material	$\gamma_m = 16\ \mathrm{kN/m^3}$
Overload on the fill	$q = 100\ \mathrm{kN/m^2}$
Angle of internal friction of the supported soil	$\emptyset_b = 25°$
Angle of friction of the backfill material	$\emptyset_m = 20°$
Lengths of reinforcement	$L = 0{,}7H$
Depending on the vertical spacing of the reinforcements:	$Sv = 1\ m$
	$Sv = 2\ m$
	$Sv = 3\ m$

However, S_V was varied across three specific values (Table 2) to observe its effects on the results.

The impact of different vertical spacing values on the friction coefficient f^* and the tensile forces (T_m and T_p) was examined [9]. The calculations were performed using Equations 1 and 2.

$$\boldsymbol{f^*} = \frac{\tau_{max}}{\sigma_{v0}} \quad \text{(Eq. 1)}$$

Where:

τ_{max} : Maximum shear stress that can be developed on the reinforcement surface

σ_v : Vertical stress

$$\boldsymbol{T_m = \sigma_h . S_V} \quad \text{(Eq. 2)}$$

Were

S_V : Represents the vertical spacing between reinforcement layers, and

σ_h: is the horizontal stress at the intersection of the line of maximum tension.

The horizontal stress σ_h is obtained from Equation 3.

$$\boldsymbol{\sigma_h = K . \sigma_V} \quad \text{(Eq. 3)}$$

σ_V where is the vertical stress determined according to the Meyerhof method, and K is the internal earth pressure coefficient within the mass.

3. RESULTS

Figures 1 through 5 present the results obtained for different values of the reinforcement length$L$, allowing one to observe the influence of the reinforcement length on the mechanical performance of the structure as a function of the relative height $(s = \frac{z_0}{H})$.

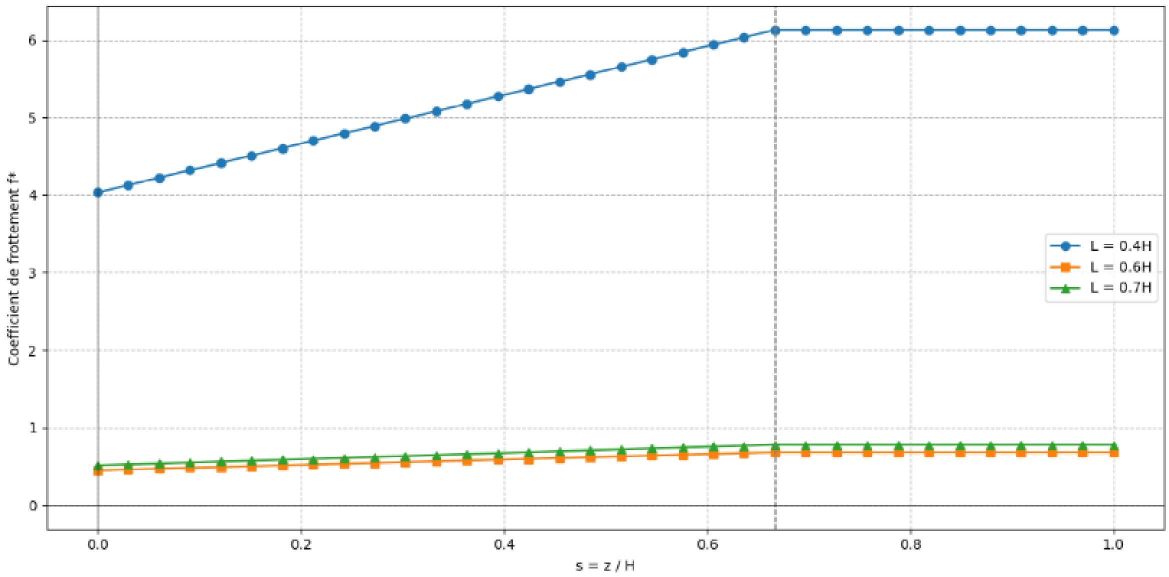

Figure 1: Variation of the apparent friction coefficient as a function of relative height for various reinforcement bed lengths

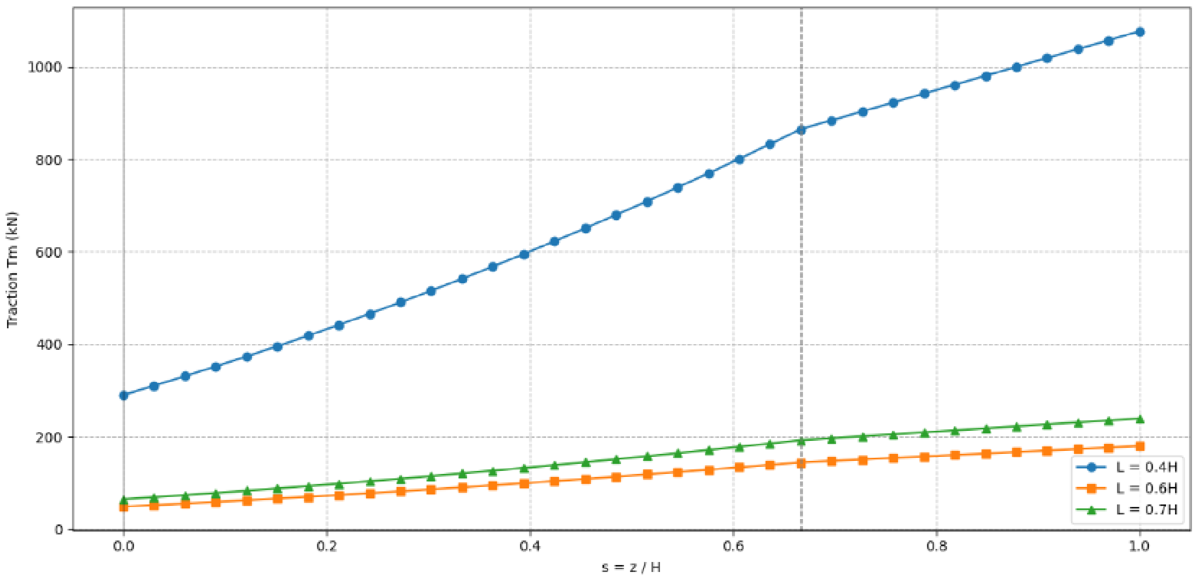

Figure 2: Variation of the maximum tensile forceT_m as a function of relative height with respect to variations in the length of the reinforcement beds

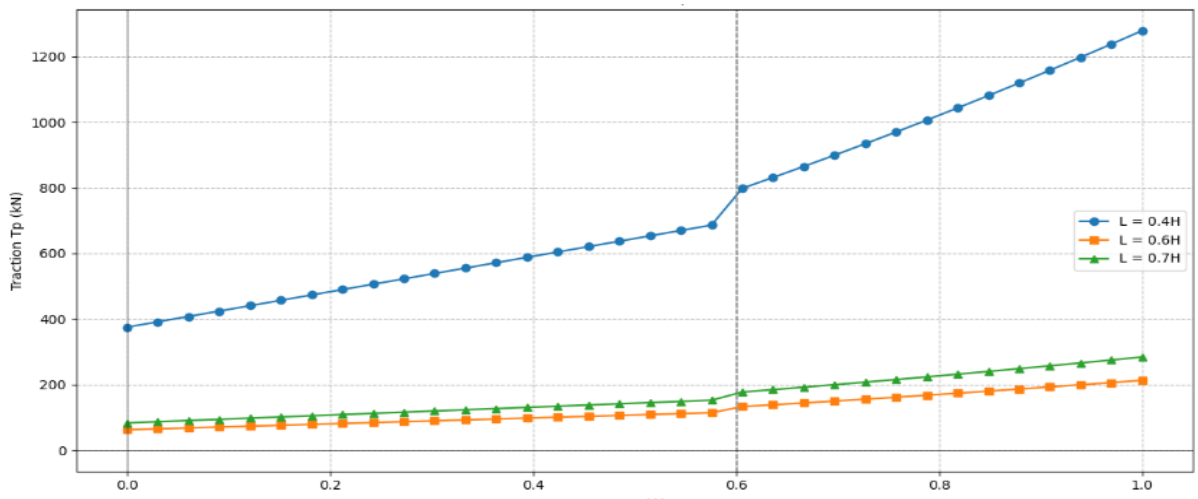

Figure 3: Variation of the tensile force at the facing T_P as a function of relative height with varying reinforcement bed lengths

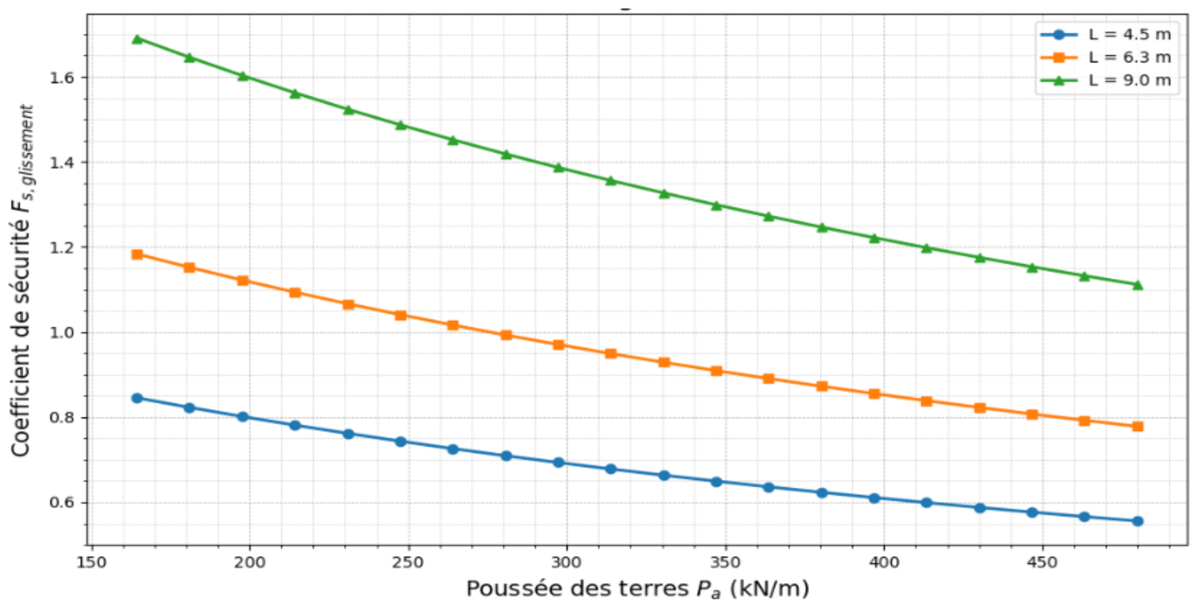

Figure 4: Variation of the slip safety factor as a function of earth pressure with respect to variations in the length of the reinforcement beds

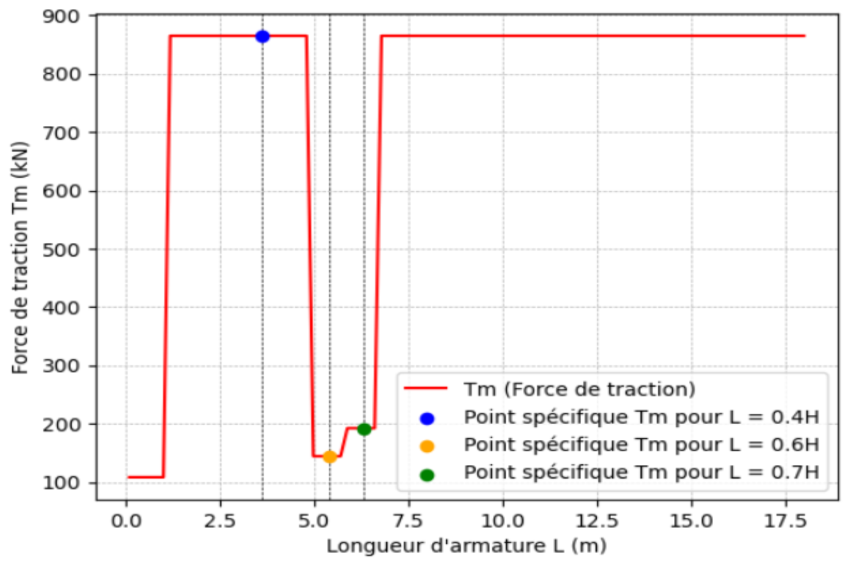

Figure 5: Variation of Tm as a function of reinforcement length L

Figures 6 through 8 illustrate the results obtained for several levels of vertical spacing of the structure's reinforcement.

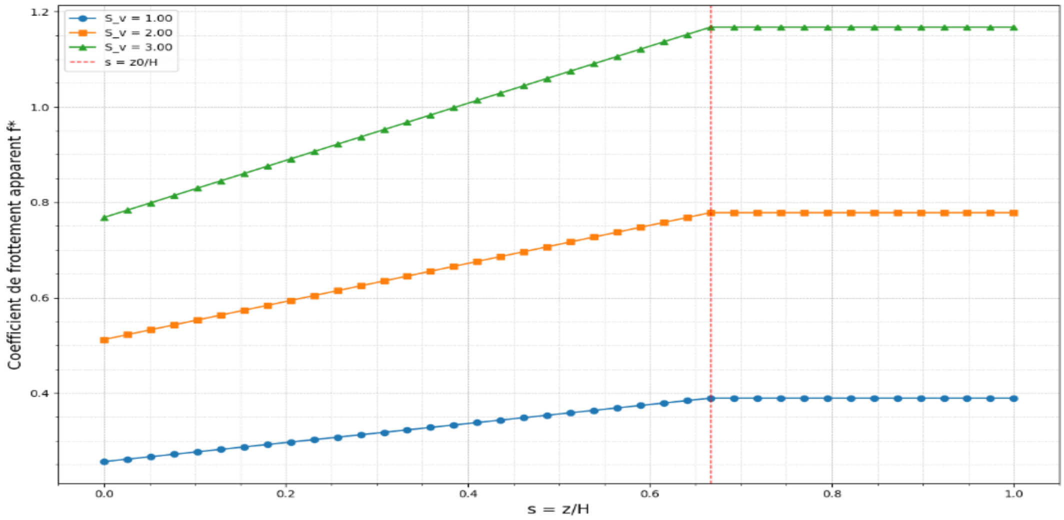

Figure 6: Behavior of the apparent friction coefficient f^* as a function of relative depth s for different values of S_V

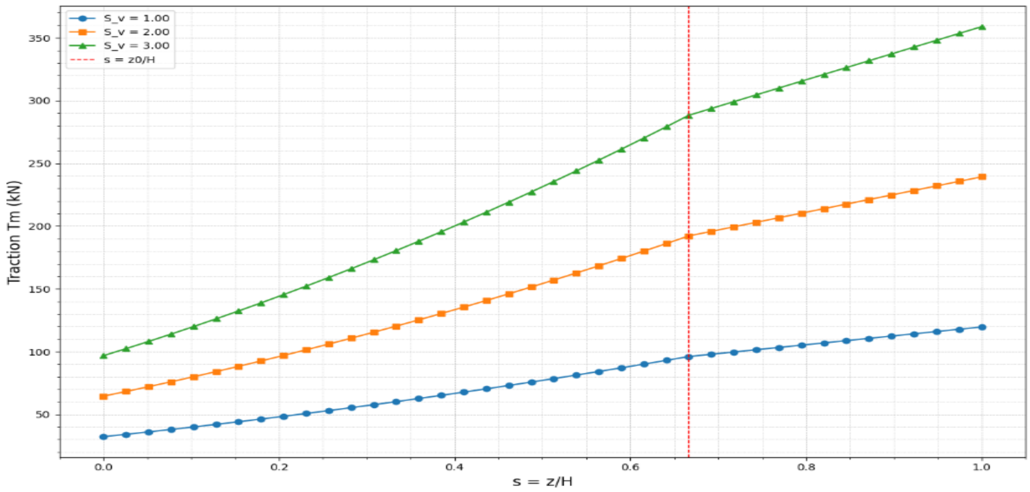

Figure 7: Behavior of the tensile stress T_m as a function of relative depth s for different values of S_V

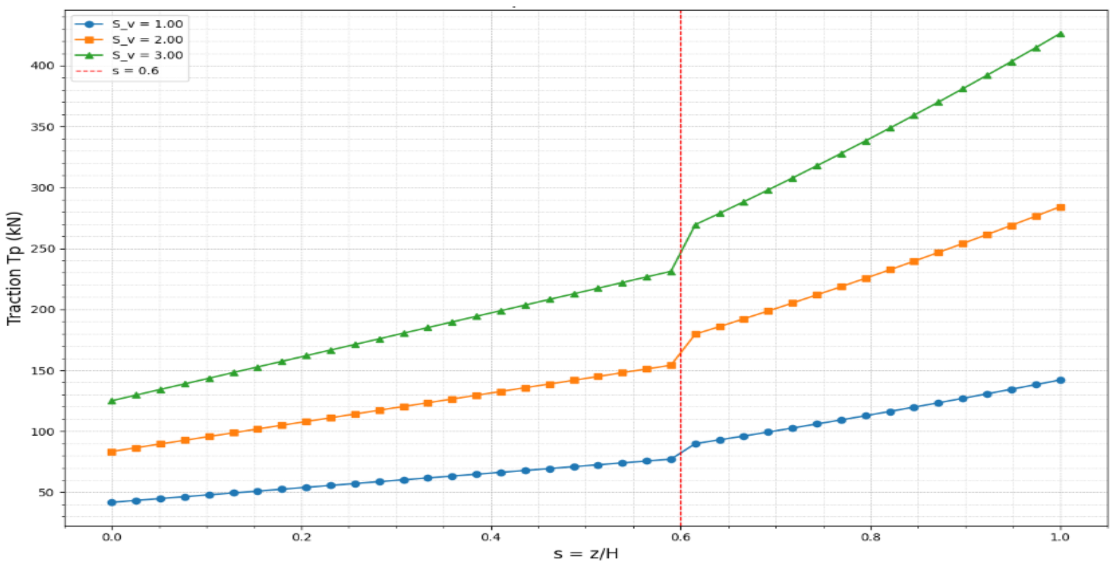

Figure 8: Behavior of the tensile force T_p as a function of the relative depth s for different values of S_V

Analysis of Figures 1 through 5 shows that regardless of the length of the reinforcement beds used, the values of f^* ,T_m , andT_p increase linearly with depth up to the threshold relative depth$s = \frac{z_0}{H}$. Beyond this value, f^* becomes constant, indicating that the adhesion no longer varies with depth, while the tensile forces continue to increase more gradually forT_m and more sharply forT_p . Furthermore, for a given wall height, the greater the earth pressure, the higher the risk of sliding.

It should be noted that:

The longer the reinforcement bars, the greater the structure's resistance to sliding. A longer reinforcement bar increases the contact area between the reinforcement and the soil. This allows for a better distribution of tensile forces over a larger surface area, which strengthens the adhesion between the backfill and the supported soil. Better adhesion results in increased resistance to sliding, as the friction forces generated are greater.

However, it is not possible to precisely determine the influence of reinforcement length on the coefficient of friction and tensile forces. To this end, additional simulations were conducted to observe the behavior of these parameters, for a given depth, as a function of variations in reinforcement length L (Figure 5). These visual analyses provide a better understanding of how changes in reinforcement length affect the performance of reinforced earth structures.

Analysis of Figure 5, which shows the maximum tensile force as a function of variations in reinforcement length, reveals that there are maximum and minimum values for this tensile force depending on the chosen reinforcement length. It can be observed that, for a short reinforcement length, the reinforcement bed bears the full accumulated load, just as it does when the length is excessive. However, an optimum exists; once this length is adopted, the stresses are considerably reduced.

Nevertheless, reinforcing bars remain crucial for the stability of reinforced earth structures, underscoring the importance of controlling their contributions. Thus, according to our analysis, the regulatory reinforcing bar length corresponding to L=0.7H, as provided in the documentation, appears very consistent. Consequently, this reinforcing bar length should be considered an optimal choice to ensure the safety and performance of the structures.

Analysis of Figures 6 through 8 shows that regardless of the spacing between the reinforcement layers adopted, the values of f^* ,T_m , andT_p increase linearly with depth up to the threshold relative depth$s = \frac{z_0}{H}$. Beyond this value, f^* becomes constant, indicating that the bond strength no longer varies with depth, while the tensile forces continue to increase more gradually forT_m and more sharply forT_p .

However, it should be noted that the larger the value ofS_V , the greater the increase in the coefficient of friction f^* and in the tensile forcesT_m andT_p .

This means that wider spacing between reinforcing bars leads to poor load distribution at the soil-reinforcement interface, resulting in greater tensile stresses on the reinforcing bars and facing.

4. CONCLUSIONS

This research presented an in-depth parametric study of the interactions between soil and reinforcing bars in reinforced earth structures, highlighting the importance of the geotechnical parameter s on the slip safety factor [12], [13]. By using the Python programming language for numerical modeling, we were able to simulate different configurations and analyze the impact of reinforcement length, vertical spacing, internal friction angle, and backfill density.

The results clearly show that each parameter plays a significant role in the stability of the structures. For example, increasing the length of the reinforcements and optimizing their spacing can significantly improve the internal resistance of the structures.

By incorporating these results into the design process for reinforced earth structures, this study provides a solid foundation for safer and more economically viable designs. Numerical simulations offer valuable tools for predicting structural performance based on specific geotechnical conditions, which will help improve design practices in the field of civil engineering.

Declaration by Authors

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