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Deterministic Cost Optimization of Soil Nailing Walls for Highway Applications

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Abstract. In modern times, retaining structures are becoming increasingly important, especially in the context of infrastructure development. It is crucial that a structure's stability should be analyzed with efficiency, but without compromising safety measures. Therefore, by using Python to automate Plaxis 2D, this study aims to perform a Deterministic Design Optimization (DDO) of a soil nailing wall of a highway section in. The DDO use the Sequential Least Squares Programming (SLSQP) algorithm. This approach also incorporates cost parameters to identify a design that meets safety requirements while being as cost-effective as possible. The main objective of the method is to determine the most cost-effective geometry that still ensures structural safety. In this study, the optimization process resulted in an almost 16% cost reduction compared to the original design, without compromising the acceptable Factor of Safety (FoS).

Keywords: Optimization, Stability, Nailing, Cost.

1 Introduction

The soil nail wall is an important type of retention wall used in both Brazil and in the world. A soil nail wall can be classified as a reinforcement method in which passive metallic bars, commonly made of steel, are drilled and grouted in soil or weathered rock with a slight inclination in order to stabilize excavations. In addition, both a shotcrete wall on the slope's face and a drainage system at the bottom of each slope section are applied to finish the structure. This technique is mostly used in highway sections when natural slopes are not a feasible option due to technical or economic reasons. Key advantages of this method include its low cost, rapid construction, and its applicability across a wide range of soil types.

In current practice, methods such as the Finite Element Method (FEM) are widely employed—especially with geotechnical software like Plaxis 2D—to design infrastructure such as soil nail walls. In this context, parameters such as the Factor of Safety (FoS) are used to assess structural stability using a strength reduction technique, where the soil's shear strength parameters are progressively reduced until the model reaches a state of failure. While a higher FoS implies greater safety, it can lead to oversized and unnecessarily expensive designs. Therefore, design optimization is essential to achieve a balance between structural safety and cost-efficiency.

However, even with suitable software, manual optimization can be time-consuming, as several interdependent design parameters must be adjusted to meet safety and cost requirements. Given that programs like Plaxis allow interaction with programming languages, it becomes feasible to automate this process using a Python-based optimization script—an approach known as Deterministic Design Optimization (DDO).

Hence, in this study, the main goal is to use the DDO method to determine the optimal lengths of three different nail groups in a soil nailing wall of a Brazilian highway project to achieve the required FoS at a minimum cost.

2 Problem Setting

2.1 Study site

The highway section analyzed in this study is located in the Southeast region of Brazil. For confidentiality purposes regarding the project's executor, the exact location of the project will not be disclosed. Yet, it is worth noting that the site is in a typical Brazilian geological formation, called "Serra", which is a mountainous region located in between the coastal plain (Atlantic coastline) and the inland Brazilian Highlands (highland plateau). Along the extension of the Highway, there are various soil nailing walls, due to the geometry of the road alongside the mountain region.

In this study, section 16+0.00 will be analyzed. It consists of many soil and rock layers and is divided into three nail walls, each separated by a berm of 3 meters. The two lower ones extend 8 meters in height with an inclination of 1V:0.5H, but the high wall extends almost 5 meters in height with also an inclination of 1V:0.5H. In Fig. 1, the geometry of the slope, the length and angle of the reinforcements chosen in the original project are shown, along with the respective Standard Penetration Tests (SPTs) and Mixed Boring tests.

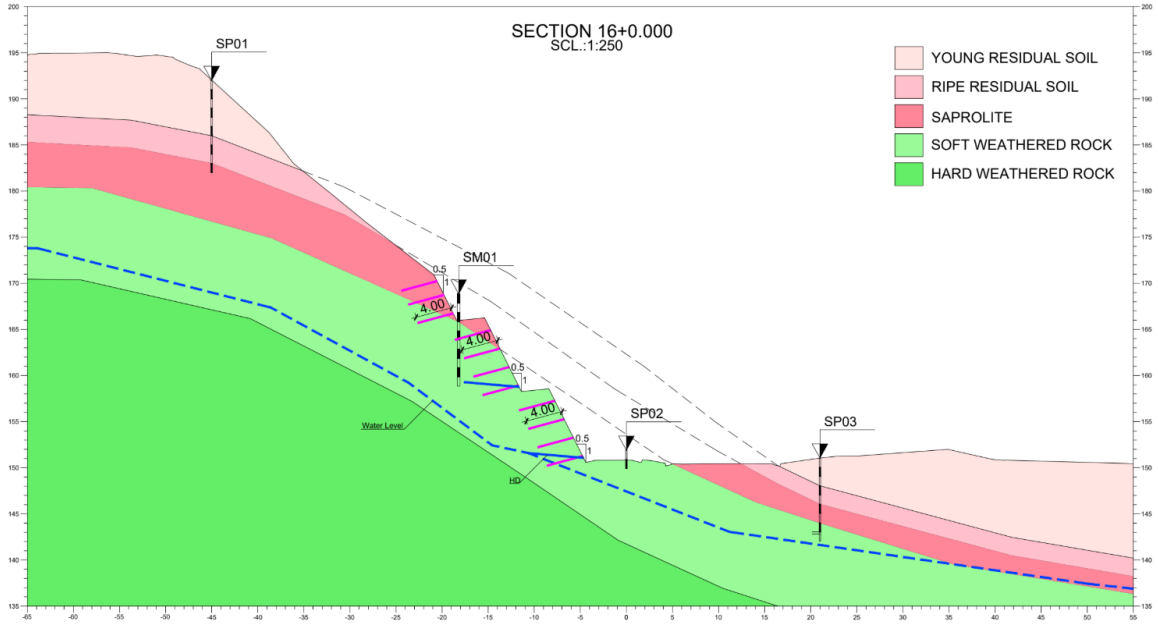


Figure 1. Geometry of section 16+0.00 of Highway project

2.2 Geotechnical data

Based on the SPT profiles shown in Fig. 1, the subsoil layers in the project area were classified into categories commonly found in geological formations of the Brazilian Serra region. These classifications, applied to both soil and rock layers, were defined according to the results of in situ tests and are presented with their respective abbreviations in Table 1, along with descriptions. Furthermore, for the project in question, it is needed to determine the geotechnical characteristics of these soil and rock layers, but to do that, different types of tests were executed, such as the STPs, direct shear tests, among others. By using the data recovered from the tests made by the company's it was possible to determine many soil parameters.

In addition, to determine the secant young modulus (E_{50}) and Poisson's ratio (ν) for the diverse types of soil, empirical correlations developed by Teixeira and Godoy [1] that are based on SPT results for residual soils in Brazil can be used. For the three types of soils, the hardening soil failure criteria were applied. Due to the method chosen, by following the recommendations of the Bentley Systems [2], the unloading - reloading stiffness (E_{ur}), the oedometric stiffness modulus (E_{oed}) and unloading reloading Poisson's Ratio (ν_{ur}) can be determined. Table 2 synthesizes all the soil parameters adopted.

Table 1. Classification of soils and rocks

Abbreviation	Soil Name	Description
SRM	Ripe Residual Soil	The most altered type of residual soil, it has the lowest shear strengths
SRJ	Ripe Residual Soil	A lesser altered soil type; in general, it has better geotechnical properties
SAP	Saprolite	Strongest soil layer present in Serra formations, it is a transition layer between soil and rock materials
RAM	Soft Disturbed Rock	Generally, the upper and most fragile rock layer because of the many fractures
RAD	Hard Disturbed Rock	The hardest gneiss type of rock found in this subsoil, must be excavated with explosion techniques

To classify the rock layers below, the Generalized Hoek-Brown failure criteria was adopted. The values of the rock unit weight (γ), the unconfined uniaxial compressive strength (σ_{ci}), the Geological Strength Index (GSI) and the Hoek Brown parameter (mi) were obtained directly from the Highway Project. Also, for the young modulus (E) and Poisson's ratio (ν), according to Bowles [3], their values depend on different rock materials, in which, for this study, all the rock types are granites. Furthermore, according to Bentley Systems [2], the intact rock mass modulus (Ei) is reduced to an in-situ version (E_{rm}), using the disturbance factor (D), which are 0 for RAM and 0.7 for RAD, along with the GSI. Table 3 shows the rock parameters included in this study.

Table 2. Adopted soil parameters.

Color code	Classification	Higher Nspt value	γ (kN/m³)	c (kPa)	ϕ (°)	Plaxis Soil Model	$E_{50} = E_{oed}$ (MPa)	E_{ur} (MPa)	ν_{ur}
255-228-225	SRM	15	16.5	22.6	24.7	Hardening Soil	33.75	84.38	0.2
255-192-203	SRJ	30	17.4	26	28.5	Hardening Soil	67.50	168.75	0.2
255-133-153	SAP	40	19.7	35.2	30.7	Hardening Soil	90.00	225.00	0.2

Table 3. Adopted rock parameters.

Color code	Classification	γ_{unsat} (kN/m³)	γ_{sat} (kN/m³)	E_{rm}	ν	σ_{ci} (MPa)	*mi*	GSI
152-251-152	RAM	22	22.5	0.64	0.27	5	28	20
100-237-102	RAD	24	24.5	2.62	0.27	30	32	65

2.3 Structural elements

In this section of the Highway, according to the original Geotechnical Project, the three soil nail walls are all equivalent and have mesh of 2 by 2 meters in each wall. Also, the diameter of the borehole is 75mm and the diameter of the nails is 16mm. Plus all nails are inclined at 15° and supported by a 12 cm thick concrete facing. The unit weight of the soil nail was calculated following the recommendations of Bentley Systems [2]. The equivalent stiffness parameter (E_{eq}) of the grouted nails was determined according to Babu and Singh [4]. The maximum skin friction (T_{max}) was determined according to Springer [5], which relates SPT values to the specific maximum skin friction ($q_{s,max}$). The elastoplastic deformation model was adopted with the maximum tensile force (R_{td}) being calculated as recommended by ABNT [6], which helps determine the maximum bending moment (M_p) and maximum axial force (N_p). Table 4 presents the nail type selected for the project. Since all nails—except one—are installed in RAM material, only a single nail type was used for the entire section.

In addition, the slope face is protected by a concrete facing, whose parameters are defined according to Bentley Systems [2] and are a function of the unit weight of the adjacent soil or rock materials, as well as the

height of the facing. These parameters are the axial stiffness (EA), the bending stiffness (EI), the equivalent plate thickness (d_{eq}) and the Specific weight per length of facing and per out-of-plane width (w). Table 5 displays the facing parameters adopted for both SAP and RAM materials. "Shotcrete wall 1" was applied in the highest wall, while "Shotcrete wall 2" was used in the others.

Table 4. Soil nail properties

Material	Adjacent soil	E (MPa)	γ_{eq} (kN/m³)	Avg. nSPT	Sh x Sv (m)	D (m)	T_{max} (kN/m)	M_p (kNm/m)	N_p (kN/m)
Nail type 1	RAM	30.5	3	50	2.0 x 2.0	0.075	38.0	5.0	75.0

Table 5. Shotcrete wall properties

Material	h (m)	EA (kN/m)	EI (kNm/m²)	d_{eq} (m)	w (kN/m/m)	ν
Shotcrete wall 1	4.95	1.60E+07	1.92E+04	0.12	1.818	0.2
Shotcrete wall 2	8	2.59E+07	3.11E+04	0.12	1.68	0.2

3 Methodology

3.1 Model definition

For the 16+0.00 section of the Highway Project, accurate modeling is essential. Because of this, in this study, the current section was modeled and optimized in Plaxis 2D. On this topic, the 11 soil nails that are divided into 3 walls require 12 construction stages. The first stage (stage 0) consisted of the gravity loading process, with the original topography. The following consists of excavating excess soil to the top level of the highest wall (stage 1). Subsequent stages involved a soil or rock excavation to the midpoint between two adjacent nails, followed by the nail installation in the borehole and construction of the reinforced concrete facing (stages 2 to 10). In two of these stages, horizontal drains (HD) will also be constructed at the bottom of the two lowest walls. Fig. 2 showcases the original geometry the section, including the shotcrete walls and nails, along with the excavation level in each step (stages 6 and 10). Additionally, an overload of 25 kN/m was applied over the Highway and a 10 kN/m overload was considered above the service road in stage 10. The last stage (stage 11) is to calculate the structure's FoS.

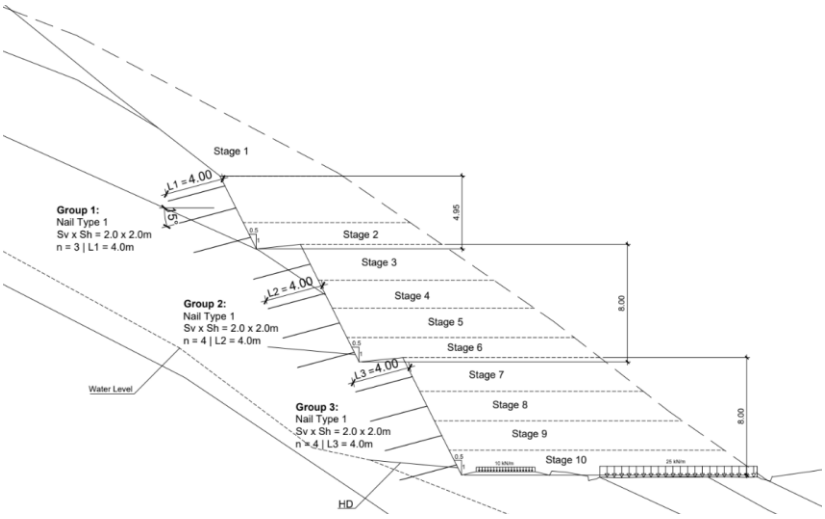


Figure 2. Highway section geometry, parameters and excavation steps

3.2 Optimization Procedure

The design optimization process is structured around several critical steps: problem definition, data collection, design variable definition, optimization criterion and constraints formulation. This section details the application of this framework to the present study. The objective is to minimize the total length of the soil nails while satisfying the constraint of a minimum FoS of 1.50.

(1) Problem definition: The engineering problem consists of ensuring the stability of the soil nail wall at section 16+0.00 of the Highway Project.

(2) Data collection: the geometrical characteristics of the section are shown in Figs. 1 and 2, along with the soil, rock, nail and shotcretes parameters that the structure is made of. Especially, the nail inclination is predefined. All these data are part of a baseline numerical model created in Plaxis 2D.

(3) Design variable definition: The design variables for this study are the lengths of the soil nails. These nails are divided into three groups according to the wall they are part of, resulting in three nail lengths for the section, quantified from the highest to the lowest wall (L_1, L_2 and L_3, respectively).

(4) Optimization criterion: The defined criterion is to minimize the cost using total nail length, for this the Sequential Least Squares Programming (SLSQP) algorithm was chosen. As described by Nocedal and Wright [7], this method uses a quasi-Newton approach on a Lagrange function with linearized constraints to achieve convergence. The algorithm handles boundaries and constraints guiding its progression by estimating the problem's gradient via the finite-difference method. It requires a well-chosen initial guess to aid convergence. Eq. (1) shows the optimization function.

$$\min_{L_1,L_2,L_3} \; cost \cdot (L_1 + L_2 + L_3)\,. \tag{1}$$

(5) Constraints formulation: To define the feasible search space for the optimization, the following constraints were established: the nail lengths are bounded between a minimum and maximum of 3 and 5 meters, respectively, for the three groups; FoS_{min} is defined as 1.50 and FoS_{sup} as 1.51, so that the given FoS (L_1, L_2, L_3) have an accuracy of two decimal digits. The convergence tolerance is 0.005, which was chosen due to the numerical instability associated with FoS results in Plaxis.

To run the algorithm, a baseline model is created using Plaxis every structure item, except the soil nails, then a python written code opens the base model, runs the SLSQP, adding a new set of design variables. After this, it saves the FoS and nail cost for every made iteration, stopping when the FoS reaches the optimization criterion, respecting the established constraints. Then the code outputs the nail lengths, FoS and cost of the optimized project. Fig. 3 summarizes the optimization procedure for this study, presenting how the DDO loop created in Python exchanges information with Plaxis 2D.

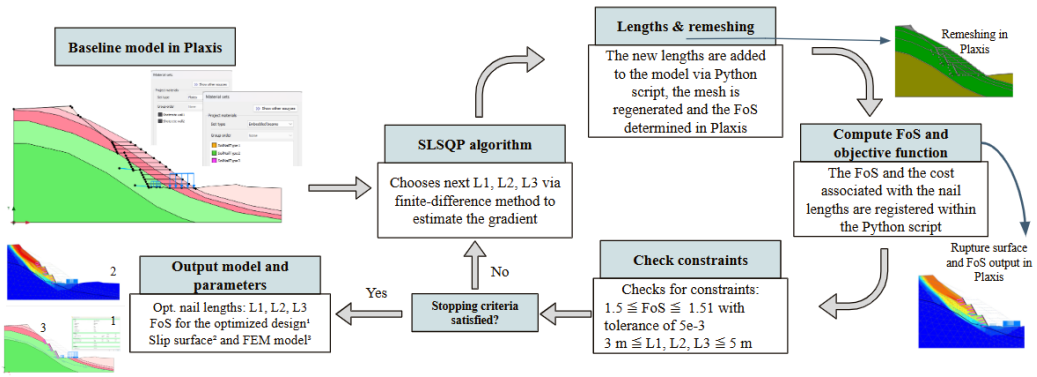


Figure 3. Schematic of the DDO method (exchange of information with Plaxis 2D model)

4 Results

4.1 Optimization results

When analyzing the section 16+0.00, the original proposed design, with one nail type and all nail lengths with 4 m, the global Fos obtained using FEM is 1.520, however, after the DDO algorithm is executed, it returns

an optimized structure in which the reached FoS is 1.512. At first glance, it may seem that the reduction was not expressive, yet it is when comparing the respective lengths obtained that the DDO algorithm stands out. Table 6 exhibits the respective nail lengths and FoS for the original section and the optimized one. The minimum nail length was set to 3 meters to simplify the analysis, given that the shortest height is 5 m, a decision based on FHWA [8] guidelines which state that lengths below 60% of the wall's height are rare. The optimal solution's asymmetry is justified by the geometry: the lower wall, which resists a greater height, requires longer nails, whereas the middle and upper walls, having smaller heights, allow for reduced lengths.

Table 6. FoS results

Factor of safety (FoS) and nail lengths				
Section	L1 - highest wall (m)	L2 - middle wall (m)	L3 - lowest wall (m)	FoS
Original	4.00	4.00	4.00	1.520
Optimized	3.00	3.00	4.00	1.514

The results indicate that, although the FoS showed no significant reductions compared to the original section, the optimization algorithm reduced the nail lengths needed for stabilizing the structure in two walls, proving that the extra one meter in the highest and middle walls were unnecessary. Since the algorithm iterates until convergence (tolerance of 5e-3), Fig. 3 graphically presents the FoS evolution throughout the iterations.

In Fig. 4, the algorithm does not seem to follow a clear optimization pattern; however, after two consecutive iterations with the same FoS within the set tolerance, the process stops and outputs the result. This fluctuation occurs because the addition of new elements in Plaxis, such as nails, forces the program to regenerate the mesh, producing slight FoS variations. And with the SLSQP algorithm, even minimal differences hinder convergence, increasing the required iterations needed to achieve it.

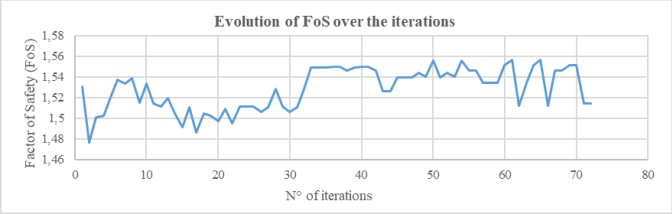


Figure 4. Evolution of FoS over the iterations

Fig. 5 compares the slip surfaces of the original (a) and optimized (b) sections. Showing both intersect the superior wall and have displacements within the same order of magnitude. This indicates that even when the nail lengths are reduced by 1 m in the superior and middle walls, the slip surfaces remain similar, showing the results' effectiveness.

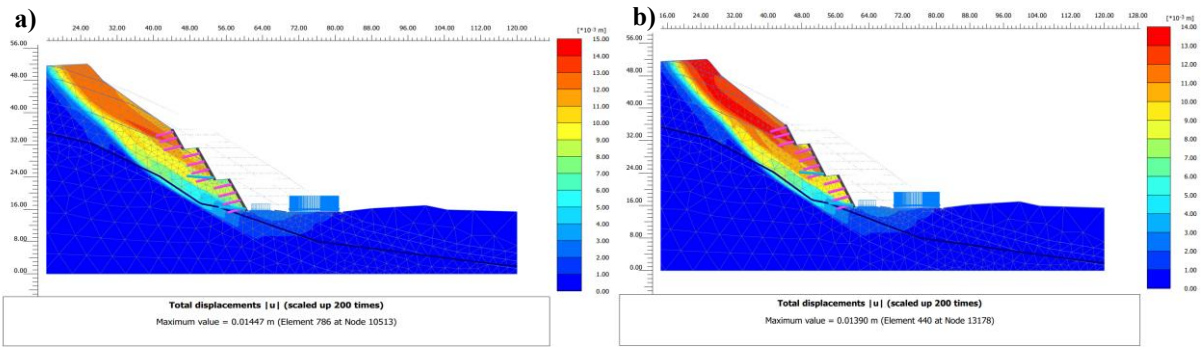


Figure 5. Slip surfaces result of the slope (a) in the original configuration, (b) the optimized configuration

4.2 Cost analysis

Given that the optimization algorithm aims to minimize nail lengths, it also reduces the cost associated with the nails' execution. To effectively assess the cost, the price of R$ 370.17/m ($67,67/m) was used, given that it

represents 7 mm nails (approximately the ones in the project) with less than 6 meters in length, according to SINAPI [9]. Table 7 summarizes the costs of the original and the optimized structure, along with reduction parameters.

Table 7. Cost analysis of original and optimized structures

Section	Nail cost/m (R$/m)	Total nail length (m)	Section nail cost (R$)	Cost reduction (R$)	Economy
Original	370.17	44	R$ 16 287.48	**R$ 2 591.19**	**15.91%**
Optimized	370.17	37	R$ 13 696.29		

It is important to take into consideration that the optimization process requires a sometimes-high computational cost to run the SLSQP algorithm. In a lab computer designed to run simulations, with an i9 processor with 3.20 GHz of speed, 128 GB RAM memory and a 16 GB graphics card, the convergence process took almost 2 hours to be finished. However, given that this process resulted in an economy of almost 16% in nail costs, it is safe to state that the method achieved its objective of reducing costs without compromising structural safety.

5 Conclusions

The Deterministic Design Optimization (DDO) analysis proved effective, achieving a cost reduction of up to 16% while satisfying the minimum required Factor of Safety (FoS). A key benefit of this method is its ability to intelligently distribute reinforcement, assigning greater nail lengths only to critical regions, which results in a more efficient and leaner structure.

While computational time is a consideration, the DDO method is significantly faster than manual optimization, particularly for complex projects with numerous variables. The method's value grows with problem complexity, demonstrating its scalability. Furthermore, the automated framework is highly replicable and can be readily adapted to new projects by modifying the baseline model and parameters, thereby accelerating the design process.

For optimal performance, two practical considerations are crucial. First, establishing a detailed baseline model is essential for reducing per-iteration computational time and speeding up convergence. Second, a convergence tolerance (set to 0.005 in this study) is necessary for the algorithm to manage minor FoS variations caused by the automatic remeshing in each iteration. This approach ensures the method's robustness, allowing it to yield significant cost savings despite minor numerical fluctuations.

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