

Techniques for Optimizing Parameters of Soil Nailed Vertical Cut

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Abstract

In this paper a finite-element analysis was carried out using Plaxis^{2D} software to model a vertical cut reinforced by nails. Optimization of the effect of three input parameters on stability design is a key element of the analysis. We compare results obtained by three techniques of design optimization; Taguchi's Design of Experiment (DOE), Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). The effect of three input factors on stability design was considered: nail length to wall height ratio (A), nail inclination (B) and vertical spacing (C). By altering the parameter variables, the design served to build and acquire a statistically significant mathematical model for optimizing soil nailing wall parameters. The aim is to minimize a single objective function of safety factor and identify the optimal parameters of design among all possibilities. DOE method and result analysis were carried out using MINITAB 18 software, while GA and PSO algorithm analysis were implemented by coding in MATLAB. According to the results, it was found that 9m of length, 2m of vertical spacing and 10° of inclination is the optimal combination minimizing safety factor. The results produced from this study show that all three techniques arrive at the same optimal combination of minimum response.

Key words: optimization, Taguchi method, genetic algorithm, particle swarm optimization

1 Introduction

Depending on the type of soil considered and the type of work to be carried out, an appropriate reinforcement solution should be chosen which matches both the nature of the soil in place and its environment. Two major techniques can be used to increase the mechanical characteristics of soils: by modifying the internal structure of the soil in place [1,2] and strengthening the soil by adding inclusions. More specifically, soil improvement techniques make it possible to increase the compactness of the soil in place, either by reducing the volume of voids...etc. [3]. Soil reinforcement is a special and recent field of soil improvement, it covers a range of techniques which consist of placing resisting inclusions in

the soil, now it is accepted as a more general concept which includes such techniques as micro -piles, stone columns, in-situ stabilized columns, soil nailing, texsol and membranes...etc. [4]

Most problems in soil reinforcement engineering involve analysis for stability. Thus, retaining walls, geosynthetics, slopes and soil nailing are designed for safety against failure.

Soil nailing is a ground stabilization technique that can be used on either natural or excavated slopes and retaining walls to make them more stable as construction proceeds from the top to bottom [5]. Soil nailing is an efficient and economical technique compared to other reinforcement techniques. Nails inclusions within a soil mass can operate as a reinforcement function by developing tensile forces which contribute to the stability of excavation [6].

Optimization problem is defined as finding the best solution from the feasible solution in a pool which contains all solutions [7]. In the field of geotechnical engineering optimization has become increasingly important, in the recent literature, researchers have applied the advanced optimization techniques to different purposes: finding the best design with regard to geometry, shape, weight and cost ...etc.

The geometric parameters adopted for nails such as their number, length, diameter, and inclination to stabilize a soil nailing wall present the main considerations for engineers to decide whether optimal design will be appropriate regarding stability and economy. One of the main reasons in failing to perform accurate calculations when dealing with excavations is the adoption of inappropriate constitutive models [8]. For optimum design of nailed wall, it is necessary to cast the problem in an optimization framework.

Presently, optimization techniques such as Genetic Algorithm (GA) [9,10], Particles Swarm Optimization (PSO) [11], Ant Colony Optimization (ACO) [12], Topology [13] and Artificial Neural Networks (ANNs) [14] are widely used in civil engineering. Generally, each optimization technique has its advantages and disadvantages, which means that not all optimization problems can be solved effectively by a given optimization method [15].

In this study we propose to approach the problem of optimizing parameters of soil nailed vertical cuts by using three techniques. The proposed methods discussed here are Taguchi's design of experiment (DOE), Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). Each of the methods will be explained in the context of our problem and a comparison between their results of optimization is carried out.

2 Finite elements model for soil nailed wall

The soil nail wall system was numerically simulated, using a two-dimensional finite element Plaxis^{2D} software version 8.2, with a plane strain problem and long-term behavior simulated using drained analysis conditions. To provide information for the performance of the soil nailing wall, the soil was modelled using Mohr-Coulomb model, an elastic perfectly plastic model, which in general can be considered as a first order approximation of real soil behaviour (sandy soil). The model requires five basic input parameters: Young's modulus E , Poisson's ratio ν , cohesion C , friction angle ϕ , and dilatancy angle ψ . Fifteen (15) - noded triangular elements are used for generating finite element mesh of appropriate density. Coarse mesh density is adopted globally, which is refined to fine density mesh around nails. Left and right boundary of the model were fixed in horizontal direction while the bottom boundary was fixed in all directions.

Using the staged construction technique available in Plaxis^{2D}, top-down construction sequence was simulated in calculation stage of soil nailing [16].

Figure 1 shows the simulated soil nail wall with dimensions and mesh boundaries and fixity conditions.

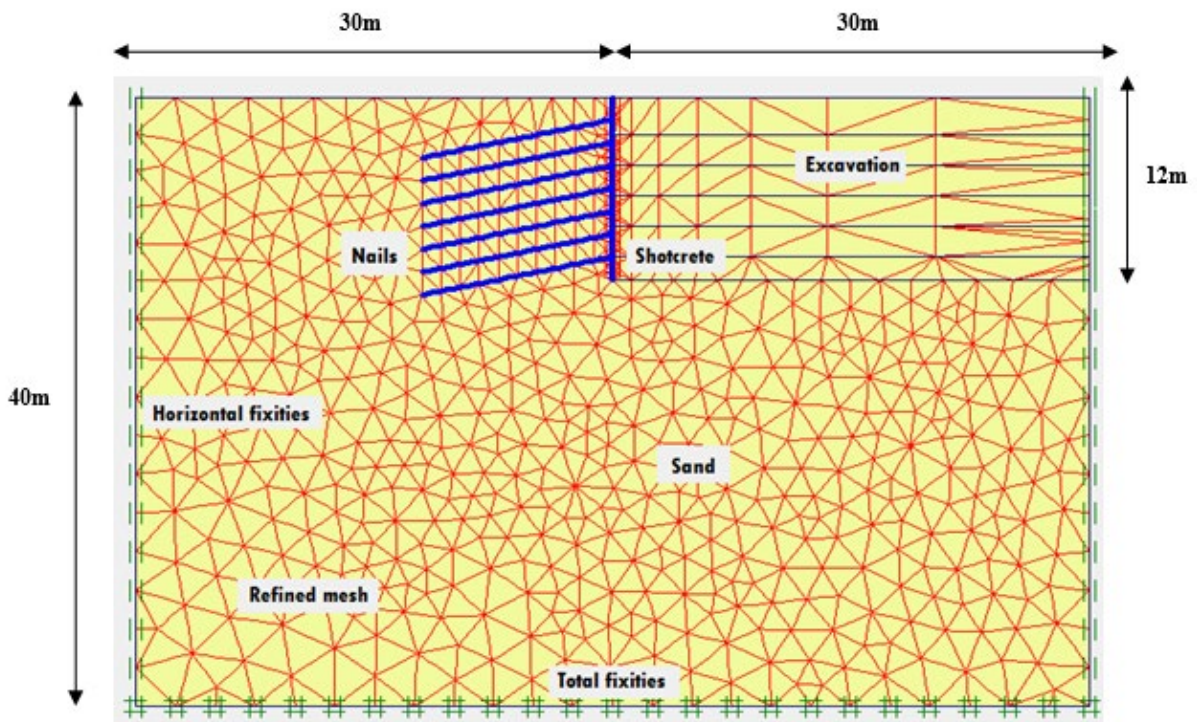


Figure 1: Geometry and FE mesh of soil nailing case in Plaxis^{2D} [16,17]

The physical and mechanical properties of the soil model are shown in Table 1:

Table 1. The physical and mechanical properties of soil layer

Soil properties	Sand
Unit weight γ (kN/m ³)	18.0
Cohesion C (kN/m ²)	10
Friction angle ϕ (deg)	35
Dilatancy angle ψ (deg)	5
Young's modulus E (kN/m ²)	$6.5 \cdot 10^4$
Poisson's ratio ν	0.3

Plate elements were used to model the nails and the shotcrete (facing); the most important parameters of plates are flexural rigidity (bending stiffness) EI and axial stiffness EA [17], their stiffness values are shown in Table 2.

Table 2. Material properties input for modeling

	Axial stiffness EA (kN / m)	Bending stiffness EI (kN.m ² /m)
Grouted soil nail	6.8 x 10 ⁴	12.5
Shotcrete	2.5 x 10 ⁶	1.22 x 10 ⁴

3 Parametric analysis

Several studies have been carried out detailing the effect of parametric variation on the stability of soil nailed wall, slope stability, and excavation, such as, nail inclination [18,19], nail length [20,21], vertical and horizontal spacing [22], surcharge load [23], excavation height [24], grouting pressure [25,26], hole diameter, soil cohesion, internal, friction angle Ground Surface [10], inclination and thickness of shotcrete ...etc.

Length of nails, vertical spacing and nail inclination are chosen in these optimization techniques among the factors of soil nailing wall that may influence the stability. The stability of nailed wall is evaluated in terms of factor of safety, so in this case one response is evaluated. The goal of this optimization from computerized simulation models was to obtain the minimum response safety factor and to find the optimal combination of soil nailing inputs factors. The safety factor was calculated using the phi reduction technique available in Plaxis^{2D}, in which the shear resistance parameters are reduced by steps until the soil body fails as in Eq. (1) [20].

$$\Sigma Msf = \frac{\tan\theta_{input}}{\tan\theta_{reduced}} = \frac{C_{input}}{C_{reduced}} \quad (1)$$

Where:

θ_{input} = input value of angle of internal friction (°)

$\theta_{reduced}$ = reduced value of angle of internal friction at failure (°)

C_{input} = input value of cohesion (kPa)

$C_{reduced}$ = reduced value of cohesion at failure (kPa).

In this case study, the length to height ratio will be considered for lengths of 9m, 12m and 14.5m whose excavation height is constant and equal to 12m.

Table 3: Length to height ratio values

Length (m)	Length to height ratio (A)
9	0.75
12	1
14.5	1.2

Table 4: Selected parameters and levels

Control Factors		Levels		
		1	2	3
A	Length to height ratio	0.75	1	1.2
B	Vertical spacing (m)	1	1.5	2
C	Inclination (Degree)	10	15	20

3.1 Mathematical model

The simulation of input-output data collected after modeling are used to establish the relation between input factors and response variable according to some modeling algorithm by combining techniques such as regression model. It is necessary to determine the appropriate function, and the focus is now on the nature of the relationship between the response and the factors, rather than on identifying important factors.

The regression equation is calculated by the mean values of safety factor under different conditions of input parameters.

Using ANOVA analysis, it is possible to evaluate the significance of the regression model selected. The main idea is to compare if the residues present normal distribution [27].

A multiple regression model is adopted as shown in equation (2), it is used as the objective function for applying the two algorithms Particle swarm Optimization (PSO) and Genetic Algorithm (GA).

$$F_s = +1.02532 A - 0.124717 B + 0.00855556 C + 1.13475 \quad (2)$$

Table 5: Model summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0046	95.44%	94.85%	93.89%

From the regression model the R-squared value obtained is 95.44%. This value is high enough to show good agreement and great significance of the predicted model. The standard deviation S is used to evaluate the effectiveness of the regression model, S is equal to 0.0465 which represent the distance between the data values and the fitted values, it clearly confirms that the model can certainly predict the safety factor well [28].

4 Optimization Techniques

4.1 Taguchi's design of experiments

Design of Experiments (DOE) is one of the most famous optimization techniques. In the 1920's in England, Ronald Aylmer Fisher introduced a powerful statistical technique to study

the effect of multiple variables simultaneously [29]. In the late 1940's Dr. Taguchi's standardized a version of DOE, popularly known as the Taguchi method. In the early 1980's it was introduced in the USA. Today it is one of the most effective quality construction tools in all types of manufacturing activities used by engineers [29-30]. There are five types in Design of experiments:(1) Screening design, (2) Factorial design, (3) Response surface method designs, (4) Mixture, (5) Taguchi.

DOE using the Taguchi approach has become a much more attractive tool to practicing engineers and scientists [31]. It is a systematic method to determine the relationship between factors affecting a process and the output. In other words, it is used to find cause-and-effect relationships [32]. This information is needed to manage processing inputs to optimize the output. DOE can show how to carry out the fewest number of experiments while maintaining the most important information [33].

Taguchi experimental designs, often called orthogonal arrays (OA) use the signal to noise (S/N) ratio as the measurable value of the quality characteristics of the choice [27].

When using the Taguchi method with three levels an L27 or L18 orthogonal array are the most commonly used. L9 is usually adopted also. However, this requires many experiments (27 or 18 runs, respectively), consuming time, and resources compared to nine trials. An experiment can be defined as a series of tests in which a set of input variables is modified in a controlled manner to observe and identify the response of the model affected by these changes [27].

In this section, L9 orthogonal array is adopted. When minimizing the objective function, the smaller-the-better quality characteristic was used to get the minimum factor of safety and the optimal vertical cut parameters, we will compute the following S/N ratio.

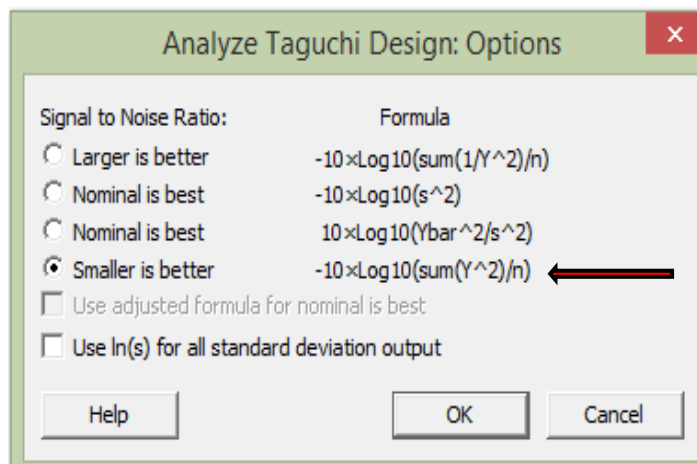


Figure 2: Smaller the better equation

Where n is the number of experiments and Y is the response in that run.

Table 6 shows the transformation result of data from the experiments into a proper S/N ratio.

Table 6: L9 orthogonal design array and measured responses and S/N ratios.

N°	Input factor			Response FS	S/N (dB)
	A	B	C		
1	0.75	1.2	10	1.84	-5.30
2	0.75	1.5	15	1.82	-5.20
3	0.75	2	20	1.8	-5.10
4	1	1.2	15	2.18	-6.77
5	1	1.5	20	2.18	-6.77
6	1	2	10	2.00	-6.02
7	1.2	1.2	20	2.35	-7.42
8	1.2	1.5	10	2.21	-6.89
9	1.2	2	15	2.22	-6.93

The analysis of data was carried out using MINITAB 18 software. Based on the analysis, one optimum parameter run is selected among nine of the suggested runs.

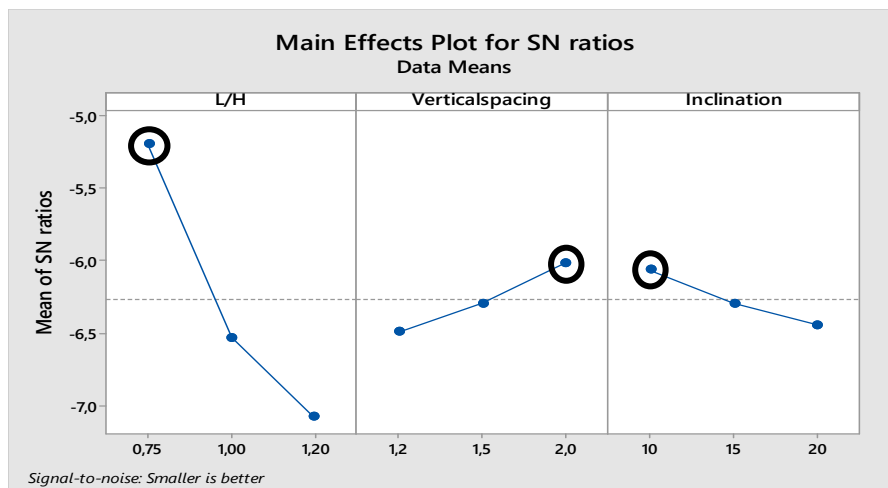


Figure 3: Main effects plot for S/N ratios

It is clear from Figure 3 that minimum safety factor is achieved at the combination of controls parameter 9m, 2m and 10° which represent length, vertical spacing and inclination respectively. The optimal combination (A1-B3-C1) was selected with the highest signal-to-noise ratio.

4.1.1 Confirmation test

Once the optimal level of the design parameters has been obtained, the next step is to predict and verify the required improvement using the optimal combination of design parameters. Table 7 shows the comparison of the predicted safety factor value with the actual safety factor using the optimal soil nailing parameters, good agreement between the predicted and experimental safety factor was observed.

Table 7: Results of the Confirmation Experiment

Input and output parameters	Prediction combination A1B3C3	Experimental combination A1B3C3
A: Length to height	0.75	0.75
B: Vertical spacing (m)	2 m	2 m
C: Inclination (°)	10°	10°
Fs	1.71	1.68
S/N ratio (dB)	-4.72	-4.51

4.2 Optimization using Genetic algorithm (GA)

Genetic algorithm (GA) is a powerful metaheuristic algorithm it is perhaps the most well-known of all evolution-based search algorithms [28].

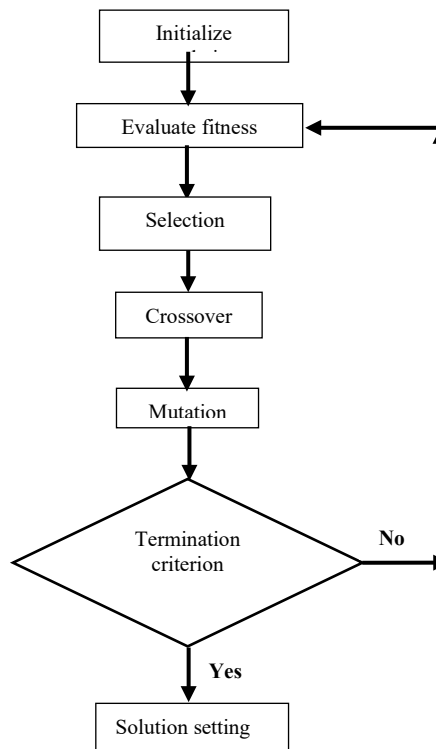


Figure 4: Flowchart of Genetic Algorithm (GA) [17]

This algorithm is created based on the theory of evolution of organisms in nature. It was first introduced by John Holland 1962. GA is executed iteratively on a set of coded chromosomes, called a population, with three basic genetic operators: selection, crossover and mutation [34]. Each member of the population is called a chromosome or individual and is represented by a string. The flowchart for GA is given in Figure 4.

In GA, a population is created with a random group of individuals. The individuals in this population will then be evaluated based on the function provided. Through this evaluation

function, the performance of each individual will be scored. Then, two individuals with the highest performance will be selected to perform crossover and mutation to create better individual, this process continues until a suitable solution has been found [28].

The parameters for GA are set as follows: Population size is 100, crossover fraction is 0.8, mutation rate 0.05, roulette wheel is used as selection method [17]. MATLAB provides an optimization toolbox that includes a GA-based solver. The obtained optimal values of vertical cut parameters are shown in Table 8.

Table 8: Optimum parameter with Genetic Algorithm

Variables	A	B	C	Fs
Optimal value	0.75	1.99	10	1.69

4.3 Optimization using particle swarm optimization (PSO)

Particle Swarm Optimization is a metaheuristic search algorithm which was originally introduced by the scientists Eberhart and Kennedy in 1995, to find optimal solution in engineering design optimization [29]. The structure of PSO is based on the concept of social models, swarm theories and the composite practice of social insects such as bees, ants, bird flocking and fish schooling, to search for a food source and avoid a predator by applying information sharing phenomena.

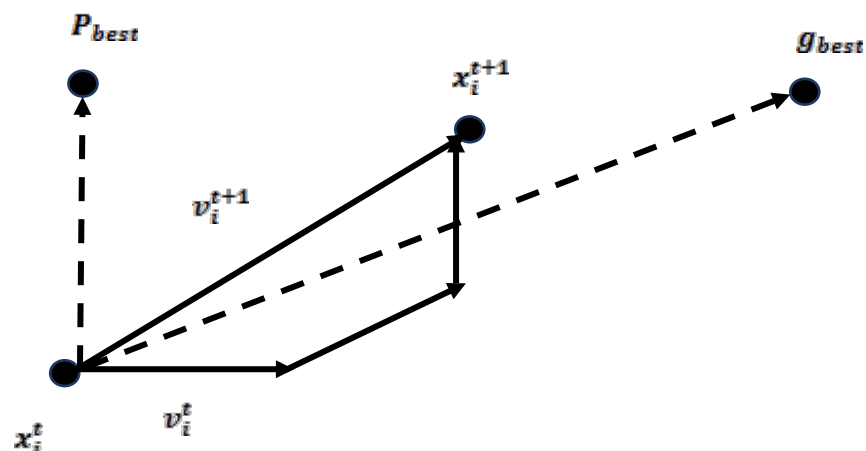


Figure 5: The movement of the particle by basic PSO [33]

For an optimization problem, the optimization of the swarm of PSO particles contains a population of candidates called swarm, this can be translated in the population which is made up of individual particles which mutually try to find an optimal solution in the multidimensional search zone by contracting between them [35]. The path of the particle in the search space is adjusted by updating the velocity of the particle and the information gain from the highest performing individual [28]

At each iteration, the individuals (particles) move towards the best solution that is experienced by them (best staff) and at the same time towards the best solution obtained by the other particles (best overall) [36]. Each particle is constantly updated via pbest and gbest to create a new population and the entire population searches for the region of the solution completely.

The new location of the particle is calculated as:

$$X_i^{t+1} = X_i^t + V_i^{t+1} \tag{3}$$

Each repetition of particle speed is updated using:

$$V_i^{t+1} = wV_i^t + c_1 \times r_1 \times (X_{pbest} - X_i^t) + c_2 \times r_2 \times (X_{gbest} - X_i^t) \tag{4}$$

Where X(t+1) denotes a new position of the particle.

V(t) defines the velocity of the particle, r1, r2 is the random number generated between 0 and 1. “w” inertia weight has been added to control the velocity, C1 and C2 are the acceleration factors to compute Xpbest particle’s personal best position and Xgbest global best position.

Swarm has a solution candidate called a particle, each particle in the PSO algorithm represents a possible solution, each individual particle flies in the search space with a speed which is dynamically adjusted according to its own flight experience and the experiences of flight of his companions.

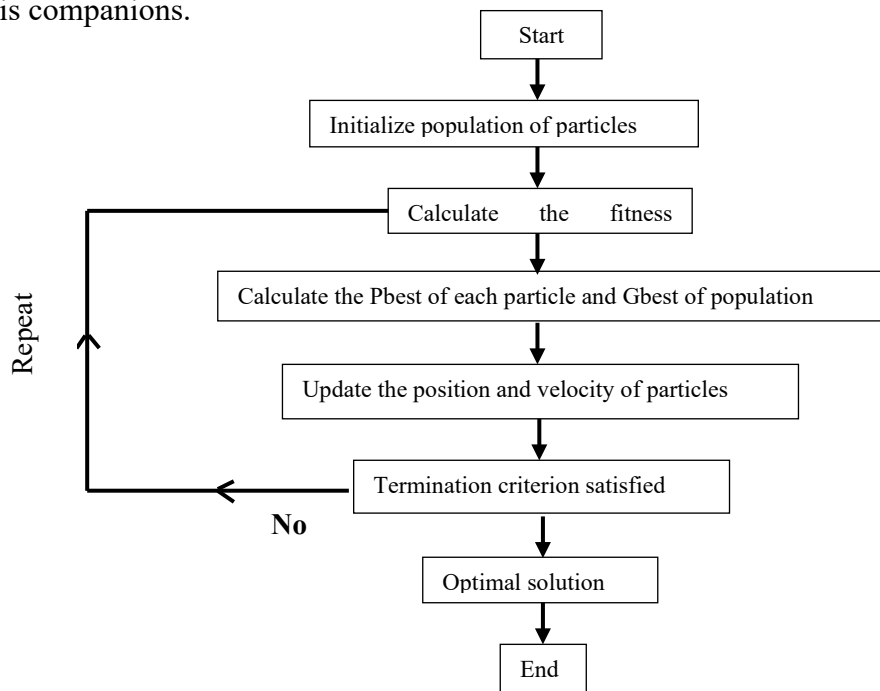


Figure 6: Particle Swarm Optimization (PSO)

The best position of each particle throughout the optimization process is the best solution found by the particle, then the best position experienced by the whole group is the currently best solution found by the whole of the group [37].

For particle cooperation in the PSO algorithm there are two principles:

- Communication: inform the best solution of a particular particle to the other particles of the swarm.

- Learning: when the particles get closer to each other, they really learn the best localization solution.

The simplified steps of the PSO algorithm for the single objective case are illustrated in Figure 6.

To get the optimal solution, particle swarm optimization can be used also in minimizing the objective function of this problem [35]. The appropriate choice of parameters improves the speed of convergence of the algorithm. To compare two specific algorithms (GA and PSO), the population size and the number of iterations should be the same, so population size and number of iterations are considered 100 and 50 respectively. The following parameters are adopted in the present PSO optimization using MATLAB.

Table 9. The parameters for PSO optimization

Variable	Value
Swarm population size	100
Maximum N° iterations	50
Inertia coefficient	0.5
Personal acceleration coefficient C1	2
Social acceleration coefficient C1	2

In Figure 7 is shown the fast convergence characteristic of the proposed PSO for the best result in 100 iteration.

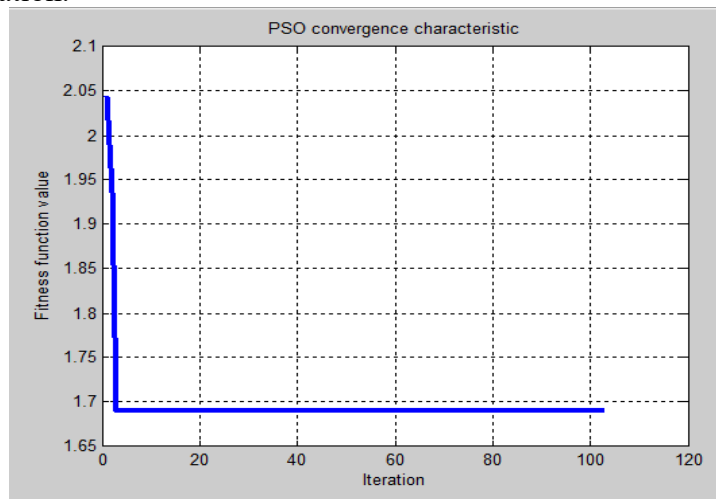


Figure 7: Convergence characteristics of PSO optimization

5 Results and discussions

By integrating the finite element analysis and the different optimization techniques an efficient design methodology can be developed. The optimum parameters obtained with three optimization techniques are summarized in Table 10.

Table 10: Results of optimal parameters of vertical cut using different optimization methods

Optimization Method		Input factors			F _s
		A	B	C	
Taguchi	L9	0.75	2	10	1.71
GA		0.75	2	10	1.69
PSO		0.75	2	10	1.67

From the results obtained, it is found that the parameter design of orthogonal array L9 provides a simple, systematic, and efficient methodology for optimizing the process parameter.

From this study, the optimal parameter values of our design consist of:

- Length of nails: all three techniques provided the same value of length 9 m i.e. (0.75 H), it is revealed that the overall safety factor increases with the increase of nail length indicating additional stability of the soil nailed wall, from (Clouterre Recommendations 1991) [38], nail lengths are usually in the range of 0.8H to 1.2H, where H is the retained height of the wall.
- Vertical spacing: the three methods gave the same value of 2 m, typically from [38], [39] and [22], spacing of 1 m to 2m between nails is adopted, it depends on soil type, from simulation results when the vertical spacing increases safety factor decreases this is due to the increase in the area served by the nail [16].
- Inclination: the three techniques agreed that the optimal value is 10°, according to [39] and [22], it was found that the effectiveness of the nail tends to decrease when the inclination of the nail exceeds 15° below the horizontal.
- The prediction model deduced for soil nailing wall parameters is in very good agreement with the values obtained experimentally (simulations) and confirm our results.

6 Conclusion

In this article we applied an optimization methodology for parameters of soil nailed vertical cut by comparing three methods: the Taguchi method, the Genetic Algorithm and Particle Swarm Optimization. The potentials of the three methods in estimating optimal parameters were explored and conclusions drawn.

- It has been demonstrated that the presented techniques are all capable of quickly finding the optimal solution.
- The optimal parameter values adopted for our design corresponding to the lowest factor safety, consisting of: 10° of nail inclination, 2 m vertical spacing between nails and 9 m of nail's length are satisfactory and in accordance with the recommendations Clouterre 1991 and consulted research.
- We noticed that PSO shares many similarities with the GA genetic algorithm, the

system is initialized with a population of random solutions and searches for optima by updating the generations, unlike PSO which does not have evolution operators such as crossover and mutation [36], the value of the safety factor resulting from the two methods is closely similar.

- The effectiveness of the Taguchi optimization method was conducted and verified using confirmation experiment.
- The advantages of Taguchi method over the other methods are that numerous factors can be simultaneously optimized, and more quantitative information can be extracted from fewer experimental trials.
- Application of DOE for Taguchi method can reduce the number of simulations, thereby reducing the computational cost significantly.
- The three methods can constitute a valuable tool for optimization of soil nailed walls in general, more parameters and different geometries can be considered in future analyses
- It should be noted that the obtained model is only valid in the selected ranges of the parameters.

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