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Optimal Design of Pile Foundations using a Metaheuristic Optimization Algorithm: A Geotechnical Engineering Case Study

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Abstract **–** The optimal design of a pile system was presented in this work as a multi-objective optimization problem that includes maximization for the pile capacity and its skin friction while minimization to the cost of material and excavations. The contradiction among maximum lifting forces due to specific soil conditions and minimum fabrication cost drives the pile design problem to be a nonlinear complex problem. The proposed methodology presents a robust procedure to solve this issue using metaheuristic algorithms. In the respective sections, Dynamic Differential Annealed Optimization, Genetic Algorithms, Particle Swarm Optimization, Simulated Annealing, Differential Evolution, Harmony Search, Artificial Bee Colony Algorithm, Firefly Algorithm, and Grey Wolf Optimizer were used to solve the optimal design of a pile system and the results shows that Dynamic Differential Annealed Optimization can be considered as the best solver for this geotechnical problem.

Keywords – Piles, Soil Analysis, Deep Excavations, Metaheuristics, Optimization Problem, Dynamic Differential Annealed Optimization

I. INTRODUCTION

A pile foundation is a type of deep foundation used to transfer the loads from a structure to a deeper, more stable layer of soil or rock below the surface [1][2]. This is typically done when the soil [3]at the surface is not strong enough to support the weight of the structure [4]. Piles can be made of various materials such as concrete, steel, or timber, and they are typically driven into the ground using specialized equipment [5]. Piles can be installed in various ways, including bored piles and driven piles [6], A bored pile, also known as a drilled pile or cast-in-place pile, is created by drilling a hole [7] into the soil and then filling the hole with concrete or another material. The process involves the use of a drilling rig to create the hole, and it is typically used in softer soil [8] conditions or when the ground is too hard for driven piles [9]. A driven pile, on the other hand, is typically made of concrete or steel and is installed by driving it into the ground using a pile driver. is typically used in dense or hard soil conditions and is often more economical than bored piles. and also be used in a wide range of structures, including buildings, bridges, and other types of infrastructure [10] [11]. Designing pile foundations involves selecting the size, and spacing of the piles based on various factors such as the load capacity of the soil, the structural loads, and the available construction equipment. This process can be very complex and time-consuming, and traditional design methods may not always yield the best possible design [12]. So, optimization algorithms [13] can help engineers find the best possible design by exploring large solution spaces and quickly finding high-quality solutions. These algorithms can take into account a wide range of design parameters and constraints, and can use mathematical models to simulate and predict the performance of different pile foundation designs under different conditions [14][15]. The definition of pile design optimization involves achieving a foundation with a satisfactory performance at the lowest possible cost. However, compared to the widespread use of optimization techniques in the field of structural engineering, optimizing pile foundations has been a relatively recent development due to three primary challenges. The first of these is the difficulty of accurately predicting the performance of pile foundations [16], given the uncertainty surrounding soil parameters, the complexity of pile-soil-raft interactions, and the imprecise constitutive laws of layered soil, despite numerous studies being available based on elastic-plastic theory [17][18]. In the pursuit of optimizing pile design, certain researchers have introduced the principles and theories of structural optimization and implemented gradient-based methods that necessitate the fulfillment of differentiability and continuity requirements for constraints and objectives, respectively. In 2011, BELEVIČIUS, Rimantas et al. conducted an experimental comparison of various global optimization algorithms to determine their suitability for achieving optimal placement of piles in real grillages. The algorithms compared included random search, metaheuristics such as simulated annealing and genetic algorithms, and local optimization combined with random search. Ultimately, the researchers were able to attain their desired results through the application of simulated annealing and the nonlinear optimization algorithm NEWUOA, combined with a heuristic random search [19]. in 2013, Yazdani, H., Hatami, K., and Khosravi, E. investigated the use of the ant colony optimization (ACO) algorithm to optimize piled-raft foundations . To account for soil-pile interactions, the researchers employed the nonlinear p-y, t-z, and Q-z springs within the OpenSees platform to model the side and tip capacities of the piles [20]. In 2017, Singh, G., & Walia, B. S. trained two artificial neural networks (ANNs) to predict unit skin friction and unit end bearing capacity based on soil properties. The researchers also determined two correlation factors using four popular nature-inspired optimization algorithms: particle swarm optimization (PSO), fire flies, cuckoo search, and bacterial foraging. Comparison of the results indicated that PSO was the most effective algorithm for these types of constrained problems [21]. In this work, Dynamic differential annealed optimization algorithm was used to find the optimal design variable of a pile for a certain soil parameters. This algorithm was compared with particle swarm optimization and artificial bee colony for validation purposes and the results show the efficiency of the dynamic differential annealed optimization on pile problems.

II. Problem Discretization

The properties of the soil layers significantly affect the optimal design of a pile or group of piles that can support a given superstructure. These properties are the source of some generated forces on the body of a pile that are shown in Figure 1

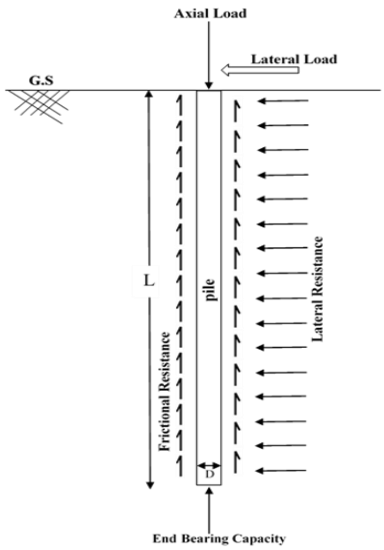

Fig. 1 Forces distribution on a pile foundation

This kind of problem has to be expressed as a multi-objective optimization engineering problem where the bearing capacity and skin friction should be maximized at the same time with the minimization of material cost and excavations. The design problem can be formulated as follows:

Maximize:

$$f = F(X), \tag{1}$$

Minimize:

$$g = G(X), \tag{2}$$

where F is the summation of bearing capacity and skin friction

$$F(X) = \sum_{i=1}^{n} S_i + B_i \quad i = 1,2, \dots, n \tag{3}$$

i is the index of a single pile among n number of possible piles, S is skin friction on a single pile, and B is the bearing capacity. $G(X)$ is the total weight of the pile system including concrete and reinforcement steel and equations (1) and (2) have to be subjected to design constraints. **Hata! Başvuru kaynağı bulunamadı.** shows the design variables, and **Hata! Başvuru kaynağı bulunamadı.** reveals the design parameters of the soil and structure

Table 1 Limitations on the design variables.

Variable	Notation	Lower limit	Upper limit
Length	L (m)	1	30
Diameter	D (m)	0.2	2
Number of piles	N	1	6
Spacing	S (mm)	10	100

Table 2 Design parameters

Parameter	Notation	Units	Value
Load	P	KN	5000
Lateral load	Pl	KN	2000
Soil Unit Weight	ɣ	kN/m^3	20
Soil Cohesion	C	kPa	50
Soil Friction Angle	∅	o	30
Friction angle	β	rad	Equation (7)
Shape factor	kp		0.5
Concrete Compressive Strength	fck	MPa	25
Reinforcement Steel Yield Strength	fyk	MPa	500
Partial safety factor for concrete	fsc		1.5
Partial safety factor for steel	fss		1.15
Design axial load on pile	NEd		$P \times fsc$
Elastic modulus of concrete	Ecm		$33000 \times \sqrt{fck}$
Design yield strength of steel	Es		$\frac{fyk}{1.15}$
Reduction factor for concrete strength	rcc		1.0
Reduction factor for concrete cover	rct		1.0
Reduction factor for steel yield strength	k_1		0.3
Reduction factor for steel strain	k_2		0.8

III. BEARING CAPACITY

The bearing capacity of a pile is the maximum load that a pile can carry without excessive settlement or failure of the soil. It is the combined capacity of both the end-bearing capacity (resistance offered by the soil at the tip of the pile) and the skin friction capacity (resistance offered by the soil along the shaft of the pile). For end-bearing capacity q_b, is a simplified versions [22] of the ultimate bearing capacity equations for piles and can be calculated using the following formula:

$$q_b = C\,(kp\,d + 4\tan(\beta)) \times \left(L + \frac{kp\,C}{ɣ}\ \tan(\beta)\right) \quad (4)$$

where C is the soil cohesion, kp is the shape factor, d is the equivalent diameter of the pile, $gamma$ is the soil unit weight, β is the friction angle in radians, and L is the length of the pile. For skin friction capacity, this paper calculates the ultimate bearing capacity using the following formula:

$$q_a = ɣ\ L\,\frac{d^2}{4} + \frac{2\,C\,kp\,d}{ɣ} \quad (5)$$

where ɣ, kp, d, C, and L have the same meaning as in the previous formula. The ultimate bearing capacity q_{ult} is then taken as the minimum of the two calculated values

$$q_{ult} = \min(q_b, q_a) \quad (6)$$

the equivalent diameter of the pile, and friction angle can be estimated from the following two equations:

$$\beta = atan2(1, \tan(\emptyset)), \quad (7)$$

$$d = D + 2\,\frac{kp\,C}{ɣ}\,tan(\beta), \quad (8)$$

where ∅ should be converted to radian. The method used in this paper is a simplified static analysis approach that uses the soil unit weight, cohesion, and friction angle to calculate the ultimate bearing capacity of the pile. The minimum of the two values calculated by this code is taken as the ultimate bearing capacity, which is a conservative approach that ensures the pile can support the applied load without excessive deformation or failure. This approach is commonly used in geotechnical engineering practice to ensure the safety and stability of foundations and other structures.

IV. Skin Friction

Skin friction is the resistance developed along the surface of a pile or shaft that is in contact with the soil. When a pile or shaft is loaded, the soil around it tends to deform, and this deformation generates resistance between the soil and the pile. The resulting force is called skin friction. The skin friction is a function of the load, the type and properties of the soil, and the length of the pile or shaft. It is an important factor to consider in the design of pile foundations, as it contributes to the total capacity of the foundation.

$$S_f = \gamma L \left(1 + 2 \frac{tan(\beta)\, kp}{d} d\right) * tan(\beta) \tag{9}$$

V. Pile Design for axial load

The area of required steel in the pile can be calculated as

$$As = \frac{\pi}{4} D^2 \left(\frac{N_{Ed}}{1000\, rcc\, fck\, k_1\, k_2\, Es} + \sqrt{\left(\frac{N_{Ed}}{1000\, rcc\, fck\, k_1\, k_2\, Es}\right)^2 + 2\frac{L}{D.\ rct)}} \right) \tag{10}$$

The number of bars required for axial load is

$$n = ceil\left(\frac{As}{\left(\frac{S}{10}\right)^2}\right) \tag{11}$$

Provided area of steel for axial load is

$$As_{prov} = \frac{\pi.n}{4}\left(\frac{S}{10}\right)^2 \tag{12}$$

Where S is the spacing between reinforcement bars while N is the number of piles in the system. Design shear force on the pile V_{Ed} is calculated using the formula

$$V_{Ed} = 0.4\, N_{Ed}\ , \tag{13}$$

where N_{Ed} is the design axial load on the pile which is in turn estimated as a percentage of the applied load P.

$$N_{Ed} = P\, f_{sc} \tag{14}$$

The area of steel required for shear resistance is As_v. The shear resistance is the ability of a pile to resist forces acting perpendicular to the axis of the pile, such as wind or seismic forces. The shear resistance of a pile is provided by stirrups, which are typically placed vertically around the perimeter of the pile. In equation (15), As_v is calculated as $0.001 As_{prov}$, where $As_{prov}$is the provided area of steel in the pile. The factor of 0.001 is a conversion factor used to convert the area of steel from square millimeters to square meters, as other variables in the code are in SI units.

$$As_v = 0.001 As_{prov} \tag{15}$$

Once As_v is calculated, the shear resistance of the pile can be determined using the expression:

$$V_{sw} = As_v\, \frac{f_{yk}}{\frac{S}{10}} \tag{16}$$

Then,

$$Ast_{min} = 0.5\, fss\, As_{prov} \left(1 - \frac{\sqrt{1 - \frac{V_{Ed}}{400\, rcc\, fck\ D\, L}}}{0.435\, fss\, Es\, d}\right) \tag{17}$$

Ast_{min} is the minimum area of steel required for shear resistance in the pile. It is calculated using the formula specified in Eurocode 2, which is a European standard for the design of concrete structures. The formula takes into account the axial load and shear force on the pile, as well as the geometry and material properties of the pile, and the partial safety factors for concrete and steel. The purpose of calculating Ast_{min} is to ensure that the pile is designed to resist shear forces that may occur during its service life. If the provided area of steel for shear resistance, As_v, is less than Ast_{min}, additional steel reinforcement will be required to meet the design requirements.

VI. Pile Design for lateral load

The effective diameter of the pile for lateral loading is

$$d_2 = d - \frac{S}{50} \tag{18}$$

Design lateral force on the pile should be:

$$P_{lat} = \frac{Pl}{2} \tag{19}$$

The area of steel required to resist the lateral load on the pile is calculated using the following equation

$$Ast = \frac{P_{lat}\ d_2}{2\, fss\ Es\, (1 - \frac{d_2}{2}\sqrt{fss\ \frac{Es}{Ecm\ fck}})} \tag{20}$$

VII. CONSTRAINTS

A. Shear capacity

A constrain has to be added to ensure that the pile has the sufficient shear capacity to resist the design shear force such that

$$V_{sw} > V_{Ed} \quad (21)$$

B. Laterally stability

For safe design, a constraint should be considered to ensure that the pile is laterally stable under the design lateral load. A large penalty value has to be added to the objective value if the shear resistance of the stirrups for lateral load $V_{sw\ Lat}$ is less than the design lateral force

$$V_{sw\ Lat} > P_{lat} \quad (22)$$

where $V_{sw\ Lat}$ can be estimated using the following equations

$$V_{sw\ Lat} = \frac{\text{AsprovLateral fyk}}{\text{s/10}} \quad (23)$$

The provided area of steel $AsprovLateral$ is based on the number of bars required and the spacing of the bars S.

$$AsprovLateral = \frac{nLateral\,\pi}{4}\left(\frac{s}{10}\right)^2 \quad (24)$$

$$nLateral = ceil\left(\frac{Ast}{0.25\,\pi\frac{(d^2-{d_2}^2)}{100}}\right) \quad (25)$$

Equation (23) calculates the number of bars required to resist the lateral load by dividing the area of steel by the area of each bar. The ceil function is used to round up the result to the nearest integer value.

C. Shear resistance

The design criteria for Ast and Ast_{min} is that the actual area of steel provided Ast should be greater than or equal to the minimum required steel area for shear reinforcement Ast_{min}. In other words, Ast has to be greater than or equal to Ast_{min}. If Ast is less than Ast_{min}, it means that the provided shear reinforcement is not sufficient to resist the shear forces and the design needs to be revised.

D. Minimum spacing and concrete cover

Further constraints can be added to the design criteria including that the spacing between reinforcement bars should be less than the equivalent diameter

$$\pi d - S \leq 0 \quad (26)$$

On the other hand. d has to be greater than the minimum concrete cover C_min which is taken 0.05 mm in this work

$$d - C_{min} \leq 0 \quad (27)$$

E. Equilibrium condition

For pile design, it is important to ensure that the load capacity of the pile is greater than the sum of the applied loads and the weight of the pile. The bearing capacity of a pile is the maximum load that it can support without experiencing excessive settlement or failure. To ensure the pile can safely support the applied loads, the sum of the applied loads and the weight of the pile should be less than the bearing capacity. This ensures that the pile will not experience excessive settlement or failure, and will provide the required support for the structure or foundation.

VIII. METAHEURISTICS FOR GEOTECHNICS

Metaheuristic algorithms [23] are a class of optimization algorithms that are designed to solve complex optimization problems that cannot be solved using traditional algorithms. They are inspired by natural processes [24] and use heuristics to guide the search for optimal solutions. Unlike traditional algorithms, metaheuristic algorithms do not guarantee that the optimal solution will be found, but instead try to find a good solution within a reasonable amount of time. They are often used in situations where the problem is too complex for traditional algorithms or where the search space is very large. Some popular metaheuristic algorithms include:

Genetic Algorithms, Particle Swarm Optimization, Simulated Annealing, Ant Colony Optimization, Tabu Search, Differential Evolution, Harmony Search, Artificial Bee Colony Algorithm, Firefly Algorithm, and Grey Wolf Optimizer. These algorithms [25] are used in a wide range of applications, including engineering design, finance, logistics, scheduling, and data mining, among others. Metaheuristic algorithms are important because they can solve complex optimization problems that cannot be solved by traditional algorithms. In many real-world applications, the problems are too complex, too large, or too dynamic to be solved using exact mathematical methods.

Metaheuristics provide a powerful and flexible tool for solving such problems. Some of the key benefits of metaheuristic algorithms include:

- They can find good solutions to complex problems in a reasonable amount of time, without the need for complete information about the problem.
- They are flexible and can be adapted to different types of optimization problems and different problem domains.
- They can handle non-linear and non-convex optimization problems, as well as problems with multiple objectives.
- They can be used in situations where traditional algorithms are not feasible, such as when the search space is too large or the problem is too complex.
- They can be used in combination with other optimization methods to improve the quality of the solution.

Overall, metaheuristic algorithms provide an important tool for solving complex optimization problems in a wide range of applications, from engineering and logistics to finance and data analysis. They are increasingly being used in both research and industry and have shown promising results in many different fields.

Metaheuristic algorithms can be applied to a variety of geotechnical problems, including slope stability analysis, foundation design, and ground improvement design. Here are some general steps to follow when applying metaheuristics to geotechnical problems:

1) Define the optimization problem: First, you need to define the geotechnical problem you want to optimize. This could be, for example, minimizing the factor of safety of a slope stability problem or minimizing the settlement of a foundation under a certain load.

2) Formulate the problem as an optimization problem: Once you have defined the geotechnical problem, you need to formulate it as an optimization problem with appropriate objective function(s) and constraints. This involves identifying the decision variables, the objective function(s), and any constraints that must be satisfied.

3) Choose a metaheuristic algorithm: There are many metaheuristic algorithms that can be used for geotechnical problems, including Genetic Algorithms, Particle Swarm Optimization, Simulated Annealing, Ant Colony Optimization, and Differential Evolution. The choice of algorithm will depend on the problem and the characteristics of the solution space.

4) Implement the algorithm: Once you have chosen the metaheuristic algorithm, you need to implement it in a computer program. There are many software packages available that implement metaheuristic algorithms, or you can write your own code.

5) Test and validate the results: Finally, you need to test and validate the results of the metaheuristic algorithm. This involves comparing the optimized results with the original problem to ensure that the algorithm has found a good solution. Sensitivity analysis can also be used to test the robustness of the solution.

The application of metaheuristics to geotechnical problems can be a powerful tool for solving complex optimization problems. However, it is important to carefully define the problem and choose an appropriate algorithm to ensure that the results are accurate and reliable.

IX. Dynamic Differential Annealed Optimization

Dynamic Differential Annealed Optimization (DDAO) [26] is not a commonly used optimization algorithm in the field of geotechnical engineering. Differential Annealing (DA) is a variant of the Differential Evolution (DE) algorithm, which is often used for optimization problems with continuous variables and nonlinear constraints. However, Dynamic Differential Annealed Optimization is a relatively new algorithm that has not been widely studied or applied in geotechnical engineering. Therefore, in the case of planning to use Dynamic Differential Annealed Optimization for the optimal design of pile foundations, one should consider discussing its advantages and limitations compared to other optimization algorithms that are more commonly used in geotechnical engineering. You may also want to clearly explain the rationale for using this algorithm and how it can be applied to the specific problem of optimal pile foundation design. Several optimization algorithms are commonly used in geotechnical engineering, including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Simulated Annealing (SA), Harmony Search (HS), Artificial Bee Colony (ABC). These algorithms are well-suited for solving optimization problems with continuous variables and nonlinear constraints, which are common in geotechnical engineering. They have been widely studied and applied to various geotechnical problems, such as slope stability analysis, pile foundation design, and earth dam design. The choice of optimization algorithm depends on several factors, including the specific problem being solved, the characteristics of the objective function and constraints, and the computational resources available. Therefore, it's a good practice to compare the performance of different algorithms and select the one that provides the best solution for the given problem.

X. OPTIMAL DESIGN

DDAO, PSO, and ABC were run to their capacity and the results are shown in Table 3 in terms of solution; pile diameter (D), length of the pile (L), number of piles (N), and spacing between reinforcement bars (S). The minimum cost multi-objective function for each metaheuristic algorithm is the same for DDAO, PSO, and ABC, and that means that DDAO has the same performance as ABC and PSO. In other words, the present comparison reveals that DDAO can be used as a reliable solver for geotechnical problems. Geotechnical engineering involves the application of the principles of soil mechanics and rock mechanics to the design of foundations, retaining structures, and other geotechnical systems. Optimization algorithms can be used to solve a variety of geotechnical problems, including:

- Foundation design: Optimization algorithms can be used to optimize the design of shallow and deep foundations to ensure that they can safely support the loads imposed by the structure.
- Slope stability analysis: Optimization algorithms can be used to determine the minimum factor of safety for slopes under various loading conditions and to optimize slope stabilization measures.
- Soil stabilization: Optimization algorithms can be used to determine the most cost-effective soil stabilization techniques for improving the strength and stability of weak or compressible soils.
- Groundwater management: Optimization algorithms can be used to optimize the design of groundwater management systems, such as dewatering systems and drainage systems, to minimize construction costs and environmental impacts.
- Pile design: Optimization algorithms can be used to optimize the design of pile foundations to ensure that they can safely support the loads imposed by the structure and minimize construction costs.
- Retaining wall design: Optimization algorithms can be used to optimize the design of retaining walls to ensure that they can safely resist the lateral pressures imposed by the soil and minimize construction costs.

Overall, optimization algorithms can help geotechnical engineers make informed decisions by identifying the best solutions that meet project objectives while minimizing costs and risks. Figure 2 illustrates the convergence curve of the dynamic differential annealed optimization algorithm on the pile design problem. The curve shows the fast convergence, minimum possible standard deviation, and within less than 50 trials the algorithm reached the best solution.

Table 3 Optimal solutions obtained from DDAO, PSO, and ABC

Algorithm	***D***	***L***	***N***	***S***	**Minimum cost**
DDAO	1	0.5	4	100	196.6441
PSO	1	0.5	4	137.22	196.6441
ABC	1	0.5	4	119.21	196.6441

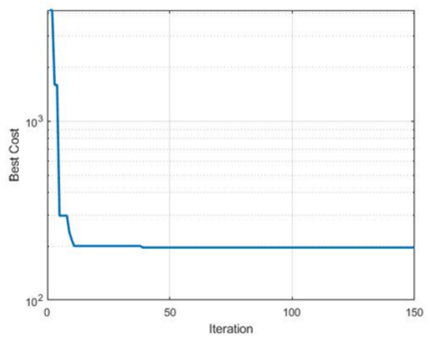

Fig. 2 Convergence curve of the DDAO

XI. Conclusion

Optimal pile design under specific soil conditions was conducted in this work, and three metaheuristic algorithms were used to solve the problem; dynamic differential annealed optimization, particle swarm optimization, and artificial bee colony. The statistical results show that dynamic differential annealed optimization is competitive, powerful, and reliable on geotechnical engineering problems. This relatively new algorithm has never been seen before for geotechnical problems and this work recommends it for other applications like the design of retaining walls.

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