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Comparative study of metaheuristics on optimal design of gravity retaining wall

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ABSTRACT

Retaining walls are typical geotechnical engineering applications analyzed extensively in the literature. However, the optimal design of these walls is still unsolved due to the optimization problem's complexity and the unrecognized best solver that can be used. Most similar works present a single optimizer for this problem. This work used six metaheuristics to formulate and solve the optimal gravity retaining wall problem design. The comparative study was achieved among particle swarm optimization, grey wolf optimizer, artificial bee colony, dynamic differential annealed optimization, fertilization optimization algorithm, and whale optimization algorithm. The problem and its results were discussed in detail within the respective sections.

KEYWORDS

gravity retaining wall, geotechnics, metaheuristics, optimization algorithms

1. INTRODUCTION

The functionality of the retaining walls is usually supporting the soil mass. However, it can also be constructed for aesthetic landscaping purposes. Retaining walls play a crucial role in construction projects as they help to provide structural support and prevent soil erosion [1]. Various types of retaining walls are available for different purposes, like gravity, semi-gravity, cantilever, and counterfort walls. Gravity retaining walls have become an increasingly popular choice in many construction projects because they have several advantages over other types of retaining walls. First, they are relatively simple to design and build. They do not require special equipment or techniques, making them a cost-effective solution. Second, gravity walls rely on their weight to overcome the pressure of the soil they hold back. This makes them a reliable and stable solution for retaining soil and other materials [2]. Third, due to its design that is based on self-weight and gravity, it can be built with locally available materials and can be built to be a sustainable and eco-friendly solution. Finally, they are suitable for many construction projects, from small residential walls to large-scale commercial and industrial projects. These features make gravity retaining walls an increasingly popular choice among construction professionals. When creating retaining walls, an engineer needs to estimate some of their measurements. This estimation enables the engineer to assess the stability of test sections of the walls. Much research has been carried out to introduce methods for cantilever retaining wall design but, only a small amount of work has been done [3]. The most common structures in civil engineering applications are concrete retaining walls. Retaining walls are a versatile technique for geotechnical engineers [4] that allows for construction on slopes along them and on sites with narrow space in towns and cities [5]. The purpose of constructing the retaining wall is to provide support against the sideways force exerted by the soil, which occurs when there is an unnatural slope in the ground elevation that exceeds the soil's comfort angle [6]. Designing

retaining walls commonly involves a trial-and-error process in which designers should improve an initial model of a wall before coming up with the best suitable design, but there is no assurance that the chosen final model is economic one [7]. In order to achieve cost-effectiveness and minimize the weight of concrete retaining walls, optimization techniques are utilized, making retaining wall optimization essential for achieving economic efficiency [8]. In this work, Particle Swarm Optimization (PSO) [9], Grey Wolf Optimizer (GWO) [10], Artificial Bee Colony (ABC) [11], Dynamic Differential Annealed Optimization (DDAO) [12], Fertilization Optimization (FO) algorithm [13], and Whale Optimization Algorithm (WOA) [14] are used in a comparative study on retaining wall design problem. The results show that the WOA is the best solver among this group of algorithms.

2. METHODOLOGY

Retaining structures are subject to consistent forces. When analyzing a retaining structure, the primary concerns are overturning, sliding, and bearing stress modes. Additionally, it is essential to ensure that the structure can resist failure due to the tension. The force generated by the active soil pressure, the weight of the retained soil, the weight of the structure, any soil situated above the base, and any other external loads work in conjunction to counteract the overturning moment at the base of the wall. During the calculation of the overturning moment, no account is taken of the passive forces acting on the base or the shear key of the base. If the stability examinations yield unwanted results, the sections can be replaced and rechecked. Figure 1 reveals the usual failure modes that can be considered for retaining wall design [15].

According to Rankine's theory, the active and passive earth pressure coefficients (K_a) and (K_p) are:

$$K_a = \frac{1 - \sin\phi}{1 + \sin\phi}, \quad (1)$$

$$K_p = \frac{1 + \sin\phi}{1 - \sin\phi}, \quad (2)$$

where ϕ is the internal friction angle. The safety factor for overturning, FS_o at the toe is defined as:

$$FS_o = \frac{\sum M_R}{\sum M_O}, \quad (3)$$

where the total of the moments against overturning about the toe is denoted as $\sum M_R$, and the sum of the moments that tend to cause overturning about the toe is denoted as $\sum M_O$. In the sliding mode of failure, the active force's horizontal forces are considered. The horizontal forces that provide resistance are produced by several factors, including the weight of the gravity wall and the soil on the base, any surcharge loads, the friction between the base of the wall and soil, and the passive force of the soil acting on the toe and the base shear key sections. The following is the definition of the sliding FS_s safety factor:

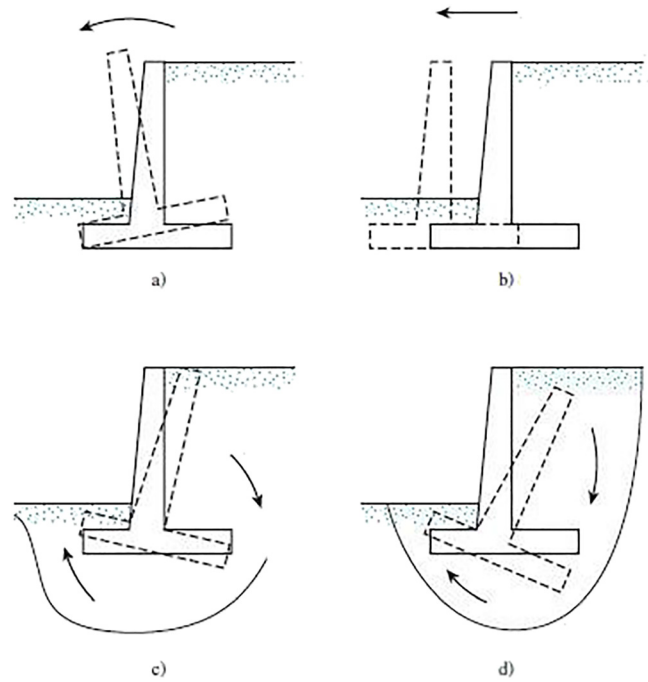


Fig. 1. Failure modes of retaining wall: a) overturning, b) sliding, c) bearing capacity failure, d) deep-seated shear failure

$$FS_s = \frac{\sum F_R}{\sum F_o}, \quad (4)$$

where $\sum F_o$ is the total of the forces that are horizontally sliding and $\sum F_R$ is the total of the forces that are horizontally resisting. When conducting a structural bearing analysis, the base supporting the wall is regarded as a shallow foundation, with the maximum and minimum stresses experienced by a foundation base can be defined as:

$$q_{\max\min} = \frac{\sum V}{B} \left\{ 1 \pm \frac{6 \cdot E}{B} \right\}. \quad (5)$$

In the given equation, B represents the base width; $\sum V$ represents the total upward forces resulting from the weight of the wall and the soil situated above the base, while $q_{\min}$ and $q_{\max}$ denote the bearing stresses experienced at the toe and heel, respectively. Symbol E expresses the eccentricity of the resultant force and is defined as:

$$E = \frac{B}{2} - \frac{\sum M_R - \sum M_O}{\sum V}, \quad (6)$$

where E is calculated by dividing the total moments around the toe by the sum of the vertical forces acting on the wall. Additionally, FS_B denotes the safety factor for bearing capacity and is defined as:

$$FS_B = \frac{q_u}{q_{\max}}, \quad (7)$$

the ultimate bearing capacity of the foundation is represented by q_u .

3. FORMULATION OF THE OPTIMAL DESIGN

The optimal design process for any structure involves three main phases: structural modeling, optimum design modeling, and optimization algorithm:

1. Structural modeling, the problem is defined by identifying a group of design variables that satisfy the design objectives while also adhering to any constraints that may exist;
2. Optimum design modeling involves a detailed examination of the problem to identify the appropriate design parameters, variables, constraints, and objective functions;
3. The optimization process begins with an initial design or set of designs and works towards finding the optimal solution in designing an economical retaining wall.

3.1. Structural modeling

The objective of designing an optimal retaining wall is to minimize its construction cost and weight, while satisfying any constraints. The objective function can be written as:

Minimize: (X) = weight of the retaining wall.

Subjected to

$$g_i(x) \leq 0, \quad i = 1, 2, \dots, p, \quad L_k \leq X_k \leq U_k, \quad k = 1, 2, \dots, n, \quad (8)$$

where $f(X)$ is a function of the design variables X , and the inequality constraints g_i , L_k and U_k are lower and upper bounds constraints, respectively. The i is the index of a specific constraint up to p , the total number of design constraints. At the same time, k is the index of a variable in a proposed solution up to n the total number of variables of the retaining wall problem.

3.2. Variables used in the design process

The five primary design variables used in the program formulation for the gravity retaining wall are: X_1 (width of the base), X_2 (projection), X_3 (thickness at the bottom of the stem), X_4 (thickness at the top of the stem), and X_5 (thickness of the base slab), which all pertain to the various dimensions of the wall. The mathematical model used for optimizing the design of a gravity retaining wall is illustrated in Fig. 2. All the design variables are proportional to the stem height of the retaining wall. Table 1 reveals the minimum and maximum limits of the decision variables as a function of the stem height H .

4. CONSTRAINTS ON THE DESIGN OF RETAINING WALL

The design constraints for a retaining wall can be grouped into geotechnical and structural categories. These

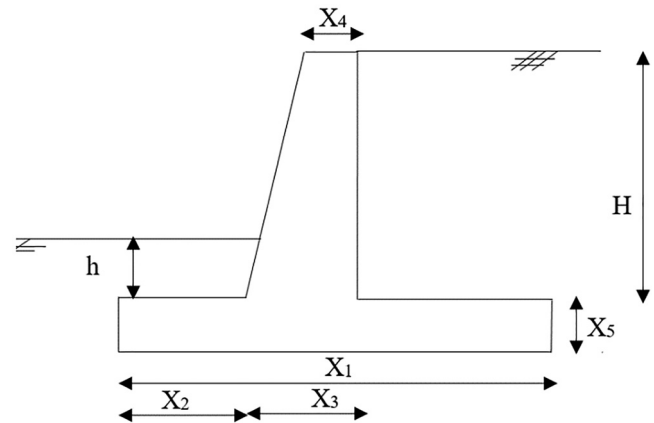


Fig. 2. Gravity retaining wall design variables

Table 1. Limits on the decision variants

Design variables	Lower bounds	Upper bounds
X_1	$0.5H$	$0.7H$
X_2	$H/6$	$H/6$
X_3	0.3	3
X_4	0.3	1.5
X_5	$H/10$	$H/10$

constraints are related to the potential failure modes and are determined by the decision variables. A suitable wall design should have a minimum safety factor for failure modes sliding, overturning, and bearing capacity. Table 2 summarizes the constraints on the design of the gravity retaining wall.

4.1. Overturning failure mode

In the case of an overturning failure mode, the wall must be prevented from rotating around its toe by ensuring that the moments caused by vertical forces (stabilizing moments) are more significant than the moments caused by horizontal forces (overturning moments). The primary source of stabilizing moments is the self-weight of the structure, while the active earth pressure is the main cause of overturning moments. Overturning failure occurs when the lateral earth pressures on a retaining wall are more significant than the wall's resistance, leading to the wall overturning.

Table 2. Failure modes

Constraints	Mode of Failure
$g_1(x)$	Overturning Stability
$g_2(x)$	Maximum bearing capacity
$g_3(x)$	Minimum bearing capacity
$g_4(x)$	Sliding stability
$g_5(x)$	No tension condition

$$g_1(x) = FS_o - \frac{M_{vtotal}}{M_{htotal}} \leq 0. \quad (9)$$

In the given context, M_{vtotal} represents the cumulative vertical moment exerted by the forces that resist overturning at the toe, while M_{htotal} refers to the total horizontal moment exerted by the forces that promote overturning at the toe. The factor of safety against overturning is denoted by FS_o .

4.2. Bearing failure mode

A foundation must have a sufficient bearing capacity to withstand the stresses acting on the structure's base to prevent bearing failure,

$$g_2(x) = p_{\max} - SBC \leq 0, \quad (10)$$

the SBC is the safe bearing capacity of the soil, $p_{\max}$ is the maximum pressure at the interface between the soil and the gravity wall,

$$g_3(x) = -p_{\min} \leq 0, \quad (11)$$

where $p_{\min}$ represents the minimum pressure that exists at the interface between the foundation soil and the wall structure.

4.3. Sliding failure mode

Sliding failure mode happens when the horizontal forces acting on a retaining wall are insufficient to impede its movement. Excessive soil pressures on the backfill side of the wall are usually the primary cause of this type of failure. These pressures can overcome the wall's resistance and cause it to slide away from the soil it is retaining,

$$g_4(x) = FS_s - \left(\frac{V_{total} \cdot \mu + \text{horizontal force from passive pressure}}{H_{total}} \right) \leq 0, \quad (12)$$

where the numerator of Eq. (12) is the resistance to sliding, and H_{total} is the total horizontal components. FS_s is the safety factor for sliding.

4.4. Tension failure mode

The tension failure mode can occur when the force exerted on the foundation is not situated within the "middle third of the base" as this is necessary for ensuring stability,

$$g_5(x) = E - \frac{B}{6} \leq 0. \quad (13)$$

5. METAHEURISTIC ALGORITHMS

Metaheuristics [16] are usually employed to determine a function's global minimum or maximum within a limited

search space. Driving an objective function to its minimum or maximum points leads the algorithm to find the optimal set of variables. When striving for optimal design of a retaining wall, the weight function, which is dependent on the design variables, needs to be minimized. This can lead to estimating the optimal set of variables that can return minimum weight (minimum cost) and considering the design constraints. PSO, DDAO, ABC, FO, GWO, and WOA will be discussed in a comparative study on the retaining wall design problem.

6. STATISTICAL RESULTS

Table 3 illustrates the design parameters used to estimate the best possible design of the gravity retaining wall.

The minimum possible weight of the wall was calculated by six optimization algorithms, and the results are shown in Table 4. The results were collected from 30 independent runs and sorted to minimum weight (best), biggest weight (worst), average weight (mean) over 30 runs, and the Standard Deviation (STD) for each algorithm on the wall problem. At first glance, PSO, and FO algorithms return solutions for the minimum weight because they have the minimum best values during their runs. However, their solutions are not feasible because of the relatively high value of the STD from their independent runs.

Table 5 reveals the five design variables obtained from the best possible solutions from the six competitive metaheuristics.

The most crucial point is the solution of the PSO violates the constraint g_4 while the solution of the FO algorithm violates the constraints g_1 , and g_4 respectively, as it is shown in Table 6. Another reason is that the solutions of the PSO and FO are far away from the common best values of the rest of the competitive algorithms, which are around 138. Thus, it is feasible to consider the best optimization algorithm that can solve the retaining wall optimization problem is the WOA, which has minimum best value 137.5931 and has low STD on this problem.

Table 3. Design parameters

Parameter	Unit	Symbol
Density of soil	kN m ⁻³	γ_s
Height of the stem	m	H
Internal angle of friction	°	ϕ
Unit weight of concrete	kN m ⁻³	γ_c
Factor of safety against overturning		FS_o
Coefficient of friction under base		μ
Factor of safety against bearing capacity failure		FS_B
Factor of safety against sliding		FS_s
Safe bearing capacity of soil	kN m ⁻²	SBC



Table 4. Statistical results of the metaheuristics on the retaining wall problem

Algorithm	Best	Worst	Mean	STD
PSO	91.3969	300.0373	200.1728	53.6068
DDAO	138.1532	141.4502	139.3929	0.8805
ABC	138.1003	138.1009	138.1004	0.0001
FO	98.0304	197.0167	153.2858	17.4301
GWO	138.1086	138.3110	135.9900	11.7073
WOA	137.5931	138.8432	138.1995	0.3055

Table 5. Design variables obtained from the competitive study

Algorithm	Design parameters				
	X_1	X_2	X_3	X_4	X_5
PSO	2.7874	0.4825	0.3000	1.1720	0.48
DDAO	2.6466	0.7015	0.4283	1.0669	0.48
ABC	2.8000	1.0189	0.3000	1.1700	0.48
FO	2.7682	0.8800	0.3436	0.4607	0.60
GWO	2.7397	0.9604	0.3443	1.1354	0.48
WOA	2.7144	0.5229	1.1378	0.3459	0.48

Table 6. Constraints values of the competitive algorithms

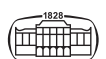
Algorithm	g_1	g_2	g_3	g_4	g_5
PSO	-0.1607	-196.2268	-45.3154	$6.661 \cdot 10^{-16}$	-0.4249
DDAO	-0.0106	-158.5149	-12.9154	-0.0002	-0.1091
ABC	-0.1366	-189.6786	-38.3217	$-1.1859 \cdot 10^{-12}$	-0.3625
FO	0.0324	-211.9465	-32.7715	0.2036	-0.4269
GWO	-0.0782	-175.8526	-26.6723	-3.2320	-0.2416
WOA	$-5.4061 \cdot 10^{-6}$	-155.1244	-6.8750	$-5.9807 \cdot 10^{-9}$	-0.0611

7. CONCLUSION

The nonlinearity and complexity nature of the retaining wall design problem makes it a perfect target for optimization algorithms as a possible solver. The large number of metaheuristics in the literature is another problem in choosing the best optimizer for the optimal design of a retaining wall. This paper fills this gap by introducing a competitive study among six metaheuristic algorithms on a gravity retaining wall. PSO, ABC, DDAO, FO, GWO, and WOA are among the optimizers used. The research paper demonstrates that the optimal design of gravity retaining walls are best achieved using the whale optimization algorithm. However, six algorithms are relatively low compared with hundreds of existing algorithms that need more extensive comparative studies that can be topics for future works.

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