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Research Article

Comparative study of optimum cost design of reinforced concrete retaining wall via metaheuristics

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ABSTRACT

Design engineers may find various options of metaheuristic method in optimization of their problems. Because of the randomization nature of metaheuristic methods, solutions may trap to non-optimum solutions which are just optimums in a limited part of the selected range of the design variables. Generally, metaheuristics use several options to prevent this situation, but the same optimization process may solve different performances in every run of the process. Due to that, a comparative study by using ten different algorithms was done in this study. The optimization problem is the cost minimization of an L-shaped reinforced concrete (RC) retaining wall. The evaluation is done by conducting 30 multiple cycles of optimization, and comparing minimum cost, average cost and standard deviation values.

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1. Introduction

Metaheuristic methods are iterative methods, which are generally used for optimizing mathematical and engineering problems including constraints. Due to constraints, the nature of the problems is non-linear, and metaheuristics can easily handle these problems. A metaheuristic method has several formulations to reach the optimum value. These formulations may be given for different types of generation of new variables with random values within the solution range. Also, the formulations of metaheuristics have several inspirations using a metaphor. The metaphors are listed in Table 1. The details about special features of algorithms can be seen in the cited papers given in Table 1.

Reinforced concrete (RC) structures are consisting of two materials, and these materials have different costs, strength and mechanical behaviour. For that reason, the optimum cost design problem is highly constrained by structural state limits such as stress capacities, ductile behaviour requirements, minimum and maximum reinforcements.

In the design of structures, the stress on critical sections must be provided according to the internal forces such as flexural moment, axial force and shear forces. The ductile behaviour of structures are provided by considering several rules defined in the design codes. The basic rule for the members under flexural moment is the limitation of the reinforcement bars to provide the yielding of rebar before the fracture of the concrete. Due to this reason, the stress limitations cannot be directly considered as single material structures. In that case, the balance between the stress of concrete in the compressive section of the member and the stress of rebar in tensile section must be investigates as seen in Fig. 1. The symbols of Fig. 1 are defined in Table 1.

If the maximum reinforcement is not enough for the design flexural moments, doubly reinforced design can be employed. In the wall type structures and retaining walls, doubly reinforced design is not preferred in practice. In that case, the reinforcements are limitated with singly reinforced design, and calculation is done for the unit meter of wall by taking b_w as 1m. Additionally, stirrups are not provided to carry shear forces in the RC retaining walls.

In addition to the structural state limits, RC retaining walls also contains geotechnical state limit. The geotechnical limit states are checked to provide stability of retaining walls. These controls include overturning, sliding and bearing capacity of the wall according to forces of self-weight, stresses under the footing, surcharge load and soil loads.

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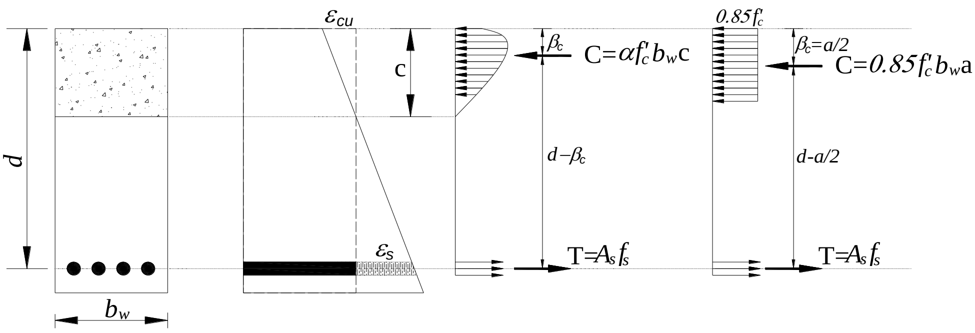

Fig. 1. A RC cross-section under flexure (Kayabekir et al., 2020).

Table 1. Notation of RC section with stress.

Symbol	Definition
b_w	web width, or diameter of circular section
d	distance from extreme compression fiber to centroid of longitudinal tension reinforcement
c	distance from extreme compression fiber to neutral axis
β_c	distance from centroid of compressive stress block to face of compressive section
f_c'	specified compressive strength of concrete
f_s	calculated tensile stress in reinforcement at service loads
A_s	area of nonprestressed longitudinal tension reinforcement

Due to that, the optimum design of RC retaining walls have been solved via several metaheuristic methods including Genetic Algorithm (Kaveh et al., 2013), Particle Swarm Optimization (Ahmadi-Nedushan and Varaee, 2009), Big Bang-Big Crunch (Camp and Akin, 2012), Harmony Search (Kaveh and Abadi, 2011), Firefly Algorithm (Sheikholeslami et al., 2014), Simulated Annealing (Ceranic et al., 2001), Charged System Search (Yepes et al., 2008), Biogeography-based optimization (Aydogdu, 2017), Flower Pollination Algorithm (Mergos and Mantoglou, 2019), Gravitational Search Algorithm (Khajehzadeh et al., 2013).

In the present study, the optimization of L-shaped retaining walls was done by using 10 different algorithms given in Table 2. Optimum results were compared by conducting 30 multiple cycles of optimization of design data. The evaluation is presented according to minimum, average cost and standard deviation of 30 independent runs.

Table 2. Metaphor used in metaheuristic.

Algorithm	Metaphor	Citation
Genetic algorithm (GA)	Natural selection	Holland (1974)
Differential Evolution (DE)	Natural selection	Storn and Price (1997)
Particle Swarm Optimization (PSO)	Behaviours of colonies	Kennedy and Eberhart (1995)
Harmony Search (HS)	Musical performance of musician	Geem et al. (2001)
Artificial Bee Colony Algorithm (ABC)	Natural behaviours of bee colonies as food-searching	Karaboğa (2005)
Firefly Algorithm (FA)	Flashing ability of firefly	Yang (2009)
Teaching-Learning-Based Optimization (TLBO)	Principle of teach to students by a teacher and self-learn by them in a class	Rao et al. (2011)
Grey Wolf Optimization (GWO)	Conception of leadership hierarchy with hunting behaviour in nature belonging grey wolfs	Mirjalili et al. (2014)
Flower Pollination Algorithm (FPA)	Flowering process of plant's	Yang (2012)
Jaya Algorithm (JA)	Victory	Rao (2016)

2. Design Methodology

The algorithms used in the study are chosen from classical algorithms, proved algorithms with their success on engineering problems and recent algorithms. The most known classical algorithms such as GA, DE and PSO are chosen. The proved algorithms used in the comparative study are HS, ABC and FA. The recent ones are FPA, GWO and parameter-free algorithms such as TLBO and JA. JA also contain a single phase of optimization, and it is the most basic one to apply on an engineering problem.

The design steps are summarized in the flowchart given as Fig. 2. This flowchart is a general one for metaheuristic algorithms.

In the methodology, the design constants (constant parameters of RC retaining wall), ranges of design variables, algorithm specific parameters, population number and a maximum iteration number are defined. Then, an initial solution matrix containing sets of candidate design variables is generated within the selected range of design variables. The number of sets of design variables is equal to the population. Then, the analysis of the RC retaining wall is done, and the total material cost of the wall is calculated for all set of design variables. The cost is saved since it is the objective function tried to minimize. If one of the design constraints is not provided, the cost is penalized with a huge value. After the generation of the initial solution matrix, the iteration process starts. The solution matrix is updated by using special features of the algorithms, and the updated solutions are saved instead of previous ones if the cost is smaller than the cost value of the previous ones. The iterations of updating the solution matrix continue for maximum number of iterations.

3. RC Retaining Wall Example and Optimum Results

The figure of the retaining wall is shown in Fig. 3. The design variables are listed in Table 3 including limit values of the range of optimization. The problem has 4 design variables and it have 16 design constraints given in Table 4. The first 4 of the design constraints are about the geotechnical state limit. The other ones are related to structural state limits. These limits are considered according to ACI318: Building Code Requirements for Structural Concrete (2014). The design constants and coefficients used in the study are given as Table 5.

The optimum results are provided by the usage of 20 populations and 5000 iterations and applying as 30 cycles. The results are presented in Tables 6-8 for walls with H=3m, 7m and 10m, respectively.

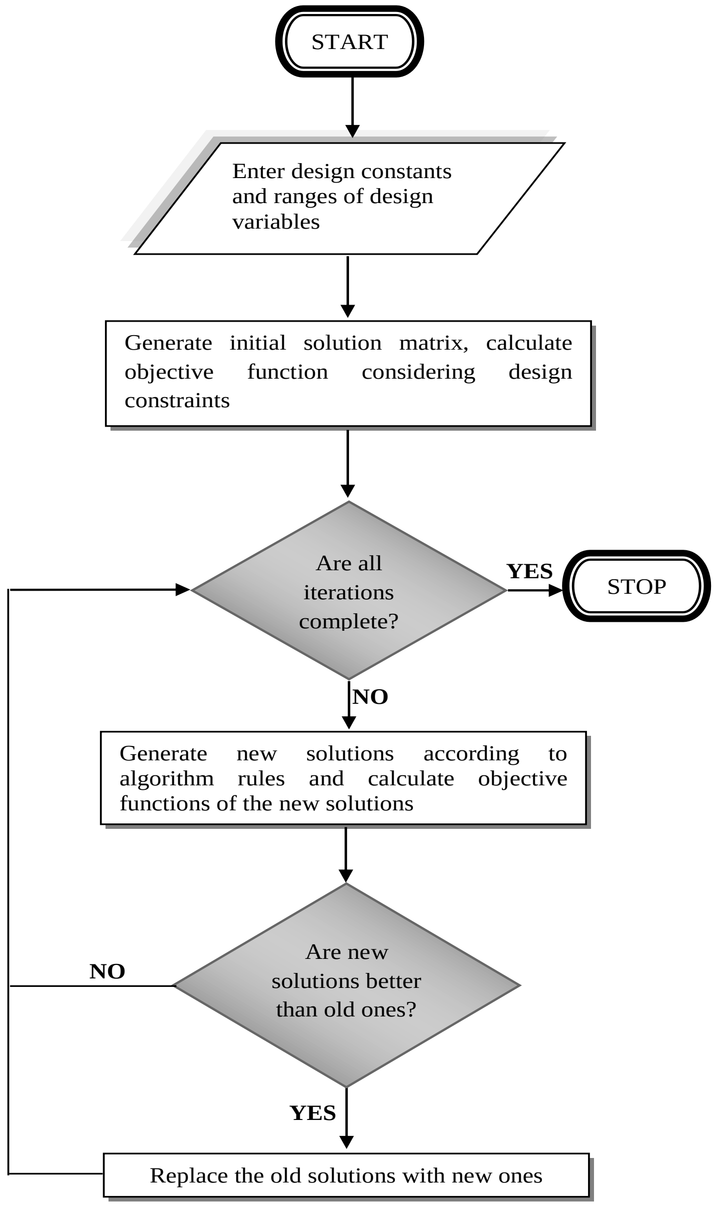

Fig. 2. General flowchart of optimization process.

Table 3. The design variables and ranges.

Definition	Symbol	Limit/Value	Unit
Heel slab/back encasement width of retaining wall	X_1	0-10	m
Upper part width of cantilever/stem of wall	X_2	0.2-3	m
Bottom part width of cantilever/stem of wall	X_3	0.3-3	m
Thickness of bottom slab of retaining wall	X_4	0.3-3	m

Table 4. The design constraints.

Description	Constraints
Safety for overturning stability	$g_1(X)$: $FoS_{ot,design} \geq FoS_{ot}$
Safety for sliding	$g_2(X)$: $FoS_{s,design} \geq FoS_s$
Safety for bearing capacity	$g_3(X)$: $FoS_{bc,design} \geq FoS_{bc}$
Minimum bearing stress (q_{min})	$g_4(X)$: $q_{min} \geq 0$
Flexural strength capacities of critical sections (M_d)	$g_{5\text{-}7}(X)$: $M_d \geq M_u$
Shear strength capacities of critical sections (V_d)	$g_{8\text{-}10}(X)$: $V_d \geq V_u$
Minimum reinforcement areas of critical sections (A_{smin})	$g_{11\text{-}13}(X)$: $A_s \geq A_{smin}$
Maximum reinforcement areas of critical sections (A_{smax})	$g_{14\text{-}16}(X)$: $A_s \leq A_{smax}$

Table 5. The design constants.

Definition	Symbol	Value	Unit
Difference between top elevation of bottom-slab with soil in behind of wall (active zone)/stem height	H	3-7-10	m
Weight per unit of volume of back soil of wall (active zone)	γ_z	18	kN/m³
Surcharge load in active zone (on top elevation of soil)	q_a	10	kN/m²
Angle of internal friction of back soil of wall	Φ	30°	-
Allowable bearing value of soil	q_{safety}	300	kN/m²
Thickness of granular backfill	t_b	0.5	m
Maximum Coefficient of soil reaction	K_{soil}	200	MN
Compressive strength of concrete	f_c	25	MPa
Tensile strength of steel reinforcement	f_y	420	MPa
Elasticity modulus of concrete	E_s	200000	MPa
Weight per unit of volume for concrete	γ_c	25	kN/m³
Weight per unit of volume for steel	γ_s	7.85	t/m³
Width of wall bottom slab	B	1000	mm
Concrete unit cost	C_c	50	$/m³
Steel unit cost	C_s	700	$/ton
Coefficient for load increment	C_l	1.7	-
Reduction coefficient for section bending moment capacity	FiM	0.9	-
Reduction coefficient for section axial load capacity	FiN	0.9	-
Reduction coefficient for section shear load capacity	FiV	0.75	-
Constant load coefficient	G_K	0.9	-
Live load coefficient	Q_K	1.6	-
Horizontal load coefficient	H_K	1.6	-

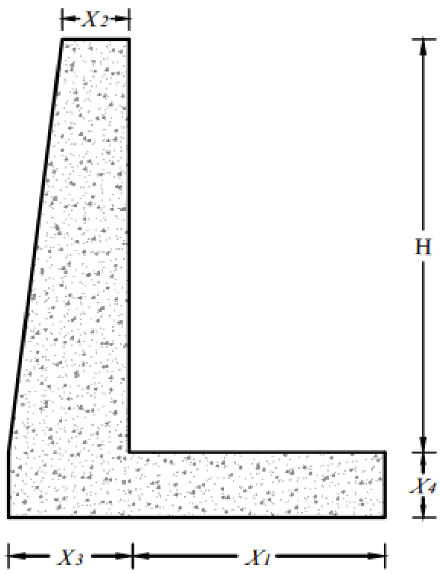

Fig. 3. The L-shaped design retaining wall.

Table 6. The optimum results (H=3 m).

Algorithm	X_1	X_2	X_3	X_4	Min. Cost	Ave. Cost	Standard Dev.
GA	2.2229	0.2002	0.3016	0.3004	108.68944	114.84902	15.98500
DE	2.2234	0.2000	0.3000	0.3000	108.58173	116.65465	34.03933
PSO	2.2234	0.2000	0.3000	0.3000	108.58173	108.58173	0.00000
HS	2.2234	0.2000	0.3000	0.3000	108.58246	108.59081	0.00801
FA	2.2234	0.2000	0.3000	0.3000	108.58173	108.58178	0.00004
ABC	2.2236	0.2000	0.3000	0.3000	108.58564	109.03591	0.78806
TLBO	2.2234	0.2000	0.3000	0.3000	108.58173	108.58173	0.00000
FPA	2.2234	0.2000	0.3000	0.3000	108.58173	108.58173	0.00000
GWO	2.2234	0.2000	0.3000	0.3000	108.58173	110.14573	2.65610
JA	2.2234	0.2000	0.3000	0.3000	108.58173	108.58173	0.00000

Table 7. The optimum results (H=7 m).

Algorithm	X_1	X_2	X_3	X_4	Min. Cost	Ave. Cost	Standard Dev.
GA	4.7632	0.2005	0.7533	0.5275	605.01168	621.63784	35.41998
DE	4.7608	0.2000	0.7493	0.5150	604.75489	614.48449	38.08353
PSO	4.7610	0.2000	0.7492	0.5152	604.75519	654.04851	122.48324
HS	4.7693	0.2000	0.7425	0.5242	604.85495	605.35279	0.32382
FA	4.7598	0.2000	0.7505	0.5143	604.75832	604.79833	0.02365
ABC	4.7616	0.2001	0.7473	0.5116	604.85052	606.95079	3.92429
TLBO	4.7608	0.2000	0.7492	0.5150	604.75489	604.75489	0.00000
FPA	4.7608	0.2000	0.7493	0.5150	604.75489	604.76417	0.03294
GWO	4.8056	0.2000	0.6763	0.4991	606.83137	621.57701	11.35595
JA	4.7609	0.2000	0.7492	0.5150	604.75489	604.75489	0.00000

Table 8. The optimum results (H=10 m).

Algorithm	X_1	X_2	X_3	X_4	Min. Cost	Ave. Cost	Standard Dev.
GA	6.8824	0.2007	1.6700	0.7535	1469.46405	1500.24786	21.94036
DE	6.7810	0.2000	1.6843	0.7202	1467.19368	1558.93810	175.31755
PSO	6.7788	0.2000	1.6841	0.7190	1467.20136	167998.77360	372082.280
HS	6.7759	0.2000	1.6803	0.7144	1467.40149	1468.68387	0.66989
FA	6.7904	0.2000	1.6834	0.7236	1467.25477	101320.66730	299559.777
ABC	6.7924	0.2000	1.6802	0.7220	1467.30247	1469.01494	2.10107
TLBO	6.7809	0.2000	1.6843	0.7201	1467.19369	1467.19380	0.00014
FPA	6.7810	0.2000	1.6843	0.7202	1467.19368	1467.27857	0.28631
GWO	7.0103	0.2082	1.6741	0.7993	1481.74107	1504.86350	15.40662
JA	6.7810	0.2000	1.6843	0.7202	1467.19368	1520.97722	53.46521

4. Conclusions

In this study, an optimization application was performed intended for weight minimization of an L-shape retaining wall to detect the best design algorithm providing the required constraints and conditions. In this regard, all processes were applied by using thirty cycles, and statistical calculations were made according to mean and standard deviation results given in Tables 6-8 for 3m, 7m and 10m, respectively.

According to the results, it can be recognized that the minimum weight of 3m L-shape retaining wall is 108.58173 and this was reached via 7 algorithms from 10. On the other hand, two of these algorithms are not effective in means of mean and deviation values. These algorithms are GWO and especially DE. PSO, TLBO, FPA and JA are very successful due to the least deviation as zero. FA can be considered an effective method to find the best results due to its error value is slightly much from them.

It can be seen that for H=7 m, which is the second model used for wall height, the best weight value (604.75489) was obtained with DE, TLBO, FPA and JA. TLBO and JA achieved this by making without a deviation. Although DE achieved to this, standard deviation value of weight function is very big cause that weight is so different and far from minimum weight in every cycle. Additionally, also FPA, which has an error that it is pretty close of both methods, can be preferred for determination of minimum weight.

Finally, if the 10m retaining wall is evaluated, it can be seen that again DE, FPA and JA are effective methods in finding the best value. But, the most successful one is FPA, because it did not make big deviations. DE and even JA extremely deviated while reaching the minimum weight. In this case, this shows that both methods find very different results for weight in every cycle. Also, TLBO is effective to find a result which is slightly different than the optimum result with small deviation.

When these three wall models were evaluated, noticed that successful algorithm number decreases as long as increasing of wall height. Also, DE is not steady in terms of to find the minimum weight in every cycle of optimization with regards to all wall heights. To sum up, FPA and TLBO are the most convenient algorithms, which can be preferred among whole metaheuristics thanks to that it succeeds in terms of achievement for providing of desired results for all heights.

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