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Optimization of buttressed earth-retaining walls using hybrid harmony search algorithms

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ABSTRACT

This paper represents an economic optimization of buttressed earth-retaining walls. We explore the optimum solutions using a harmony search with an intensification stage through threshold accepting. The calibration of the resulting algorithm has been obtained as a result of several test runs for different parameters. A design parametric study was computed to walls in series from 4 to 16 m total height. The results showed different ratios of reinforcement per volume of concrete for three types of ground fill. Our main findings confirmed that the most sensitive variable for optimum walls is the wall-friction angle. The preference for wall-fill friction angles different to 0° in project design is confirmed. The type of fill is stated as the main key factor affecting the cost of optimum walls. The design parametric study shows that the soil foundation bearing capacity substantially affects costs, mainly in coarse granular fills (F_1). In that sense, cost-optimum walls are less sensitive to the bearing capacity in mixed soils (F_2) and fine soils of low plasticity (F_3). Our results also showed that safety against sliding is a more influential factor for optimum buttressed walls than the overturning constraint. Finally, as for the results derived from the optimization procedure, a more suitable rule of thumb to dimension the footing thickness of the footing is proposed.

1. Introduction

The common procedure for economic structure design adopts the cross-section dimensions and material grades restricted by professional practice. To satisfy the limit states prescribed by codes, it is necessary to analyze the stresses and compute the required reinforcement. As the initial dimensions or material grades could be excessive or insufficient, a trial-and-error approach is generally used. Therefore, the cost of the structure depends on the experience of the designer. To achieve an economic wall design, a more efficient process, as well as an accurate model, is needed. Cost efficient design is not a straightforward method, as it is determined by boundary conditions such as type of fill, base-friction angles, soil foundation bearing capacity and surcharge loads. As an alternative to this procedure, either exact or heuristic optimization approaches can be used.

Metaheuristic algorithms have proven their efficiency and versatility in solving large-scale and highly nonlinear optimization problems [1]. There has been a tremendous amount of research in metaheuristics during the last years, most of them nature-inspired on swarm intelligence, biological systems, physical and chemical systems [2]. Several heuristic search algorithms belonging to this category are harmony search (HS), simulated annealing (SA), threshold accepting (TA), genetic algorithms (GA), ant colonies (ACO), particle swarm optimization (PSO), tabu search (TS), flower pollination algorithm (FPA), teaching-learning based optimization (TLBO), among others. Rajeev and Krishnamoorthy [3] pioneered by applying genetic algorithms to the optimization of weight in steel structures, followed by Coello et al. [4], who applied GA to Reinforced Concrete (RC) beams. Sarma and Adeli [5] reviewed major works on cost optimization of RC structures published in the past few decades. The robustness of ACO, GA, HS, PSO, SA, TS, FPA, and TLBO has been investigated through five benchmark steel frame designs [6–8]. The results showed the benefits of incorporating intensification and diversification to navigate the large variable spaces presented in these optimization problems effectively.

Other RC structures have been the subject of numerous optimization studies. The optimum design of frame structures was performed by using the Eagle Strategy with Differential Evolution [9]. Kripka et al. [10] used SA to minimize the costs of the beams in RC

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Nomenclature

b	stem thickness
c	footing thickness
h	stem height
m_i	wall measurement
p	toe length
p_i	unit prices
q	uniform surface loading on top of the fill
t	heel length
z	footing length
v_c	total volume of concrete
$x_1, \ldots, x_n$	design variables
z	length of the footing
$A_1, \ldots, A_{12}$	reinforcement variables
R_{st}	reinforcement of the stem
R_{ft}	reinforcement of the footing
R_t	total weight of steel
C	wall cost
F	objective function
F_1, F_2, F_3	types of fills
H	total height of the wall
H_2	foundation depth
M_{of}	moment reaction at the base of the wall
M_{ou}	total favorable overturning moment
$P(\gamma, \phi, \delta)$	earth pressure
P_p	passive earth pressure on the toe
Q	Surface loading on top of the fill
α	angle slope of the buttress
γ	density of the fill
γ_{fs}	safety coefficient against sliding
γ_{fo}	safety coefficient against overturning
ϕ	internal friction angle
δ	wall-fill friction angle
σ	maximum bearing pressure
μ	base-friction coefficient

buildings using a grid model. Carbonell et al. [11] aimed to achieve the most economical design of RC road vaults by a multi-start global best descent local search, a meta-SA and a meta-TA. Prestressed concrete precast road bridges were optimized with hybrid SA [12] and the hybrid glowworm swarm algorithm [13]. De Medeiros and Kripka [14] adopted HS to minimize the cost of RC columns according to different environmental impact assessment parameters. Camp and Assadollahi [15] used big bang-big crunch (BB-BC) technique to optimize RC footings. Luz et al. [16] used hybrid stochastic hill climbing algorithms with a neighborhood move based on the mutation operator from the genetic algorithms to minimize the cost of RC open abutments of road bridges. García-Segura et al. [17] proposed a Hybrid HS for the design of post-tensioned concrete box-girder pedestrian bridges. Yepes et al. [18] used a multiobjective SA to optimize a RC I-beam. Recently, García-Segura and Yepes [19] proposed a multiobjective HS to optimize a post-tensioned concrete box-girder road bridge.

Optimum cantilever retaining walls have recently been studied considering different metaheuristics. Recent works on retaining walls studied through SA [20] and TA [21] strategies compared the effect of base soil friction angles on the design parameters variations. Talatahari and Sheikholeslami [22] used an enhanced charged system search method to optimize the cost of gravity and RC retaining walls. Sheikholeslami et al. [23] used the Hybrid Firefly algorithm to minimize the cost of cantilever retaining walls. Swarm intelligence techniques such as particle swarm optimization (PSO), accelerated PSO, (APSO), firefly algorithm (FA) and cuckoo search (CS) were compared to find the influence of surcharge load and backfill slope on the cost and weight optimum cantilever walls [24]. Bekdaş [25] proposed a HS strategy for post-tensioned axially symmetric cylindrical RC walls. Despite there being limited research on geotechnical engineering optimization problems, the studies of Khajehzadeh et al. [26], who studied the design of gravity-retaining walls subjected to seismic loading, are also worth mentioning.

If the wall is taller than 9 m, the thickness of the stem becomes greater, as well as the volume of concrete. To make the stem lighter, a ribbed plate (buttressed) is preferred to a solid plate. Earth-retaining buttressed walls made of reinforced concrete (RC) are common structures in civil engineering. Various design factors influence the appearance and, consequently, the performance with regard to life span, cost or environmental impact [27]. Earth-retaining buttressed walls for roads and building structures are analyzed in this study. The method followed in this paper consists of a computer module evaluation of geometric and steel reinforcement according to the optimization variables. The cost of every solution is computed, and the limit states are checked. The hybrid HS together with a TA strategy is used for a cost optimization and a design parametric study. Our paper is divided into five sections: (1) formulation of the optimal design problem; (2) the structural evaluation; (3) the proposed HSTA algorithm and calibration; (4) results obtained and discussion of the numerical experiments; and (5) conclusions.

2. Optimization problem definition

The structural concrete problem proposed consists of an economic optimization. The objective function cost (C) to be minimized is defined in Eq. (1). The objective function considers the unit prices p_i, and the measurements (m_i) of the eight cost units in which the wall is divided. Basic prices are given in Table 1 and correspond to prices considered in an earlier study of earth-retaining walls by Yepes et al. [20]. The prices included the

Table 1
Unit costs.

Unit	Cost (€)
m^3 of concrete HA-25 in stem	56.66
m^3 of concrete HA-30 in stem	60.80
$m^3$of concrete HA-35 in stem	65.32
m^3 of concrete HA-40 in stem	70.41
m^3 of concrete HA-45 in stem	75.22
m^3 of concrete HA-50 in stem	80.03
m^3 of concrete HA-25 in foundation	50.65
m^3 of concrete HA-30 in foundation	54.79
m^3 of concrete HA-35 in foundation	59.31
m^3 of concrete HA-40 in foundation	64.40
m^3 of concrete HA-45 in foundation	69.21
m^3 of concrete HA-50 in foundation	74.02
kg of steel B400S	0.56
kg of steel B500S	0.58
m^3 stem formwork	21.61
m^2 of foundation formwork	18.03
m^2 of earth removal	3.01
m^3 front in-fill	4.81
m^3 of backfill	5.56