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CO_2 and cost optimization of reinforced concrete footings subjected to uniaxial uplift

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ABSTRACT

A multi-objective optimization of CO_2 emissions and cost for the design of reinforced concrete footings under uniaxial bending moments is developed. The analysis and design procedures are based on specifications prescribed by the American Concrete Institute (ACI 318-11) for concrete design as well as geotechnical limit states. In addition, a theoretical analysis procedure for reinforced concrete footings subjected to uniaxial uplift is derived and compared to simplified analysis procedures typically used in practice. The multi-objective optimization uses a hybrid Big Bang–Big Crunch algorithm. Pareto fronts for cost and CO_2 emissions are developed for design examples to compare the theoretical analysis to simplified analysis and investigate trade-offs between CO_2 emissions and cost. Also, design results show the impact on CO_2 emissions and cost by allowing uplift of the footing.

1. Introduction

In the analysis and design of spread footings, the interaction between the soil and the reinforced concrete poses many challenges to the designer. In practice, there are many assumptions that can be made to simplify the analysis and design of spread footings. However, regardless of any assumptions; the footing must safely and reliably support the superstructure, provide stability against soil bearing capacity failure and excessive settlement, have sufficient shear and moment capacities in both the long and short dimensions; the bearing capacity of the foundation concrete cannot be exceeded, and the configuration of the steel reinforcement must meet all building code requirements.

Economical design has always been central in the practice of engineering. More recently, sustainable design has become of greater interest in engineering practice. As the annual emissions of carbon dioxide (CO_2) has grown by about 80% since 1970 and were estimated to be 77% of total anthropogenic greenhouse gas emissions in 2004 [31]; the consideration of CO_2 emissions in structural concrete design has become a prudent area of research. Large emissions of CO_2 are produced during the manufacturing of Portland cement, the principal binder used in concrete. Due to these large CO_2 productions, efforts have been made to design concrete structures which are more sustainable. A detailed method for developing low-cost and low-CO_2 emission designs of reinforced concrete spread footings is relatively new [7,16,34,35]. In addition, there has been no investigation into the comparison of footing designs based on simplifying analysis procedures with theoretical analysis procedures for low-cost and low-CO_2 emissions, subjected to uniaxial bending, which consider all of the geotechnical and structural limit states using metaheuristic methods.

In practice, there are many simplifying analysis procedures that are made which yield conservative design results. If cost or the CO_2 emissions are not of significant concern to the design engineer, then applying simplifying analysis procedures is acceptable. However; if the material and construction costs or CO_2 emissions of the spread footing are of significant concern, using simplifying analysis procedures which yield over-designed footings and result in increased costs and CO_2 emissions may not be desired. Theoretical analysis procedures are presented for the design of spread footings subjected to uniaxial bending, within or outside the kern, that more accurately describe the bearing pressure distribution beneath the footing. A comparison is made between designs developed from the simplified analysis procedures and those developed from the theoretical analysis procedures.

Big Bang–Big Crunch (BB–BC) has been shown to be a computationally efficient heuristic method to solve a variety of optimization problems. Erol and Eksin [11] proposed the original BB–BC algorithm, which involved exploiting the power of the mean

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using an abstract model of the lifecycle of the universe. In each "Big Bang" stage, a set of normally distributed solutions is generated about the weighted mean of the solution space. After the solutions are evaluated, a "Big Crunch" stage computes a new center for the next "Big Bang" based on the fitness of the various solutions. Over successive cycles of Big Bangs and Big Crunches, the standard derivation of the normal distribution of new solutions decreases and the search tends to become more localized in the neighborhood of the best solution. When some measure of the averaged solution and/or the best solution ceases to improve over a number of cycles, the optimization is assumed to have converged.

Erol and Eksin [11] established that a simple BB–BC algorithm can outperform enhanced and classic genetic algorithms (GA) for many benchmark optimization functions. Camp [5], Kaveh and Talatahari [14,15], Camp and Akin [6], and Camp and Assadollahi [7] proposed hybrid forms of the BB–BC algorithm to solve structural engineering optimization problems. Results indicated that these hybrid BB–BC algorithms improved both the quality of the optimization and its computational efficiency when compared to published solutions generated by GA and ant colony optimization (ACO).

While there is little research on optimization of spread footings, the literature has numerous studies on optimizing the design of reinforced concrete structures. For example, Coello et al. [9], Rafiqa and Southcombea [28], Rajeev and Krishnamoorthy [29], Camp et al. [3], Lee and Ahn [19], Lepš and Šejnoha [20], Sahaba et al. [30], Govindaraj and Ramasamy [13], and Kwak and Kim [17,18] all applied various types of GAs to the cost optimization of reinforced concrete structures. Paya et al. [24], Perea et al. [26], and Paya-Zaforteza et al. [25] optimized reinforced concrete structures using simple and hybrid simulated annealing (SA) algorithms. Villalba et al. [33] optimized reinforced concrete retaining walls for CO_2 emissions using SA. Yepes et al. [37] developed an innovative hybrid multistart optimization strategic method based on a variable neighborhood search threshold acceptance strategy (VNS-MTAR) to optimize reinforced concrete retaining walls for cost and CO_2 emissions. Camp and Akin [6] used a hybrid BB–BC algorithm to develop low-cost retaining wall designs, and then Camp and Huq [8] applied the same methods to design low-cost and low-CO_2 reinforced concrete frames. Camp and Assadollahi [7] applied a hybrid BB–BC algorithm to design low-cost and low-CO_2 reinforced concrete footings, subjected to concentric loading. de Medeiros and Kripka [10] accounted for environmental impact assessment parameters in the optimization of reinforced concrete columns. García-Segura et al. [12] used a hybrid glowworm swarm algorithm to optimize concrete I-beams. Park et al. [22] minimized cost and CO_2 emissions associated with reinforced concrete columns in high-rise buildings. Park et al. [23] considered the influence of design factors on the CO_2 emissions and costs of reinforced concrete columns. Yepes et al. [38] considered the cost and CO_2 optimization of precast-prestressed concrete U-beam road bridges using a hybrid glowworm swarm algorithm.

2. Design of reinforced concrete footings subjected to uniaxial uplift

This study is an extension of the design optimization presented by Camp and Assadollahi [7] with several significant modifications: reinforced concrete footings are subjected to uniaxial eccentric loading along one of the principal axes of the footing; uplift of the footing is allowed while preventing overturning; and a modified BB–BC algorithm is applied to improve the quality and consistency of the multi-objective designs. In addition, the design of footings using simplified analysis, typical in engineering practice, is compared to designs conforming to a more theoretical approach. Allowing uplift and relaxing typical simplifications in the geotechnical analysis of uniaxial loaded footings presents a more challenging optimization problem. A modified multi-objective BB–BC algorithm was developed and applied to the design optimization of uniaxial loaded reinforced concrete footings that improved the efficiency of the solution on the Pareto front.

The forms of the two objective functions for this optimization are consistent with those presented by Camp and Assadollahi [7]. Both the cost objective function and the CO_2 emission objective function include the cost of excavation, formwork, reinforcing steel, concrete, and compacted backfill. The cost values include material cost and associated cost for labor and installation.

The general form of the optimization problem is given as

$$\text{Minimize:} f_{cost} = \sum_{i=1}^{R} C_i u_i(x_1, x_2, \ldots, x_n) \text{ or } f_{CO_2} = \sum_{i=1}^{R} E_i u_i(x_1, x_2, \ldots, x_n) \tag{1}$$

$$\text{Subject to:} p_j(x_1, x_2, \ldots, x_n) \le 0 \tag{2}$$

where f_{cost} is the cost function, f_{CO_2} is the CO_2 emission function, C_i are the unit costs, E_i are the unit CO_2 emissions, u_i is the amount of material and construction units, x_i are the design variables, n is the number of design variables, R is the number of material and construction units, and p_j are the penalty functions.

To gain better insight on the relationship between low-cost and low-CO_2 emission designs, a multi-objective optimization is applied using the weighted aggregation approach. In general, this approach consists of adding all the single-objective functions together using different weighting coefficients.

The general form of the weighted aggregation approach is given as

$$\text{Minimize: } f_{multi} = \sum_{h=1}^{m} \zeta_h \mathrm{f}_h(x_1, x_2, \ldots, x_n) \tag{3}$$

$$\text{Assuming: } \sum_{h=1}^{m} \zeta_h = 1 \tag{4}$$

where f_{multi} is the multi-objective fitness function, ζ_h are nonnegative weights, f_h are the single-objective fitness functions, and m is the number aggregated single-objective functions.

When designing a reinforced concrete spread footing, both structural and geotechnical limit states must be considered. Structural limit states include the shear capacity of the footing (one-way shear and two-way shear); the flexural capacity; the bearing capacity of the column, dowels, and footing; and development length requirements for the reinforcing. Structural limit states conform to the specifications prescribed by the American Concrete Institute building code (ACI 318-11) [1] for structural concrete. Geotechnical limit states include the bearing capacity of the surrounding geomaterial and the allowable settlement of the footing. Structural limit states are satisfied using factored loads while geotechnical limit states are satisfied using service loads.

2.1. Analysis of reinforced concrete footings subjected to uniaxial loading

Uniaxial loading occurs on a rectangular spread footing when the applied force acts through a point displaced from the center along one of the principal axes, or if there is a moment load M applied to the footing. The eccentricity e is the perpendicular distance from the center of the footing to the applied load. For a