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Optimal design of pad footing based on MINLP optimization

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Abstract

The paper presents an optimal design of pad footing, based on multi-parametric mixed-integer non-linear programming (MINLP) optimization. For this purpose, the MINLP optimization model PADFOOT was developed. The model comprises an accurate objective function of the structure production costs, subjected to design, resistance, rotation and settlement constraints in order to satisfy the requirements of the ultimate and serviceability limit states according to Eurocode specifications. In order to interpret the applicability of the optimization model, the paper presents an example of determining the cheapest possible pad footing and the optimal design for the given design parameters. As the model was developed in a general form, the optimization of the pad footing can be performed for different economic conditions and different design parameters. The optimal design of pad footing was investigated for a typical industrial concrete building.

Keywords: Computational modeling; Numerical analysis; Pad footing; Structural optimization; MINLP

1. Introduction

The main requirements of modern geotechnical structures are safety and economy. The safety is guaranteed by design constraints, and economy can be achieved by minimization of the cost function. To obtain the design of geotechnical structures which better fulfill engineering requirements, economics must be considered explicitly in the design process, rather than evaluated after satisfying the safety requirements. Therefore, the design of a system should be formulated as problems of optimization in which a construction cost is optimized while all other requirements are satisfied.

One of the most frequently used geotechnical structures is a pad footing (see Fig. 1). According to the standards (EN 1992-1, 2004; EN 1997-1, 2004), the pad footing must satisfy ultimate limit state (ULS) and serviceability limit state (SLS) conditions. The pad footing must be designed to withstand the structural failure STR (bending failure, shear failure and constraints of a concrete design code), geotechnical failure GEO (bearing failure, sliding, settlement), loss of equilibrium EQU (eccentricity) of the structure by overturning and combined failure in the ground and structure. The concept of geotechnical and structural failure possibilities was taken from the Bond and Harris (2008), see Fig. 1.

In the recent past, various methods and algorithms have been applied for the optimization of structures. The optimization of geotechnical structures is still uncommon to date (Pucker and Grabe, 2011). Until now, optimization methods are used in geotechnics e.g. to determine slope stability (Jelušič et al., 2014; Jelušič and Žlender, 2013). The optimization was designed to be used for identifying the failure mechanisms and finding the required reinforcement strength of a reinforced slope (Jelušič et al., 2014). Optimization methods have been proposed for calibrating

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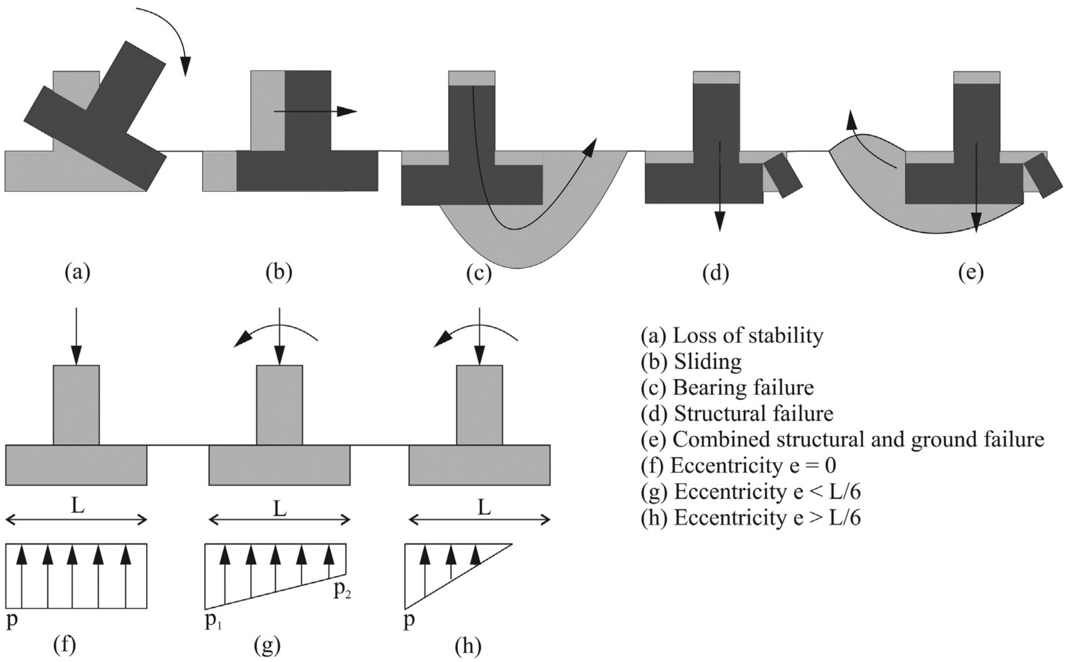

Fig. 1. Geotechnical and structural failure possibilities (a–e), and loading actions on pad footing (f–h).

geotechnical models from laboratory tests (Jelusic, 2015). In these methods, geotechnical parameters are identified by matching model predictions to experimental data, i.e. by minimizing an objective function that measures the difference between the two. A target reliability based design optimization procedure was proposed by Basha and Babu (2008) for determining the penetration depth, anchor pull, and section modulus for an anchored cantilever sheet pile wall, considering rotational, sliding, and flexural failure modes. Shinoda (2015) presented a simple slip surface search algorithm based on the particle swarm optimization (PSO) that improves convergence performance without increasing the number of analysis parameters. A lower bound plane strain and axisymmetric limit analysis, in conjunction with finite elements and an optimization procedure, has been used to calculate the bearing capacity of foundations (Kumar and Chakraborty, 2015; Bhattacharya and Kumar, 2017). A multi-objective optimization problem that covers geotechnical design (safety) constraints, design robustness, and cost efficiency was published by Gong et al. (2014). Pucker and Grabe (2011) presented the settlement and volume optimization of a strip foundation with a SIMP-method (Solid Isotropic Material with Penalization). The minimal settlement of the strip foundation depending on the material volume used was obtained. Very recently, Ukritchon and Keawsawasvong (2016) proposed the ant-colony optimization technique for the optimal design of continuous footing. The proposed optimization method is demonstrated through the actual design of the footing for supporting a large machine moving on rails. The genetic algorithm (GA) was applied to optimize the reinforced concrete strip foundation by Hui et al. (2015). The results showed that the method can effectively optimize reinforced concrete strip foundations.

As pad footings are made of more than one material, the objective function to be minimized should be the cost (Sarma and Adeli, 1998). A simplified procedure of pad footing cost optimization with geographic variation of construction costs was presented by Wang and Kulhawy (2008). The authors neglect several important cost items and do not consider the actual constraints of a concrete design code and geotechnical design code. The optimization problem is formulated in terms of three geometrical design variables and the pad footing is subjected only to vertical load. However, it seems that the cost optimization of pad footing subjected to vertical, lateral and moment loads (including detailed construction cost function and considering structural and geotechnical design codes) has not yet been researched (see Fig. 1). Moreover, since practical engineering design requires that some design variables belong to an ordered set of values, the solutions of the presented optimization models are discrete values. Therefore, the optimization model is formulated in terms of five geometrical design variables and one material variable. The geometry of pad footing subjected to vertical actions, lateral actions, moments and eccentricity is presented in Fig. 2. The pad footing for a single column may be made square in plan, but where there is a large moment acting about one axis it may be more economical to have a rectangular base.

In order to improve the economic effectiveness of a predominantly statically loaded pad footing, this paper introduces a cost optimization of the geotechnical structure. The optimization was performed by the mixed-integer nonlinear programming (MINLP) approach. The MINLP is a combined continuous-discrete optimization technique. It handles continuous and discrete binary 0–1 variables simultaneously. While continuous variables are normally