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# Optimum design methodologies for pile foundations in London

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ABSTRACT

Given the importance of pile foundations in geotechnical engineering for supporting high-significance structures such as bridges, high-rise buildings, power plant stations, offshore platforms and museums, it becomes a necessity to find the best pile foundation design in terms of performance and economy. The number of piles required might exceed several hundreds or even thousands while the pile foundation cost might exceed 20% of the construction cost of the superstructure. In this work the problem of finding optimized designs of pile foundations is examined and is performed in accordance to two design code recommendations, namely Eurocode 7 and DIN 4014. The proposed structural optimization procedure is implemented in two real-world cases both located in London, UK in order to assess the efficiency of the proposed design formulation.


## Introduction

Pile-supported structures are known to have existed in pre-historic times, references to cedar timber piles in Babylon can be found in the Bible. In the Middle Ages, pile foundations supported a wide assortment of structures particularly in Venice and in the Netherlands. Piled foundations are a convenient method for supporting structures built over water or where uplift loads must be resisted. Inclined or raking piles have been also used to resist lateral forces. Piles supporting retaining walls, bridge piers and abutments and machinery foundations resist both vertical and horizontal loads. The main types of piles used are driven piles, driven and cast-in-place piles, jacked piles, bored and cast-in-place piles and composite piles [1]. The first three of the above types are also called *displacement piles* since the soil is displaced as the pile is driven or jacked into the ground. In the case of bored piles, and in some forms of composite piles, the soil is first removed by boring a hole where concrete is placed or various types of precast concrete or other proprietary units are inserted.

Following the decision that piling is necessary, the engineer must make a choice from variety of types and sizes. Usually, there is only one type of pile which is satisfactory for a particular site condition [2]. In this work bearing piles will be examined although any type of piles may also be considered in the proposed formulation. *Bearing piles* are required when the soil at normal foundation level cannot support ordinary pad, strip, or raft foundations or where structures are sited on deep filling which is compressible and settling under its own weight.

The foundation cost, of real-world structural systems, can vary from 5% to 20% of the construction cost of the superstructure while the number of piles required might exceed several hundreds or even thousands. In the first part of this study the modelling of the soil-pile structure interaction using the finite element method is described while in the second part a formulation of an optimization problem is proposed, aiming at achieving the most economical-optimized design of the pile

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foundation layout. Two different design procedures are adopted and are incorporated in the optimization procedure: the German foundation code DIN 4014 [3] and the Eurocode 7 (EC7) [4] design procedures. Due to the nature of the problem, a mesh generator is used in order to create automatically the finite element mesh both for pile members and soil. Two real-world structures are considered for assessing the proposed formulation. In particular, the 16-storey and the 31-storey (Hiscocks House at Stonebridge Park and Hyde Park Cavalry Barracks both in London, UK) buildings are used as benchmark tests, for the comparative study and a significant reduction of the pile foundation cost is achieved. Although, the proposed framework is used for the design of building structures, it can also be applied with proper modifications implementing the requirements and specifications imposed for other type of structures (such as nuclear power stations, bridges etc.).

## The design procedures

Two different design procedures are considered in this work in order to assess the performance of the designs obtained during the optimization process: the German foundation code DIN 4014 [3] and the Eurocode 7 [4]. Both standards are based on the following main design criteria: (i) axial bearing capacity, (ii) acceptable settlements, (iii) strength of pile as a structural element and (iv) lateral bearing capacity and acceptable horizontal displacements.

Although, both design codes provide design considerations for determining the pile resistances, comparing the two design codes it can be said that the implementation of a limit-state design procedure (suggested by the Eurocode 7) represents a significant change in the design philosophy of the DIN regulation. In particular the following limit-states should be considered and an appropriate list should be compiled (loss of overall stability, bearing resistance failure of the pile foundation, uplift or insufficient tensile resistance of the pile foundation, failure in the ground due to transverse loading of the pile foundation, structural failure of the pile in compression, tension, bending, buckling or shear, combined failure in the ground and in the pile foundation, combined failure in the ground and in the structure, excessive settlement, excessive heave, excessive lateral movement and unacceptable vibrations).

The expression used to calculate the ultimate bearing capacity of a single pile according to DIN 4014 is:

$$Q_u = Q_{su} + Q_{pu} \tag{1}$$

where $Q_u$ is the ultimate bearing resistance of the pile, $Q_{su}$ is the skin friction resistance load of the single pile while $Q_{pu}$ is the point resistance load of the single pile and they are given by:

$$Q_{su} = \pi D \sum f_{su} \Delta z \tag{2}$$

$$Q_{pu} = A_p q_{pu} \tag{3}$$

where $f_{su}$ is the ultimate skin friction resistance stress, $q_{pu}$ is the ultimate point resistance stress. $A_p$ is the pile base area, $D$ is the pile shaft diameter and $\Delta z$ is the effective length of the pile. The total allowable compressive load ($Q_{all}$) is calculated as follows:

$$Q_{all} = \frac{Q_u}{FS} \tag{4}$$

where a safety factor ($FS$) equal to 2 is used, according to DIN 1054 [5]. The ultimate bearing capacity of a pile group ($Q_{u,g}$) is given by the equation:

$$Q_{u,g} = N(Q_{pu} + f \cdot Q_{su}) \tag{5}$$

where $N = m \times n$ is the number of piles of the group, $m$ is the number of rows and $n$ is the number of columns and $f$ is a reduction factor of the side friction resistance of the single pile, calculated from:

$$f = 1 - \frac{\theta}{90}(2 - 1/m - 1/n) \tag{6}$$

$$\theta = \arctan(D/s) \tag{7}$$

where $s$ is the axial distance between the piles.

In the case of Eurocode 7, the design value of the ultimate pile resistance ($R_{u,d}$) is given by the following equation:

$$R_{u,d} = \frac{R_{pu,k}}{\gamma_{pR}} + \frac{R_{su,k}}{\gamma_{sR}} \tag{8}$$

where $R_{pu,k}$ and $R_{su,k}$ are the characteristic values of the base and shaft resistance, respectively, while the partial safety factors are set to $\gamma_{pR} = 1.6$ and $\gamma_{sR} = 1.3$. For the application of an axial loading $V_{k}$, the design value of an action $F_d$ should be equal to:

$$\mathrm{F_d} = \gamma_G \cdot P_k + \gamma_Q \cdot Q_k \tag{9}$$

where $P_k = 0.8 \cdot V_k$ and $Q_k = 0.2 \cdot V_k$ are the characteristic values of the permanent and variable actions respectively, while the corresponding partial safety factor are set to $\gamma_G = 1.0$ and $\gamma_Q = 1.3$ according to the factors R4 and formulation T4 of Eurocode 7 [4].