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Foundation and overall structure designs of continuous spread footings along with soil spatial variability and geological anomaly

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ABSTRACT

Spatial variability of soil properties and geological anomaly can be very important in the case of low weight buildings with continuous spread footings inducing differential settlements which can have harmful consequences on the structure. They are also the major source of uncertainty in the choice of the soil design parameters. In this study, the design of continuous spread footings is performed with two approaches: the first approach with a foundation design using a one-dimensional finite element modeling and the second approach with an overall structure design using a three-dimensional finite element modeling. These approaches are compared for two cases: the first case dealing with the spatial variability of soil modulus and the second case with the spatial variability of soil modulus coupled with the presence of a geological anomaly (low stiffness zone of soil). Spatial variability of soil modulus is modeled by geostatistical methods using data from a real construction site. The values of the maximum settlements, maximum differential settlements and maximum bending moments obtained from the both approaches for the first case are nearly close together where the latter values for the second case are significantly greater than the first case. These results show that in the case of the presence of a geological anomaly on the construction site, the overall structure design appears the more appropriate approach compared to the foundation design in the design of continuous spread footings.

1. Introduction

Soil exhibits spatial heterogeneities resulting from the history of its deposition and aggregation processes, which occur in different physical and chemical environments. This inherent or natural variability can be also accompanied by a geological anomaly. A geological anomaly is any inclusion that is of different properties from that normally expected in a design soil profile. This anomaly may include weak pockets or lenses of clay in a sand layer, cavities or boulders in soils. The presence of these unfavorable materials could lead to unsatisfactory foundation and overall structure performance.

The natural variability accompanied by a geological anomaly can be very important in the case of superficial geotechnical works inducing differential settlements, which can have harmful consequences on the structure. For example in low weight buildings with continuous spread footings, damage can range from sticking doors and hairline plaster cracks to complete destruction. Kumar et al. studied the sources of these natural variability and the presence of a geological anomaly in foundation design parameters [1]. Raychowdhury et al. studied the shallow foundation response variability due to parameter uncertainty [2].

In foundation design, a low weight building is simply modeled with a one-dimensional modeling of a continuous spread footing with a loading [3]. However, in overall structure design, this low weight building is modeled with a two or three dimensional modeling of its continuous spread footings along with building elements such as columns, beams, walls and slabs [4].

In these conventional designs and dimensioning computations, continuous spread footings are often designed on the basis of the deterministic approaches where natural variability of soil and uncertainty related to imperfect knowledge of the presence of a geological anomaly of soil, in their longitudinal directions are usually not considered. These effects and the soil–shallow foundation interaction along the longitudinal direction of continuous spread footings need to be taken into account and studied in order to perform an accurate analysis leading to correct designs.

In this research work, two approaches are used for the design of continuous spread footings: the first approach with a foundation design using a one-dimensional finite element modeling (1D) and the second approach with an overall structure design using a three-dimensional finite element modeling (3D). These approaches

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are compared for two cases: the first case, taking into account the spatial variability of soil modulus (E_s) and the second case, taking into consideration the spatial variability of soil modulus accompanied by the presence of a geological anomaly as a lens of clayey soil of weak mechanical properties. Through these both approaches and cases, the soil–shallow foundation interaction along the longitudinal direction of continuous spread footings is then studied in order to better understand the influence of the spatial variability of E_s and a geological anomaly on the maximum settlement, maximum differential settlement and maximum bending moment.

In order to achieve this goal, geological conditions of the studied construction site and available data from the geophysical and geotechnical investigations are presented. Thereafter, the appropriate geostatistical methods (collocated ordinary cokriging and conditional simulations [5,6]) are used to model the spatial variability of Young's soil modulus (E_s) on a construction site. This spatial variability are then used through the finite element modeling of the Winkler soil–foundation interaction model in the longitudinal direction [7–14] along with and without the presence of a geological anomaly for both geotechnical and structural designs of continuous spread footings. From these numerical models, the maximum settlements, maximum differential settlements, maximum bending moments and their uncertainties are obtained in order to perform a statistical analysis that describes the longitudinal behavior of continuous spread footings in 1D and 3D models. Finally, a comparison between the obtained results from foundation and overall structure designs is done to study firstly, the influence of the spatial variability of soil modulus and secondly, the influence of this spatial variability coupled with the presence of a geological anomaly on the behavior of continuous spread footings.

2. Soil–shallow foundation interaction model

In the conventional calculations of the shallow foundations design, the behavior is only studied in a cross section to represent the transverse behavior of the foundation elements. In the case of a continuous spread footing and particularly when a differential settlement may appear, the longitudinal behavior of spread footing should be taken into consideration.

In the past, many researchers have worked on the soil–structure interaction which is referred to as beams and plates on elastic foundations. Most of the previous work began with Winkler's well known model with one parameter [15], which was originally developed for the analysis of railroad tracks. This model is expressed by the following equation (Eq. (1)):

$$p(x) = k_s \cdot b \cdot w(x) \quad (1)$$

where k_s is the coefficient of subgrade reaction, $w(x)$ is the deflection, b is a width of the foundation and $p(x)$ is the reactive pressure of the foundation. Winkler's idealization considers the soil as being a system of identical but mutually independent, closely spaced, discrete, linearly elastic springs. According to this idealization, deformation of foundation due to applied load is confined to loaded regions only. Furthermore this model cannot transmit the shear stresses which are derived from the lack of spring coupling [16,17]. Vlassov and Leontiev [18], recognizing the difficulty to determine values of k_s for soils, postulated a two-parameter model. The continuity in this model is characterized by the consideration of the shear layer. Kerr [19] attempted to make Winkler's model more realistic by assuming some forms of interaction among the spring elements that represent the soil continuum even though it requires more parameters (three-parameter mathematical model).

Winkler's model, due to its simplicity, has been extensively used to solve many soil–foundation interaction problems and has given satisfactory results for many practical problems. Furthermore, this model seems, from a practical point of view, to be appropriate for lightweight structures such as a low weight building.

The differential equation governing the deflection, $w(x)$, of a homogeneous elastic bending beam with constant bending stiffness resting on Winkler's model and subjected to a vertical continuous load, $q(x)$, can be written as [20]:

$$E_c \cdot I \frac{d^4 w(x)}{dx^4} + k_s \cdot b \cdot w(x) = q(x) \quad (2)$$

where $E_c \cdot I$ is the constant bending stiffness of the beam (E_c and I are respectively Young's modulus of concrete and the moment of inertia of the cross section of the foundation). When the deflection $w(x)$ is known, the bending moment and shear force can be determined.

Numerous expressions or semi-empirical models are available to determine the soil reaction modulus (k_s) as a function of the studied applications [9,21–24]. The Vesic semi-empirical model (Vesic [25]), commonly used in the design of continuous spread footings, is considered in this study in order to obtain a value of the soil reaction modulus (Eq. (3)).

$$k_s = \frac{0.65}{b} \cdot \sqrt[12]{\frac{12 E_s b^3}{E_c h^3}} \cdot \frac{E_s}{1 - \nu_s^2} \quad (3)$$

where E_s is the Young's soil modulus, ν_s the Poisson's ratio of soil, b, h and E_c are respectively width, height and Young's modulus of a continuous spread footing.

Soil reaction modulus (k_s) is not an intrinsic parameter of soil. The calculation of this modulus is a function of soil parameters (E_s, ν_s), the parameters related to the geometry of the continuous spread footing (b, h) and a mechanical property of the continuous spread footing (E_c) (Eq. (3)).

Induced reactions of the whole structure in the Winkler model (be it a single foundation beam or an overall superstructure) deduced on the basis of a certain distribution of a subgrade coefficient if applied in the opposite sense on the supporting soil mass with a given directly determined geotechnical property as the Young modulus (E_s) and the Poisson ratio (ν_s) of soil, cannot ensure that the very same settlements which have been assumed for the subgrade system will be developed also on the soil surface.

When the structure rigidity is significant, using the Winkler model is valid. This has been pointed out earlier in the well known study carried out by Stavridis et al. for the two dimensional analysis of the concrete tunnel frame [16].

3. Finite element models for foundation and overall structure designs of continuous spread footings

The influence of the soil spatial variability on a spread footing, using a finite element model, was studied by Cassidy et al. [26]. The finite element method has been largely used in numerous studies to model the soil–structure interaction: Denis et al. studied soil–shallow foundation interactions [27], Dubost et al. [7] and Niandou et al. [8] analyzed soil–pile interaction, Elachachi et al. [9–11], Buco et al. [12–14] studied soil–buried pipe interactions.

In this section the finite element models for foundation and overall structure designs of the considered continuous spread footings in this study are presented. We take a low weight building with four continuous spread footings with lengths of 10 m and 6 m along with concrete columns (cross section: $20 \times 20\ \text{cm}^2$), beams (cross section: $20 \times 20\ \text{cm}^2$) and floor slab (thickness: 15 cm). Continuous spread footings, for low weight buildings with relatively lightly loaded walls, consist of concrete strips with a rectangular cross section, placed under masonry walls. We take the common dimensions of a spread footing for a low weight