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Problem Solving in Foundation Engineering using foundationPro

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To Allah

Preface

The main purpose of this book is to stimulate problem-solving capability and foster self-directed learning in foundation engineering subject for civil and construction engineering students and practicing professionals. It also explains the use of the foundationPro software, available at no cost, and includes a set of foundation engineering applications. Reading this or any other textbook is not enough and cannot be sufficient to perform safe and economical designs of foundations as a considerable experience and judgment are required. The overall layout of the book chapters is as follows: first, to introduce the general idea behind the title of the chapter; second, to briefly discuss the theories and methodologies and to summarize the equations and charts needed in the chapter; third, to provide a step-by-step procedure on how to deal with design problems related to the title of the chapter; fourth, to induce a number of design problems and solve these problems by hand, and then using the foundationPro software; fifth, to present a number of suggested projects to allow the reader to practice the concepts learned in the chapter; and finally, to introduce a list of references and additional useful readings about that specific chapter. In total, this book consists of four chapters. Chapter 1 deals with the design of shallow foundations resting on homogeneous soil based on bearing capacity and elastic settlement requirements. Chapter 2 presents the axial capacity of single pile foundations in homogeneous and nonhomogeneous soils based on bearing capacity and elastic settlement requirements. Chapter 3 is similar to Chap. 2 but for single drilled shaft foundations. Chapter 4 deals with the design of mechanically stabilized earth retaining walls with strip reinforcement.

Additional materials are and will be available at http://www.foundationpro.net. These materials include the following:

1. foundationPro software which includes the following applications: Shallow-1, Pile-1, Pile-2, Shaft-1, Shaft-2, and MSE Wall-1.

2. Video tutorials on how to use the various applications of foundationPro software.
3. foundationPro Forum which can be visited for general discussions about foundationPro applications. The forum can be accessed by visiting http://www.foundationpro.net/forum/.

Peoria, IL, USA Mohammad Yamin

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Contents

Chapter 1
Shallow Foundations on Homogeneous Soil

Abstract This chapter deals with single shallow foundations resting on homogeneous soil. Calculations of various loads (vertical, horizontal, and bending moment) a foundation can withstand are explained in details in this chapter. The calculations were performed to satisfy both bearing capacity and elastic settlement requirements. For the bearing capacity condition, the effects of many factors were considered in the analyses such as various loading conditions, foundation shapes, foundation embedment, soil compressibility, and groundwater table. Then again, the effects of several factors were considered in the elastic settlement analyses such as foundation rigidity, foundation embedment, and variation in the elastic modulus of soil with depth. Additionally, a step-by-step procedure is introduced in this chapter to develop bearing capacity and elastic settlement design charts which can be useful in the design process of shallow foundations. A number of design problems are also presented in this chapter and their solutions are explained in details. These problems were first hand-solved, and then, resolved using the Shallow-1 application of the foundationPro program. Finally, a set of design projects is suggested at the end of this chapter to allow the reader practice the concepts learned.

Keywords Shallow foundation • Bearing capacity • Elastic settlement • Shallow-1 • foundationPro

1.1 Introduction

This chapter deals with single shallow foundations on homogeneous soil. Calculations of various loads a foundation can sustain are explained in details in this chapter. Allowable and ultimate loads (vertical, horizontal, and bending moment) on a single foundation are estimated based on bearing capacity and elastic settlement requirements.

In the bearing capacity analyses, the classical bearing capacity equations for a single foundation were utilized. Various loading conditions (vertical, horizontal, and bending moments) and foundation shapes (circular, rectangular, and continuous/strip) were included in the analyses. Effect of soil compressibility on bearing capacity was also included in the analyses. Effects of the depths of foundation embedment and groundwater table were considered in the bearing capacity equation.

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In the elastic settlement analyses, the modified settlement equation by Mayne and Poulos (1999) was utilized. This improved equation deals with circular and rectangular foundations. It considers the foundation rigidity which depends on the foundation dimensions, thickness, and elastic modulus. Also, this equation takes into account the depth of foundation embedment. Additionally, this improved elastic settlement equation considers not only a unique value for the elastic modulus of the soil underneath the foundation, but also the linearly increasing elastic modulus with depth.

A step-by-step procedure was introduced in this chapter to develop bearing capacity and elastic settlement design charts. These design charts present the relationship between various applied loads on the foundation and foundation dimensions for different shapes, depths, and allowable settlement. These charts can be useful in the foundation design process to find what will control the final design, the bearing capacity, or the elastic settlement of the foundation.

Fourteen design problems are presented in this chapter. First, these design problems were hand-solved and solution was explained in details, and then the foundationPro program was used to resolve the problems to replicate and verify the hand solution. Also, the program was used to investigate a wider and detailed solution and design alternatives for the hand-solved problems. Since the foundationPro includes a set of several applications, the Shallow-1 application of the foundationPro is the responsible application to perform bearing capacity and elastic settlement calculations for shallow foundations resting on homogeneous soil. Therefore, only Shallow-1 application will be used throughout this chapter to replicate the hand-solved problems. Five design projects are suggested at the end of this chapter to allow the reader to practice and apply the learned concepts.

1.2 Theory

This section explains how to estimate the allowable and ultimate loads that can be applied to a single shallow foundation resting on homogeneous soil. The foundation loads are estimated to meet both bearing capacity and elastic settlement requirements. All bearing capacity and elastic settlement equations are listed and all variables used in the equations are defined in the following subsections. These subsections are not meant to explain the bearing capacity and elastic settlement theories, rather to summarize the final equations from each theory which will be used in the analyses.

To determine the bearing capacity and the elastic settlement of a shallow foundation resting on homogeneous soil as shown in Fig. 1.1, soil properties (c' = cohesion, ϕ' = friction angle, μ_s = Poisson's ratio, E_s = elastic modulus of foundation soil, γ_1 and γ_2 = unit weight of the soil above and below the groundwater table, respectively) are required to perform the analysis. Depth of foundation (D_f) and depth of groundwater table (D_w) if exists are also required for the calculations. Three different foundation shapes are considered: circular (Fig. 1.2a), square/rectangular (Fig. 1.2b), and strip/continuous (Fig. 1.2c).

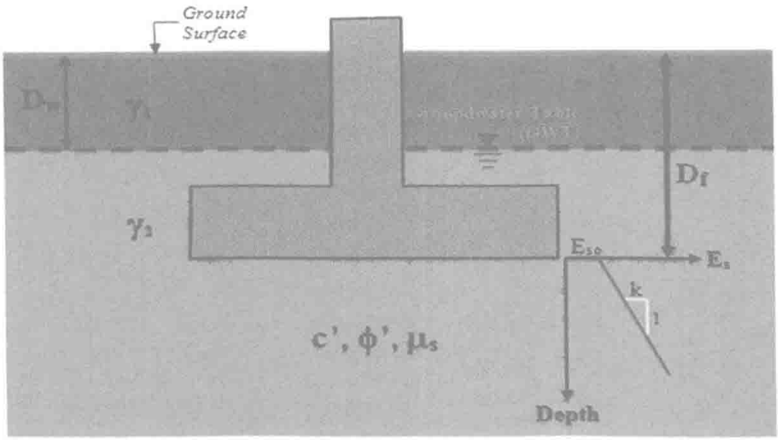

Fig. 1.1 Definition of various parameters for a shallow foundation on homogeneous soil

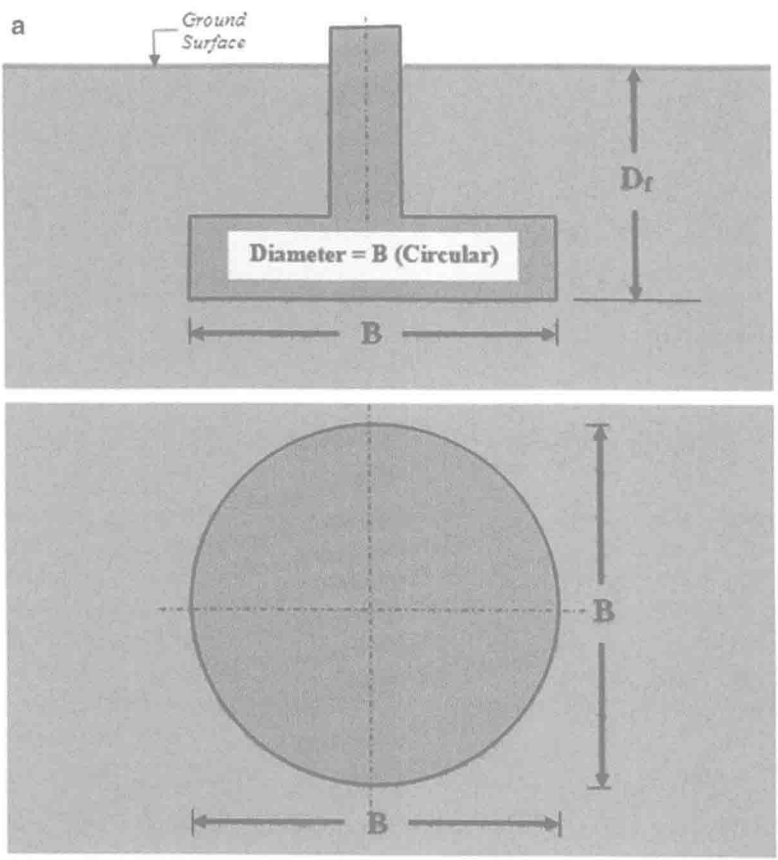

Fig. 1.2 Different foundation shapes: (**a**) Circular foundation; (**b**) square/rectangular foundation; (**c**) strip/continuous foundation

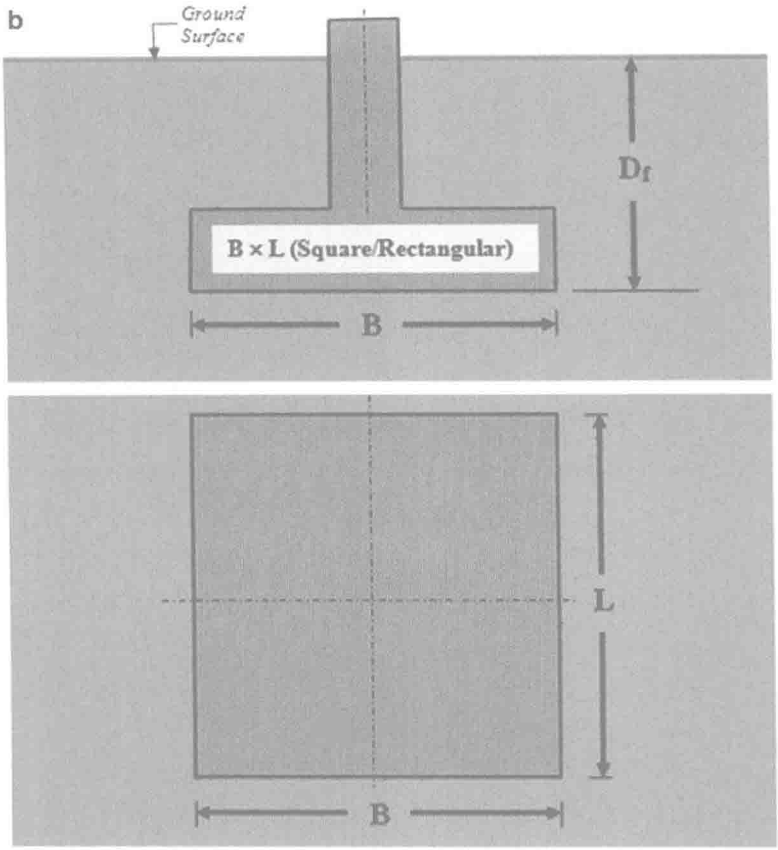

Fig. 1.2 (continued)

1.2.1 Bearing Capacity of Shallow Foundation

To estimate the allowable and ultimate loads (vertical, horizontal, and bending moment) a foundation can carry according to the bearing capacity of foundation; first, one should determine the ultimate bearing capacity of the foundation. Terzaghi (1943) was the first to present an equation for bearing capacity for different foundations with some limitations. To account for these limitations, Meyerhof (1963) suggested the following equation to estimate the ultimate bearing capacity of a single shallow foundation resting on homogeneous soil:

$$q_{\mathrm{u}} = c' N_c F_{\mathrm{cd}} F_{\mathrm{ci}} F_{\mathrm{cc}} F_{\mathrm{cs}} + q N_q F_{q\mathrm{s}} F_{q\mathrm{i}} F_{q\mathrm{c}} F_{q\mathrm{d}} + \frac{1}{2} \gamma B N_\gamma F_{\gamma\mathrm{s}} F_{\gamma\mathrm{d}} F_{\gamma\mathrm{i}} F_{\gamma\mathrm{c}} \tag{1.1}$$

In the above equation, c' represents soil cohesion, q is the effective stress at the base of the foundation, γ is the unit weight of the foundation soil, and B is the width of

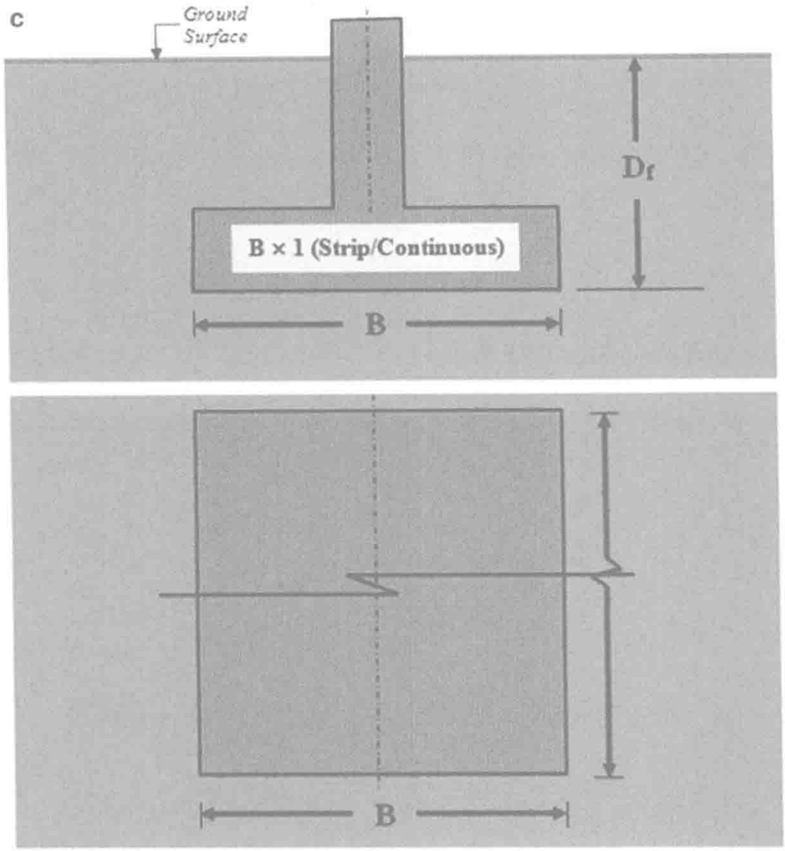

Fig. 1.2 (continued)

foundation or diameter in case of circular foundation. $F_{cs}, F_{qs}, F_{\gamma s}$ are the shape factors, $F_{cd}, F_{qd}, F_{\gamma d}$ are the depth factors, $F_{ci}, F_{qi}, F_{\gamma i}$ are the load inclination factors, N_c, N_q, N_γ are the bearing capacity factors, and F_{cc}, F_{qc}, $F_{\gamma c}$ are the soil compressibility factors.

To determine the various factors defined earlier in the bearing capacity equation, one should use the following equations which were suggested by several researchers and investigators:

1.2.1.1 Bearing Capacity Factors

Reissner (1924) derived the following equation to calculate N_q:

$$N_q = \tan^2\left(45 + \frac{\phi'}{2}\right) e^{\pi \tan(\phi')} \tag{1.2}$$

where ϕ' is the soil friction angle.

Also, Prandtl (1921) derived the following equation to determine N_c:

$$N_c = (N_q - 1)\cot\left(\phi'\right) \tag{1.3}$$

The following equation was put forth by Caquot et al. (1953) and Vesic (1973) to estimate N_γ:

$$N_\gamma = 2(N_q + 1)\tan\left(\phi'\right) \tag{1.4}$$

1.2.1.2 Effect of Foundation Depth

To account for the depth of foundation, Hansen (1970) suggested the following depth factors to be used in the ultimate bearing capacity equation:

– For a soil with $\phi' = 0$:

$$F_{cd} = 1 + 0.4\eta \tag{1.5}$$

$$F_{qd} = 1$$

$$F_{\gamma d} = 1$$

– For a soil with $\phi' > 0$, the depth factors can be calculated as follows:

$$F_{qd} = 1 + 2\tan\phi'\left(1 - \sin\left(\phi'\right)\right)^2\eta \tag{1.6}$$

$$F_{cd} = F_{qd} - \frac{1 - F_{qd}}{N_c\tan\left(\phi'\right)} \tag{1.7}$$

$$F_{\gamma d} = 1$$

where

$$\eta = \frac{D_f}{B} \tag{1.8}$$

The ratio $\eta \leq 1$ applies for most shallow foundation cases. However, η in Eqs. (1.5) and (1.6) is replaced with η' when $\eta > 1$. η' should be in radians and can be calculated as

$$\eta' = \tan^{-1}\left(\frac{D_f}{B}\right) \tag{1.9}$$

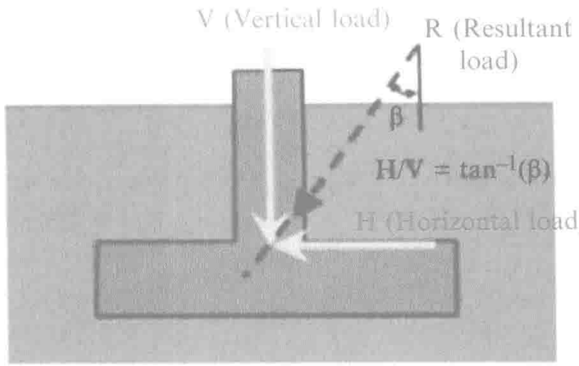

Fig. 1.3 Vertical and horizontal loads on foundation

1.2.1.3 Effect of Load Inclination

When a vertical load (V) and horizontal load (H) are applied to a foundation as shown in Fig. 1.3, the net resultant load (R) on the foundation will be inclined an angle β with the vertical. To account for this load inclination in the bearing capacity equation, Meyerhof (1963) and Hanna and Meyerhof (1981) suggested the following load inclination factors:

$$F_{ci} = F_{qi} = \left(1 - \frac{\beta^{\circ}}{90^{\circ}}\right)^2 \tag{1.10}$$

$$F_{\gamma i} = \left(1 - \frac{\beta}{\phi'}\right)^2 \tag{1.11}$$

where β is the inclination of the resultant applied load on the foundation with respect to the vertical:

$$\beta = \tan^{-1}\left(\frac{H}{V}\right) \tag{1.12}$$

1.2.1.4 Effect of Soil Compressibility

To account for the effect of the soil compressibility on the bearing capacity of shallow foundations, the derived procedure by Vesic (1973) based on the expansion of cavities in infinite soil can be followed. Hence, the soil compressibility factors F_{cc}, F_{qc}, and $F_{\gamma c}$ are estimated as follows:

$$F_{\gamma c} = F_{qc} = \exp\left\{\left(-4.4 + 0.6\frac{B}{L}\right)\tan\left(\phi'\right) + \left[\frac{(3.07\sin(\phi'))\ (\log 2I_r)}{1 + \sin(\phi')}\right]\right\} \tag{1.13}$$