FOUNDATION ANALYSIS AND DESIGN

Third Edition

Joseph E. Bowles

COMPUTER PROGRAM DISCLAIMER

Neither the publisher or the author warrants the included programs to execute other than the displayed output if the programs and data are correctly entered into a computer. Any use of the programs to solve problems other than those displayed is the sole responsibility of the user as to whether the output is correct or is correctly interpreted.

This book was set in Times Roman by Santype-Byrd.
The editors were Julienne V. Brown and Susan Hazlett;
the production supervisor was Leroy A. Young.
New drawings were done by J & R Services, Inc.
The cover was designed by Charles A. Carson;
the cover photograph was taken by Robert Capece.
R. R. Donnelley & Sons Company was printer and binder.

FOUNDATION ANALYSIS AND DESIGN

234567890 DODO 898765432

ISBN 0-07-006770-8

Library of Congress Cataloging in Publication Data

Bowles, Joseph E.
Foundation analysis and design.

Bibliography: p.
Includes indexes.
1. Foundations. 2. Soil mechanics. I. Title.
TA775.B63 1982 624.1'5 81-13649
ISBN 0-07-006770-8 AACR2

PREFACE

This edition is the latest in the continuing process of producing an up-to-date compendium of methods and procedures for the analysis and design of foundations. As in the earlier editions the primary focus is on interfacing structural elements with the underlying soil. This is where the major focus of foundation engineering lies in both the author's opinion and that of many others. Engineering of dams, fills, and embankments, and flow of water in soil masses may more properly fall under the general category of geotechnical engineering. In some cases the latter considerations may be major factors in designing or constructing a foundation; therefore, some background material on several of these topics has been included.

Most engineers now recognize that it is not possible or very practical to identify foundation engineering as soil mechanics/properties with structural engineers designing the foundation elements. A foundation engineer must be versed in both the geotechnical aspects of soils as well as the structural behavior produced by the often complex foundation-soil interaction. The latter statement reflects the general design philosophy contained in this text.

I have undertaken a fairly extensive revision; however, none of the chapter titles have been changed and in most cases the section headings have been retained. Chapters 2, 8, 9, and 16 have been almost totally rewritten, with very substantial rewriting undertaken in Chaps. 3, 4, 10, and 11. This was done to produce a more logical sequencing of topics and to include new methodology which was in transition when the second edition was being rewritten. The material is about 80 percent SI to reflect both the general trend in textbooks and the anticipated status of SI for most of the useful life of the book.

In many cases there is no "unique" design equation/methodology and one or more of several alternatives tends to be preferred by certain engineers or in geographical areas. I have attempted to present those alternatives where they seem to be widely enough used to warrant the text space. Where it was practical, examples are analyzed using one or more of the alternatives so the reader obtains both familarity and an opinion about the procedure. In several examples a "feel" of a probable answer is produced by use of the alternatives—a common engineering office practice where the input data are uncertain—either as a direct computation or as an average from the several alternatives. I have attempted to include realistic example (and home) problems for the reader, with the examples being somewhat less edited. About 50 percent of the home problems are new, and more answers are included than in the earlier editions.

Several methods such as the footing on slope, grid analysis of mats, and the sheet and lateral pile solutions using the finite-element method have been compared via examples with the solutions of others or with alternative methods. This has been done to illustrate that these new methods are adequate. In passing it should be noted that the finite-element solution contained herein for beams, sheet piles, and lateral piles is extremely widely used. It is the author's opinion that the simplest solution which produces a satisfactory and economical design is preferred. Solutions which require esoteric mathematics to produce miniscule computational refinement in a mathematical model based on soil data which are uncertain at best are not very practical. Many solutions of this type do not get further than the pages of a technical journal and others soon disappear from engineering practice after a short time.

I have included about 560 references so that almost every topic can be researched in depth. I have tried to avoid using obscure references which could be obtained only with great difficulty by the average user. Most worthwhile material eventually gets published in some form by ASCE, ASTM, TRB, CGJ, at a specialty conference, or in the proceedings of the ICSMFE, which are not very difficult to access. I have retained the use of the list of publication abbreviations (above included) at the beginning of the bibliography to reduce its size. It is hoped that no significant work has been omitted; however, in the interest of space, not all the work on a given topic is cited. Generally the most recent or those works with the best bibliography coverage were included. I hope also that I have not offended the junior authors of coauthored references by the use of "et al." when there are more than two authors.

I wish to express appreciation to the many users both in the United States and abroad who have written or called with comments or constructive criticism or simply to make inquiry about a procedure. I should also like to thank those who took part in the McGraw-Hill user survey to provide input for this revision and include: Jack Bakos of Youngstown State University; William Baron of Clemson University; William Gotolski of Pennsylvania State University; and Roy V. Snedden of the University of Nebraska. I would also like to thank the final manuscript reviewer William Baron of Clemson University.

Finally I should like to acknowledge the considerable contribution of my wife Faye, who helped as usual with the typing and the myriad other operations to produce the manuscript.

Joseph E. Bowles

CONTENTS

Appendixes

CHAPTER
ONE

INTRODUCTION

1-1 FOUNDATIONS—DEFINITION AND PURPOSE

All structures designed to be supported by the earth, including buildings, bridges, earth fills, and earth, earth and rock, and concrete dams, consist of two parts. These are the superstructure, or upper part, and the substructure element which interfaces the superstructure and supporting ground. In the case of earth fills and dams, there is often not a clear line of demarcation between the superstructure and substructure. The *foundation* can be defined as the substructure and that adjacent zone of soil and/or rock which will be affected by both the substructure element and its loads.

The foundation engineer is that person who by reason of experience and training can produce solutions for design problems involving this part of the engineered system. In this context, *foundation engineering* can be defined as the science and art of applying the principles of soil and structural mechanics together with engineering judgment (the "art") to solve the interfacing problem. The foundation engineer is concerned directly with the structural members which affect the transfer of load from the superstructure to the soil such that the resulting soil stability and estimated deformations are tolerable. Since the design geometry and location of the substructure element often have an effect on how the soil responds, the foundation engineer must be reasonably versed in structural design.

A number of practical considerations are a part of the engineering of a foundation:

1. Visual integration of geologic evidence at a site with any field or laboratory test data.

2. Establishing of an adequate field exploration and laboratory testing program.
3. Design of the substructure elements so that they can be built—and as economically as possible.
4. Appreciation of practical construction methods and of likely-to-be-obtained construction tolerances. Stipulation of very close tolerances can have an enormous effect on the foundation costs.

These several items are not directly quantifiable and thus require a considerable application of common sense.

A thorough understanding of the principles of soil mechanics in terms of stability, deformations, and water flow is a necessary ingredient to the successful practice of foundation engineering. Of nearly equal importance is an understanding of the geological processes involved in the formation of soil masses. It is now recognized that both soil stability and deformation are dependent on the stress history of the mass. It has been common until recently to associate foundation engineering solely with soil mechanics concerns, leaving the interfacing elements to the structural (or other) designer. Current trends are to recognize that foundation engineering is a systems problem and cannot be nicely compartmentalized as some persons would prefer. Readers may determine the validity of this statement as they progress through the text.

The science of soil mechanics and its relationship to geological processes has progressed considerably over the past fifty years. However, because of the natural variability of soil and the resulting problems associated with testing, which will be elaborated upon in Chap. 3, the design of a foundation still depends to a large degree upon "art," or the application of engineering judgment. A subset of this application is the assessment of the tolerable risk associated with the foundation.

The primary focus of this text will be on analysis and design of the interfacing elements for buildings and retaining structures and those soil mechanics principles particularly applicable to these elements. These interfacing elements include both near surface members such as footings and mats and deep elements such as piles and caissons. Retaining structures of concrete (commonly termed retaining walls) and metal (as sheetpiling) are considered in later chapters. Soil mechanics principles include both stability, including soil water effects, and deformation analyses. Soil stability can often be enhanced by various improvement techniques, the most common being compaction, and several of the more popular of these methods will be briefly considered in Chap. 6.

1-2 FOUNDATION CLASSIFICATIONS

Foundations for structures such as buildings, from the smallest residential to the tallest high-rise, and bridges are for the purpose of transmitting the superstructure loads. These loads come from column-type members with stress intensities ranging from perhaps 140 mPa for steel to 10 mPa for concrete to the supporting capacity of the soil, which is seldom over 500 kPa but more often on the order of 200 to 250 kPa. The reader can readily note that this interface connects materials whose differences in useful engineering strength can vary by a factor of several hundred. The transmission of these large superstructure loads to the soil may be by use of:

1. Shallow foundations—termed footings, spread footings, or mats. Foundation depth is generally $D \leq B$ (see Chap. 4).
2. Deep foundations—piles or caissons with $D > 4$ to $5B$ (see Chaps. 16 to 19).

Any structure used to retain a soil or similar mass such as grain, coal, or ore in a geometric shape other than that occurring naturally under the influence of gravity is a *retaining* structure. Any foundation not classed as shallow, deep, or a retaining structure may be termed a *special* foundation.

Typical foundation types are:

1. Foundations for buildings (either shallow or deep)
2. Foundations for smokestacks, radio and television towers, bridge piers, industrial equipment, etc. (either shallow or deep)
3. Foundations for port or marine structures (may be shallow or deep and with retaining structures extensively used)
4. Foundations for rotating, reciprocating, and impact machinery, and for turbines, generators, etc. (either shallow or deep and may require vibration control)
5. Foundation elements to support excavations or retain earth masses as for bridge abutments and piers, or retain grain, ore, coal, etc. (retaining walls or sheet-pile structures)

Foundations for buildings are extremely numerous; foundations for the several other types of superstructures are constructed in somewhat lesser numbers.

1-3 FOUNDATION SITE AND SYSTEM ECONOMICS

A building foundation must be adequate if the structure is to perform satisfactorily and be safe for occupancy. Other foundations must be adequate to perform their intended functions in a satisfactory and safe manner; however, buildings usually have more stringent criteria for safety and performance than other structures—notable exceptions being nuclear-plant facilities, turbines for power generation, and certain types of radio-antenna equipment. Foundations for nuclear plants require extremely rigid design/performance criteria for safety reasons. The other foundations support extremely expensive machinery which is often very sensitive to small soil deformations.

More recently, and after loss of life from several avoidable failures, dam designs where soil is the principal construction material are being more carefully made. One might note that more principles of soil mechanics and geology apply to earth dams than to the majority of foundation engineering problems. In addition to the stringent criteria of the superstructure, instability and water flow through the base soil are serious considerations. A further area of concern is the inevitable deformation of the base soil and subsidence in the superstructure (dam fill material). Careful attention to the occurrence of the latter deformations can allow the designer to avoid a base crack in the dam and the resulting piping failure, or a crest crack and the associated overtopping failure.

Almost any reasonable structure can be built and safely supported if there is unlimited financing. Unfortunately, in the real situation this is seldom, if ever, the case, and the foundation engineer has the dilemma of making a decision under much less than the ideal condition. Also, even though the mistake may be buried, the results from the error are not and can show up relatively soon—and probably before any statute of limitations expires. There are reported cases where the foundation defects (such as cracked walls or broken mechanical fixtures) have shown up years later—also cases where the defects have shown up either during construction of the superstructure or immediately thereafter.

Since the substructure is buried, or is beneath the superstructure, in such a configuration that access will be difficult should foundation inadequacies develop after the superstructure is in place, it is common practice to be conservative. A one or two percent overdesign in these areas produces a larger potential investment return than in the superstructure.

The designer is always faced with the question of what constitutes a safe, economical design while simultaneously contending with the inevitable natural soil heterogeneity at a site. Nowadays that problem may be compounded by land scarcity requiring reclamation of areas which have been used as sanitary landfills, garbage dumps, or even hazardous waste disposal areas. Still another complicating factor is that the act of construction can alter the soil properties considerably from those used in the initial analyses/design of the foundation. These factors result in foundation design becoming so subjective and difficult to quantify that two design firms might come up with completely different designs that would perform equally satisfactory. Cost would likely be the distinguishing feature for the preferred design.

This problem and the widely differing solutions would depend, for example, on the following:

1. What constitutes satisfactory and tolerable settlement; how much extra could, or should, be spent to reduce estimated settlements from say 30 to 15 mm ?
2. Has the client been willing to authorize an adequate soil exploration program ? What kind of soil variability did the soil borings indicate ? Would additional borings actually improve the foundation recommendations ?
3. Can the building be supported by the soil using
    - *a.* Spread footings—least cost.
    - *b.* Mats—intermediate in cost.
    - *c.* Piles or caissons—several times the cost of spread footings.
4. What are the consequences of a foundation failure in terms of public safety ?

What is the likelihood of a lawsuit if the foundation does not perform adequately ?

5. Is sufficient money available for the foundation ? It is not unheard of that the foundation alone would cost so much the project is not economically feasible. It may be necessary to abandon the site in favor of one where foundation costs are affordable.
6. What is the ability of the local construction force ? It is hardly sensible to design an elaborate foundation if no one can build it, or if it is so different in design that the contractor includes a large "uncertainty" factor in the bid.
7. What is the engineering ability of the foundation engineer ? While this factor is listed last, this is not of least importance in economical design. Obviously engineers have different levels of capability just as in other professions (lawyers, doctors, professors, etc.) and in the trades such as carpenters, electricians, and painters.

If the foundation fails because of any cost shaving (in reality implicitly accepting a higher risk), the client tends to quickly lose appreciation for the temporary financial benefit which accrued. At this point, facing heavy damages and/or a lawsuit, the client is probably in the poorest mental state of all the involved parties. Thus, one should always bear in mind that absolute dollar economics may not produce good foundation engineering.

The foundation engineer must look at the entire system: the building purpose, probable service-life loading, type of framing, soil profile, construction methods, and construction costs to arrive at a design that is consistent with the client/owner's needs and does not excessively degrade the environment. This must be done with a safety factor which produces a tolerable risk level to both the public and the owner.

Considering these several areas of uncertainty, it follows that risk and liability insurance for persons engaged in foundation engineering is very costly. In attempts to reduce these costs as well as produce a design which could be obtained from several engineering firms (i.e., a "consensus" design) there is active discussion (and the practice has already been undertaken in several areas) of having the foundation engineer submit the proposed design to a board of qualified engineers for a "peer review."

1-4 GENERAL REQUIREMENTS OF FOUNDATIONS

A foundation must be capable of satisfying several stability and deformation requirements such as:

1. Depth must be adequate to avoid lateral expulsion of material from beneath the foundation—particularly for footings and mats.
2. Depth must be below the zone of seasonal volume changes caused by freezing, thawing, and plant growth.