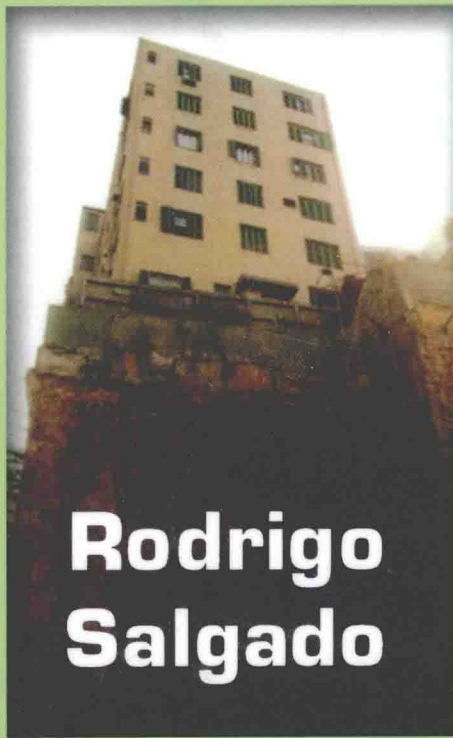
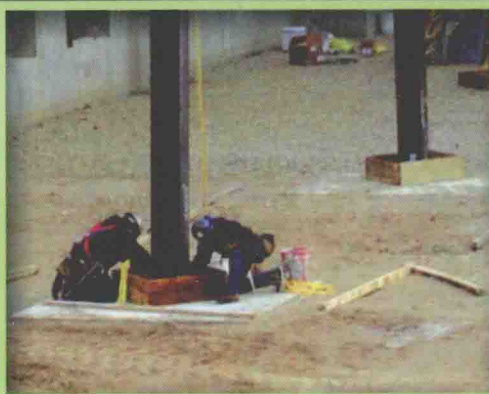
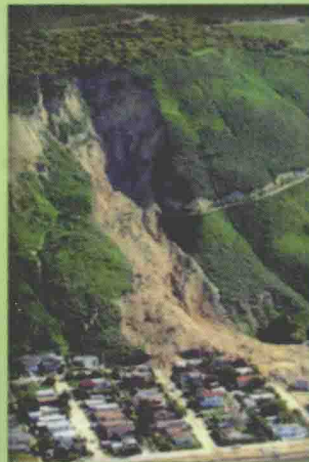


# The Engineering of Foundations



**Rodrigo  
Salgado**



# **The Engineering of Foundations**

**Rodrigo Salgado**  
*Purdue University*

Boston Burr Ridge, IL Dubuque, IA Madison, WI New York San Francisco St. Louis  
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## THE ENGINEERING OF FOUNDATIONS

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**To Mônica, for the unwavering support and encouragement.**

R.S.

# PREFACE

---

*I keep six honest serving-men  
(They taught me all I knew)  
Their names are What and Why and When  
And How and Where and Who.*

**Rudyard Kipling**

**F**oundation engineering is the fascinating subject that deals with the safe and economical transfer to the ground of loads from structures of various types (such as buildings, bridges, and industrial facilities), functions, and sizes. Foundation engineers draw on their knowledge of mechanics, of how to measure or estimate various soil and rock properties, of how structures respond to foundation movements, and of basic economic concepts to determine the best, most economical foundations for these structures. Because of the need for knowledge from so many different fields, and because of the natural complexity of soils and rocks, many years of study and practice are required to master foundation engineering. This makes the writing of a foundation engineering text for senior undergraduate and first-year graduate students a challenging task.

Albert Einstein once suggested that things should be made simple, but no simpler. This certainly applies to foundation engineering and to a text on the subject. Due to the large scope of the subject, simplicity is desired so that all of the information, analyses, and techniques can be understood. The essence of knowledge, however, is to have it so that we can apply it. Oversimplification leads to spotty knowledge, which is hard to put to use in realistic practical problems. In this text, I attempt to present the subject of foundation engineering in a logical framework, in a natural sequence, and in as simple a presentation as possible. I emphasize conceptual understanding and avoid an oversimplistic treatment of soil. An example of this philosophy is how I treated one of the keys to the successful practice of foundation engineering: the estimation of soil parameters for use in calculations. In practice, these parameters are not given to us so that all we have to do is to plug them into an equation or two and arrive at an answer. Much of the work in foundation design resides in determining or estimating these parameters, and I have devoted significant attention to this.

## **STRUCTURE OF THE TEXT AND ANCILLARY MATERIAL**

The book is organized into four parts and seventeen chapters. I have found in my teaching that having the subject divided in well-targeted chapters facilitates learning of the material. The first part is introductory. In it, I discuss foundation engineering

and foundation design in the context of civil engineering and civil engineering projects and discuss the different approaches to foundation design and the interaction of foundations and the structures they support. In the second part, I review the basics of soil and rock mechanics and how to determine soil and rock properties. The third part focuses on foundations in soil and rock. Foundation engineers must also contend with both temporary and permanent soil slopes and with excavations and retaining structures. These are addressed in the fourth and last part.

I have covered the construction of shallow foundations and the installation of deep foundations in more detail than is usually found in foundation engineering texts. It is important for engineers to understand what can and cannot be constructed in the field. It is also important, notably for deep foundations, to recognize the strong link between foundation response and installation techniques. On the analysis side, a derivation or at least an indication of how it is obtained accompanies each equation. Additionally, load and resistance factor design (LRFD) is an integral part of the book, as it is being increasingly adopted in the codes prepared by different organizations or promoted by their efforts (notably, in the United States, by the efforts of FHWA and AASHTO).

Three types of problems are proposed at the end of most chapters: conceptual, quantitative, and design. Conceptual problems are intended to test one's understanding of the topics. Quantitative problems are intended as relatively straightforward application of analyses and equations. Design problems simulate the types of decisions and calculations done in real problems, emphasizing how to start from information typically available in practice to arrive at intermediate or final results that are needed in design. Many of the examples and problems have been designed in a way that requires the solution to start at the same point as problems found in practice start, with the information typically collected from borings, penetration tests, and so on, from which stiffness or strength parameters of the soil or rock must be estimated.

The list of references is separated into cited references, references that are not cited but whose reading may benefit those with a deeper interest in a certain topic, and ASTM standards and procedures that are pertinent to each chapter.

The text web site contains a gallery with my photos and those of others who have agreed to let me post them. The gallery is organized according to the book chapters for easy consultation. The web site also contains other resources, including some programs and spreadsheets.

## **USE OF TEXT IN UNDERGRADUATE AND GRADUATE COURSES**

Readers and instructors often find useful to know how the author of a text would use it in his own teaching. Typically, students taking a course in foundation engineering have already studied soil mechanics, and, in a few cases, rock mechanics and engineering geology as well. Therefore, chapters 2–6 are useful in the review of previously seen material in the foundation engineering courses. They contain some key concepts for the estimation of design values of soil shear strength and stiffness; thus, I refer to specific material in these chapters throughout the semester. Some of the material in chapters 2–6 is advanced. For example, strain analysis,

the Mohr circle of strains, and slip surfaces are treated in some detail. These are rarely covered in basic soil mechanics courses in the United States, and can be skipped without loss of continuity. However, I have found that the more curious undergraduate students benefit from having access to this material, and, in my opinion, graduate students should be exposed to it to have a deeper understanding of soil mechanics. I also use Chapters 2–6 in the soil mechanics courses I teach at Purdue University. Throughout the book, sections containing more challenging material are identified with an asterisk (\*) so that both readers and instructors know they can skip them if more basic coverage of the subject is desired.

In my undergraduate foundation engineering course, I cover the following topics, in order:

1. Foundation engineering (Chapters 1 and 2)
2. Site exploration (Chapter 7)
3. Shallow foundations (Chapters 2, 8, 9, 10, and 11)
4. Deep foundations (Chapters 12–13)
5. Retaining structures (Chapter 16)
6. Slopes (Chapter 17)

In my graduate foundation engineering course, I cover the following topics (without skipping sections):

1. Foundation engineering (Chapter 1)
2. Foundation design (Chapter 2)
3. Site exploration (Chapter 7)
4. Shallow foundations (Chapters 8–11)
5. Deep foundations (Chapters 12–15)

It would be presumptuous of me to suggest a specific order. Each instructor feels comfortable with a different sequence that reflects the instructor's view of the subject and the specific needs of the students. The book was written to be flexible and to accommodate such needs.

## ACKNOWLEDGMENTS

I was sitting in my office at Purdue University one day, when a nice gentleman knocked on my door and introduced himself as Thomas Casson of McGraw-Hill. I invited him to sit down, and, as soon as he did, he asked me whether I would like to write a book on foundation engineering for McGraw-Hill. This is how this book started. Tom's visit was timely, for after considering this for a while, I found that I was ready to write it. I felt that the progress of the underlying science and up-to-date design methods were not yet found in foundation engineering texts, and thus that there was a space that needed filling. I thank Tom for providing the spark and Suzanne Jeans and Bill Stenquist of McGraw-Hill for keeping it alive afterwards. Bill Stenquist believed in the project and in how I wanted to shape the book. I thank him for the support throughout the project. Jeff Lachina and Lori Kozey of Lachina Publishing Services made the book into a reality, and I appreciate the dedication and effort they put into it.



My interest in foundations and geotechnical engineering came about despite of myself, and those responsible deserve mention. As a young boy in Brazil, I spent more time on construction jobsites than on soccer fields (where, I have to admit, I many times wish I were). Both my grandfather, Paulo, and my father, Carlos, are civil engineers who owned their own civil engineering firms. As a result, there was plenty of opportunity for visits to construction sites that allowed a (very) early exposure to foundation engineering practice. I thank them, and my father in particular, for grounding me on the realities of construction before I ever saw any of the theory of design. My interest in reading and writing goes back to the devotion that my grandmother, Sueli, showed in instilling in me a love for books, for knowledge, and for language at an age of which I remember few things (one of which is getting pointed to this or that book and then discussing with her what I had liked or disliked in the various stories).

My good fortune continued in the work I did after graduation, which brought me in contact with things and with world-class people that continued to lift my interest in the subject. I have benefited from interactions with academic and professional colleagues in joint work, committee work, and other venues. In particular, James K. Mitchell and Michele Jamiolkowski were important examples of how effective the full integration of research, practice and education can be.

I am very grateful to Monica Prezzi and Dimitrios Loukidis. Their reviews of the manuscript were extremely helpful, and I appreciate the time and the dedication they devoted to this task. I thank Hoyoung Seo and Prasenjit Basu for helping me put together the solutions manual for the end-of-chapter problems. Sita Gentil helped with suggestions related to the cover design. Tanusree Chakraborty, Grace Abou-Jaoude, Umashankar Balunaini, and Dongwook Kim helped me with the preparation of some figures. Grace Abou-Jaoude and Umashankar Balunaini assisted with obtaining figure permissions. Tanusree Chakraborty, Umashankar Balunaini, and Dongwook Kim assisted with final proofreading. Antonio Carraro and Tejas Murthy assisted with some photos taken at Purdue University facilities. Antonio Carraro, Dimitrios Loukidis, and Monica Prezzi tested early versions of the manuscript in their courses at Colorado State University and Purdue University, and the feedback they provided was very complete and helpful. I tested the manuscript on the courses I teach at Purdue University, and received helpful comments and questions from graduate and undergraduate students, to whom I am thankful. In particular, I would like to mention Major Aaron Altwies of the United States Air Force and Ioannis Zevgolios, who provided me with comments on an early version of the manuscript, and Hoyoung Seo, Prasenjit Basu, and Umashankar Balunaini, who took the request for comments more seriously than I ever intended.

The formal reviews done by colleagues at universities throughout the world played an important role in the writing of this textbook. I would like to thank the following reviewers for their generosity in taking the time to provide thoughtful and helpful comments and suggestions:

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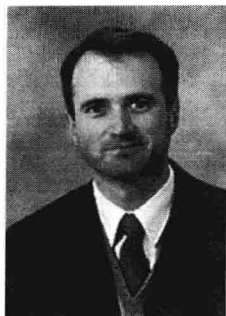
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Finally, we, as professionals and people, are the product of our interaction with family, friends, and colleagues throughout our lives. So there is a little bit of very many people in this book, and, even if I did not name them, the gratefulness is there.

Rodrigo Salgado  
 West Lafayette, IN

## ABOUT THE AUTHOR

---



**Rodrigo Salgado** entered the Federal University of Rio Grande do Sul, Brazil, first as a chemical engineering major, then transferred to civil engineering. He graduated in 1986. After several years working first as a student intern, then as an engineer with a geotechnical specialty contractor and with PETROBRÁS, the Brazilian oil company, he came to the United States for graduate school. He obtained an MS in 1990 and a PhD in 1993 at the University of California, Berkeley. Immediately upon graduation, he joined the faculty at Purdue University, where he is today a professor. He has been a visiting scholar at the Technical University of Turin, a visiting professor at the University of Newcastle, and a Gledden Senior Fellow at the University of Western Australia. Professor Salgado is the recipient of numerous awards, including the Shamsheer Prakash Research Award in 2005 for the solutions of problems in geotechnical engineering using advanced analysis methods, the ASCE Casagrande Award in 1999 for his contributions in the fields of foundation engineering and earthquake engineering, and the ASCE Walter L. Huber Civil Engineering Research Prize in 2004 for his research on foundation engineering. He was an invited participant at the National Academy of Engineering Frontiers of Engineering Symposium in 2005. His research has been sponsored by, among others, NSF, FHWA, INDOT, and INTEL. He has served on ACI, ASCE, and ABMS technical committees.

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# The World of Foundation Engineering

*Technology moves so rapidly that the challenges and problems of tomorrow are certain to be different than those of today, and it is probable that most of tomorrow's problems will come as surprises, since our ability to predict the future is very poor. I believe that the best way to adapt is to have a thorough mastery of first principles, as these never change and can always be applied to new problems.*

**James K. Mitchell**

The duties of professionals in any discipline are not restricted to the very specific, advanced type of work for which they receive training in colleges and universities. Every profession has its own language and its own set of rules, which the effective professional knows well. In this chapter, we will examine the current practices in the foundation engineering profession. We start by defining what is meant by foundation engineering. We then go on to discuss the education and licensing processes a foundation engineer must go through to practice the profession in its plenitude. We follow that with a brief discussion of the foundation engineering industry. The discussion is pursued in the context of the global economy, which to a considerable extent has become a reality. In the paradigm of the global economy, barriers to trade, including engineering services, will weaken considerably, forcing the engineer to deal with technical, cultural, legal, and language issues that could be ignored safely in the past. The chapter concludes with a discussion of units, which are needed in any engineering calculation.

## 1.1 The Foundation Engineering Industry

### Foundation Engineering and Foundation Engineering Problems

Engineering is the creative use of experience, empirical methods, and engineering science to solve engineering problems. Engineering involves the search for solutions to problems that require significant technical and scientific knowledge and that change the environment in some way or make new things possible. For example, a civil engineer may be interested in connecting one bank of a river to the other, while a chemical engineer may be interested in the manufacturing of a certain chemical in industrial scale.

An engineering problem is subjected to a number of constraints arising mainly because of economic and environmental reasons. More formally, an engineering problem may be defined in a general way as the need or wish to change something from a current state A to a new state B in the most economical fashion, under safe conditions, with minimum or no harm to the environment. Additional requirements arising out of legal and aesthetic issues also need to be fulfilled. Fortunately, there are also a number of tools available to the engineer that facilitate achieving an optimal design solution: engineering science, empirical rules, and experimental techniques.

Foundation engineers are called upon to determine the best way of transferring to the ground the loads from structures (such as buildings, warehouses, and bridges), machines, highway signs, and a variety of other sources. Therefore, we may define foundation engineering as the process of solving problems that involve the safe and economical transfer of structural loads to the ground. Foundations may take many different configurations, being in the most general terms classified as shallow (covered in Chapters 8–11) or deep (covered in Chapters 12–15). The most common types of shallow foundations are concrete footings, typically built of reinforced concrete in shallow excavations with plan areas most often in the 1–10 m<sup>2</sup> range. Piles are the most common type of deep foundations. These are slender structural elements made of wood, steel, or concrete that, in onshore applications, have diameters ranging from 0.1 m to in excess of 1 m and lengths ranging from a few to many tens of meters.<sup>1</sup> Foundation engineers are also called upon to safely and economically design and build retaining structures of all kinds. Construction dewatering and excavations are also often part of foundation works. Reinforced concrete design of foundations and retaining structures is often done by a structural engineer; in such cases, the best results are obtained when the structural and foundation engineers work in close cooperation. As opposed to the specific discipline of foundation engineering, the term “geotechnical engineering” has a more general meaning than the term “foundation engineering,” as the subject encompasses a broader spectrum of soil or rock problems, including geoenvironmental problems such as landfill design, waste containment, and groundwater cleanup.

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<sup>1</sup> In offshore applications, piles can have diameters of several meters and lengths in excess of 100 m.