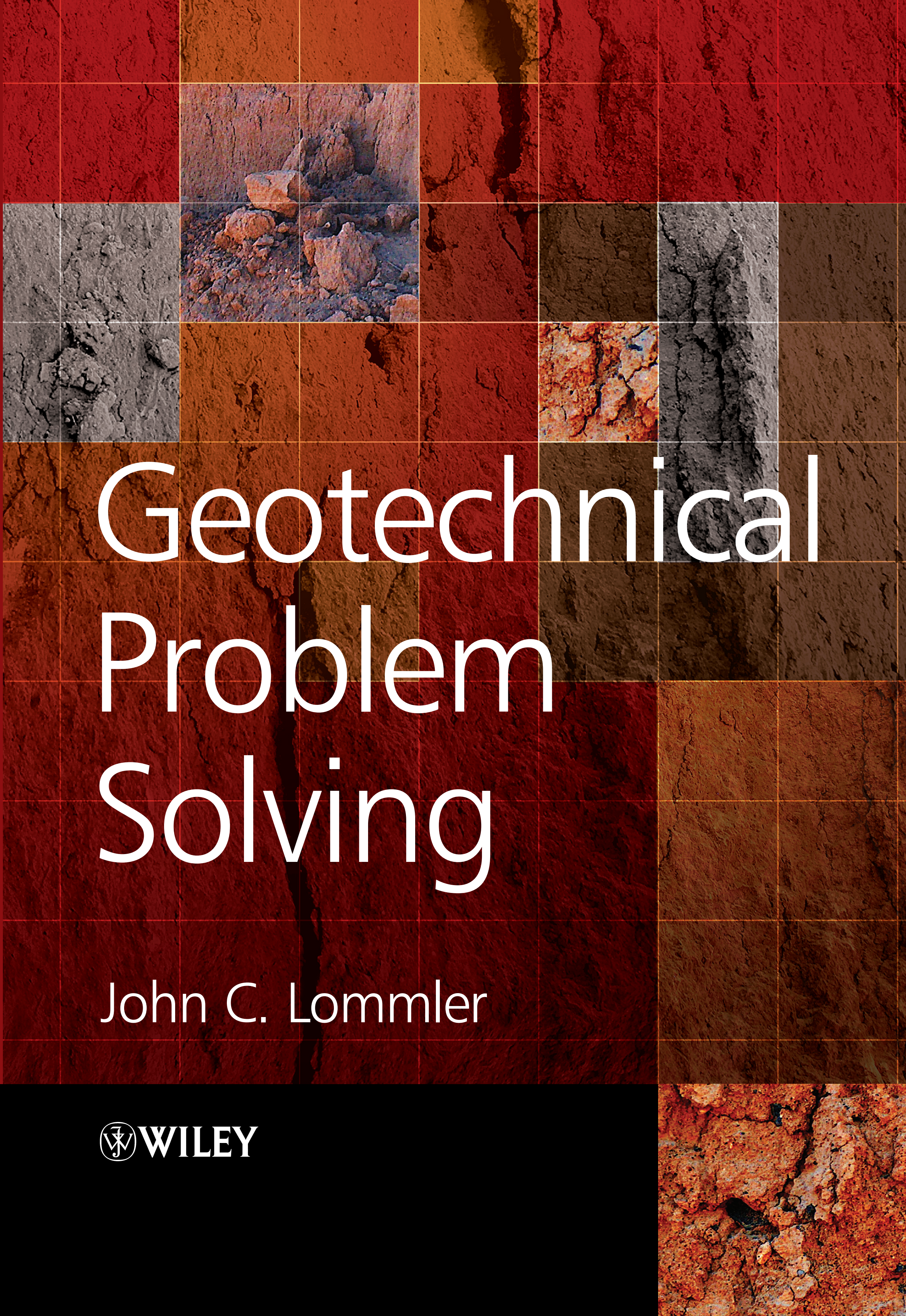

Geotechnical Problem Solving

John C. Lommler

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Principal Geotechnical Engineer, USA

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A John Wiley & Sons, Ltd., Publication

This edition first published 2012
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Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

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Library of Congress Cataloging-in-Publication Data

Lommler, John C.
Geotechnical problem solving / John C. Lommler.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-119-99297-4 (hardback)
1. Engineering geology. 2. Soil mechanics. 3. Soil-structure interaction. I. Title.
TA705.L64 2012
624.1′51–dc23
2011044002

A catalogue record for this book is available from the British Library.

Set in 10/12.5pt Palatino by Aptara Inc., New Delhi, India

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Preface

7 December 2007, 6:19 am

For several years, my friend Ralph Peck has been gently encouraging me to participate more actively in the geotechnical engineering community and to write a book. A few weeks ago he told me about starting to write his famous book, *Soil Mechanics in Engineering Practice*. The day he started to write was December 7, 1941, better known as "Pearl Harbor Day." Talk about hard times to write a book! Ralph told me it took seven years to write that first book and that it was impossible, or nearly impossible, to finish, but worth the effort.

I suggested to Ralph that at 61 years old, I am past my prime for writing, and that in 1948 at the age of 36, when "Terzaghi and Peck" was published, he was in his prime. Ralph pointed out that although he was 36, Terzaghi was 65 years old, and that the old gentleman wrote papers and books until the day he died at age 80.

Although Ralph is too much of a gentleman to say it directly, he does suggest by comparison to his generation, that my generation of geotechnical engineers took the money, kept information proprietary, and did not share our experience with the engineering community at large. I guess (alright I know) that Dr. Peck is right, and so this book is my first serious attempt at sharing with you the practicing engineer.

For his example, and his encouragement, we all owe a great debt of gratitude to Ralph B. Peck, thanks Ralph.

John C. Lommler, Ph.D., P.E.
Sandia Park, New Mexico

1

General Topics

1.1

How to Use this Book

I want you the reader to be a good, if not great, problem solver. Problem solving is what engineers do, and it represents your value to society. When a client or employer pays for an engineer's services, they are purchasing a solution to their problems. Often this process is called designing, investigating or analyzing, but in the end it all comes down to solving a problem or a series of problems.

Engineering problems involving geotechnical issues are difficult to solve, primarily because geotechnical parameters are difficult to measure, difficult to characterize and difficult to analyze. Some of the geotechnical difficulty comes from spatial variability in a large volume of soil on a building site. Some of the geotechnical problem is due to correlating field and/or laboratory measurements to the soil parameters required for analysis, and some of the problem is associated with limitations of analysis methods. I want to help you figure out how to solve geotechnical problems, and I want you to enjoy the problem-solving process.

I want to be your personal mentor, and if you have a mentor, I want to help them mentor you. If you are a student, I want you to start thinking about what is required to become a practicing engineer and to start now to develop the problem-solving tools you need.

Right from the start, I want you to accept the fact that you will never be able to include all of the physical processes involved in natural systems in your model of reality. You have to simplify real-world problems by use of models that have a few essential parameters, or, to use mathematical terminology, you need to limit the number of variables included in your models (equations). Later, in Section 1.2, I will discuss and explain the phenomenon of increasing complexity. Let's just say for now that you will need to know how to adjust the number of variables considered in your problem-solving efforts to fit the needs of your particular problem.

Speaking of adjustment of the number of variables considered in your engineering problems brings me to a rather thorny engineering management problem that

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frequently arises between problem-solving engineers and project managers. Before starting to work on the solution of an engineering problem, there needs to be agreement between the engineer and the manager on the level of detail and complexity to be included in the planned analyses. If the project manager thinks that the problem at hand is a simple issue, and you perform a highly complex analysis without informing the project manager, he or she will be unpleasantly surprised. There is going to be an issue over your charging excessive analysis hours to the project manager's budget. Fights over man-hour budgets for engineering analysis tasks versus the actual number of man-hours expended to solve the problem are quite common in consulting engineering practice these days. Matching the complexity of an engineering investigation and analysis to the requirements of the problem is called applying the "graded approach ." I will give you more information about the graded approach to problem solving in Section 1.3.4, and don't worry, we will include a discussion of how to handle surprises requiring more work than was initially anticipated.

Unlike most engineering/technical books that you have used, the presentation given here is conversational and personal from me to you. I want to give you practical advice on solving geotechnical problems and give you keys to the use of material that may not have been included in your college work. This "advanced" geotechnical material may be familiar to you, or it may be new; in either case, I want to help you understand the underlying assumptions and limitations of various geotechnical problem-solving techniques. You may not agree with my preferred choices of analytical methods. I would be surprised and a bit suspicious if you did agree with me on everything presented. It is alright to disagree, but we have to agree to base our disagreements on logic and interpretation of physical principles, not on arbitrary preferences. You may conclude that the available data and problem requirements need a more intensive analysis than I suggest is required. That's fine; if you need to do more detailed analysis work to feel comfortable with the solution, it's your choice. Just be ready to defend your man-hour charges with your boss, project manager, or client, or come in early or stay late and do the extra work on your own time. Having confidence in your solution to an engineering problem gives a sense of self-satisfaction. Remember that increasing your problem-solving skills increases your personal worth. Please do not think of extra work as giving "the company" something for nothing, consider it as money in your personal problem-solving account. It is your engineering career, not theirs.

During the early part of my career, I was a structural engineer. It was common in an earlier time for geotechnical engineer s to start their careers as structural engineers. My friend Ralph Peck was a famous geotechnical engineer who started as a structural engineer. He had a Ph.D. in structural engineering and no formal degrees in geotechnical engineering. I converted to geotechnical engineering during my graduate studies to help me understand how settlement-induced load redistributions in a structure could lead to structural failure. By the time my Masters degree studies were completed, I was hooked on geotechnical engineering. When I started working as a consulting geotechnical engineer, it quickly became quite clear to me that my structural engineering work had not been a waste. Knowledge of structural engineering helped me communicate with my structural clients because I knew what they needed from their geotechnical consultant. I have included material in this book to help geotechnical engineers understand what structural engineers need for their work, and I've tried to clarify geotechnical engineering topics to structural engineers so they can better communicate their project requirements to geotechnical engineers.

I have included what I consider to be important topics on selection and interpretation of soil laboratory tests, on analyses of shallow and deep foundations, retaining structures, slope stability, behavior of unsaturated soils including collapsible and expansive soils, and geotechnical Load and Resistance Factor Design(LRFD) topics, to name a few. I want you the reader to develop problem-solving tools for each of these geotechnical problems. We will start you with simpler standard practice approaches in each article, and work up to the advanced material. I'll give you examples of standard practice analysis methods including their assumptions and limitations. I don't want you to pick a standard practice approach for solving your problem if it doesn't fit the requirements of *your* problem! Advanced problem-solving methods are often required to deal with problems that have additional complexity. I do not believe that so-called advanced geotechnical material is only for Ph.Ds. I am convinced that if you graduated from college with a degree in engineering (or science and mathematics), you *can* use all of the material covered in this book.

In each section of this book, I will give suggested references and include a "Further Reading" section that provides materials for your study and consideration. At the end of each section, I will include a list of the references discussed in the section. I hope you will forgive me, but I do not like to repeat figures and equations from other books. Some equations and discussions are essential and I cannot avoid repeating them, but hopefully with added insights. Over the years I have grown weary of seeing the same material repeated and repeated over and over. I will refer you to the books where these materials are covered, and I hope you will take the opportunity to grow your geotechnical reference library.

It is my goal to help you understand the "how" and "why" of each topic, and to give you tools to use to solve problems that are not always included in text books, but are present in the real world. My advice is that you do not need a geotechnical engineering "cookbook." What you need is an understanding of geotechnical principles so that you can use them as tools to solve your engineering problems.

1.2

You Have to See it to *Solve* it

1.2.1 Introduction to Problem Solving

A question that I am asked by students and 60 year old engineers alike goes something like this, "Why is geotechnical engineering and engineering in general so difficult? When are the codes and requirements going to be simplified like they were in the good old days?" Give me a chance, and I'll answer these questions, but I need to build my case for the answer.

Did you ever notice that there is one person in the group that almost always disagrees with your opinion, conclusion, report, presentation, problem solution, etc? Sometimes they start by saying, "I'm just a Devil's Advocate here, but . . .." Personally, I don't want to give the Devil or his attorneys the credit for this phenomena, I believe that skepticism is a natural human trait that at least 10 to 15% of your students, clients, or associates will possess at any given moment. No matter how hard you try to convince these people that you have considered all of the important problem variables, they always seem to come up with new variables for consideration. How do they always manage to complicate your work?

I have come to believe (but cannot prove) that all problems in engineering have at least 10 to 15 variables that could be measured, analyzed, and used in their solution. The ideal or perfect solution to a given problem is a function that considers the impacts and interactions of all of these 10 to 15 variables. This hypothetical perfect solution considers all of the theoretical complexity involved. The engineering profession accepts two to three of these variables as the primary variables required in analysis and design. Analysis based on these two or three variables is referred to as standard practice, see Figure 1.2.1 below.

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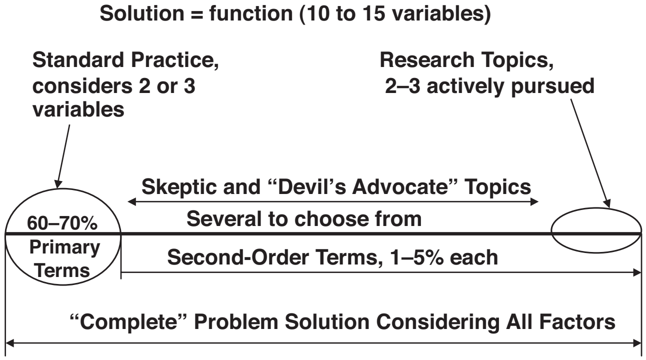

Figure 1.2.1 Engineering standard practice versus complete problem solution

After removing the primary two to three variables from the solution set, the remaining seven to 13 variables are not considered to be standard practice , and I will call them second-order term s. These second-order terms may not often have a great impact on any given problem, *but* sometimes they do have significance. When second-order terms are important to the solution of an experienced engineer's problem, and when he or she has a feel for the magnitude of the impact of these terms is referred to as "experience" or "engineering judgment."

Thinking of an engineering problem as a number line of issues or variables, such as Figure 1.2.1, helps us to see an aerial view of the problem landscape. On the left end of the scale, say from one to three are the engineering design issues that make up standard practice. Let's assume that standard practice includes 60 to 70% of the weighted factors of significance . The 30 to 40% that standard practice is off the mark is covered by standard factors such as factors of safety, load factors, resistance factors, and so on. Presumably, standard practice suggests that if you are 60% correct and use a factor of safety of 3.0, or if you are 70% correct and use a factor of safety of 2.5, you should safely bound your problem.

On the right end of the scale in Figure 1.2.1, three issues from the remaining seven to 13 are commonly selected engineering research issues. These second-order terms on the right end of the scale are the habitation of university researchers and professors seeking research funding. If you want to get the problem solved, the design completed, stay in budget and meet your client's schedule, then you need to stay with the "engineering standard practice analyses" end of the problem scale. If you want a research topic, and you don't want to cover the same old ground of standard practice variables, then you need to select a second-order variable for study that may prove to be more significant than is currently understood. And finally, if you want to argue with others at conferences and monthly technical meetings, as many skeptics do (and you know who you are), please feel free to bring up issues from the portion of the problem scale that is not considered by standard practice or by current mainline researchers.

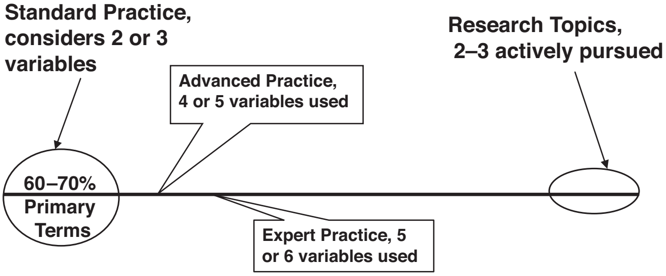

Figure 1.2.2 Advanced practice, expert practice, and research topics

1.2.2 Advanced and Expert Practice

Imagine that a client like a national laboratory, government agency, or high-tech project owner wants you to analyze something out of the ordinary. The measurements, analysis tools and advanced theories required involve something that is not covered by standard design practice. This type of engineering work is often referred to as advanced practice or expert practice. You can see from Figure 1.2.2 that standard practice is bounded by advanced and expert practice. These high-tech practices may be the standard of practice in some other parts of the United States or in other continents outside North America, such as in Europe or Asia. The point is that the definition of standard practice varies from place to place, and it varies with time.

After a natural disaster like Hurricane Katrina in New Orleans on 29 August 2005 or a major failure like the I-35W bridge collapse in Minneapolis on 1 August 2007, standard practice often expands rapidly to deal with issues uncovered during forensic analyses.

1.2.3 Theories Can Be Wrong. . .

You may say, "Standard practice or the accepted notion of what variables are important can be wrong. What about Albert Einstein and his proof that the standard idea of ether as the element that fills space was wrong?" You have a point, just like those skeptics I'm talking about.

Albert Einstein is famous for his attack on the concept of ether as the substance that fills space and transmits light. The concept of ether was an accepted principle of physics in the nineteenth century. Ralph Peck and I read the Einstein biography by Walter Isaacson (Isaacson, 2007) shortly after it came out in 2007. Ralph's eyesight was failing at the time, so he had a reader named Nida read the book to him. I recommended the book to my mother, a retired accounting professor from Kent State University. Nida and my mother commented on the parts of the Isaacson book that illustrated how human and fragile Dr. Einstein was in his personal and family relationships.

Ralph and I were drawn to the sections of Isaacson's book that illustrated how Einstein solved problems and developed theories. Ralph commented that Einstein solved problems by visualizing the solution. Einstein used analogies such as an elevator, a train, or a spacecraft traveling at the speed of light to frame problems and suggest their solutions. Ralph also pointed out that Einstein's physics journal papers were short and directly to the point, a trait that Ralph admired and strived to accomplish in his own work. I was taken by the contrast of Einstein's early work where he visualized problems, and his later work where he focused on mathematical formulations. Einstein accomplished a large amount of highly significant work when he relied on visual models or analogies to help guide his theories, and after 30+ years of work he never came up with a solution to the Unified Field Theory problem, although he formulated endless equations that appeared promising but failed.

Theories may be wrong, but we have to prove them wrong. Clearly seeing the issues involved seems to be the best guide to working through a complex problem.

1.2.4 Seeing is Better than Not Seeing . . .

My point in all of this is that you need a simple, visual model to understand and solve engineering problems. Focusing on two or three primary variables, as is the custom in standard design practice helps clarify the solution model because most people can see things in two or three dimensions. Clarifying the complex problem of changing engineering practice was my intention in showing "Problem Solutions" and "Standard Practice" and numerous potential variables in Figure 1.2.1 as a one-dimensional number line.

For those few of you who are experts and can see problems in five- or six- dimensional space, and have the mathematical tools to solve equations in these spaces, consider your selves blessed. It's up to you to reconfigure these complex problems in ways that are easy for the rest of us to see. *We have to see a problem clearly to solve the problem.*

1.2.5 Why is Standard Engineering Practice Changing?

The concept of seeing problems clearly brings me to a question that seems to be on many engineers' minds these days. Why does engineering practice seem to be becoming more and more complicated? To help you see this problem and predict the answer to this question, please refer to Figure 1.2.3.

As time goes on, more and more clients become involved in designs that require solutions to complex problems and require application of advanced engineering practice. Infrastructure failures, such as the failure of levees in New Orleans and the collapse of the World Trade Center towers in New York, raises questions about the

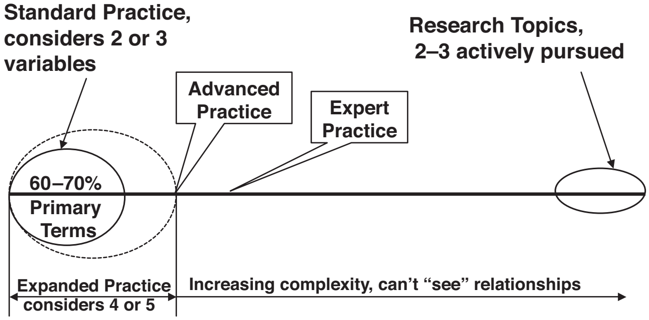

Figure 1.2.3 Growth of standard practice requirements

variables and principles used in standard engineering design practice. These problems become topics for funded university research. As university research into these advanced topics is published and made available to the engineering community through technical journals and conference proceedings, more and more engineers and clients want to work at a higher level. Computer programs are written that incorporate advanced topics, and everyone wants to have the latest and greatest computer modeling tools. The result of all of this pressure to do more is that standard practice expands to cover advanced practice, as illustrated in Figure 1.2.3. The amount of engineering analysis work increases, the cost and effort increases, and the complexity increases as we consider first three, then four, and then five or more variables in the problem solution. When asked if engineering practice will ever get easier, like in the good old days, my answer is *no*!

1.2.6 An Example of Increasing Complexity of Standard Practice . . .

As an example of how the engineering design process becomes more complex, consider paving design, which is an interaction problem between traffic, pavement, aggregate base, soil subgrade , drainage and weather. Let's say that a local university professor gets funding from the State Department of Transportation to do research on the standard problem of paving design. Say, for instance, that paving in their State is failing prematurely. Standard practice indicates that performance of paving depends on climate, traffic volume, wheel loads, and paving-base-subgrade strength. The premature paving failures could be related to excessive traffic, overweight vehicles, severe winters, or inadequate strength of a portion of the paving section.

But then one day an engineer from the Department of Transportation drives down a roadway in the State and notices that rainfall water is soaking into and seeping out of the paving. As he drives along, the Department engineer starts to think that maybe water in the paving section is the real problem behind premature paving failures.

After the engineer convinces his colleagues, the Department puts out a supplemental request for paving research on the topic of the effect of water in the paving section. The local university professor researching paving performance submits a proposal to further his study to include the affects of water in the paving section. His new paving proposal is accepted and research into the permeability of pavement and the affects of water on paving is funded, conducted, reported, and guess what, it does affect the life span of the paving section. As a result of findings of this research, the State Department of Transportation requires that two more variables related to paving permeability and paving saturation's affect on paving life be included in all standard paving designs. Referring to Figure 1.2.3 above, note that addition of a fifth and a sixth variable into the paving standard design practice increases the amount of work required and as a result increases the design complexity. In this way, the scope of standard practice increases and the work required increases, but likely the budget to do this additional work is not increased. From this analogy, I suggest that increasing complexity is to be expected. As time goes on, the size of the circle representing standard practice in Figure 1.2.3 will become larger and larger, and the ability of most engineers to see the impact and interaction of the design variables will be clouded. An engineer I know told me that he is working with an EPA standard contaminate transport model that has *23* input parameters. How's that for increased complexity!

1.2.7 Helping You See . . .

This book is designed to help you see each geotechnical problem clearly, so you can solve your problem. The discussions of each geotechnical problem are presented in a sequence from basic principles of standard practice to more complicated advanced practice issues. For those of you interested in advanced topics, a reference section is included with each problem discussion. These references to advanced material are included for those who have the need to dig into the body of available information.

To help you see concepts, analogies will be used. Don't worry that we're already introducing complexity; the definition used here for an analogy is a simple example that is similar to or has the same physical principles as the more complex problem. These simple analogies give you a visual key to help see the concept in your mind. An example of a simple analogy is the concept of frictional resistance in a granular soil, which is like a sliding wooden block on a table. At low strains the soil's frictional resistance or friction angle is higher, which is like static friction of the block on the table. At higher strains the soil's frictional resistance or friction angle is lower, which is like sliding friction of the block on the table.

We are going to discuss problem solutions from simple to complex, but how do you know which problem solution method to use on your problem. How do you decide when to use a simple, quick method or a highly complex, sophisticated method? How do you adjust the number of problem variables to fit your clients' scope and budget and still solve the problem? The answer is you need to understand and use

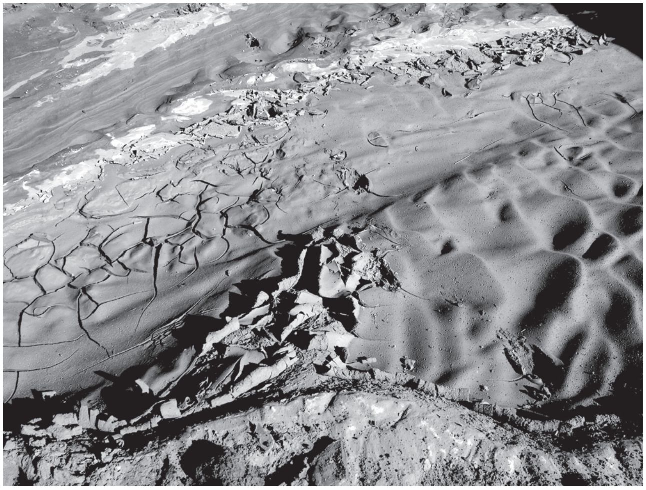

Figure 1.2.4 Would you expect to find expansive soil in a nearby boring?

the "graded approach." What is the graded approach? It's just a case of good old common sense, check out Section 1.3.4 for the answer to this question.

Please remember two things: (1) geotechnical engineering is not physics, we use constitutive equations that are based on tests that are designed to solve specific problems. Our tests and equations are *not* "laws of physics;" (2) whether it is geotechnical engineering, physics, accounting or everyday life . . . to *solve* it you have to *see* it. What do you see in Figure 1.2.4?

Reference

Isaacson, W. (2007) *Einstein, His Life and Universe*, Simon & Schuster, New York, 675 pages.

1.3

My Approach to Modern Geotechnical Engineering Practice – An Overview

1.3.1 Introduction

This book is intended to bridge the gap between geotechnical material covered in university civil engineering course work and the geotechnical topics required for practicing civil, structural, and geotechnical engineers to solve real world problems. Over the past decade or so there has been a tug of war between competing groups for the size and content of curricula included in undergraduate civil engineering programs. Several groups, the American Society of Civil Engineers comes to mind, have adopted programs requiring a Masters degree or an additional 30 credit hours of specialized training beyond the bachelor's degree to qualify for a professional engineering license. Will these additional training requirements discourage potential engineering students from entering the profession? Maybe it will. The fact remains that additional knowledge and skills beyond the bachelor's degree and even beyond a Professional Engineer's License are required to become a fully competent senior engineer.

For a long time, I've had the idea for a book to explain practical geotechnical problem solving to practicing engineers. My basic thought was to discuss alternate analysis methods and approaches. I'm not embarrassed to admit that I have struggled for years with many geotechnical topics, conflicts between competing theories of soil mechanics, and issues of increasing complexity, as discussed in Section 1.2. Having a mentor to help you through these geotechnical topics is a good thing, a very good thing.

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In the later part of my career, my mentor was Ralph Peck. Ralph Peck was one of the founding fathers of soil mechanics and foundation engineering (now called geotechnical engineering or geo-engineering), and I was honored to have him as a friend and mentor. This book was gently suggested by Ralph. He also suggested that I keep working and forget about retirement. Since engineering mentors are in short supply world-wide, it is my hope that this book will help mentor you in geotechnical engineering.

As you have probably figured out by now, this book is not a text book (although I hope that advanced students may find it useful), nor is it a book of standard cook book solutions that don't match your design problem. It is my intent that this book will give you the why and how; that is, it will give you the understanding of the principles involved so that you can solve your own project problems. I will include some real world problems that illustrate my approach to geotechnical problem solving, and I will discuss alternate approaches and even theories that apparently conflict with one another so that you understand the different positions taken by experts.

Ralph Peck said, "The highest calling of an engineer is to make engineering as clear as possible." That is my intent.

1.3.2 Summary of Problem-Solving Approach

We have several choices of analytical techniques to solve the many classes of geotechnical problems. Each geotechnical analysis involves many levels of assumptions that are used to reduce a very complex situation to a solvable model of the real problem. As described in Section 1.2, there will be at least one person in the group that will disagree with your selection of field testing, laboratory testing, analysis procedure, computer program selection, analysis results, conclusions, and report format. Your only defense against opposing opinions is to have a logical, well-defined, thought-out approach to the problem, often referred to as a problem solution plan. If you can clearly define why you did something, a defense to opposing opinions can be constructed. If you just did something because "that is the way we always do it," or if you grabbed an equation out of a textbook because it was convenient and available, you are in for serious difficulties. Maybe not today, maybe not tomorrow, but some day you will be asked the question, "Why?" My experience has been that it is easier to answer your own questioning of why when you have time to think, rather than to deal with someone else (like a government QA auditor) pushing you later. Besides, exploring the "why" to any engineering problem is just plain fun. It's kind of like solving a mystery. I like fun, how about you?

1.3.3 Geotechnical Overview and Approach

The first thing you need to do when solving a geotechnical problem (or any problem for that matter) is to slow down enough to think. You have to start with your best understanding of what the problem really is. Both your client and your boss (if you have one) will tell you what the problem is all about. You should listen carefully and take notes, but do not jump to the conclusion that they have fully or even properly characterized the problem. Consider your client's and your boss's direction as data or input into the problem characterization process. The first thing I do is collect information in the most open-minded manner than I can muster. This information often includes:

- A site location plan or map.
- A drawing showing the facility or building on the site, hopefully with site topography (i.e., showing existing and planned ground surface elevations).
- Any available architectural or engineering drawings and plans.
- Site photographs.
- Historical aerial photographs, hopefully a series of photographs from well before site development to just before construction and to date.
- A geologic map of the site and surrounding area.
- Geologic publications for the surrounding area and a site or project geologic reconnaissance report if available.

After reviewing all of the above information, I start to develop a theory of what types of soil and bedrock problems may be (or have been) encountered on the site. Then I look up at the sign on my office wall that says, "You have to see it to solve it," and I let out a short gasp of air, sighing about the distance to the site, my lack of available time, my overly full schedule, and I remember that seeing the site is often the most important piece of a geotechnical engineer's work. Ralph Peck told me many stories of how Karl Terzaghi (The Father of Soil Mechanics) used extensive site visits often lasting one or two weeks to identify the critical pieces of information required to solve difficult geotechnical problems.

Ralph told me that Karl Terzaghi always keenly studied the geology of every site, he frequently visited his project sites and studied the landscape for signs of earlier landforms that would give him clues to the magnitude of the soil's pre-consolidation pressures, the nature of groundwater on the site, and existing shearing stresses that might have affected soils at his project site. For those of you who are interested in Terzaghi's methods of site investigation, I recommend the book *From Theory to Practice in Soil Mechanics, Selections from the Writings of Karl Terzaghi,* copyright 1960 by John Wiley & Sons, Inc. I found a used copy on the internet that was originally owned by Robert L. McNeill.

OK, now that you have done a thorough office study of available information, it is time to visit the site. When you get to the site, step back, climb up on the high ground and take in the landscape. Make notes and take photographs of everything you see at the site. Sometimes you are investigating a site for a future planned facility, and other times you may be investigating an existing damaged facility. For those latter cases, don't allow the client or his attorney to take you on "the tour" of their damaged building without doing your own investigation of site geology and a reconnaissance of the surrounding area. An example illustrates this point.

Worked example

On the way to the site, I heard that we were going to a very expensive house that had severe floor settlement and numerous cracks in the walls. I heard that the construction inspection reports indicated that all fill under the house was compacted to 95 to 100% of modified Proctor maximum density. I heard that one engineer expected that settlement was due to soft clays and that another engineer was convinced that expansive soils were present. I also heard a theory that roof drainage soaked foundation soils due to poor site drainage and that foundation support soils had collapsed.

When we arrived at the site, the driver pulled up to the front of the house and everyone bolted for the front door, except me. I went in the opposite direction. I walked out about 1000 feet perpendicular to the front of the house, turned around and surveyed the terrain. What I saw were outcropping layers of sandstone and layers of shale. The rock layers were upturned, with the sandstone forming ridges that ran approximately perpendicular to the front of the house. The shale material was highly weathered and buried beneath clayey soil between the sandstone ridges, see Figure 1.3.1.

Figure 1.3.1 Upturned sandstone with highly weathered shale

Following the sandstone ridges toward the house, it was clear that one ridge ran under the left end of the house, another ridge ran under the center of the house, and a third ridge ran under the right end of the house. It seemed to me to be a perfect geology for a differential settlement problem, see Figure 1.3.2.

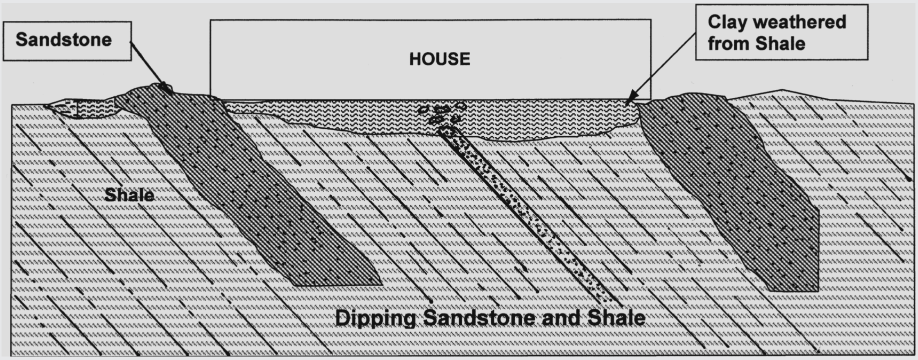

Figure 1.3.2 Ridges of sandstone and weathered shale under house

Based on field observations, I had my proposed theory of how the house settled, and now I was ready to join the others in touring the damaged structure. After reviewing room after room with settled floors and cracked walls, I started to become confused, because not all of the observed crack damage fit my proposed "theory of the case." After the tour, I asked a junior engineer to map all of the crack damage on a building plan drawing. The client gave me a copy of the original geotechnical report, and it showed soft, wet, and moderate to high plasticity clay in some borings to more than 20 feet, and refusal on sandstone at three feet in other borings. Checking the geotechnical report's boring location plan showed that borings with shallow sandstone lined up with my ridges of sandstone, and the borings with soft wet clay lined up with the shale zones located between ridges of sandstone. Settlement of the house's floors generally matched this pattern of little or no settlement where sandstone was indicated to be shallow. One immediate problem was the presence of exterior wall cracks indicating that the front and back walls were settling more on their ends than in the middle. But sandstone was located at the ends, so the ends should not have settled more than the middle unless there was a problem with my geologic model.

To resolve this problem with my theory, we dug test pits adjacent to the ends of the front and back wall of the house. Soil under the house footings was probed and determined to be very soft and wet. Further investigation disclosed that soils beneath the house footings were over-excavated and replaced with three feet of compacted fill. Although compaction tests indicated that the fill was compacted to greater than 95% of modified Proctor maximum density, the contractor blended off-site select granular fill soil with expansive clay and clay shale from the site. The 50–50 blend was done to save money. The expansive clay and clay shale mixed into the fill beneath the footings did not become wetted and softened until well after the house was built. Upon wetting, the expansive clay and clay shale lost strength turning to a muddy consistency resulting in settlement of the house footings.

After all of the competing engineers' theories of "what happened" to this house were reviewed based on detailed findings, it was apparent that they all had part of the problem correct. Expansive soils were present, and there had been collapse upon wetting, and so on. The common issue with all of the competing theories was that they all had most of the issues correctly characterized, but they missed important parts of the problem.

1.3.4 What Do I Do? Answer: The Graded Approach

There are several competing methods of solving each class of geotechnical problem. Some of these solution methods apparently conflict with other published methods. Some of these methods require much more field and laboratory testing data and analysis work to develop a problem solution, which of course cost more money. How do you select the right method for your problem?

I've found that many engineers are ready and raring to go, ready to dive into a geotechnical problem, but they are unsure how to start work or which solution techniques to use. Often they wait for the principal engineer to outline the approach for them, and then when the problem is laid out for them, they start to work. As a young engineer told me last month, "You better start writing down what you know because you'll be dead before you give it all to us, and then what will we do!" I hope she is wrong about my eminent demise, but she has a point. Older engineers do need to pass the information along.

I hate to break it to our younger readers, but money is involved in the geotechnical investigation and design process. It would be wonderful if we could use all of our high tech tools on each and every project. But no, it's true, the person or the agency with the money controls the work scope of the project. The engineer does not control the project unless he controls the money. This is not necessarily a bad thing. The client knows what he has to spend, and he has some idea of what he wants or needs. It is the engineer's role to guide and discuss options with the client until a reasonable accommodation has been made. You might think that large United States government national laboratories want the highest technology that money can buy applied to their projects. Not true. They want and need value as much or more than most clients because of the federal scrutiny involved with their budgets. A Los Alamos National Laboratory engineer once told me when referring to my proposed geotechnical work scope, "We don't need a super computer on this one. A small laptop will do!"

The point of this LANL engineer's comment was that the scope of work including the extent of field investigation, the complexity of laboratory testing, and the engineering analyzes had to fit the size and intent of the project. The building he was referring to was a large metal building used to store landscaping equipment: lawn mowers and tractors. The final cost of the investigation for this landscaping equipment storage building with a break room for the landscape workers was less than the quality assurance budget on a geotechnical investigation for a LANL facility where the primary mission of the lab was conducted. Federal government agencies often refer to this notion of the work scope fitting the project size and project importance as the "graded approach." By this they mean that small, less important projects require lesser work scopes, and that large, important projects require more costly, larger work scopes.

To the best of my knowledge, the United States Department of Energy developed the concept of the graded approach. I went on the internet to the US Department of Energy (DOE), Brookhaven National Laboratory (BNL) website. BNL conducts research in the physical, biomedical, and environmental sciences, as well as in energy technologies and national security. They have a definition of the graded approach on their website as:

A process for determining that the appropriate level of analysis, controls, documentation, and actions necessary are commensurate with an item's or activity's potential to

- Create an environmental, safety, or health hazard;
- Incur a monetary loss due to damage, or to repair/rework/scrap costs;
- Reduce the availability of a facility or equipment;
- Adversely affect the program objective or degrade data quality;
- Unfavorably impact the public's perception of the BNL/DOE mission.

I am always impressed at how DOE documents can be read without clearly understanding what they mean. I believe the operative word in the DOEs definition of graded approach can be summarized simply as the appropriate level of analysis. What is appropriate analysis for safety evaluation of a nuclear reactor is likely overkill for analyses of a parking lot subgrade.

Having read the above material, you may be fooled into thinking that the purpose, size and type of structure (a nuclear facility, a large hospital, or a landscaping shed) being scoped for a geotechnical investigation are the only factors that control the cost and extent of the geotechnical work. Not so. Several other important factors have to be added for selection of an appropriate level of analysis, including: complexity of the structure, complexity of the site stratigraphy and geology, requirements of the people in charge, and needs of the public.

Even if a project is small and seemingly unimportant, a small project's loading and geometry can still be complex. This presents a dilemma for the geotechnical engineer: how to simplify the complexities or how to deal with these complexities within a limited budget. Geology should be easy for geotechnical engineers to understand. If the geology and the site stratigraphy are highly complex, no matter what type of structure is planned, the complex site requires a greater scope and number of tests, and quite likely more complex analyses to obtain a solution with similar reliability to a simple site with uniform stratigraphy and geology. But what does "the public" have to do with the geotechnical work scope?

The answer to this question about the impact of "the public" on a geotechnical work scope may have an infinite number of answers, and if not infinite at least a very, very large number of answers. I will give two examples that come to mind:

1. Simple levees and hurricane Katrina – Levees have always been considered to be simple geotechnical structures, being much less important than dams. When I first started my geotechnical career, I couldn't wait to work on dams. The bigger the better. Levees were just a pile of dirt pushed up along a stream . . . not too interesting. When a dam fails, like the Vaiont Dam or the Teton Dam, now there's a real disaster. The 305-foot high earthen Teton dam structure failed, washing out more than 1500 homes, killed 11 people and over 18 000 livestock animals, and caused $322 million in damages. The 858-foot high Vaiont Concrete Dam in Italy failed when a massive landslide located above the dam dropped debris into the reservoir splashing out a flood wave that drowned 2000 people. After the flood the concrete Vaiont Dam remained intact.

But then hurricane Katrina came along and it changed the public's perception. Small, apparently simple earthen levee structures less than 15 feet high failed, resulting in the death of 1253 people, damage to thousands of homes, and causing approximately $28 billion in damages. Even though engineers and politicians may have considered the New Orleans levees as simple structures in the past, the public now considers them as very important. It is not just the size of the structure; it is the consequences of failure that count. Changes to the design and analysis practices of levees are still on-going, years after the disaster occurred.

2. A simple, single-span bridge investigated by a typical state Department of Transportation (DOT) for a bid-build project may require two to four borings, depending on the width and span of the structure. The embankment, retaining walls and bridge foundations may be analyzed and designed by correlations to standard penetration test (SPT) blow count supplemented by grain-size, plasticity index (PI) and water content laboratory testing used to classify the soils encountered. The DOT is probably not in a big hurry to finish the geotechnical work, and they would

rather save money (read initial cost) than time. The same bridge investigated by a design-build team may be a much different matter. Design-build teams nearly always have to develop an aggressive schedule for completion of a transportation project, and they have to provide performance assurances like "no more than 2 inches of embankment settlement in five years after completion of the project." To make accurate predictions of consolidation settlement rates of embankments built on soft saturated clay deposits, and to monitor progress of preloading settlements to provide assurance that the 2-inch limit will not be exceeded, the design-build team has incentives to do more field testing, more detailed laboratory testing, much more geotechnical analyses using advanced techniques, and to install a sophisticated monitoring system. The monitoring system in the field is used to provide weekly updates on the progress of embankment vertical settlements and lateral deformations (excessive lateral deformations could damage nearby structures or critical utility infrastructure). Data from field monitoring is used to update the settlement model providing revised estimates of time required to preconsolidate foundation soils. Design-build geotechnical investigations for the single-span bridge with its approach embankments described above may easily expand to include 36 borings and 36 piezocone tests not two to four typical bridge borings. The increased cost and expanded complexity of the design-build team's geotechnical scope of work to fulfill their contractual schedule and performance requirements may be five to ten times greater than the typical geotechnical investigation for a design-bid-build project. From a cost-benefit perspective, the extra geotechnical investigation and analysis costs are well worth it to the design-build team managers.

1.3.5 Geotechnical Investigations for $15 per Foot

At our Albuquerque monthly geotechnical meeting, we call it the Albuquerque Soil Mechanics Series, I recently discussed how the scope of a geotechnical investigation varies with the client, the project complexity, and so on, in a similar fashion to the discussion presented above. After the meeting, one of our older members pulled me aside and reminded me of geotechnical practice in the 1960s and early 1970s when we did things a bit differently. In those days a client would call up and ask for five borings for a new office building. We would discuss building height, location, and structural type and then I would suggest boring depths. Let's say we agreed upon 30-foot deep borings. So right on the phone I would say 150 feet of borings and the resulting report will cost about $2300. The client would say that sounds good, and we would schedule the drilling rig, often for the same afternoon or the next morning. If we found a big surprise at the site during drilling, I would drive to a pay phone booth (no cell phones in those days) and call the client to discuss a major change in project scope and budget. Often, he or she would ask me to stop drilling and move to