JIE HAN

PRINCIPLES AND PRACTICE OF GROUND IMPROVEMENT

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PREFACE

Ground improvement is popular in many countries to solve difficult geotechnical problems, especially when construction necessarily occurs in problematic soils and under difficult geotechnical conditions. Many recent developments in equipment, materials, and design methods have made ground improvement technologies more effective, efficient, and economic. However, the state of practice for most ground improvement technologies is that the practice is ahead of theory. Some contractors have developed their proprietary technologies, design methods, and construction techniques for their competitive advantages. Most of the existing books on ground improvement are focused on the concept, application, and case study. However, few books have been devoted to the principles and design methods of ground improvement. This book covers both theoretical and practical aspects in the design and construction of a variety of ground improvement technologies commonly used in practice. This book includes detailed design procedures for most of the ground improvement methods, which enable their easy implementation in practice. The design examples and homework assignments in this book will help readers better understand the principles of each ground improvement technology and how to apply the principles to solve real problems. This book can be used as a textbook for upper-level undergraduate students and graduate students and a reference book for researchers and practicing engineers. It can also be used a guide for contractors and installers to implement ground improvement technologies in field.

Writing this book was part of my big dream when I left China in 1993 to pursue my Ph.D. degree at the Georgia Institute of Technology. At that time, I set three goals: (1) to obtain a Ph.D. degree in the United States, (2) to publish technical papers on internationally well-recognized journals, and (3) to write a book on ground improvement in English. The first two goals were fulfilled in the late 1990s. The last goal has taken much longer than I expected.

I started to become interested in ground improvement in 1985 when I took the class of ground improvement at Tongji University in China, taught by Prof. Shulin Ye, as part of my bachelor's degree. I became a master's student in 1986, studying under Prof. Ye on stone columns. After I received my master's degree in 1989, I became a faculty member at Tongji University, continuing my research in ground improvement, including stone columns, deep mixed columns, grouting, dynamic compaction, and micropiles. I was fortunate to get involved in writing the first Shanghai ground improvement design code. I also coauthored a textbook on ground improvement in Chinese with Prof. Shulin Ye and Prof. Guanbao Ye right before I left China. The selection of the Georgia Institute of Technology for my Ph.D. study was also related to ground improvement because I had read the research report *Design and Construction of Stone Columns*, written by then Prof. Richard D. Barksdale for the U.S. Federal Highway Administration. I arrived at Georgia Tech at a great time. I was exposed to many new and innovative subjects and ideas and learned a great deal about the scientific aspects of geotechnical engineering. My Ph.D. research on fiber-reinforced polymeric piles, under the supervision of Prof. J. David Frost, provided me the great opportunity of learning composite mechanics and geosynthetics. This led me to my first job in the United States at one of the leading geosynthetics manufacturers, the Tensar Corporation. I started with a design engineer and was promoted to a senior engineer and then manager of technology development. I was exposed to many practical problems related to geosynthetic-reinforced earth structures. After several attempts at obtaining faculty positions, I joined Widener University in 2001 and taught the first ground improvement class there. Since transfering to the University of Kansas, I have worked closely with my colleague, Prof. Robert L. Parsons, and been involved in many research projects, which were sponsored by the federal agencies, Kansas Department of Transportation, and the geosynthetics and ground improvement industries.

Many people have made positive impacts on my career in geotechnical engineering, especially in ground improvement. In addition to my master's advisor, Prof. Ye, and my Ph.D. advisor, Prof. Frost, I have been fortunate to have opportunities to work with internationally recognized scholars Dr. J.P. Giroud, Prof. Dov Leshchinsky, Dr. James Collin, Prof. Mo Gabr, Prof. Hoe Ling and others. As part of the major U.S. Strategic Highway Research Program (SHRP) II R02 project team led by Prof. Vernon R. Schaefer and Mr. Ryan Berg, I had the opportunity to work with the top researchers and experts in ground improvement, including Prof. James Mitchell. I have also been fortunate enough to work with many talent and hard-working students and visiting scholars through the years.

I appreciate the review comments and suggestions from the experts in this field, including Dr. Dimiter Alexiew, Prof. Jinchun Chai, Dr. Xin Chen, Prof. Jian Chu, Prof. Masaki Kitazume, Prof. Dov Leshchinsky, Prof. Paul Mayne, Prof. Shuilong Shen, Prof. Burak Tanyu, Dr. Mark Wayne, Prof. Ming Xiao, and Mr. Kenny Yee. During the preparation of this book, I received great help from my current and former students, especially Yan Jiang, Shaymaa Kadhim, Deep Khatri, Xiaohui Sun, Fei Wang, and Zhen Zhang. I am also thankful for Mr. Serge Varaksin to provide the beautiful photo for the book cover. Many organizations and individuals have granted me permissions to republish their figures and tables in this book and their generous support is greatly appreciated.

Finally, I would like to acknowledge the editors at John Wiley & Sons, Inc. for their patience and great support. My heartfelt thanks go to my dear wife, Jing Ye, and two sons, Terry and Shawn, for their understanding and support for me to complete this book.

Please go to www.wiley.com/go/GroundImprovement for instructor materials.

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CHAPTER 1

Introduction

1.1 INTRODUCTION

With civilization and urbanization, there have been increased demands for the use of land for better living and transportation. More and more houses, commercial buildings, high-rise office buildings, highways, railways, tunnels, levees, and earth dams have been constructed and will be continuously built in the future. As suitable constrsuction sites with favorable geotechnical conditions become less available, the need to utilize unsuitable or less suitable sites for construction increases. Engineers have faced increased geotechnical problems and challenges, such as bearing failure, large total and differential settlements, instability, liquefaction, erosion, and water seepage. The options to deal with problematic geomaterials and geotechnical conditions include: (1) avoiding the site, (2) designing superstructures accordingly, (3) removing and replacing problematic geomaterials with better and non-problematic geomaterials and (4) improving geomaterial properties and geotechnical conditions (Hausmann, 1990). It becomes increasingly necessary to improve geomaterials and geotechnical conditions for many projects.

Ground improvement has become an important part of geotechnical practice. Different terminologies have been used in the literature for ground improvement, such as soil improvement, soil stabilization, ground treatment, and ground modification. The term "ground improvement" has been most commonly used in the literature and practice and therefore adopted for this book.

1.2 PROBLEMATIC GEOMATERIALS AND CONDITIONS

1.2.1 Problematic Geomaterials

Geomaterials include all the materials used for geotechnical applications, which consist of natural geomaterials, processed or manufactured geomaterials, and improved geomaterials. Natural geomaterials are mainly soil and rock. O'Neill and Reese (1999) proposed a terminology of intermediate geomaterial, which has properties and behavior between soil and rock. Cohesive intermediate geomaterial has an unconfined compressive strength from 0.5 to 5.0 MPa, while a cohesionless intermediate geomaterial has the number of blow counts of a standard penetration test (SPT) between 50 and 100. Most rocks and intermediate geomaterials are strong and stiff and therefore suitable for geotechnical applications. However, natural soils, especially soft clay and silt, loose sand, expansive soil, collapsible soil, and frozen soil can be problematic to geotechnical applications.

Processed or manufactured geomaterials are produced from other materials. For example, crushed stone aggregates are produced from rock. Recycled asphalt pavement (RAP) aggregates are produced from aged asphalt pavements. Lightweight aggregates are produced by heating raw shale, clay or slate in a rotary kiln at high temperatures, causing the material to expand, and then cooling, crushing, and screening it for different applications. Processed or manufactured geomaterials are mainly used for fill materials, which have a wide variety, ranging from granular fill, lightweight fill, uncontrolled fill, recycled material, fly ash, solid waste, and bio-based byproducts to dredged material. Due to the large variations of fill materials, some of them can be used to improve soil properties (e.g., granular fill and fly ash), but others can be problematic to geotechnical applications (e.g., uncontrolled fill and sludge). Uncontrolled fill or uncompacted fill is mostly loose and underconsolidated; therefore, it settles under its own weight.

Improved geomaterials are the geomaterials treated hydraulically, mechanically, chemically, and biologically. For example, fibers can be mechanically mixed with sand or clay to form fiber-reinforced soil. Lime or cement can be added into soil to form lime or cement-stabilized soil. Denitrifying bacteria can be introduced into soil to generate tiny, inert nitrogen gas bubbles to reduce the degree of saturation of sand (He et al., 2013). As a result, the liquefaction potential of the sand is minimized. Improved geomaterials are often the end products of ground improvement; therefore, they are not problematic to geotechnical applications.

Table 1.1 lists problematic geomaterials and their potential problems. Some natural geomaterials and fill are the targets of ground improvement. When natural geomaterials are discussed in this book, soil and rock are often referred because these terms are commonly used in practice.

1.2.2 Problematic Conditions

In addition to problematic geomaterials, geotechnical problems may occur due to problematic conditions induced naturally and/or by human activities. Natural conditions include geologic, hydraulic, and climatic conditions, such

Table 1.1 Problematic Geomaterials and Potential Problems

Type of Geomaterial	Name	Potential Problems
Natural	Soft clay	Low strength, high compressibility, large creep deformation, low permeability
	Silt	Low strength, high compressibility, high liquefaction potential, low permeability, high erodibility
	Organic soil	High compressibility, large creep deformation
	Loose sand	Low strength, high compressibility, high liquefaction potential, high permeability, high erodibility
	Expansive soil	Large volume change
	Loess	Large volume change, high collapsible potential
Fill	Uncontrolled fill	Low strength, high compressibility, nonuniformity, high collapsible potential
	Dredged material	High water content, low strength, high compressibility
	Reclaimed fill	High water content, low strength, high compressibility
	Recycled material	Nonuniformity, high variability of properties
	Solid waste	Low strength, high compressibility, nonuniformity, and high degradation potential
	Bio-based by-product	Low strength, high compressibility, and high degradation potential

as earthquakes, cavities and sinkholes, floods, wind, and freeze–thaw cycles. Geotechnical conditions are part of geologic conditions, which exist close to the ground surface and are more related to construction and human activities. Examples of problematic geotechnical conditions are existence of problematic geomaterials, a high groundwater table, inclined bedrock, and steep natural slopes. Human activities, mainly the construction of superstructures, substructures, and earth structures, can change geotechnical conditions, which may cause problems for projects, for example, excavation, tunneling, pile driving, rapid drawdown of surface water, elevation of surface water by levees and dams, and groundwater withdrawal. Human activities can also change other conditions, such as the application of static, dynamic, and impact loads.

1.3 GEOTECHNICAL PROBLEMS AND FAILURES

Common geotechnical problems include bearing failure, large total and differential settlements, hydrocompression, ground heave, instability, liquefaction, erosion, and water seepage. The theoretical bases and reasons for these geotechnical problems are provided in Table 1.2.

Failures can happen if geotechnical problems are not properly addressed and become excessive, which typically results in significant financial loss, sometimes even cause loss of life.

1.4 GROUND IMPROVEMENT METHODS AND CLASSIFICATION

1.4.1 Historical Developments

Ground improvement methods have been used since ancient times. For example, about 6000 years ago (in the Neolithic Age), the Banpo people in China used rammed columns to support wooden posts in the ground (Chen et al., 1995). Soil compaction methods using rammers have also been employed since the Neolithic Age. Different types of rammers were used, from stone rammers (in the Neolithic Age) to iron rammers (about 1000 years ago). One type of rammer was operated by 8–12 people, each pulling a rope connected to the rammer to raise it and then letting it fall freely to pound the ground (Chen et al., 1995). About 3500 years ago, reeds in the form of bound cables (approximately 100 mm in diameter) were used in Iraq as horizontal drains for dissipation of pore water pressure in soil mass in high earth structures (Mittal, 2012). About 2000 years ago, The Romans used lime for roadway construction. More than 1000 years ago in the Han dynasty, Chinese people built earth retaining walls using local sand and weeds for border security and paths to the Western world. About 500 years ago (in the Ming dynasty of China), lime was mixed with clayey soil in proportion (typically 3:7 or 4:6 in volume) to form compacted lime–soil foundations for load support (Chen et al., 1995).

Modern ground improvement methods were developed since the 1920s. For example, the use of vertical sand drains to accelerate consolidation of soft soil was first proposed in 1925 and then patented in 1926 by Daniel D. Moran in the United States. Cotton fabric was used as reinforcement by South Carolina Highway Department in the United States for roadway construction in 1926. The vibro-flotation method was developed in Germany to densify loose cohesionless soil in 1937. The first type of prefabricated vertical drains was developed by Walter Kjellman in Sweden in 1947. Fernando Lizzi developed and patented the root pile method to underpin existing foundations in Italy in 1952. In the 1960s, there

Table 1.2 Geotechnical Problems and Possible Causes

Problem	Theoretical Basis	Possible Causes
Bearing failure	Applied pressure is higher than ultimate bearing capacity of soil	High applied pressure Inclined load Small loading area Low-strength soil
Large total and differential settlements	Hooke's law and particle re-arrangement	High applied pressure Large loading area Highly compressible soil Nonuniform soil Large creep deformation
Hydrocompression	High applied pressure is higher than threshold collapse stress	High applied pressure Collapsible soil Water
Ground heave	Swelling pressure is higher than applied pressure	Water Expansive soil Frozen soil Low temperature
Instability (sliding, overturning, and slope failure)	Shear stress is higher than shear strength; driving force is higher than resisting force; driving moment is higher than resisting moment	High earth structure Steep slope High water pressure Soft foundation soil High surcharge High loading rate
Liquefaction	Effective stress becomes zero due to increase of excess pore water pressure	Earthquake Loose silt and sand High groundwater table
Erosion	Shear stress induced by water is higher than maximum allowable shear strength of soil	Running water High speed of water flow Highly erodible soil (silt and sand)
Seepage	Dacy's law	High water head Permeable soil

were several developments of ground improvement methods, including the steel reinforcement for retaining walls by Henri Vidal in France, dynamic compaction by Louis Menard in France, deep mixing in Japan and Sweden, and jet grouting in Japan. In 1986, J. P. Giroud acclaimed the development from geotextiles to geosynthetics is a revolution in geotechnical engineering (Giroud, 1986).

1.4.2 Classification

Many ground improvement methods have been used in practice. The research team for the U.S. Strategic Highway Research Program (SHRP) II R02 project Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform identified 46 ground improvement methods, as provided in Table 1.3 (Schaefer and Berg, 2012).

Different authors or organizations have classified ground improvement methods (Table 1.4) based on different criteria, including Mitchell (1981) in his state-of-the-art report for soil improvement, Hausmann (1990), Ye et al. (1994), the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) TC17 committee (Chu et al., 2009), and the SHRP II R02 team led by Schaefer and Berg (2012). Clearly, each method of classification has its reasoning and advantages but also has its limitations. This situation results from the fact that several ground improvement methods can fit in one or more categories. For example, stone columns can serve the functions of densification, replacement, drainage, and reinforcement; however, the key function of stone columns for most applications is replacement. In this book, the method of classification proposed by Ye et al. (1994) is adopted with some minor modifications. In addition, the ground improvement methods can be grouped in terms of shallow and deep improvement in some categories or cut-and-fill improvement in other categories. In this book, shallow improvement is considered as having an improvement depth equal or less than 3 m, while deep improvement

Table 1.3 Ground Improvement Methods for Transportation Infrastructure

Aggregate columns	Fiber reinforcement in pavement systems	Micropiles
Beneficial reuse of waste materials	Geocell confinement in pavement systems	Onsite use of recycled pavement materials
Bio-treatment for subgrade	Geosynthetic reinforced construction platforms	Partial encapsulation
Blasting densification	Geosynthetic reinforced embankments	Prefabricated vertical drains (PVDs) and fill preloading
Bulk-infill grouting	Geosynthetic reinforcement in pavement systems	Rapid impact compaction
Chemical grouting/injection systems	Geosynthetic separation in pavement systems	Reinforced soil slopes
Chemical stabilization of subgrades and bases	Geosynthetics in pavement drainage	Sand compaction piles
Column-supported embankments	Geotextile encased columns	Screw-in soil nailing
Combined soil stabilization with vertical columns	High-energy impact rollers	Shoot-in soil nailing
Compaction grouting	Hydraulic fill + vacuum consolidation + geocomposite drains	Shored mechanically stabilized earth wall system
Continuous flight auger piles	Injected lightweight foam fill	Traditional compaction
Deep dynamic compaction	Intelligent compaction/roller integrated compaction monitoring	Vacuum preloading with and without PVDs
Deep mixing methods	Jet grouting	Vibro-compaction
Drilled/grouted and hollow bar soil nailing	Lightweight fill, expanded polystyrene (EPS) geofoam, low-density cementitious fill	Vibro-concrete columns
Electro-osmosis	Mechanical stabilization of subgrades and bases	
Excavation and replacement	Mechanically stabilized earth wall systems	

Source: Schaefer and Berg (2012).

Table 1.4 Classification of Ground Improvement Methods

Reference	Criterion	Categories
Mitchell (1981)	Construction/function	1. In situ deep compaction of cohesionless soils 2. Precompression 3. Injection and grouting 4. Admixtures 5. Thermal 6. Reinforcement
Hausmann (1990)	Process	1. Mechanical modification 2. Hydraulic modification 3. Physical and chemical modification 4. Modification by inclusions and confinement

(*continued*)

Table 1.4 (*Continued*)

Reference	Criterion	Categories
Ye et al. (1994)	Function	1. Replacement 2. Deep densification 3. Drainage and consolidation 4. Reinforcement 5. Thermal treatment 6. Chemical stabilization
ISSMGE TC17 (Chu et al., 2009)	Soil type and inclusion	1. Ground improvement without admixtures in noncohesive soils or fill materials 2. Ground improvement without admixtures in cohesive soils 3. Ground improvement with admixtures or inclusions 4. Ground improvement with grouting type admixtures 5. Earth reinforcement
Schaefer and Berg (2012)	Application	1. Earthwork construction 2. Densification of cohesionless soils 3. Embankments over soft soils 4. Cutoff walls 5. Increased pavement performance 6. Sustainability 7. Soft ground drainage and consolidation 8. Construction of vertical support elements 9. Lateral earth support 10. Liquefaction mitigation 11. Void filling
This book	Function	1. Densification 2. Replacement 3. Drainage and consolidation 4. Chemical stabilization 5. Reinforcement 6. Thermal and biological treatment

has an improvement depth greater than 3 m. The fill reinforcement includes the methods using metallic or geosynthetic reinforcement for fill construction, while the in situ ground reinforcement includes the methods using ground anchors or soil nails for cut construction.

1.4.3 General Description, Function, and Application

Table 1.5 provides the general descriptions, benefits, and applications of most ground improvement methods to be discussed in this book.

1.5 SELECTION OF GROUND IMPROVEMENT METHOD

1.5.1 Necessity of Ground Improvement

When superstructures are to be built on ground, there are five foundation options (Figure 1.1): (a) bearing on natural ground, (b) bearing on replaced ground, (c) bearing on compacted/consolidated ground, and (d) bearing on composite ground, and (e) bearing on piles to deeper stratum. Options (b), (c), and (d) involve ground improvement methods. The final selection often depends on geotechnical condition, loading condition, performance requirement, and cost. Option (a) is preferred and also more economic when the load on the foundation is low and competent geomaterial exists near the ground surface. Option (e) is more suitable for high foundation loads on problematic geomaterials with high-performance requirements, which is often most expensive. Options (b), (c), and (d) are more suitable for intermediate conditions and requirements between option (a) and option (e).

There are also four options for earth retaining structures as shown in Figure 1.2: (a) unreinforced cut-and-fill slopes, (b) unreinforced cut-and-fill earth walls, (c) reinforced cut-and-fill slopes, and (d) reinforced cut-and-fill