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

Table 1.5 General Descriptions, Functions, and Applications of Ground Improvement Methods

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Densification	Shallow compaction	Traditional compaction Level = 5	Apply static or vibratory load on ground surface in a certain number of passes to densify problematic geomaterial	Increase density, strength, and stiffness; reduce deformation, permeability, collapsible potential, and ground heave	Suitable for a wide range of fills to a lift thickness of 0.3 m; used to compact fill
		High-energy impact roller compaction Level = 2	Apply a lifting and falling motion by a roller with high-energy impact on ground surface to densify or crush problematic geomaterial	Increase density, strength, and stiffness; reduce deformation, permeability, collapsible potential, and ground heave; crush rock and concrete into rubble	Suitable for a wide range of geomaterials to a depth of 2 m; used to improve subgrade and foundation soil and compact fill
		Rapid impact compaction Level = 2	Use an excavator to drop a weight repeatedly on ground surface to densify problematic geomaterial	Increase density, strength, and stiffness; reduce deformation, permeability, collapsible potential, and ground heave	Suitable for granular geomaterials up to 6 m deep; used to improve subgrade and foundation soil and compact fill
		Intelligent compaction Level = 2	Apply and adjust compaction energy based on on-board display from measurements in real time to densify problematic geomaterial	Increase density, strength and stiffness; reduce deformation, permeability, collapsible potential, and ground heave, identify areas of poor compaction, and maximize productivity	Suitable for granular geomaterials; used to improve subgrade and foundation soil and compact fill
	Deep compaction	Dynamic compaction Level = 5	Drop a heavy weight from a high distance to apply high energy on ground surface, causing liquefaction of saturated problematic geomaterial and densification of unsaturated problematic geomaterial	Increase density, strength and stiffness; reduce deformation, liquefaction, collapsible potential to a greater depth	Suitable for granular geomaterials, collapsible soil, and waste material with less than 15% fines to a depth of 10 m; used to improve foundations
		Vibro compaction Level = 5	Apply a vibratory force and/or water by a probe on surrounding problematic geomaterial, causing liquefaction and densification	Increase density, strength, and stiffness; reduce deformation, liquefaction, and collapsible potential to a greater depth	Suitable for clean sands with less than 15% silt or less than 2% clay to a typical depth of 5−15 m; used to improve foundations
Replacement	Shallow replacement	Overexcavation and replacement Level = 5	Remove problematic geomaterial and replace with good-quality geomaterial	Increase strength and stiffness; reduce deformation, liquefaction, collapsible, and ground heave potential	Suitable and economic for a wide range of geomaterials with limited area and limited depth (typically to 3 m deep and above groundwater table)

(*continued*)

Table 1.5 (*Continued*)

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Replacement	Deep replacement	Sand compaction columns Level = 5*	Displace problematic geomaterial by driving a casing into the ground and backfill the hole with sand (densified by vibration during casing withdrawal)	Increase bearing capacity and stability; reduce settlement and liquefaction potential; accelerate consolidation	Suitable for a wide range of geomaterials to a typical depth of 5−15 m; used to improve foundations
		Stone columns Level = 5*	Jet water or air to remove or displace problematic geomaterial by a probe and backfill the hole with stone to form a densified column by vibration	Increase bearing capacity and stability; reduce settlement and liquefaction potential; accelerate consolidation	Suitable for a wide range of geomaterials (undrained shear strength >15 kPa) to a typical depth of 5−10 m (up to 30 m); used to improve foundations
		Rammed aggregate columns Level = 4	Predrill a backfilled with aggregate, densified by ramming	Increase bearing capacity and stability; reduce settlement and liquefaction potential; accelerate consolidation	Suitable for a wide range of geomaterials to a typical depth of 5−10 m with a deep groundwater level; used to improve foundations
		Vibro-concrete columns Level = 3	Drive a vibrating probe to the ground to displace problematic geomaterial, replaced with concrete	Increase bearing capacity and stability; reduce settlement	Suitable and economic for very soft soil to a typical depth of 5−10 m; used to improve foundations
		Geosynthetic-encased columns Level = 2*	Drive a steel casing to the ground to displace problematic geomaterial, replaced with a geosynthetic casing and fill	Increase bearing capacity and stability; reduce settlement; accelerate consolidation	Suitable and economic for very soft soil (undrained shear strength <15 kPa) to a typical depth of 5−10 m; used to improve foundations
Drainage, dewatering, and consolidation	Drainage	Fill drains Level = 5*	Place a layer of permeable fill inside a roadway or earth structure	Reduce water pressure and collapsible and ground heave potential; accelerate consolidation; increase strength, stiffness, stability	Suitable for low permeability geomaterial; used for roads, retaining walls, slopes, and landfills
		Drainage geosynthetics Level = 4	Place a layer of nonwoven geotextile or geocomposite in ground or inside a roadway or earth structure	Reduce water pressure and collapsible and ground heave potential; accelerate consolidation; increase strength, stiffness, stability	Suitable for low permeability geomaterial; used for roads, retaining walls, slopes, and landfills
		Open pumping Level = 5	Use sumps, trenches, and pumps to remove a small amount of water inflow in open excavation	Remove water to ease construction	Suitable for a small area, relatively impermeable soil, and lowering of the groundwater table by a limited depth in open excavation

(*continued*)

Table 1.5 (*Continued*)

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Drainage, dewatering, and consolidation	Dewatering	Well system Level = 4	Use well points and/or deep wells to remove a large amount of water inflow in open excavation	Remove water to ease construction and increase stability of excavation	Suitable for a large area, relatively permeable soil, and lowering of the groundwater table by a large depth for excavation
		Electro osmosis method Level = 2	Create electric gradients in soil by installing anode and cathode to induce water flow and collect and discharge the water by a cathode well point	Remove water to ease construction	Suitable for relatively impermeable silt or clayey soil
	Consolidation	Fill preloading Level = 5	Apply temporary surcharge on ground surface for a duration and then remove the surcharge for construction	Increase soil strength; reduce settlement	Suitable for saturated inorganic clay and silt; used to reduce settlement for foundation soil
		Vacuum preloading Level = 3	Apply vacuum pressure on ground surface and/or through drains into the ground for a desired duration and then remove the pressure for construction	Increase soil strength; reduce settlement	Suitable for saturated inorganic clay and silt; used to reduce settlement for foundation soil
Chemical stabilization	Shallow stabilization	Chemical stabilization of subgrade and base Level = 5	Mix lime, cement, and/or fly ash with subgrade and base course in field and then compact the mixture; have chemical reaction with soil particles to form a cementitious matrix	Increase strength and stiffness; reduce ground heave potential	Suitable for unsaturated clay and silt; mainly used for roadway construction with a typical lift thickness of 0.3 m or less
	Deep stabilization	Grouting Level = 3	Inject grout into ground to fill voids, densify soil, and have chemical reaction with soil particles to form a hardened mass	Increase strength and stiffness; reduce permeability, liquefaction, and ground heave potential	Different grout suitable for different geomaterial; mainly used for remedying measures or protective projects
		Jet grouting Level = 4	Inject high-pressure cement-based fluid into ground to cut and then mix with geomaterial to form a hardened column by chemical reaction with soil particles	Increase strength, stiffness, and stability; reduce permeability, liquefaction, and ground heave potential	Suitable for a wide range of geomaterials; mainly used for remedying measures and protective projects to a typical depth of 30 m or less
		Deep mixing Level = 4*	Mix cement or lime from surface to depth with geomaterial by mechanical blade to have chemical reaction with soil particles after mixed to form a cementitious matrix	Increase strength, stiffness, and stability; reduce permeability, liquefaction, and ground heave potential	Suitable for a wide range of geomaterials; mainly used for foundation support, earth retaining during excavation, containment, and liquefaction mitigation

(*continued*)

Table 1.5 (*Continued*)

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Reinforcement	Fill reinforcement	Geosynthetic-reinforced slopes Level = 5	Place geosynthetics in slope at different elevations during fill placement to provide tensile resistance	Increase stability	Suitable for low plasticity fill; mainly used for slope stability
		Geosynthetic-reinforced embankments Level = 5	Place high-strength geosynthetic at base of embankment to provide tensile resistance	Increase bearing capacity and stability	Suitable for embankments over soft foundation; mainly used for enhancing embankment stability
		Geosynthetic-reinforced column-supported embankments Level = 3	Place geosynthetic reinforcement over columns at base of embankment to support embankment load between columns	Reduce total and differential settlements; accelerate construction; increase stability	Suitable for embankments over soft foundation with strict settlement requirement and time constraint
		Mechanically stabilized earth walls Level = 5	Place geosynthetic or metallic reinforcements in wall at different elevations during fill placement to provide tensile resistance	Increase stability	Suitable for low plasticity free-draining fill
		Geosynthetic-reinforced foundations Level = 3*	Place geosynthetic reinforcements within fill under a footing to provide load support	Increase bearing capacity and reduce settlement	Suitable and economic for granular fill over soft soil with limited area and depth
		Geosynthetic-reinforced roads Level = 4	Place geosynthetic reinforcement on top of subgrade or within base course to provide lateral constraint	Increase bearing capacity and roadway life; reduce deformation and base thickness requirement	Suitable for granular bases over soft subgrade
	In-situ ground reinforcement	Ground anchors Level = 4*	Insert steel tendons with grout at end in existing ground to provide tensile resistance and prevent ground movement	Increase stability and resistance to uplift force	Suitable for granular soil or rock; used for temporary and permanent slopes and walls during excavation and substructures subjected to uplift force
		Soil nails Level = 4	Insert a steel bar with grout throughout the whole nail in existing ground to provide tensile resistance and prevent ground movement	Increase stability	Suitable for low plasticity stiff to hard clay, dense granular soil, and rock; used for temporary and permanent slopes and walls during excavation
		Micropiles Level = 4	Insert a steel reinforcing bar in a bored hole, grout in place to form a small diameter pile (<0.3 m) and provide vertical and lateral load capacities	Increase stability; protect existing, structures during ground movement	Suitable for a variety of geomaterials; used for slopes, walls, and unpinning of existing foundations

(*continued*)

Table 1.5 (*Continued*)

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Thermal and biological treatment		Ground freezing Level = 2	Remove heat from ground to reduce soil temperature below freezing point and turn geomaterial into solid	Increase strength; reduce water flow and ground movement	Suitable for saturated clay and sand; used for temporary protection during excavation
		Biological treating Level = 1	Utilize vegetation and roots to increase shear strength of soil or change soil properties by biomediated geochemical process, including mineral precipitation, gas generation, biofilm formation, and biopolymer generation	Increase strength and stiffness; reduce erodibility and liquefaction potential	Suitable for cohensive and cohesionless geomaterials; requires more research and field trial before it is adopted in practice

[a]Level of technology establishment: rating scale 1 = not established, 3 = averagely established, and 5 = well established (most of the ratings are based on the recommendations by the SHRP II R02 team; however, some ratings with an asterisk * are adjusted or added from the international perspective and the author's judgment).

earth walls. Among these options, cut and fill are two different situations. Option (a) is often adopted when there is open land. It is also least expensive and easy for vegetation. Options (b) and (d) are often adopted when there is limited space. Option (b) using slurry walls, gravity walls, or cantilever walls is often most expensive among all the options but gains large useful land. Reinforced earth walls are typically less expensive than slurry walls, gravity walls, and cantilever walls. Option (c) is between option (a) and options (b) and (d) in terms of land requirement/utilization and cost. Option (c) has flexibility of different slope angles and may still establish vegetation. Ground improvement methods can be used for options (b), (c), and (d).

For roadway construction, options for subgrade and base course (or ballast) can be: (1) natural subgrade and granular base, (2) lime/cement-stabilized subgrade and base, and (3) geosynthetic-reinforced subgrade and base.

For all applications, unimproved conditions should be evaluated against performance criteria first. If unimproved conditions satisfy the performance criteria, no ground improvement is needed; otherwise, ground improvement is required.

1.5.2 Factors for Selecting Ground Improvement Method

Selection of ground improvement method should consider the following conditions: (1) structural conditions,

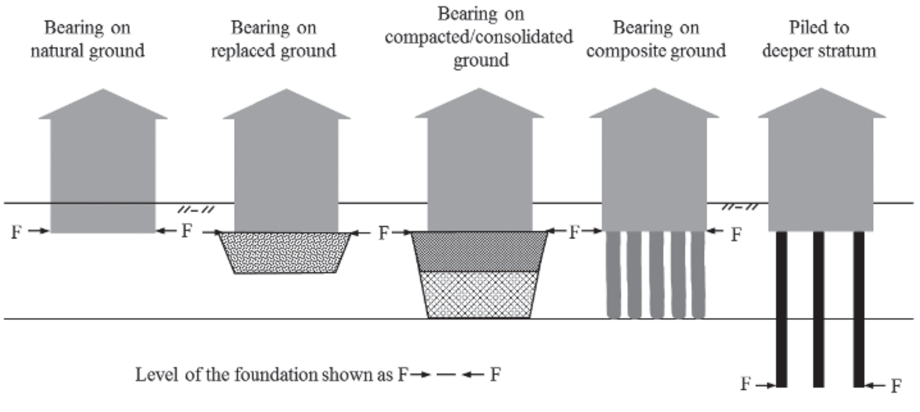

Figure 1.1 Options for foundations (modified from Mitchell and Jardine, 2002).

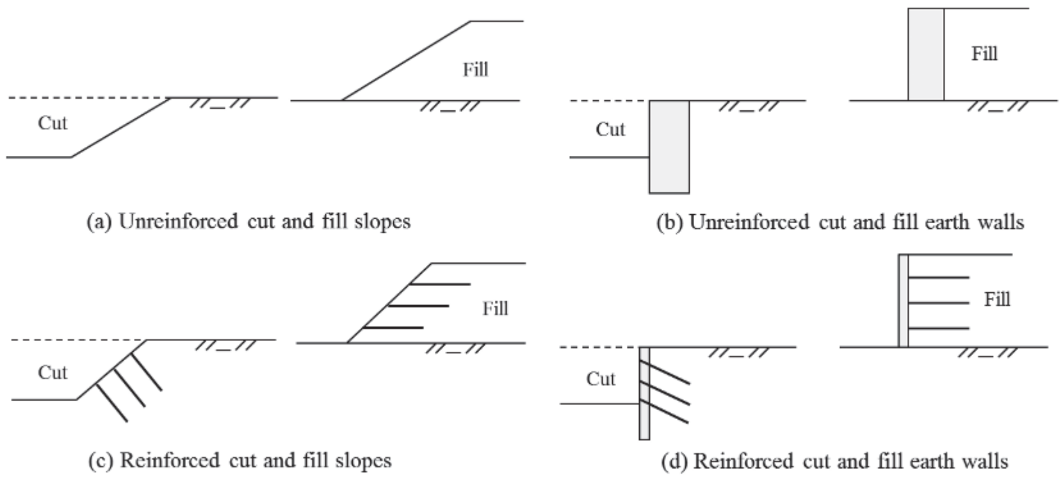

Figure 1.2 Options for earth retaining structures.

(2) geotechnical conditions, (3) environmental constraints, (4) construction conditions, and (5) reliability and durability.

Structural Conditions The structural conditions may include type, shape, and dimension of structure and footing, flexibility and ductility of structural and footing elements, type, magnitude, and distribution of loads, and performance requirements (e.g., total and differential settlements, lateral movement, and minimum factor of safety).

Geotechnical Conditions The geotechnical conditions may include geographic landscape, geologic formations, type, location, and thickness of problematic geomaterial, possible end-bearing stratum, age, composition, distribution of fill, and groundwater table. Soil type and particle size distribution are essential for preliminary selection of ground improvement methods as shown in Figure 1.3. This guideline is suitable for ground improvement methods for foundation support. The thickness and location of problematic geomaterial are also important for the selection of ground improvement methods. For example, when a thin problematic geomaterial layer exists at a shallow depth, the over excavation and replacement method is one of the most suitable and economic method. When a relatively thick loose cohesionless geomaterial layer exists near ground surface,

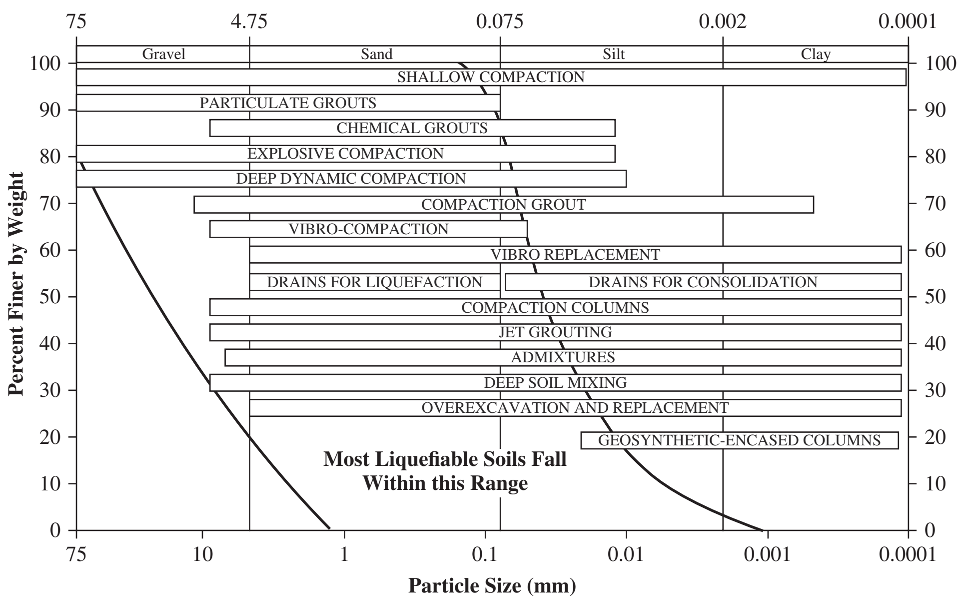

Figure 1.3 Available ground improvement methods for different soil types (modified from Schaefer et al., 2012).

dynamic compaction and vibro-compaction methods are suitable ground improvement methods. When a relatively thick soft cohesive geomaterial layer exists near ground surface, preloading and deep mixing methods may be used. When a site needs to be excavated, tieback anchors, soil nails, deep mixed columns, and jet-grouted columns may be used. When a site needs to be elevated, geosynthetic-reinforced slopes and walls can be good choices. The level of groundwater table often affects the selection of ground improvement methods. For example, when deep excavation happens in ground with a high groundwater table, deep mixed column walls may be better than soil nailed walls because they not only can retain the geomaterial but also can cut off water flow.

Environmental Constraints The environmental constraints may include limited vibration, noise, traffic, water pollution, deformation to existing structures, spoil, and headspace. For example, dynamic compaction induces vibration and noise, which may not be suitable in a residential area. The wet method to construct stone columns by water jetting produces spoil on site, which may be troublesome for a site with limited space. Under such a condition, the dry method may be used instead. Preloading induces settlements at nearby areas, which may be detrimental to existing structures.

Construction Conditions The selection of a ground improvement method should consider the following construction conditions: (1) site condition, (2) allowed construction time, (3) availability of construction material, (4) availability of construction equipment and qualified contractor, and (5) construction cost.

The selection of a ground improvement method must consider whether the site is accessible to its associated construction equipment, such as access road and headspace.

Construction time is one of the most important factors for the selection of a ground improvement method. For example, preloading is a cost-effective ground improvement method to improve soft soil; however, it takes time for the soil to consolidate. The use of prefabricated vertical drains can accelerate the rate of consolidation, but sometimes it still may not meet time requirement. As a result, other accelerated ground improvement methods may be used, such as deep mixing and vibro-concrete column methods.

Most ground improvement methods use specific materials during construction. For example, stone columns and rammed aggregate columns use aggregate. Cement is used for deep mixing and grouting. When natural material is used, such as aggregate or sand, the cost of the material depends on the source of the material and its associated transportation distance. For example, in a mountain area, aggregate is often less expensive; therefore, stone columns or aggregate columns are often a cost-effective solution. In general, the use of locally available material results in more cost-effective ground improvement.

To select a ground improvement method, engineers should gather information about possible qualified contractors and their available construction equipment. It is preferable to use a locally available qualified contractor because this will reduce the mobilization cost and the contractor is more familiar with local conditions.

Construction cost is always one of the key factors that dominate the selection of a ground improvement method. The construction cost should include mobilization, installation, material, and possible disposal costs.

Reliability and Durability Reliability of a ground improvement method depends on several factors, such as the level of establishment, variability of geotechnical and structural conditions, variability of construction material, quality of the contractor, quality of installation, and quality control and assurance. Several researchers have reported that samples from deep mixed columns have a high variability in terms of their unconfined compressive strengths. Automatic or computer-controlled installation processes can reduce the variability of improved geomaterials. The number of well-documented successful or failure case histories is also the evidence of the reliability of a specific ground improvement method.

Ground improvement methods are used for temporary and permanent structures. For permanent structures, the durability of the construction material should be evaluated or considered in the design. For example, geosynthetics have creep behavior. The corrosion of steel reinforcement with time reduces its thickness. The strength of cement-stabilized soil in seawater degrades with time (Ikegami et al., 2002).

1.5.3 Selection Procedure

Figure 1.4 presents the flowchart for the selection of a ground improvement method. For a large and important project, use of a new technology, and/or improvement of a complicated geotechnical site, it is recommended to have a field trial on a representative area on the site so that the design parameters can be verified or adjusted to achieve better performance.

The online interactive technology selection system developed by the SHRP II R02 team at http://www.geotechtools.org/ can be used to assist the selection of ground improvement methods.

1.6 DESIGN CONSIDERATIONS

A design for a ground improvement method typically requires the inputs on geometry of structures, geotechnical conditions, loading conditions, material characteristics, and performance criteria. Typical design parameters and

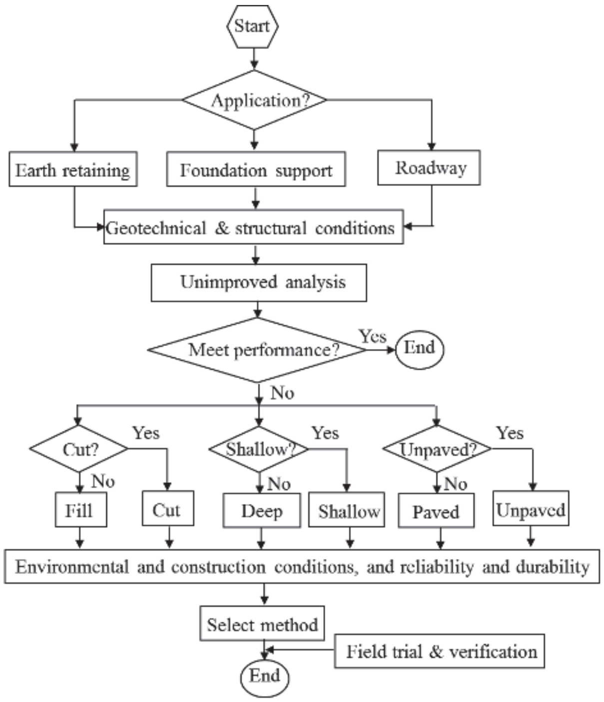

Figure 1.4 Flowchart for selection of ground improvement method.

maximum limits should be considered during design, such as diameter, spacing, and depth of columns, drop energy and improvement depth of compaction, and geosynthetic spacing. Trial-and-error methods may be used for some design procedures. The final design should meet the performance criteria. The outputs of a design typically include the size of improvement zone, plan layout, cross section, amount and properties of materials, and sometimes construction rate and sequence.

In this book, allowable strength design (ASD) is adopted instead of reliability-based design, considering the fact that design methods for most ground improvement methods have not been calibrated using the reliability-based approach due to limited test data. In other words, factors of safety instead of load and resistance factors or partial factors are used in this book.

1.7 CONSTRUCTION

Construction is one of the most important components of ground improvement. No matter how correct the concept is and how good the design is, the design of a ground improvement method must be implemented correctly in the field to reach its maximum performance extents. Chu et al. (2009) provide an overview of construction processes used in geotechnical engineering, including ground improvement methods. Construction should be delivered based on plans and specifications.

There are five types of specifications for transportation construction suggested by the American Association of State Highway and Transportation Officials (AASHTO) Highway Subcommittee on Construction Quality Construction Task Force in 2003 and are listed in Table 1.6. The method specifications have been mostly adopted for ground improvement methods. However, the method specifications with performance criteria have been increasingly used.

Table 1.6 Types of Construction Specifications

Type	Description
Method specifications	Specifications that require the contractor to produce and place a product using specified materials in definite proportions and specific types of equipment and methods under the direction of the agency.
End-result specifications	Specifications that require the contractor to take the entire responsibility for producing and placing a product. The agency's responsibility is to either accept or reject the final product or to apply a price adjustment commensurate with the degree of compliance with the specifications.
Quality assurance specifications	Specifications that require contractor quality control and agency acceptance activities throughout production and placement of a product. Final acceptance of the product is usually based on a statistical sampling of the measured quality level for key quality characteristics.
Performance-related specifications	Specifications that use quantified quality characteristics and life cycle cost (LCC) relationships that are correlated to product performance.
Performance-based specifications	Specifications that describe the desired levels of fundamental engineering properties that are predictors of performance and appear in primary prediction relationships.

Source: AASHTO (2003).

1.8 QUALITY CONTROL AND ASSURANCE

Both quality control and quality assurance ensure the quality of construction; however, they are done at different stages and by different entities. The SHRP II R02 project states: "Quality Control refers to procedures, measurements, and observations used by the contractor to monitor and control the construction quality such that all applicable requirements are satisfied. Quality Assurance refers to measurements and observations by the owner or the owner's engineer to provide assurance to the owner that the facility has been constructed in accordance with the plans and specifications" (Han et al., 2012). Quality control is done during construction while quality assurance is done during construction as well as at the end or after completion of construction. Automatic or computer-controlled installation processes and data collection systems can reduce the variability of improved geomaterials and avoid human errors so that the construction can be better controlled. Quality assurance often involves in situ testing and field monitoring.

1.9 RECENT ADVANCES AND TRENDS FOR FUTURE DEVELOPMENTS

1.9.1 Recent Advances

There have been many recent advances in ground improvement methods. Chu et al. (2009) pointed out that manufacturers have made significant contributions to these recent advances due to their constant innovations and improvements in the equipment. At the same time, researchers have helped improve design methods. Below are a few highlights of the recent advances:

- Different types of column technologies, such as geosynthetic-encased stone columns (Alexiew et al., 2003), controlled modulus (stiffness) columns, hollow concrete columns (Liu et al., 2003), multiple stepped columns (Borel, 2007; Liu, 2007a), X-shape (Liu, 2007b) or Y-shape (Chen et al., 2010) concrete columns, grouted stone columns (Liu, 2007a), T-shaped DM columns (Liu et al., 2012); and composite columns (Jamsawang et al., 2008; Zheng et al., 2009)
- Column-supported embankments (Han and Gabr, 2002; Filz et al., 2012)
- Online interactive technology selection system developed by the SHRP II R02 team (Schaefer and Berg, 2012)
- Cutter soil mixing method to construct trench walls (Mathieu et al., 2006)
- Horizontal twin-jet grouting method (Shen et al., 2013)
- Intelligent compaction on unbound geomaterial (White et al., 2007)
- Use of recycled materials in ground improvement (Han et al., 2011)
- Use of combined technology of two or more ground improvement methods: combination of deep mixed columns with prefabricated vertical drains (Liu et al., 2008); combination of short and long columns (Huang and Li, 2009); and combination of geosynthetic reinforcement and columns (Han and Gabr, 2002; Madhyannapu and Puppala, 2014)
- Sensor-enabled geosynthetics (Hatami et al., 2009)
- Computer monitoring in ground improvement construction (Bruce, 2012)
- Biological treatment (He et al., 2013)

1.9.2 Trends for Future Developments

There are a few general trends for future development in ground improvement methods, which are summarized below:

- Use of combined technologies to create more technically and cost-effective solutions
- Use of intelligent construction technologies with sensors and computer monitoring to improve efficiency and quality of ground improvement
- Use of recycled materials and other alternative materials to make ground improvement methods more sustainable
- Use of end-result or performance-based specifications
- Application of biological treatment in field

1.10 ORGANIZATION OF BOOK

This book has 10 chapters. This chapter is an introduction, which provides an overview of ground improvement methods. Chapter 2 reviews geotechnical materials, testing, and design, which are the bases for the following chapters. Chapters 3–10 are presented based on the classification of ground improvement methods in terms of their functions. Chapter 3 discusses shallow and deep compaction. Chapters 4 and 5 discuss overexcavation and replacement (i.e., shallow replacement) and deep replacement. Chapters 6 and 7 discuss drainage and dewatering and preloading and consolidation. Chapter 8 discusses deep chemical stabilization by grouting and deep mixing. Chapters 9 and 10 discuss in situ ground reinforcement (for cut situations) and fill reinforcement (for fill situations).

PROBLEMS

1.1. Give examples of three geotechnical problems that can be caused by problematic geomaterials.

1.2. List five possible geotechnical problems caused by human activities.

1.3. How can ground improvement methods be classified in terms of their functions?

1.4. What is the basic principle for soil liquefaction? List five possible ground improvement methods that can be used to mitigate soil liquefaction and explain why.

1.5. List five possible methods for shallow ground improvement.

1.6. List five possible methods for deep ground improvement.

1.7. A project site has a 5-m-thick loose gravel layer near ground surface that needs to be improved for foundation support. Which methods may be used for ground improvement? Why?

1.8. Explain why different ground improvement methods are needed for cut-and-fill walls.

1.9. What are the types of construction specifications possibly used in practice?

1.10. Explain why quality control and assurance are so important for ground improvement methods.

1.11. What are the future trends of ground improvement?

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