

# SOIL IMPROVEMENT AND GROUND MODIFICATION METHODS

**PETER G. NICHOLSON**



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## PREFACE

With very few exceptions, everything we construct in our built environment lies in or on the ground. As a consequence, the earth materials involved must be evaluated to ensure that engineering properties will adequately provide for acceptable performance of a project. There are many different properties that must be assessed based on the requirements of the project, and these will vary greatly depending on the overall (and underlying) objectives. One must be careful not to overlook other components that may affect lives and property, including natural and man-made hazards. These may involve natural, constructed and cut slopes, potential flooding and storm surges, earthquakes, and so on.

For most structures, including buildings, bridges, roadways, and engineered earth structures, there are some fundamental “rules” pertaining to the ground that must be followed in order to ensure the “success” of the structure. For example, imposed loads must be supported without ground failure, and within maximum limits of acceptable settlement or deformations. To properly evaluate the capacity of earth materials to adequately support loads, one should have a basic understanding of soil mechanics and be able to perform relatively straightforward design exercises as required for the circumstances. However, this is *as long as the strength parameters are correctly evaluated and ground conditions are well defined*. While load applications can be defined with reasonably good accuracy, it is much more difficult to make an accurate evaluation of earth material properties and their response to imposed loadings. Engineers use a number of methods to estimate the response of earth materials to various loading conditions. While performing full-scale load tests at the field site can produce one of the best evaluations, these types of tests are not often performed due to feasibility and cost restraints. This forces the engineer to rely on interpretations based on experience and a combination of laboratory and in situ test results from field investigations and sampling. Unfortunately, this, in turn, creates a whole additional level of uncertainty arising from questions about everything from testing accuracy, sample disturbance, and sample representation, to natural spatial variability of conditions and material properties in the ground, for example. These are just the basic challenges that face all geotechnical engineers when dealing with designs in or on the ground.

In many cases, the ground conditions and the earth materials are not ideal for proposed or planned development. In these instances, the geotechnical engineer must thoughtfully consider how to address potential problems with plausible solutions. Modification of the earth materials or stabilization of soils can provide a means to achieve the desired goals of assuring adequate engineering properties and/or responses for a variety of applications and conditions. Depending on the initial ground conditions, soil properties, and desired outcomes, the engineer may select from a wide choice of ground improvement and soil stabilization techniques that will help solve challenges of poor site conditions, inadequate soil qualities, mitigation of potential problems, or remedial work.

As development continues throughout the world, many of the most ideal sites have already been built upon, leaving less desirable sites for future use. This is compounded with the desire and need to build larger and safer structures in urban areas, imposing greater loads and/or requiring greater reliability than previously considered. At many locations that may have previously been considered unsuitable for development due to poor soil conditions, ground improvement techniques provide suitable alternatives for new construction. In addition, precious resources of select earth materials may be preserved with better use of existing soils that can be treated to provide acceptable engineering properties and the reuse of waste material or industry by-products.

In many instances, the combination of ground conditions and objectives requires the use of more than one approach or methodology to achieve the desired goals. This may be particularly helpful for large projects where multiple problems exist, where different types of soil strata are encountered, or when surface treatments are needed after a stabilization of deeper materials is completed. For smaller projects, the use of multiple techniques may be cost prohibitive, and a single method, albeit comparatively more expensive in some respect than some others, may be the best solution.

This text presents an overview and discussion of a number of ground improvement methodologies that have been devised over the years. Many of these are fundamental and have existed in some form for a long, long time. Others have developed with advancements in technology, and still others are continually emerging with the ever changing engineering environment. Over the past few decades, there have been significant advancements made in the tools, technology, and materials available to the engineer faced with finding workable, economic solutions to the myriad geotechnical problems that arise. In addition, construction and development have reached new

levels in size, loads, and complexity. Safety issues and environmental concerns have also played an important role in reshaping values and approaches that may have evolved since earlier references on the subjects of soil and ground improvement were published. The intent of this work is not necessarily to prepare one with all of the tools needed to plan and/or design a ground improvement program, but to provide insight to the general civil engineer, contractor, or construction manager as to what tools are now available and what approaches have been effective in solving a wide range of geotechnical challenges. With this background and knowledge, one can be better prepared to consider options when faced with difficult or less than optimal soil and site conditions.

Section I provides a short background on why and where ground improvement is needed; a brief description of the various categories of methods as they apply to controlling one or more types of engineering properties and/or performance; an overview of the types of applications available and tried; an outline of typically desired improvements (objectives); an outline of factors that control the choice of improvement method that may be most suitable; and information about technological advancements that allow new tools and materials to be implemented. Included in Chapter 3 is a brief overview of basic soil mechanics fundamentals, such as soil strength, compressibility (settlement), and fluid flow (permeability) topics. In addition, this chapter describes the performance of typical field investigations with commonly collected and reported data. It is from this data (usually contained in boring logs and geotechnical reports) and correlations with soil characteristics that many ground improvement designs are formulated.

Section II provides full coverage of the topic of soil densification. Beginning with Chapter 4 is a description of objectives and improvements attained by densification of soil, including fundamental soil engineering properties and an overview of liquefaction phenomenon, followed by a thorough explanation of the principles of shallow compaction theory, control of compacted soil engineering properties, and finally, a discussion of field applications, contractual specifications, and quality control described in Chapter 5.

Section III on hydraulic modification provides an overview of how the control of water within the ground can be used to improve soil and site conditions. Strength gains, stability in slopes, seepage, drainage, and consolidation are addressed. A wide variety of methods, including conventional drain and pumps for dewatering, are outlined, along with more innovative techniques utilizing geosynthetics (for drainage and filtration) and electrokinetics



(for dewatering, forced consolidation, stabilization of wastes, contaminant control and/or removal, and as an aid to grouting).

Section IV is devoted to the broad subjects related to stabilization by the addition of admixtures, grouting, and thermal treatments. Chapter 11 outlines the various available materials commonly mixed with soil to improve engineering properties, including natural soils and waste products. The applicability of mixing these various materials with different soil types is also discussed. In addition, Chapter 11 provides a general overview of the mixing methods, engineering property improvement objectives, and common applications for admixture treatments. Chapter 12 is devoted to describing a variety of grouting techniques, objectives, and various applications. Without the addition of materials to be mixed with existing soil, a discussion of thermal treatments is included in Chapter 13. Both heating and freezing methods are described, although heat treatments are usually cost-prohibitive and are rarely used anymore except for use in some geoenvironmental applications. Freezing technologies, on the other hand, have now advanced to the point of being incorporated as viable solutions for a variety of applications and have been used in a number of notable high-profile projects, as described in Section 13.4.3.

Section V outlines techniques that incorporate the use of structural elements for stabilization of existing ground as well as for new construction. Chapter 14 describes how geosynthetic reinforcement materials are utilized for construction of stabilized earth walls, slopes, and as an aid for construction over weak or soft foundation materials. Chapter 15 provides an overview of in situ reinforcement with structural members in the form of soil nails, anchors, tiebacks, and bolts. These methods are primarily used for slope stabilization, tunneling support, and excavation/subsurface foundation support. Chapter 16 describes the relatively simplistic, but very functional, practical, and often aesthetic applications of soil confinement. Cribbs, gabions and mattresses provide multiple functions and have been widely used for retaining walls, slope stabilization, earth structure foundations, and erosion control in channels or other high-energy flow regimes. Cellular confinement with geosynthetic materials and the use of fabricated modular blocks have also added some structural components to traditional geotechnical applications. Then Chapter 17 discusses the use of relatively newer, lightweight technologies and materials, including expanded polystyrene (EPS) foam, industrial wastes, and recycled materials.

Finally, Chapter 18 touches on the ongoing advancements, emerging trends, and new ideas that foster future advancements to soil and ground

improvement. With continuing advancements in ground modification technology, application ideas, and materials, there will certainly be new innovations and untested applications to push new limits of our understanding and appreciation for what can be accomplished.

*Note regarding ASTM Standards:* Throughout this text, references are made to test standards published by the American Standards of Testing and Materials, current at the time of writing. Rather than referencing each test standard in the list of references for each chapter, the Book of Standards is referenced as a whole and a listing of topic related standards is provided at the end of each chapter in which the standards are mentioned.

This is my gift to the practice, students, and anyone interested in an array of amazing ways we can consciously work with our environment while advancing engineering and achieving new successes.

**Peter G. Nicholson**

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**Peter G. Nicholson**

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# ABBREVIATIONS AND ACRONYMS

<b>AASHTO</b>	American Association of State and Highway Transportation Officials
<b>ADSC</b>	International Association of Foundation Drilling
<b>ASTM</b>	American Standards of Testing and Materials
<b>BPT</b>	Becker penetration test
<b>CBR</b>	California bearing ratio
<b>CDW</b>	continuous diaphragm wall
<b>CFA</b>	continuous flight auger
<b>CIP</b>	cast-in-place
<b>CIR</b>	compaction impact response
<b>CIS</b>	continuous impact settlement
<b>CKD</b>	cement kiln dust
<b>CPT</b>	cone penetration test
<b>CPTU</b>	cone penetration test (with pore pressures)
<b>CSV</b>	soil stabilization with vertical columns
<b>CVM</b>	compaction meter value
<b>DCP</b>	dynamic cone penetrometer
<b>DDC</b>	deep dynamic compaction
<b>DMT (flat plate)</b>	dilatometer test
<b>DOT</b>	Department of Transportation
<b>EERC</b>	Earthquake Engineering Research Center
<b>FHWA</b>	Federal Highway Administration
<b>FWD</b>	falling weight deflectometer
<b>GCL</b>	geosynthetic clay liner
<b>GCS</b>	geosynthetically confined soil
<b>GEER</b>	Geotechnical Extreme Events Reconnaissance
<b>GGBFS</b>	ground granulated blast furnace slag
<b>GPS</b>	Global Positioning System
<b>GRS</b>	geosynthetically reinforced soil
<b>HEIC</b>	high energy impact compaction
<b>IC</b>	intelligent compaction
<b>LKD</b>	lime kiln dust
<b>LRFD</b>	load and resistant factor design
<b>MIT</b>	Massachusetts Institute of Technology
<b>MSE</b>	mechanically stabilized earth
<b>MSW</b>	municipal solid waste
<b>NCHRP</b>	National Cooperative Highway Research Program
<b>NDM</b>	National Deep Mixing Cooperative Research Program
<b>OMC</b>	optimum moisture content
<b>PMT</b>	pressuremeter test
<b>PVD</b>	prefabricated vertical drains
<b>QA</b>	quality assurance
<b>QC</b>	quality control
<b>RAP</b>	Rammed Aggregate Pier

<b>RC</b>	relative compaction
<b>RDC</b>	rolling dynamic compaction
<b>RIC</b>	rapid impact compaction
<b>SASW</b>	spectral analysis of surface waves
<b>SCPTU</b>	seismic cone penetration test (with pore pressures)
<b>SPT</b>	standard penetration test
<b>TRB</b>	Transportation Research Board
<b>USCS</b>	Unified Soil Classification System
<b>USDA</b>	U.S. Department of Agriculture
<b>VST</b>	vane shear test
<b>ZAV</b>	zero air voids

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## SECTION I

# Introduction to Ground Improvement and Soil Stabilization



