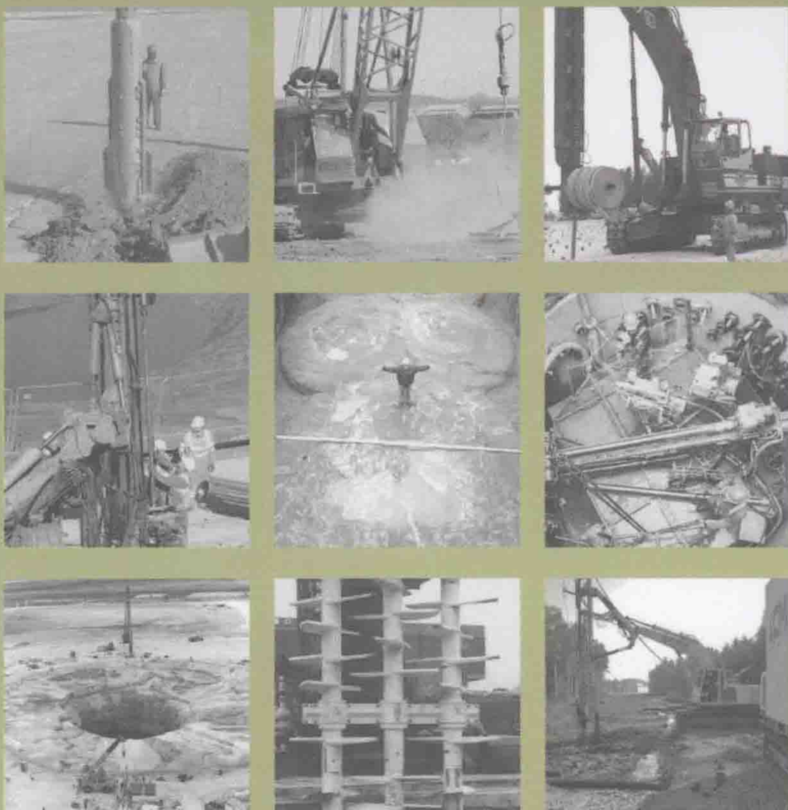
Ground Improvement

Third Edition



Edited by **Klaus Kirsch and Alan Bell**

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Preface

Ground improvement techniques continue to progress in addressing ground engineering problems across the world, particularly in urban areas where land development and reuse need to be efficient not only in the geotechnical engineering but in time, cost, and energy used. As well as in expanding markets, recent growth has also been seen across a range of methods, in increasing productivity due to investment in plant and equipment, and in improvement in technical performance and quality due to electronic monitoring and control methods. Ground improvement methods are also frequently able to demonstrate low carbon impact and excellent sustainability credentials as these issues become more important.

The third edition of this well-known book provides a comprehensive overview of the major ground improvement techniques in use worldwide today. The chapters are fully updated with recent developments and have been written by recognised experts who bring a wealth of knowledge and experience to bear on their contributions.

Ground Improvement is written for civil and geotechnical engineers and for contractors involved in piling and ground engineering of any kind. Advanced graduate and postgraduate civil engineering and geotechnical students will find the book most helpful in guiding their studies.

Editors

Klaus Kirsch was a main board director of Keller Group plc, responsible for Group operations in Continental Europe and overseas until his retirement in 2001, and thereafter served the Group as adviser for its technical development. He has been involved with some fundamental breakthroughs in foundation engineering, notably the introduction of vibro stone column technology in the USA, and was instrumental in the development of a new generation of depth vibrators. He has authored many papers and also a book on vibratory deep compaction.

Alan Bell is technical consultant to the Keller Group plc. He was managing director of Keller in the UK until 2009 and has had close involvement in ground improvement techniques and their development at both national and international levels for over 30 years, including the introduction to the UK of vibrated concrete columns. He has contributed many technical publications, and is a visiting professor at the University of Strathclyde in Glasgow.

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Chapter 1

Introduction and background

Alan Bell and Klaus Kirsch

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1.1 PURPOSE OF GROUND IMPROVEMENT PROCESSES

When faced with difficult ground conditions at a project site, an engineer has a number of possible strategies to employ in order to achieve the project objectives. The most obvious is to find another site, but this is only very rarely practicable. Pressure on land, the need to use poor sites, and the location of many cities in estuaries or river situations make this option increasingly difficult. Another option is to redesign the building or structure to accommodate the prevailing difficulties arising from the ground, and where possible this is a good solution. Yet another possibility is to remove the troublesome ground and to replace it with more suitable material, and this can often be cost effective providing the depth to be addressed and the quantities concerned are relatively small.

If none of these avoiding strategies are technically or economically realistic, then the prevailing ground conditions must be addressed. A common potential solution is to adopt a system such as piling, in order to bypass the difficult ground and found in suitable material. However, this can be expensive and time consuming and may actually be difficult to achieve in very deep ground. In addition, for some classes of geotechnical problem such as tunnelling, piling may be unsuitable. For such reasons improving the ground to achieve an appropriate engineering performance is an increasingly successful approach worldwide when faced with problem ground conditions, partially evidenced by the two earlier editions of the present book.

Ground improvement is normally understood as the modification of the existing physical properties of the ground beneath a site to sufficient depth to enable effective, economic, and safe permanent or temporary construction in practical timescales. Typical objectives would be one or a combination of the following:

(1) An increase in shear strength or density to improve bearing capacity or to provide sufficient support for excavations or tunnels
(2) A reduction in compressibility to minimise total or differential settlements of buildings or structures, or other deformations in the ground arising from excavation or tunnelling
(3) A reduction in permeability to minimise flow of ground water to prevent inundation or water damage or to isolate zones of contaminated ground water
(4) Conversely, an improvement in deep drainage in order to assist preloading or surcharge techniques
(5) Controlled displacement of the ground in order to dispel previous differential settlements or ground distortions, or to compensate for ground movements arising from excavation or tunnelling
(6) Prevention of liquefaction or reduction in lateral spreading beneath or near both new and existing structures during earthquakes, employing densification, replacement with stronger materials, or deep drainage

The ground improvement processes used to deliver these objectives form the subject matter of this book, as set out in Section 1.2.

It should be noted that recent environmental legislation coupled with the need to recycle previously developed sites has led to considerable growth in a different concept of improving the ground—namely, to minimise or remove the hazardous effects of sites contaminated by toxic waste or chemical by-products from industrial processes. This subject is beyond the scope of this book and the reader should refer to the specialist literature on these topics.

1.2 WHAT THE BOOK COVERS

This third edition of *Ground Improvement* will provide the reader with a sound basis for understanding and further study of the most widely used processes for ground improvement.

Developments in equipment and methods have continued apace since the publication of the second edition, and where relevant are included in the ensuing chapters of this book. Indeed, the editors are grateful to the authors of the following chapters in the book, all of whom are recognised experts in their respective fields. Their contributions provide an overview of the processes concerned and the key geotechnical and design considerations involved, together with details of the equipment needed for successful execution. The methods are well illustrated with relevant case histories revealing applications in practice.

Since soil strength and compressibility are highly influenced by the particle packing or density in most engineering soils, densification is a useful approach. In granular soils this is frequently achieved most efficiently using vibratory methods to force particles into more closely packed configurations.

Methods employing tools in which the vibrator can be taken deep into the ground are very efficient and are described in Chapter 2. Another important global technique is dynamic compaction, which employs large weights dropped from height to create the compactive energy needed, and is dealt with in Chapter 3.

In cohesive soils, an increase in shear strength and reduced compressibility can be achieved by consolidation, usually achieved by direct loading. The process is time dependent and can be hastened and better controlled using deep prefabricated drains and associated methods. These are comprehensively dealt with in Chapter 4.

The remaining six chapters in the book deal with various techniques involving the injection of materials into the ground in order to provide geotechnical improvement of various kinds. Chapter 5 describes permeation grouting, which involves the displacement of the ground water or air in soil pores or rock fissures, using an agent, usually termed grout, which is sufficiently fluid to permeate the ground. This agent subsequently hardens to create the intended improvements. Jet grouting is covered in Chapter 6. This technique uses powerful jets of grout, or grout with other fluids to displace or mix with the ground. In this way zones of ground with increased strength or stiffness, or barriers to flow can be formed. Soil fracture grouting is a displacement technique and employs finely controlled injection of relatively thin but multiple veins of grout to address excess building settlement, to lift structures, or to compensate for ground movement during tunnelling. It is described in Chapter 7. Compaction grouting, developed in the United States and now used around the world, is dealt with in Chapter 8. This is also a displacement method and can be used to compact or reinforce the ground with introduced grout. Recent changes in terminology originating in the United States are helpfully explained in detail. In-situ soil mixing processes continue to develop worldwide, and Chapter 9 provides comprehensive coverage of the main deep mixing processes in use across the world and describes several new techniques, such as the trench-mixing

TRD and the panel-mixing CSM approaches. Several new case histories are also included. Chapter 10 covers dry soil mixing using the Scandinavian approach, as this process has continued to see worldwide application.

In the remainder of the present chapter several topics which would not justify a separate chapter are included, such as the history of the two main means of creating improvement (see Section 1.3). Brief notes on health and safety for ground improvement sites are included in view of its common relevance (Section 1.4). The effects of ground improvement on greenhouse gas emissions have increasingly been addressed since the second edition and now warrant inclusion (Section 1.5). Overviews of two ground improvement techniques which, by their nature, have somewhat limited ranges of application have also been included. Blasting can be an effective means of improving granular soils by densification and is described in Section 1.6. The only reversible ground improvement process of ground freezing can be powerful where applicable, and is outlined in Section 1.7.

1.3 HISTORICAL DEVELOPMENT

Since earliest times humankind has found ways of dealing with poor ground in order to form pathways and later roads using such simple strategies as placing beds of reeds or saplings to support the weight of people and animals over soft ground. It is only relatively recently that the means of engineering difficult ground by compaction, consolidation, or by adding materials by permeation or mixing has seen significant advances. These processes developed during and after the Industrial Revolution, but mainly in the early twentieth century. In these years, better understanding of soil mechanical behaviour emerged through the work of Terzaghi and others; practical ground investigation became possible; and equipment and materials development reached the stage that significant volumes of soil could be treated. Two main approaches are in worldwide use today, namely deep vibratory treatment and injection or mixing of grouts. A brief historical review of these two topics follows in view of their importance.

Kirsch and Kirsch (2010) describe how depth vibrators were developed in Germany in the 1930s. Initially aimed at concrete densification, they soon were applied more effectively for sand compaction. Consequently, deep vibratory stabilisation for both natural and filled cohesionless soils was used widely for a range of applications in Germany and further afield, particularly after 1945. A further major area of application was added in 1956 when depth vibrators were employed to form stone columns in silty materials, leading to the application to cohesive soils more generally.

Further development and improvement of the special plant and equipment necessary for the execution of this ground improvement method together with the experience gained in practice considerably increased the range of application in foundation engineering, notably after the advantages of the method were recognised mitigating the liquefaction potential of soils in earthquake-prone regions by densification and/or drainage. Today the method can effectively be designed for its purpose and can be well controlled during its execution. It is interesting to note that first steps towards eventual process automation are already being used in practice.

The idea of injecting cement slurries, known as grouts, into the ground to improve their engineering characteristics also saw early development. It is believed that grouting of subsoil was first performed more than 200 years ago in France (about 1810) by the French engineer Charles Bérigny, using a suspension of pozzuolana cement in water to stabilise alluvial deposits forming the foundations of a bridge (Glossop 1961). Further development of the grouting process (procédé d'injection) in the nineteenth century was by the introduction of new hydraulic binders, particularly the invention of Portland cement in 1821. The method was already well developed at the outset of World War I with the use of pumps, pressure control, and the need for filtration all established.

Direct injection of simple cement grouts into the ground was often hampered by failure to permeate the ground, either because the pore size distribution of the soils were small in comparison to the grading of the cements or because the methods of injection, often from open-ended casings, were too crude. Low pressure permeation grouting using simple cement grouts is usually limited to gravel containing perhaps some coarse sand.

Important steps forward in addressing this limitation were accomplished by attention to the materials used for injection. Dutchman Hugo Joosten in Germany, by his invention of the Joosten system, used chemicals in the form of highly concentrated sodium silicates and calcium chloride as grout material to form precipitate silicates in situ to treat sandy cohesionless soils (Joosten 1926). These much finer-grained grouts could permeate more readily than simple cements. The method was then widely used in Berlin in the construction of the underground railway.

By the late 1950s a single shot approach was developed by mixing organic hardeners and sodium silicate before injection. Today various proprietary re-agents are available as hardeners, with widely differing properties. Another development involved creating, by fine grinding, so-called microfine or ultrafine cements, which also allow permeation into coarse sands or sometimes even finer soils, and these are also in use today. Various new chemical formulations were also developed in the 1960s and 1970s which enabled even finer grained cohesionless soils to be treated, but with limited application today due to concerns about toxicity.

Developments for dealing with some of the limitations of soil grouting also came from improvement in equipment. The invention of the tube à manchette pipe or TaM pipe (Ischy 1933), still very much employed in grouting processes today, was very significant. These pipes, consisting of grout ports with rubber sleeve valves, are placed in boreholes to attain the depths required, and are grouted in place using a relatively weak sleeve grout. One set of ports can be isolated at a time, and grout can be injected into the surrounding ground after it expands the surrounding seal and breaks the sleeve grout. This enables control of grout volume or pressure during injection at specific points in the subsoil. Littlejohn (1993) provides a useful summary of the history of injection processes.

Subsequent grouting development has concentrated more on the development of entirely new ground improvement processes using simple cement grouts, partly due to concerns over toxicity of some chemical grouts and partly to the desire for improved performance. By the early 1990s jet grouting; compaction grouting; soilfracture grouting; and soil mixing methods were all widely and successfully applied in addition to permeation grouting (e.g., Bell 1994). Since then there has been increased use of all of these, and soil mixing in particular is now more widely used. Further technical development of all grouting methods has continued, particularly in relation to electronic monitoring and control on site. Some history on these methods is included in Chapters 6 through 9.

1.4 HEALTH, SAFETY, AND ENVIRONMENTAL CONSIDERATIONS

In recent years the construction industry worldwide has seen significant improvements in the safety of construction workers and the public. Legislation, formal management systems, and motivational training have all played their part. Indeed, safety is a critical component of all construction in general and ground improvement in particular as it inevitably contains aspects that are potentially unsafe. The specialist piling and ground improvement industries are very committed to safety and minimising the environmental effects of construction. For example, the European Federation for Foundation Contractors (EFFC) holds the attainment of the highest standard of safety as a key objective and its members have established a health and safety charter, together with publications and advice on the subject.

Extensive procedures involving risk assessments, work instructions, method statements, and training, which together form site-specific project safety plans, are now commonly used in minimising safety and environmental hazards through general and specialist ground improvement contractors, as well as client and public bodies. The following provides some limited comment on the health, safety and environmental impact of ground improvement processes as a brief introduction to the subject in view of its consistent importance. However it cannot be a comprehensive presentation of the subject, and reference needs to be made to local regulations and written procedures, and the specialists in the particular processes.

1.4.1 Site mobilization and demobilization

In common with all site operations, health and safety considerations form an integral part of establishing construction activity and leaving after project completion. Clear delineation is needed for site entrances and exits, temporary roads for materials' supply trucks, pedestrian walkways, site boundaries with protection and exclusion of the general public, and clear storage and load/unload areas. The working surface, suitably lit, for all plant and equipment should be engineer-designed and capable of maintaining support in all weather. Simple site procedures can be used to ensure this work is done to the appropriate standard prior to commencement (e.g., by the use of a working platform certificate). If the platform is not integrated into the final works, a plan for its disposal is required. Overhead power lines and underground services need to be clearly identified and delineated, together with instructions as to avoidance or minimum clearances given by appropriate authorities prior to commencing work. Measures need to be introduced so that noise and dust are minimised and kept within agreed limits for the general public beyond the site boundaries, and for construction personnel on site.

Site operatives are required to be trained and experienced with certified skills, or if in training have adequate supervision from suitably experienced colleagues. Safety equipment supplied must be worn at all times and employed in accordance with training and advice given. Often the processes require physically lifting materials such as cement bags, or other heavy objects such as hoses or steel casing. Specific training in proper lifting procedures and specified max loads for any lift should be taken as a minimum approach. It is important to employ lifting devices such as winches and crane arms in all cases where limits are exceeded, and these may in some cases form part of the drilling equipment

Operational hazards on site must be identified in advance and plans put in place to deal with them. Some ground-improvement processes generate spoil from the ground and this needs to be controlled to prevent injury near drilling or boring equipment, or from flying debris necessarily generated on dynamic compaction sites. The spoil must be controlled on site to minimise deterioration of working and access areas, and measures taken for its safe re-use or disposal so as not to contaminate the immediate environment. Trip hazards such as open boreholes must be clearly marked on site.

The plant and equipment used to perform any ground improvement process needs to be in good operating condition. Since many pieces of equipment are often used together to enable the process to be efficiently executed on site, proper consideration needs to be given to all items including any attachments, not only the large plant. Safety precautions and operating instructions are generally published for each piece of equipment, including initial preparation on site, and should be reviewed prior to use and updated in the event of modifications or the introduction of revised items of equipment. Regular maintenance, inspection, and certification of all equipment at agreed intervals are needed to ensure continued safe operating equipment.

Measures including automatic cutoff devices or guarding should be in place to prevent injury to operatives near to rotating drilling or boring equipment. The correct mode for moving and operating equipment must be made clear, and in moving there must be clear guidance to ensure the safety of adjacent personnel.

One aspect particular to grouting processes is the condition of the grout hoses and hose connections. It is important that these be rated to safely withstand the pumping pressure, be operated properly and regularly checked and certified. Failure of the hoses or hose connections can result in the high-energy release of grout, potentially resulting in severe injury. Also, whipping high energy hoses for grout, air, or other fluids are highly dangerous, and whip checks at connections should be used. For both air and pressure grout equipment, clear procedures for pressure release in any circumstances including cleaning, must be identified and adhered to.

1.4.2 Hazardous materials

Material safety data sheets for all materials to be used on the project should be reviewed and training given prior to beginning work. Cements and other cementitious materials or chemicals are commonly used in grouting and soil mixing and other processes and are very caustic. Prolonged exposure to the skin or eyes can cause severe chemical burns and permanent injury. Consequently, risk assessments and the use and enforcement of safe working methods are vital. Hazards inherent from the design approach are also to be considered in minimising injury or illness in site personnel and the general public.

1.5 GREENHOUSE GAS EMISSIONS

In 1997 the Kyoto protocol was ratified by participating nations, and is a treaty aimed at stabilising greenhouse gas concentrations in the Earth's atmosphere at a level to limit anthropogenic (human) interference with the climate system. Indeed, there is now worldwide awareness, and acceptance in the scientific community, of the greenhouse gas effect on global climate. The construction industry, in common with other industries, is consequently looking at its own emissions, so that these can be better understood and consequently minimised or even eliminated. Methodology and databases are now available for identifying and calculating the key inputs. This is often done by employing the concept of carbon dioxide equivalent to the key greenhouse gases released by the process (for example, Hammond and Jones 2011).

Calculations can also be used to compare different ground improvement and other geotechnical processes such as piling methods, and this can be important in minimising the total carbon dioxide equivalent for a given project. Wintzingerode et al. (2011) list seven key potential sources of greenhouse gas emissions for ground improvement systems, namely:

- Raw materials
- Transport for materials
- Transport for personnel
- Transport for equipment
- Product manufacture
- Waste or spoil emissions
- Transport for waste or spoil

Such calculations can be used to examine different components of the construction process, and these clearly show the large impact of manufactured construction materials such as Portland cement and steel, with other inputs, notably the energy requirement for construction plant and equipment, usually much lower than for materials, as seen in comparative databases (e.g., EA 2010, GEMIS 2010). The other emissions are often very small for ground improvement projects. Nevertheless, each project must be studied separately. For example, the degradation of spoil consisting of peats or highly organic soils removed from below the water table can generate relatively large emissions (Hall 2006).

Several bases for comparison are possible and it is important to understand the implications of these. For example, Zöhrer et al. (2010) compare different methods using MJ/lineal metre for comparison. This provides a means of comparing a wide range of products, and is illustrated in Figure 2.18 in Chapter 2. The strong conclusion was the very low impact of the vibro processes by comparison with the others due to the use of quarried materials with this system.

Egan and Slocombe (2010) used several actual foundation projects for their basis of comparison and found that replacement or partial replacement of piles with vibro stone column ground improvement systems resulted in between 92.5%–96% reduction in embodied carbon dioxide, and where piles could only partially be replaced a reduction of 36.4% was noted.

Wintzingerode et al. (2011) draw attention to comparing the total emissions per unit load carried, and also the total emissions per square metre of final construction. Examples illustrate the large reductions of about a factor of 11 in carbon dioxide equivalents gained by switching from bored piles to vibro stone columns.

Pinske (2011) compared five different ground improvement methods (deep soil mixing, vibro replacement, vibro compaction, deep dynamic