A guide to ground treatment

J M Mitchell
FM Jardine

This report was largely completed before 1993 but has been reviewed and updated in the light of comments made in 1999 and 2000 by the steering group for CIRIA Research Project 604, “Treated ground – engineering properties and durability” (issued as CIRIA publication C572, 2002).
Summary

An introduction to ground treatment methods, this report explains the available techniques and their variations by systematic descriptions of the physical principles, the equipment, the methods and the effectiveness that can be expected for each. General guidance is given on the matters to be considered when ground improvement is being considered as an option. Particular attention is given to the responsibility for design and the roles of those involved in the design process and in control of the treatment. Guidance is given on selection of appropriate techniques by reference, where possible, to comparative studies and to case histories. Individual techniques are described separately, with key references on their design and use. The techniques are grouped as those that achieve improvement by vibration, adding load, structural reinforcement, structural fill, admixtures, grouting, thermal methods and vegetation.

A guide to ground treatment

Mitchell, J M and Jardine, F M

Construction Industry Research and Information Association

CIRIA publication C573 © CIRIA 2002 ISBN 0 86017 573 1

Keywords
Ground improvement, piling

Reader interest
Design, specification, construction, managers, clients and supervising engineers involved in civil and geotechnical works

Classification
Availability Unrestricted
Content Subject area review
Status Committee-guided
User Civil, geotechnical and structural engineers, engineering geologists

Published by CIRIA, 6 Storey’s Gate, Westminster, London SW1P 3AU.

All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, including photocopying and recording, without the written permission of the copyright-holder, application for which should be addressed to the publisher. Such written permission must also be obtained before any part of this publication is stored in a retrieval system of any nature.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold and/or distributed with the understanding that neither the authors nor the publisher is thereby engaged in rendering a specific legal or any other professional service. While every effort has been made to ensure the accuracy and completeness of the publication, no warranty or fitness is provided or implied, and the authors and publisher shall have neither liability nor responsibility to any person or entity with respect to any loss or damage arising from its use.
Foreword

This report presents the results of a research project carried out for CIRIA by the late J M Mitchell of Ove Arup and Partners. His untimely death prevented John Mitchell from completing both this report and what was intended as a more detailed accompanying report on deep compaction techniques. John had assembled much more material than is given in this report and, prior to preparing the final document, had reached the stage of selecting what should be included and what left out. In this, he and CIRIA’s research manager, F M Jardine, had been working closely together and had agreed the general structure and much of the content and to share authorship. Since then, with the help of John’s colleagues at Arup Geotechnics, the second author took over completion of the report. It is hoped that it does justice to John’s work and to his intentions for it.

This report was largely completed before 1993 but has been reviewed and updated in the light of comments made in 1999 and 2000 by the steering group for CIRIA Project 604 “Treated ground: engineering properties and durability”.

Following CIRIA’s usual practice, this project was guided by a steering group, which during the course of the project comprised:

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mr C Garrett (chairman)</td>
<td>then of Kent County Council</td>
</tr>
<tr>
<td>Dr A L Bell</td>
<td>Keller Ground Engineering Ltd</td>
</tr>
<tr>
<td>Dr J A Charles</td>
<td>Building Research Establishment</td>
</tr>
<tr>
<td>Dr D A Greenwood</td>
<td>then of Cementation Piling &amp; Foundations Ltd</td>
</tr>
<tr>
<td>Dr R A Jewell</td>
<td>then of GeoSyntec Consultants</td>
</tr>
<tr>
<td>Dr L M Lake</td>
<td>then of Mott MacDonald Group</td>
</tr>
<tr>
<td>Mr M P Moseley</td>
<td>Keller Ground Engineering Ltd</td>
</tr>
<tr>
<td>Mr N A Trenter</td>
<td>then of Sir William Halcrow &amp; Partners.</td>
</tr>
</tbody>
</table>

CIRIA’s research manager for the project was Mr F M Jardine.

Although the report does not include post-1993 modifications of techniques or many recent case histories, it has been reviewed by the CIRIA steering group for Research Project 604, who recommended its publication and provided comment. Some additional notes are given in italics at the start of sections to draw attention to recent changes not fully addressed in the report.

Note

Government reorganisation has meant that DETR responsibilities have been moved variously to the Department of Trade and Industry (DTI), the Department for the Environment, Food and Rural Affairs (DEFRA), and the Department for Transport, Local Government and the Regions (DTLR). References made to the DETR in this publication should be read in this context.

For clarification, readers should contact the Department of Trade and Industry.
ACKNOWLEDGEMENTS

The project was funded by Construction Directorate of the Department of the Environment, Transport and the Regions, by CIRIA and by CIRIA’s Core Programme.

CIRIA is grateful for the help and advice given to the project by many firms and individuals and particularly those who shared their knowledge with John Mitchell in many discussions about ground treatment techniques. He would have wished to acknowledge these individuals by name, but as we cannot be sure of including all, we hope they will understand the acknowledgement not being specific.

The help of members of the RP604 steering group who checked and provided additional text is also gratefully acknowledged, particularly Dr D H Beasley of Halcrow Group Limited, T J P Chapman of Ove Arup and Partners, S Everton of Gibb Limited, Mr W M Kilkenny of WS Atkins Consultants, Mr C Raison of Chris Raison Associates, Dr J M Reid of TRL, and T Schofield of Stent Foundations Limited.

CIRIA and the authors gratefully acknowledge the support of these funding organisations and the technical help and advice provided by the members of the steering group. Contributions do not imply that individual funders necessarily endorse all views expressed in published outputs.

Acknowledgement is made to the following organisations for permission to use their photographs:

- Figure 3.2 Ove Arup & Partners, and air photo Hunting Surveys Ltd
- Figure 4.9 GKN Keller, now Keller Foundations Ltd
- Figure 4.11 Cementation Piling and Foundations Ltd, now Kvaerner Foundations Limited
- Figure 4.13 Dr H J Walbancke, Binnie, Black and Veatch
- Figure 4.14 Dr H J Walbancke, Binnie, Black and Veatch
- Figure 4.15 Ove Arup & Partners
- Figure 4.18 BRE
- Figure 6.10 F M Jardine.
Contents

Summary.................................................................................................................2
Foreword...................................................................................................................3
List of tables ............................................................................................................8
List of figures ..........................................................................................................9

1 INTRODUCTION...............................................................................................13
1.1 The option of improving the ground..............................................................13
1.2 Ground improvement......................................................................................15
1.3 Principal methods for ground improvement..................................................15
1.4 Purposes and effects of ground treatment......................................................16
1.5 References.......................................................................................................19

2 RESPONSIBILITY FOR DESIGN...................................................................21
2.1 Promoter.........................................................................................................21
2.2 Designer..........................................................................................................23
2.3 Specialist contractor.......................................................................................24
2.4 References.......................................................................................................25

3 THE DESIGN PROCESS...................................................................................27
3.1 Site investigation..............................................................................................27
3.2 Assessing possible risks in ground improvement projects............................31
3.3 Choice of treatment technique.......................................................................35
3.4 Discussion with specialist contractor..............................................................36
3.5 Testing programme.........................................................................................37
3.6 Contract documents.......................................................................................40
3.7 Supervising the contract.................................................................................40
3.8 Monitoring performance.................................................................................42
3.9 References.......................................................................................................43

4 IMPROVEMENT BY VIBRATION.................................................................49
4.1 Vibro-compaction............................................................................................49
4.2 Vibro stone columns.......................................................................................55
4.3 Dynamic compaction.....................................................................................61
4.4 Rapid impact compaction..............................................................................67
4.5 Vibratory probing............................................................................................69
4.6 Compaction piles...........................................................................................74
4.7 Blasting............................................................................................................77
5 IMPROVEMENT BY ADDING LOAD OR INCREASING EFFECTIVE STRESS ......................................................... 83
  5.1 Pre-compression .................................................................................. 83
  5.2 Vertical drains .................................................................................. 89
  5.3 Inundation ......................................................................................... 99
  5.4 Vacuum pre-loading .......................................................................... 103
  5.5 Dewatering fine-grained soils .............................................................. 106
  5.6 Pressure berms ............................................................................... 111

6 IMPROVEMENT BY STRUCTURAL REINFORCEMENT .......... 113
  6.1 Reinforced soil ................................................................................. 114
  6.2 Soil nailing ...................................................................................... 124
  6.3 Root or micro-piles .......................................................................... 131
  6.4 Slope dowels .................................................................................. 135
  6.5 Embankment piles .......................................................................... 140

7 IMPROVEMENT BY STRUCTURAL FILL .................................. 145
  7.1 Removal and replacement ................................................................. 146
  7.2 Displacement ................................................................................... 150
  7.3 Reducing load ................................................................................ 153

8 IMPROVEMENT BY ADMIXTURES ........................................... 157
  8.1 Lime columns (Swedish method) ...................................................... 158
  8.2 Lime and cement columns (Japanese method) .................................. 161
  8.3 Mix-in-place by single auger .............................................................. 165
  8.4 Lime stabilisation of slopes ............................................................... 166
  8.5 Lime stabilisation of pavements ......................................................... 167
  8.6 Cement stabilisation of pavements ................................................... 170

9 IMPROVEMENT BY GROUTING ............................................... 173
  9.1 Grouting processes .......................................................................... 173
  9.2 Permeation grouting ....................................................................... 186
  9.3 Hydrofracture grouting .................................................................... 191
  9.4 Jet grouting ..................................................................................... 194
  9.5 Compaction, squeeze and compensation grouting ......................... 200
  9.6 Cavity filling ................................................................................... 206

10 IMPROVEMENT BY THERMAL STABILISATION ..................... 209
  10.1 Artificial ground freezing ................................................................. 209
  10.2 Artificial ground heating ................................................................. 216

11 IMPROVEMENT BY VEGETATION ......................................... 221
  11.1 Definition ...................................................................................... 221
  11.2 Principle ........................................................................................ 221
  11.3 Description and applications ........................................................... 221
  11.4 Limitations .................................................................................... 222
  11.5 Design .......................................................................................... 223
  11.6 References ................................................................................... 224
12 OPTIONS FOR CHOICE ................................................................. 225
  12.1 Combinations of techniques ................................................. 225
  12.2 Discussion on choice of methods ......................................... 227
  12.3 References ........................................................................... 228

APPENDICES

A1 SETTLEMENT OF FILLS ............................................................. 233
  A1.1 Under self-weight (creep settlement) ...................................... 233
  A1.2 Under increased load ........................................................... 233
  A1.3 Because of inundation ......................................................... 233
  A1.4 By consolidation ................................................................. 234
  A1.5 References ......................................................................... 234

A2 COMPARATIVE CASE HISTORIES .............................................. 237
  A2.1 Comparisons of techniques .................................................. 237
  A2.2 References ......................................................................... 245
Tables

Table 1.1 Benefits to construction work of different ground treatment techniques... 17
Table 2.1 The design and communication process for ground improvement ...... 22
Table 2.2 Responsibilities for design and construction of ground treatment works 23
Table 3.1 Geotechnical information typically needed for different treatments ...... 32
Table 3.2 Key questions for the promoter...................................................... 33
Table 3.3 Applicability of foundation soil improvement for different structures and soil types............................................................. 34
Table 3.4 Engineering risks in ground improvement........................................ 35
Table 3.5 Types of tests and observations used to control and assess ground treatment................................................................. 38
Table 3.6 Routine monitoring of vibro-replacement and dynamic compaction..... 41
Table 4.1 Adverse situations for vibro-replacement........................................... 59
Table 4.2 Adverse situations for dynamic compaction..................................... 64
Table 5.1 Effect of pre-compression on phases of settlement.......................... 84
Table 5.2 Types of vertical drains................................................................. 92
Table 5.3 Dimensions and materials of some prefabricated drains .................. 93
Table 5.4 Two examples of vacuum pre-loading............................................. 104
Table 6.1 Types of improvement by structural reinforcement.......................... 114
Table 6.2 Application of structural reinforcement methods............................. 114
Table 7.1 Lightweight fill materials.............................................................. 153
Table 8.1 Installation of data of deep chemical mixing.................................. 162
Table 8.2 Approximate cement contents for materials capable of being stabilised to produce cement-bound roadbases and sub-bases................................. 171
Table 9.1 Grouting processes associated with different types of ground........... 176
Table 9.2 Groutability of particulate grouts in soils and fissured rocks.......... 177
Table 9.3 Typical characteristics of chemical grouts...................................... 178
Table 10.1 Open and closed systems of artificial ground freezing.................... 210
Table 10.2 Ground freezing to create arches of frozen ground around tunnel excavation................................................................. 212
Table 10.3 Performance of freezing tunnel excavation.................................... 212
Table 10.4 Minimum heat treatment temperatures for different applications... 217
Table 11.1 Approaches to slope protection and erosion control....................... 223
Table 11.2 Effects of vegetation on slope stability........................................ 224
Table 12.1 Relative order of costs and settlements for foundation options........ 228
Table A1.1 Settlement of fills under self-weight............................................. 233
Table A1.2 Compressibility of untreated fills................................................. 234
Table A2.1 Some examples where alternative techniques of ground treatment were considered.......................................................... 238
Table A2.2 Average settlements produced by ground treatment and treatment costs 240
Table A2.3 Settlement of experimental houses at Corby.................................. 241
Table A2.4 Summary of some dynamic compaction trials............................ 245
Figures

Figure 2.1 Comparisons of settlement observations of foundations on piles and on improved ground ............................................................ 24
Figure 3.1 Sequence for site and ground investigation .............................. 29
Figure 3.2 Example of usefulness of aerial photographic interpretation .......... 30
Figure 3.3 Foundation options ............................................................ 36
Figure 3.4 Arrangement of a zone test ................................................... 39
Figure 3.5 Skip load test: (a) view of arrangement; (b) results of test on untreated ground ............................................................ 39
Figure 3.6 BRE levelling station ............................................................. 42
Figure 4.1 Grading range of soils usually suitable for vibro-compaction .......... 50
Figure 4.2 Principle of vibro-compaction .............................................. 50
Figure 4.3 Idealised response to vibration .............................................. 51
Figure 4.4 Effect of increasing fines content on effectiveness of vibratory compaction ............................................................ 52
Figure 4.5 Typical vibrator for vibro-replacement and vibro-compaction ........ 53
Figure 4.6 Completing one compaction point: vibro-compaction ................ 53
Figure 4.7 Grading ranges of soils usually suitable for vibro-compaction and vibro-replacement ............................................................ 55
Figure 4.8 Principle of vibro-replacement .............................................. 56
Figure 4.9 Vibro-replacement plant ........................................................ 57
Figure 4.10 Vibro-replacement: construction process ................................ 57
Figure 4.11 Stone column for strip footing of three-storey housing project; demolition debris surrounding the column .............................. 58
Figure 4.12 Idealised stress and displacement at a point below dynamic compaction .............................. 61
Figure 4.13 Laboratory modelling of dynamic compaction (6.7 kg tamper, 1.5 m drop) ............................................................ 62
Figure 4.14 Exposed face of dynamically compacted ground ...................... 62
Figure 4.15 General view of first pass of dynamic compaction at a site in Cwmbran .............................. 63
Figure 4.16 Observations of resultant peak particle velocities with distance from tamping point ............................................................ 65
Figure 4.17 Depth of influence and energy per blow for dynamic compaction .... 65
Figure 4.18 Rapid impact compactor ..................................................... 67
Figure 4.19 Tamping foot of rapid impact compactor ................................ 68
Figure 4.20 Vibratory probing ............................................................... 69
Figure 4.21 Three types of vibratory probe .............................................. 70
Figure 4.22 Vibro-compozer process ..................................................... 71
Figure 4.23 Compaction of loose sand near piles .................................... 74
Figure 4.24 Installation of compaction piles ............................................ 75
Figure 4.25 Ground settlement as a function of the number of charges .......... 76
Figure 4.26 Surface settlements after successive firings ............................ 76
Figure 4.27 Typical firing pattern ........................................................ 76
Figure 5.1 Types of settlement ................................................................. 84
Figure 5.2 Compensating primary settlement by surcharging ......................... 85
Figure 5.3 Stage construction .................................................................. 85
Figure 5.4 Settlements of a surcharged opencast backfill .............................. 86
Figure 5.5 The concept of vertical drains .................................................... 89
Figure 5.6 Vertical drain geometry ............................................................ 90
Figure 5.7 Types of drain installation and effects ............................................ 91
Figure 5.8 Installation of band drains ........................................................ 93
Figure 5.9 Two band drains and mandrels .................................................. 94
Figure 5.10 Settlement and pore pressure dissipation of soft clay with sand drains below an embankment ....................................................... 95
Figure 5.11 Collapsible soil mechanisms ...................................................... 99
Figure 5.12 Effect of loading and wetting a collapsible soil ............................. 100
Figure 5.13 Settlements of inundated cohesive fill ....................................... 101
Figure 5.14 Principle of vacuum pre-loading ............................................... 103
Figure 5.15 Arrangement of vacuum pre-loading with surcharge and vertical drains .......................................................... 103
Figure 5.16 Application range for different methods of dewatering ................. 107
Figure 5.17 Layout of an electro-osmosis system ......................................... 109
Figure 5.18 Pressure berms ..................................................................... 112
Figure 6.1 The principle of reinforced soil .................................................. 115
Figure 6.2 Concepts of reinforced soil ........................................................ 116
Figure 6.3 Reinforced earth ..................................................................... 116
Figure 6.4 Types of soil reinforcement ....................................................... 117
Figure 6.5 Wrap-around geotextile wall ..................................................... 117
Figure 6.6 Embankment on soft soil: (a) reinforcement at base, (b) safety factor and time for reinforced and unreinforced cases ............................ 118
Figure 6.7 Cellular mattress .................................................................... 118
Figure 6.8 Reinforced soil for slip repairs: slip repair to motorway cutting (top) and railway embankment (bottom) .............................................. 119
Figure 6.9 Anchored earth ....................................................................... 120
Figure 6.10 Mudwaves on filling over a geotextile on soft clay ....................... 121
Figure 6.11 Soil nailing forming a structure like a gravity wall ....................... 125
Figure 6.12 Soil nailing construction sequence .......................................... 125
Figure 6.13 Soil nail head arrangement ...................................................... 126
Figure 6.14 Tensile forces and displacements in an example of soil nailing .... 126
Figure 6.15 Soil nailing for stabilisation of a cut slope ................................ 127
Figure 6.16 Constructing a root pile .......................................................... 131
Figure 6.17 Examples of reticulated root pile structures ................................ 132
Figure 6.18 Reticulated root piles for slope stabilisation ................................. 133
Figure 6.19 Root piles for underpinning and stabilising an existing abutment .... 133
Figure 6.20 Principles of slope dowels ....................................................... 136
Figure 6.21 Stabilisation by slope dowels .................................................... 137
Figure 6.22 Measurements of earth pressures on a slope dowel .................... 137
Figure 6.23 Principle of embankment piles ................................................ 140
Figure 6.24 Embankment piles approaching an abutment .......................... 141
Figure 7.1 Removal of poor ground and replacement................................. 145
Figure 7.2 Replacement of poor ground at edges of wide embankments ......... 145
Figure 7.3 Construction over peat mires.................................................. 153
Figure 7.4 Structural fill replacing landfill............................................... 147
Figure 7.5 Displacement of soft soils ...................................................... 148
Figure 7.6 Control of filling operations .................................................... 151
Figure 7.7 Clay trapped below fill.......................................................... 152
Figure 7.8 Expanded polystyrene for embankment construction.................. 154
Figure 7.9 Cross-section of embankment approach to bridge abutment, Great Yarmouth .......................................................... 155
Figure 8.1 Structures of soil-cement.......................................................... 157
Figure 8.2 Forming a lime column ............................................................ 158
Figure 8.3 Settlement of a building founded on lime columns ..................... 159
Figure 8.4 Block formation by deep chemical mixing .................................. 162
Figure 8.5 Types of stabilised structure .................................................... 163
Figure 8.6 Cutaway section of a stabilised foundation at a reclamation boundary 164
Figure 8.7 Large-diameter mix-in-place auger ........................................... 166
Figure 8.8 Slope stabilisation by lime boreholes........................................ 167
Figure 9.1 Main processes of grouting...................................................... 174
Figure 9.2 Groutability for permeation in terms of grain size and coefficient of permeability of soil ......................................................... 179
Figure 9.3 Groutable range for chemical grouts ......................................... 179
Figure 9.4 Three types of high-shear grout mixers .................................... 181
Figure 9.5 Pan-and-paddle mixer for agitation or mixing simple slurries ....... 181
Figure 9.6 Drilling and grouting stages in rock fissure grouting: (a) downstage with top packer, (b) descending stages, (c) ascending stages .......... 182
Figure 9.7 The tube à manchette system ................................................... 183
Figure 9.8 Grout hole arrangement and injected volumes ............................ 186
Figure 9.9 Example of a treatment sequence to strengthen ground below a pile.. 187
Figure 9.10 Grouted zone prior to tunnel excavation: combined permeation of sand and gravel and hydrofracture of clay.......................... 188
Figure 9.11 Grouting of the Riccall shaft ................................................... 188
Figure 9.12 A pattern of injection holes for underpinning by permeation ....... 189
Figure 9.13 Development of hydrofractures by repeated injection ............... 192
Figure 9.14 Record of a hydrofracture injection ........................................ 192
Figure 9.15 Combining hydrofracture (to increase the area of possible grout entry) with permeation .................................................... 193
Figure 9.16 Jet grout construction: (a) monitor lowered in guide hole; (b) jetting and grouting; (c) monitor raised as column is formed ...................... 195
Figure 9.17 Jet grout monitor (triple fluid) .................................................. 195
Figure 9.18 Jet grouting for tunnel excavation in Singapore ......................... 196
Figure 9.19 Jet grouting to protect a building in conjunction with permeation grouting prior to tunnel construction .................................... 196
Figure 9.20 Jet grouting to underpin the invert of a railway tunnel ................ 198
Figure 9.21 Principle of compaction grouting ........................................... 201
Figure 9.22 Squeeze grouting for restoration of total soil stress above collapsed tunnel ................................................................. 203
Figure 9.23 Principle of compensation grouting ................................................................. 203
Figure 9.24 Sequence of operations adopted at Merthyr Tydfil, Wales .................. 207
Figure 10.1 Closed system of ground freezing ................................................................. 210
Figure 10.2 Open system of ground freezing ................................................................. 211
Figure 10.3 Cross-section of River Limmat Tunnel .......................................................... 212
Figure 10.4 Control of water irrigation for freezing above water table......................... 214
Figure 10.5 Typical scheme of freezing for a disused excavation................................. 214
Figure 10.6 Typical combustion installation for artificial ground heating..................... 218
Figure 11.1 Slope improvement with vegetation: (a) planting and seeding with surface geotextile mat, (b) wrap-around geotextile and brush layering 222
Figure A2.1 Average relative densities and compaction point spacings of vibro-compaction and compaction piles ................................................................. 238
Figure A2.2 Relative densities achieved in compacted hydraulic fills ......................... 239
Figure A2.3 Surface subsidence of hydraulic fill compacted by vibro-compaction and vibratory probing ................................................................. 239
Figure A2.4 SPT blow counts in hydraulic fill before and after three types of vibratory compaction ................................................................. 240
Figure A2.5 SPT comparisons of vibratory compaction before and after different amounts of treatment ................................................................. 241
Figure A2.6 Comparison of CPT cone resistances in hydraulic fill before and after vibratory probing and vibro-compaction ................................................................. 242
Figure A2.7 Comparison of Swedish ram soundings in sandy ground before and after vibro-compaction in vibro-compozer compaction ................................................................. 242
Figure A2.8 Comparisons of mean cone resistances (averaged over 1.5 m depths) before (open points) and after (closed points) vibro-replacement (three sites) and dynamic compaction (one site) ................................................................. 244
1 Introduction

CIRIA is publishing a series of reports on particular forms of ground improvement processes, i.e., dewatering (Preene et al., 2000), vertical drains (Holtz et al., 1991), geotextiles for soil reinforcement (Jewell, 1996), and geotechnical grouting (Rawlings et al., 2000). There are many other techniques for ground improvement, less widely used but capable of providing economic technical solutions for the many types of poor ground. This report is an introduction to ground improvement methods; it sets out the available techniques and their variations by systematic descriptions of the principles, the equipment, the methods and the effectiveness that can be expected for each. The report, therefore, is a general guide to the available techniques by which ground can be improved and to the situations for which particular techniques are appropriate.

Since the start of the research project on which this report is based, several important texts have been published on this and associated subjects, e.g., *Ground Improvement* (ed. M.P. Moseley, 1993), *Soil improvement techniques and their evolution* (Van Impe, 1989), and *Building on fill: geotechnical aspects* (Charles, 1993). Under the auspices of the International Society for Soil Mechanics and Geotechnical Engineering, Thomas Telford Ltd now publishes a quarterly journal entitled *Ground Improvement*. In addition, there have been several speciality conferences, such as the three on ground improvement systems, again sponsored by the International Society through its technical committee on this subject, TC-17. The committee’s website (http://tc17.poly.edu/ikd.htm) includes descriptions of improvement techniques and a database.

In 1999, CIRIA started a new research project to provide guidance about the engineering properties and long-term performance of treated ground. That report, CIRIA publication C572 *Treated ground: engineering properties and performance* (Charles and Watts, 2002), complements and amplifies the content of this one, without having to repeat the explanations and descriptions of the techniques given here.

1.1 THE OPTION OF IMPROVING THE GROUND

Virtually all engineering construction involves the ground. In poor ground conditions there are five options:

- to bypass the poor ground, by moving to a new site, or using deep foundations to stronger ground
- to remove the poor ground, replacing it with better material
- to design the structure to allow for the behaviour of the poor ground under load
- to treat the poor ground to improve its properties (i.e., ground improvement)
- to abandon the project (the promoter’s decision).

The fourth option, of ground treatment, gives considerable scope to engineers for finding a viable solution to the problems of poor ground. A wide range of treatments is available, techniques can be selected and combined to cope with different aspects of the poor ground, and there is increasing confidence both in what can be achieved by well-executed treatment and in its proper integration into the overall scheme for the construction. All these points are evidence of how valuable is this option.
The objective of treatment is improvement. When ground treatment is being considered as an option, it is important that all who will be involved in it should recognise not only what can reasonably be achieved by a particular technique, but also the extent of their responsibility if it is chosen.

For this reason, therefore, the first three sections of this report address issues general to all ground improvement schemes. The issues are of responsibility for design, of site investigation, of assessing and minimising the risks inherent in the chosen ground treatment scheme, and of matters relating to placing and completing a treatment contract. The recommendations given on these issues are for good practice; as such, they are intended for the benefit of promoters, project design professionals and specialist ground engineering contractors.

It is the variability of the ground – which is not only the engineering material itself, but also the medium in which the work takes place – that makes ground engineering an iterative process of discovery and innovation. When the objective of the work is to improve the ground in specific ways, success – and demonstrating it – depends upon first knowing what the existing ground is like and then, during the work and later, upon evaluating the effect of the treatment technique. Control testing and assessment of the effectiveness of the treatment are thus essential components in a scheme of ground improvement. There may also be reason to monitor the long-term performance of the treated ground and of structures built on it.

Aspects that have to be considered in selecting the appropriate ground improvement technique are discussed in general terms (Section 3.3), in the descriptions of individual techniques given in Sections 4 to 11 inclusive, and in relation to the combinations of different methods (Section 12) and to the results of comparative studies published by others (Appendix B).

In Sections 4 to 11, the techniques of ground treatment are explained under the following headings:

- definition, of the terms used for the technique
- principle, of the mechanics by which the treatment takes effect
- description, of the methods used
- applications, for which the technique is used
- limitations, that could affect the suitability of the technique
- design, by pointers to sources of design guidance
- control, of the treatment works by tests and measurements.

These explanations are necessarily introductory, but references are provided that give further and more detailed information. For techniques that are essentially standard civil engineering operations, such as earthworks, there is no text section on controls.

*It is important to recognise that the limitations are not necessarily sufficient reason for a technique to be excluded from consideration. Modification to the construction method or design may be possible – the point being that these possible limitations should be appreciated at the feasibility stage of a project. It is the nature of many ground treatment techniques that their capability is continually being extended, overcoming what were previously seen as limitations. Moreover, different techniques can be combined to cope with a greater range of situations than one method on its own.*
1.2 GROUND IMPROVEMENT

The term “ground improvement” is open to different interpretations. First, it is an intention or objective, not the process of achieving it, although the term is often used in that sense. Second, improvement is a relative condition as to which aspect and to what degree there is improvement.

From the outset of this CIRIA project there was debate in the steering group guiding the research and in the minds of the authors about what the report should be included in the report. Should the coverage be restricted to those treatment techniques that alter the state or nature of the in-situ ground materials, in the way, for example, that deep compaction by increasing their density changes the state of granular soils, and permeation of grouting changes the nature of ground by sealing its pores? If changing the ground’s nature at the micro scale is easily recognisable as resulting in an improvement of its condition, what if the treatment is of a large mass of ground by the inclusion of discrete reinforcing elements that, in themselves, do not alter either the state or nature of the ground strata? The best example of this is piling, which would not usually be thought of as ground treatment. A third question relates to the improvement of fill materials: for example, are reinforced soil embankments, reinforced foundation soil or track beds examples of ground improvement? Even less clear is the use of lightweight fills instead of increasing the stiffness and strength of the underlying weak ground. This technique has been included if only for the reason that its use is often in combination with foundation improvement.

For the purposes of the coverage of this report, the following general definition of ground treatment is suggested:

Ground treatment is the controlled alteration of the state, nature or mass behaviour of ground materials in order to achieve an intended satisfactory response to existing or projected environmental and engineering actions.

1.3 PRINCIPAL METHODS FOR GROUND IMPROVEMENT

Ground treatment techniques have developed greatly over the past 30 or so years and the possibilities for new applications appear to be increasing. This part of ground engineering is one where practice precedes theory. Research follows development, not just in trying to explain why a technique works but, more importantly, to establish rational, rather than empirical, design methods and to see how the technique can be improved and its limitations identified. In the United Kingdom, some 75 per cent of the ground improvement contracts using the techniques of vibro-replacement and dynamic compaction are for man-made ground. These two techniques, including their application to loose or soft natural soils, are probably the commonest type of ground treatment used in the UK. For overseas work, the proportions of specialist ground treatments are reversed, ie 30 per cent are for man-made ground and 70 per cent for natural ground.

There are, of course, many other techniques than the two mainly used in UK. In this report, more than 30 are described separately, but for most there are variations that extend the versatility of the basic technique. Increasingly, different techniques are being used in conjunction (see Section 12.1) to considerable advantage in time and cost.
The techniques of ground improvement have been grouped into broad categories:

- improvement by vibration (Section 4)
- improvement by adding load (or increasing the effective stresses) (Section 5)
- improvement by structural reinforcement (Section 6)
- improvement by structural fill (Section 7)
- improvement by admixtures (Section 8)
- improvement by grouting (Section 9)
- improvement by thermal stabilisation (Section 10)
- improvement by vegetation (Section 11).

Although the above headings for the groups of methods reflect what is being done to the ground to improve it, they do not characterise the way the ground is to be improved, nor do they show the purpose of the improvement.

Many of the techniques can be used for different purposes and by enhancing one aspect of soil behaviour other aspects are also improved. The use of vertical drains accelerates the gain in strength of a soft foundation and allows settlement to take place more rapidly. The purpose of permeation grouting of a water-bearing sand to be tunnelled through would be to achieve sufficient strength for safe excavation; the complementary result of low permeability and minimal water inflow is a necessary though subsidiary benefit. This latter example highlights the need for thought about the purpose of the ground treatment. The problem is not the quantity of water that would enter the tunnel, but the instability of the ground, ie the sand would run with disastrous consequences. The treatment is not to achieve a low permeability but to create a uniform mass of sufficiently strong material able to resist the water pressure and prevent piping and erosion.

### 1.4 PURPOSES AND EFFECTS OF GROUND TREATMENT

Ground treatments should not just be thought of as temporary construction expedients, although many of the techniques are used to great advantage in this way. Increasingly, the improved ground is an integral part of the finished works, eg reinforced soil, stone columns by vibro-replacement. Even techniques intended as short-term improvement contribute to the permanent works. The use of vertical drains to speed up consolidation achieves a permanent improvement and the process is usually integrated with the construction of the permanent works. Three situations can be considered in relation to the purpose of the treatment:

- temporary, eg dewatering or ground freezing, where the improvement is only during the application
- short-term, eg some forms of grouting, or the use of basal reinforcement for an embankment on a soft foundation, where the treatment has a lasting effect, but its purpose is achieved during construction
- long-term, eg soil nailing, vibro-replacement, curtain grouting of a dam, where the treatment is integral to the permanent works.

The effects of ground treatment can be considered from two angles:

- the benefit or effect on the work of construction for which the treatment is sought, eg less or faster settlement
- the effect on the properties or behaviour of the ground, eg greater strength or stiffness.
The first of these is the driving force or justification for the treatment; the second is the identification of what aspect of the ground should be improved. Cost and practicability underlie both ways of defining the purpose of the treatment. Different techniques by different methods may achieve similar effects; usually they would have to be compared against a construction method not relying on ground improvement.
Table 1.1  Benefits to construction work of different ground treatment techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Higher bearing capacity</th>
<th>Less or more even settlement time</th>
<th>Faster settlement time</th>
<th>Ground-water control</th>
<th>Reduced liquefaction potential</th>
<th>Increased erosion resistance</th>
<th>Improved face/slope stability</th>
<th>Report section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vibro-compaction</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.1</td>
</tr>
<tr>
<td>vibro-replacement</td>
<td>***</td>
<td>***</td>
<td>*</td>
<td></td>
<td>***</td>
<td>*</td>
<td></td>
<td>4.2</td>
</tr>
<tr>
<td>dynamic compaction</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
<td>4.3</td>
</tr>
<tr>
<td>vibratory probing</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.4</td>
</tr>
<tr>
<td>compaction piles</td>
<td>***</td>
<td>***</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.5</td>
</tr>
<tr>
<td>blasting</td>
<td>***</td>
<td>***</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.6</td>
</tr>
<tr>
<td>Adding load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pre-compression</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.1</td>
</tr>
<tr>
<td>vertical drains</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.2</td>
</tr>
<tr>
<td>inundation</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.3</td>
</tr>
<tr>
<td>vacuum preloading</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.4</td>
</tr>
<tr>
<td>dewatering fine soils</td>
<td>*</td>
<td>*</td>
<td>***</td>
<td>*</td>
<td>***</td>
<td>*</td>
<td></td>
<td>5.5</td>
</tr>
<tr>
<td>pressure berms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>***</td>
<td></td>
<td></td>
<td>5.6</td>
</tr>
<tr>
<td>Structural reinforcement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>reinforced soil</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.1</td>
</tr>
<tr>
<td>soil nailing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.2</td>
</tr>
<tr>
<td>root and micro-piles</td>
<td>***</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td></td>
<td>6.3</td>
</tr>
<tr>
<td>slope dowels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.4</td>
</tr>
<tr>
<td>embankment piles</td>
<td>*</td>
<td>***</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.5</td>
</tr>
<tr>
<td>Structural fill</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>remove-and-replace</td>
<td>*</td>
<td>***</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.1</td>
</tr>
<tr>
<td>displacement</td>
<td>***</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.2</td>
</tr>
<tr>
<td>reduced load</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.3</td>
</tr>
<tr>
<td>Admixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lime/cement columns</td>
<td>***</td>
<td>*</td>
<td>***</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td>8.1, 8.2</td>
</tr>
<tr>
<td>mix-in-place by single auger</td>
<td>*</td>
<td>*</td>
<td>***</td>
<td>*</td>
<td></td>
<td>***</td>
<td></td>
<td>8.3</td>
</tr>
<tr>
<td>lime stabilisation of slopes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.4</td>
</tr>
<tr>
<td>stabilisation of subgrades</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.5, 8.6</td>
</tr>
<tr>
<td>Grouting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>permeation</td>
<td>*</td>
<td>*</td>
<td>***</td>
<td>*</td>
<td></td>
<td>***</td>
<td></td>
<td>9.2</td>
</tr>
<tr>
<td>hydrofracture</td>
<td>*</td>
<td>***</td>
<td>***</td>
<td>*</td>
<td></td>
<td>***</td>
<td></td>
<td>9.3</td>
</tr>
<tr>
<td>jet grouting</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
<td>***</td>
<td></td>
<td>9.4</td>
</tr>
<tr>
<td>compaction grouting</td>
<td>***</td>
<td>***</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.5</td>
</tr>
<tr>
<td>cavity filling</td>
<td>*</td>
<td>***</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.6</td>
</tr>
<tr>
<td>Other methods</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>freezing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>***</td>
<td>***</td>
<td>10.1</td>
</tr>
<tr>
<td>heating</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td>***</td>
<td>10.2</td>
</tr>
</tbody>
</table>