

ICE Manual of Geotechnical Engineering



ICE Manual of Geotechnical Engineering

Second edition

Volume II
Geotechnical design,
construction and verification

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Foreword and endorsement

Geotechnical engineering quite literally underpins the construction industry.

Using a combination of geophysics, structural engineering and materials science, geotechnical engineers explore the interactions between soil, rock, water and structures, and develop solutions that enable buildings, tunnels, bridges, roads and other forms of infrastructure to carry the loads they are designed for, under all the conditions they may be expected to experience, over their planned lifetime and beyond.

Throughout my career, I have worked on numerous projects which have relied heavily on the skills of geotechnical engineering, so I am personally aware of the need to ensure the next generation of engineers continues to develop the knowledge and skills necessary to ensure our infrastructure continues to be built on safe, sustainable and long-lasting foundations.

I therefore commend this impressive and comprehensive work to all those who wish to develop and improve their knowledge of geotechnical engineering.

Keith Howells BSc, MBA, CEng, FICE, FCIWEM, FEng
ICE President, 2022–2023

The *ICE Manual of Geotechnical Engineering* is an essential reference document for experienced geotechnical professionals and non-specialists seeking to improve their knowledge of the subject. It covers historical aspects of how the subject evolved, the principles of soil mechanics, their application to designing and building in and on the ground, and how to manage and report geotechnical aspects of projects. The British Geotechnical Association is proud to remain affiliated with this updated edition of the document.

Dr Andrew Ridley
Chair of the British Geotechnical Association

Preface

We began to formulate the initial ideas for the first edition of this Manual as early as 2006. It had become apparent to us that civil and structural engineers not specialising in geotechnics face a daunting knowledge gap when they come up against a geotechnical problem. Most civil engineers leave university with very little grounding in geotechnical engineering. They will have a fair grasp of applied mechanics (mainly aimed at structural engineering). They will have had a basic introduction to geology and they will have studied the elements of soil mechanics and rock mechanics. But a recent graduate usually lacks a coherent understanding of the approach to, and methods of, geotechnical engineering and how these differ from other more widely practised branches of engineering. A survey carried out by ICE Publishing showed that information tends to be obtained from a wide range of sources through word of mouth, the internet and various publications. For the young practitioner this leads to a fragmented approach. Much of the geotechnical material is written by specialists for specialists, and its ad hoc application by a general practitioner is often inappropriate and can be extremely dangerous. We felt that it would be of great benefit to our profession to provide a single first-port-of-call authoritative reference source aimed at informing the less experienced engineer. To our delight this concept was endorsed by the ICE Best Practice Panel and the British Geotechnical Association and has offered a unique opportunity to provide authoritative guidance within a coherent framework of good geotechnical engineering.

It is most gratifying to note that the first edition of this Manual proved to be the most downloaded e-book of ICE Publishing's portfolio in 2022. Most of the chapters in this second edition have been extensively revised and updated to include the latest guidance documents and references. A major advance is the inclusion of carbon as a key metric in the choice of foundations and basement systems. In this regard, great emphasis is placed on avoiding unnecessary carbon emissions by avoiding over-conservatism in new designs and the application of codes sensitively in the remediation of old structures. Another important emerging challenge is the impact of climate change which will affect earthworks and slope engineering in particular.

As with the first edition, this second edition of the *ICE Manual of Geotechnical Engineering* has been a labour of love! The contribution of 99 contributors and ten section editors has made it possible to distil a great deal of experience from the profession into the chapters you see here. Don't imagine this will cover everything that a geotechnical engineer will face in their career – but it provides a 'starting point' from which to build experience while remaining grounded in robust fundamentals.

As mentioned previously, the Manual is aimed at people in the early stage of their careers who need a readily accessible source of information when working in new aspects of geotechnical engineering. However, it is expected that it should also prove valuable to all geotechnical engineering professionals. The aim has been to produce a manual that addresses the practice of geotechnical engineering in the twenty-first century including contemporary procurement, process and design standards and procedures. The grouping of chapters has been carefully chosen to facilitate a multidisciplinary and holistic approach to the solution of construction challenges. A key message is the importance of drawing on 'well-winnowed experience' for the smooth and reliable execution of projects. Such experience is best gained by working closely with a suitably experienced design or construction team.

It is hoped that this Manual will help in the training and development of the next generation of geotechnical engineers and will act as a useful source of reference to those with more experience.

The editors are grateful to all those contributors and section editors who have generously given so much of their time and knowledge in producing such a comprehensive book.

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Hilary Skinner graduated in Engineering from the University of Cambridge in 1990. After a period of research at BRE, she joined Whitby Bird (later Ramboll) as Associate Director in Geotechnics. Now a Director, she has been at COWI (previously Donaldson Associates) since 2010. She has authored or co-authored a number of papers and books for which she has been awarded the BGA Research Medal and the Halcrow Prize from the ICE. All have involved collaboration with UK and European consultants, contractors and researchers. She continues to collaborate on research into working platforms, piling and tunnelling with universities and industry bodies. Hilary is a Chartered Engineer, a Fellow of the ICE and a past Chair of the British Geotechnical Association (BGA). The importance of measurement and case history data has been critical to the development of our science, which marries theory and judgement, and this has been central to a lifelong pursuit of technical excellence in her work and our industry.

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David Toll is Chair of the British Geotechnical Association (BGA) and Professor of Engineering and Co-Director of the Institute of Hazard, Risk and Resilience at Durham University. He is a member of ISSMGE's Technical Committee TC 107 on Tropical Soils, has been Chair of the ISSMGE's Technical Committee TC 106 on Unsaturated Soil and was the inaugural Chair of the Joint Technical Committee JTC2 of FedIGS on Geo-Engineering Data. David is a Fellow of the ICE and has been Chair of both ICE North East and the Northern Geotechnical Group. He is a Fellow of the Learned Society of Wales. He has been carrying out research into climate resilience of infrastructure and information technology applied to civil engineering for over 30 years and has published over 200 papers and 12 books. He has held Visiting Professor and Research Fellow posts at Tongji University, China, National University of Singapore, Nanyang Technological University, University of Sydney, University of Western Australia and University of Newcastle, Australia. He was the founding editor of the journal *Geotechnical and Geological Engineering* and has been a member of the editorial boards for *Géotechnique*, *Transportation Geotechnics* and the *Quarterly Journal of Engineering Geology and Hydrogeology*.

Kelvin Higgins BSc, MSc, DIC, CEng, FEng, FICE, FCIHT (Editor)

Kelvin Higgins is a Senior Partner at Geotechnical Consulting Group LLP (GCG) and a Visiting Professor at Imperial College London. In 2019 Kelvin became a Fellow of the Royal Academy of Engineering and since 2012 he has been a Visiting Professor at Imperial College London. Until recently he was Chair of the British Geotechnical Association and Chair of CIRIA's Geotechnical Advisory Panel. Since joining GCG in 1986 Kelvin has worked on the application of numerical methods to engineering problems, including the design of tunnels, retaining structures, highways, dams, embankments, cuttings and foundations (offshore and onshore). During his career he has gained broad practical and design experience of foundations, highway construction earthworks (cuttings, embankments and drainage schemes), deep basements and the interaction between structures. He has acted as an expert witness in legal disputes. In addition, he has directed and facilitated research in different aspects of geotechnical engineering. Kelvin has extensive experience of the assessment of the effects of underground construction, (excavations, shafts and tunnels) on adjacent structures. This includes developing alternative designs, construction techniques and

sequencing of works to mitigate the effects of construction on adjacent structures and services by predicting the effects of construction on adjacent structures, services, operational tunnels and installations within these structures (e.g. escalators, permanent way, etc.). In many cases he has been able to demonstrate economic benefits to alternative sequences and designs. Kelvin has investigated the causes of the failures of foundations and slopes, designed remedial schemes and monitored construction. His research and publications cover earth-retaining structures, slopes, sheet piling, new monitoring technologies, soil behaviour, the performance and analysis of foundations, tunnels, embankment dams, slope stability, thermal piles, monitoring and the use of advanced numerical methods. Prior to joining GCG, he worked for Sir Alexander Gibb & Partners in the UK and internationally, where he gained experience in foundation design and the design of embankment dams. He oversaw the construction of highway schemes and other facilities in remote and challenging environments, having to adapt designs to accommodate local conditions.

Michael Brown BEng (Hons), PhD, GMICE (Editor and Section Editor)

Michael Brown is Professor of Geotechnical Engineering in the School of Science and Engineering at the University of Dundee, UK. Mike is a researcher, former practitioner and an educator at both undergraduate and post-graduate level. As Professor of Geotechnical Engineering his focus is on translating the complexities and specialist testing approaches of academia into practical outputs that can be easily deployed by practising engineers. Currently his research interests lie in offshore renewable energy, with the development of novel deep foundation systems and anchoring solutions for future floating wind. Onshore he is looking at efficiencies in deep foundation excavation and support and the development of efficient ground energy systems for deployment in diaphragm walls for heating and cooling in the UK and South America. Mike undertook his PhD at the University of Sheffield, UK, looking at the rapid load testing of piles in clay and soil rate effects in general. Based upon this work, the rapid load testing technique was made more accessible in the UK with inclusion in the *ICE Specification for Piling and Embedded Retaining Walls* and Federation of Piling Specialist (FPS) load testing guidance. Internationally he has contributed to national guidance on rapid load testing in the Netherlands and chaired the CEN working group that was responsible for the creation of ISO/CEN standards on rapid load pile testing and dynamic piles testing. These were subsequently adopted as British Standards. Based upon his expertise in deep foundation testing and developing novel foundation deployment, he is currently a UK representative on the ISSMGE Technical Committee 212 Deep Foundations, as well as a member of the International Press-in Association (IPA): IPA-TC4 concerned with press-in and rotary pile installation. Since joining the University of Dundee he has undertaken a significant amount of contract testing and research direct for industry based around specialist physical modelling and centrifuge testing. This type of work keeps Mike industrially relevant and allows him to appreciate the needs of both industry and academia. These specialist interests and skills have recently been recognised, with him being appointed as secretary of ISSMGE TC 104: Physical Modelling in Geotechnics.

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International Goodwill and to International Geotechnical Practice and Education'. In 1996 he was awarded the Harry Seed Memorial Medal of the American Society of Civil Engineers 'for distinguished contributions as an engineer, scientist and teacher in soil mechanics'. He is a Fellow of both the UK Royal Academy of Engineering and of the Royal Society of London, a Member of the US National Academy of Engineering and was appointed Commander of the Most Excellent Order of the British Empire in 2005.

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Tim Chapman is a Director at Arup, London, with deep expertise in all aspects of geotechnical engineering – his particular areas of expertise relate to ground risk minimisation for large projects and for the design of deep underground structures with and around tunnels. He has had extensive experience in the design of all types of infrastructure and devising how future infrastructure can best serve and shape future society. A current goal is helping clients to choose the right projects to meet their desired outcomes and setting up those projects to succeed far more fundamentally from the outset. He advocates that our infrastructure systems should increase national happiness by promoting prosperity and well-being as well as being fit for the future in terms of decarbonisation, social value, biodiversity and circular economy. Among other Arup roles, he led its London-based Infrastructure Design group for over a decade until April 2020 and was Office Leader for its London office, Arup's largest globally, through the COVID-19 pandemic and was also client for the creation of its new flagship head office, the smartest office space in the world and lowest carbon office building in London, designed for collaboration and inclusion, to attract staff back into a conducive space – delivered on time and under budget. Tim is a Fellow of the ICE and of the Royal Academy of Engineering. In 2011 he was awarded the ICE President's Medal for producing the institution's first significant thought piece on how to decarbonise the infrastructure sector. He is currently Co-Chair of the ICE Community Advisory Board for Fundamentals and Behaviours and Chair of the Association of Consulting and Engineering's (ACE) Risk Task Force, charged with reducing project risks for the benefit of all. For the RAEng he chairs the Sainsbury Management Fellowship helping to equip engineers with more business-facing skills and represents the RAEng on EuroCASE, the federation of European engineering academies, which seeks to influence the European Commission on key topics, one of which is 'sustainable materials for sustainability'.

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Stuart Hardy joined Laing O'Rourke's central technical group as their Geotechnical Lead in 2021, with an overview of all geotechnical works for Laing O'Rourke, from tender through to completion and beyond. After completing an undergraduate degree in Civil Engineering and a PhD in geotechnical engineering at Imperial College London, Stuart joined Mott MacDonald in Croydon and worked on the design of the new Wembley Stadium and Heathrow T5. After leaving Mott MacDonald, Stuart joined the geotechnics department of Arup's office in London and stayed for nearly 16 years, working on a number of challenging basement and foundation projects located mainly in the Middle East and London. These included the Post Building, the Exhibition Road Quarter for the Victoria and Albert Museum, Elizabeth House, the ArcelorMittal Orbit sculpture in the Olympic Park and the redevelopment of the Shell Centre building in Waterloo. For the last five years at Arup Stuart led the geotechnical design of the S1 and S2 contracts on HS2, working with the Main Civils Contractor SCS JV. Stuart is one of the UK's representatives to CEN on the redrafting of the Eurocodes and chairs the parallel BSI committee. Stuart was one of the leading authors on the CIRIA C760 publication on the design of embedded retaining walls and is a RoGEP registered Advisor and a Fellow of the ICE.

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William Powrie is Professor of Geotechnical Engineering at the University of Southampton, where he served as Dean of the Faculty of Engineering and the Environment 2010–2018. His main technical expertise is in transportation geotechnics and waste/resource management, for which he was elected Fellow of the Royal Academy of Engineering in 2009. William's research on geotechnical transport infrastructure encompasses groundwater control, in-ground construction, understanding and mitigating vegetation and climate change effects, and fundamental soil behaviour. Major projects on which he has worked include the A55 Conwy Crossing, the Jubilee Line extension and HS1. He chairs HS2's Independent Geotechnical Expert Panel. He is Convenor of the 14-university UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC), and leads the UK Rail Research and Innovation Network (UKRRIN) Centre of Excellence in Infrastructure and the Infrastructure for Port and Coastal Cities and Towns Network. William's research in waste/resource management focuses on landfill engineering and science-based policy and practice. He worked on the design and engineering risk assessment of low-level radioactive waste repositories at Drigg, and chaired the Technologies Advisory Committee for Defra's £30M research and demonstrator programme for new technologies for treating biodegradable waste. He is the author of the widely respected textbook *Soil Mechanics: Concepts and Applications*.

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Section 5: Design of foundations

Section editor: **Tony O'Brien**

Chapter 51

Introduction to Section 5

Tony O'Brien Mott MacDonald, UK

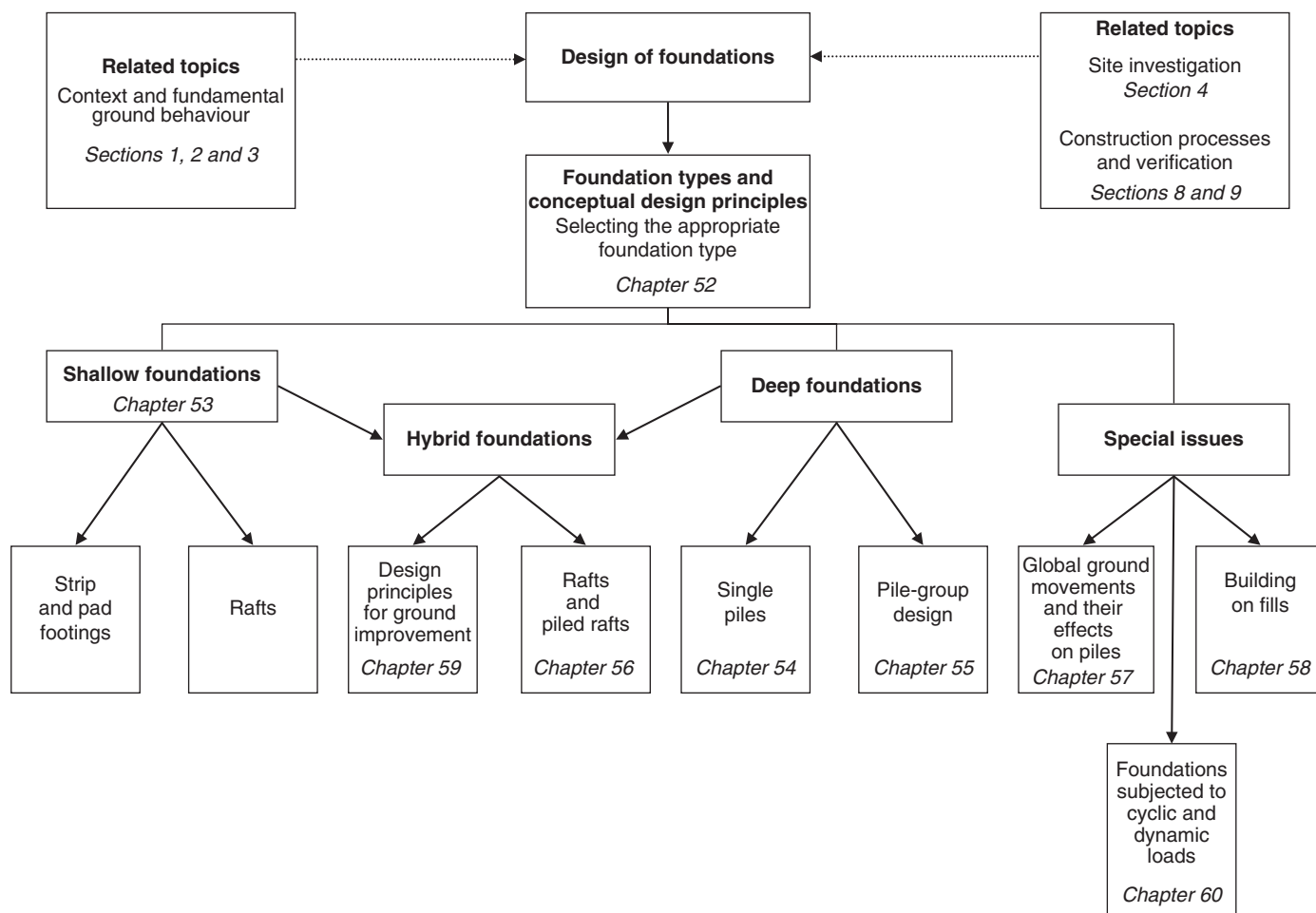


Figure 51.1 Layout of chapters in Section 5

Figure 51.1 outlines the layout and contents of Section 5 *Design of foundations*.

Foundation design is usually divided into two broad categories – shallow and deep – and these categories are also used here. In modern foundation engineering it is helpful to consider a third category: hybrid. Hybrid foundations have their own unique features, although their design usually requires an assessment of both shallow and deep foundation behaviour. Examples of hybrid foundations include deep ground improvement and piled rafts.

The final set of topics, special issues, include building on fills, the influence of global ground movements on deep

foundations, and foundations subject to cyclic and dynamic loading, including earthquakes.

In common with other sections of this manual, this section is intended to provide guidance to practising engineers. Given the enormous breadth of the subject and the vast range of ground conditions and structures which a foundation designer may encounter, this section cannot, within the available space, be completely comprehensive. The intent is to outline

- the fundamental principles of good design practice
- the key mechanisms of ground and ground–structure interaction behaviour which need to be considered

- commonly used design methods
- the need to integrate a range of specialist disciplines at different stages of the design process;

and to provide

- references for detailed study
- some brief case histories which highlight key issues.

A quote from Terzaghi (1939) is particularly pertinent (and is still relevant!):

Whoever expects from soil mechanics a set of simple, hard and fast rules for settlement computations will be deeply disappointed. ... The nature of the problem strictly precludes such rules.

Hence, it is essential for the foundation designer to think carefully about the likely deformation and failure mechanisms which may occur both during and after construction, then compile a checklist of questions which need to be considered and answered.

There have been enormous developments in foundation engineering during the last few decades. Despite these developments, failures still regularly occur, and there are also numerous examples of grossly over-conservative design and poor construction practice. There are several commercial and technical factors that can cause these problems. Technically, the following are important.

- Recognise that foundation engineering is a 'process', and that success depends on a series of interlinked activities during *both* design and construction.
- Have a coherent approach to ground risk management; the 'geotechnical triangle' is a valuable framework in this context. An understanding of the site's history and its groundwater regime are critically important.
- Have good communication across different design/construction teams.
- Develop a good understanding of ground–structure interaction. It is vitally important for geotechnical and structural engineers to have early two-way discussions, so that the overall behaviour of the proposed works are understood. In particular, the best opportunity for economic foundation design is to set realistic (rather than arbitrary and usually over-conservative) limits on foundation movement.
- Have a good awareness of relevant case histories of past foundation performance, and to carefully assess the relevant parameters for assessing stability – and in particular, foundation deformation. Sophisticated analysis is not a substitute for a proper selection of design parameters, based on well-designed and supervised ground investigations.

Chapter 9 *Foundation design decisions* provides an introduction to these themes, and these are developed in more detail throughout Section 5.

Although it is a simplification, it is fair to state that routine ground investigation and analysis methods can lead to

- over-conservative design of foundations in heavily overconsolidated soils, such as stiff clays
- unsafe foundation design in normally and lightly overconsolidated soils, such as soft clays.

Modern developments in ground investigation and geotechnical analysis can avoid these problems, although these modern techniques are still under-used across the civil engineering industry. The chapters in Section 5 highlight some of the developments that are mature enough to be used more routinely. It is hoped that Section 5 will stimulate an improvement in foundation design practice.

The second edition

The topics covered and overall layout remain as for the first edition; however, all the content has been reviewed and updated where necessary.

The issues discussed above for the first edition remain as important as they were in 2012 and are covered throughout Section 5. Some topics and issues which were introduced in the first edition are now given greater prominence, including

- sustainability and carbon reduction
- the need to avoid over-conservative design, which will enable carbon reduction.

An unfortunate trend is that limit state design codes, such as Eurocode 7, have not in general stimulated greater investment in ground investigations. For example, it was hoped that there would be greater emphasis on obtaining higher-quality data on ground stiffness, especially small strain stiffness data.

The greater focus on serviceability (movement) checks and widespread use (more specifically misuse) of advanced finite element methods, combined with a lack of high-quality ground investigation data, can often result in over-conservative foundation design. This will not help the industry achieve its targets on carbon reduction.

It is hoped that this unfortunate trend will be reversed. To support this, Chapter 52 *Foundation types and conceptual design principles* has a revised section on parameter selection, including small strain stiffness. Chapter 53 *Shallow foundations* includes a new section on bearing capacity, since VHM methods should now be considered mature enough for general use; these methods can support the design of shallow foundations under complex load combinations. It is hoped that more practitioners will consider the use of piled rafts, addressed in Chapter 56 *Rafts and piled rafts*, which has been revamped to highlight simplified design approaches for different piled raft types.

There have been important developments in deep ground improvement. Chapter 59 *Design principles for ground improvement* describes recent advances, in particular for deep soil mixing and the characterisation of soilcrete strength and stiffness. Finally, Chapter 60 *Foundations subjected to cyclic and dynamic loads* has been rewritten to reflect lessons learned from the many developments in earthquake

engineering, foundations for renewables (including offshore wind) and a new section on geotechnics associated with high-speed rail.

Reference

Terzaghi K (1939) Soil mechanics: a new chapter in engineering science. *Proceedings of the Institution of Civil Engineers* 7: 106–141.

Chapter 52

Foundation types and conceptual design principles

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The main types of foundation include: shallow foundations (pad, strip, raft); deep foundations (piles, caissons, barrettes) and hybrid foundations (deep ground improvement, piled rafts). Foundation engineering requires a broad range of skills, from an appreciation of geology and hydrogeology to structural engineering. The performance of foundations is dependent not only on how they are designed, but also on how they are constructed. The overall design process needs to be well managed, to ensure that there are good communications between different design teams and between design and construction. To provide a framework for selecting the most appropriate type of foundation, a useful mnemonic is the five Ss:

Soil, Structure, Site, Safety, Sustainability

The magnitude of allowable foundation movement is a key factor in determining the type, size and cost of foundations, and this chapter provides guidance on routine limits. Parameter selection is a common pitfall, and the critical information requirements are described.

52.1. Introduction

This chapter outlines the types of foundation that are commonly used, together with the key factors which need to be considered before selecting a particular foundation type.

Foundation engineering requires a working knowledge of

- geotechnics (including both engineering geology and geotechnical engineering)
- construction methods
- ground–structure interactions.

Professor Peck (1962) outlined the three areas of knowledge that are needed in geotechnics as

- (a) a knowledge of precedents (i.e. a knowledge of case histories)
- (b) a working knowledge of geology
- (c) familiarity with soil mechanics.

In the vast majority of cases, a foundation design is developed on the basis of an appreciation of the site, any particular site constraints, the site geology and the nature of the proposed structure. The role of analysis is then to check that a proposed foundation design will be acceptable. Although analysis is important, it is just one part of the overall design process.

Many young civil engineers will have some knowledge of (c) above, but it is important that they endeavour to develop their knowledge of (a) and (b). A knowledge of geology (and

hydrogeology) is critically important, since it enables many of the risks associated with foundation engineering at a particular site to be assessed. Simplifying assumptions have to be made before any analysis can be carried out (this includes sophisticated computer modelling). The site geology and hydrogeology have to be considered and understood as early as possible in the project. Discussions should be held with an experienced geologist. Relevant technical literature and, particularly, local case histories should be reviewed. Once this has been done then the appropriateness, or not, of certain assumptions inherent in a particular method of calculation can be judged, and the likely errors associated with the predictions from calculations can be assessed. A knowledge of case histories is probably the most important of the three attributes stated by Peck, since this enables the engineer to have an understanding of

- what has worked, or not, in the past
- the consequences of particular construction activities for subsequent performance
- past performance, against which the reliability of different methods of analysis can be compared
- when a proposed activity is going beyond what has been attempted before (and going beyond the empirical database) – this will then require a special effort and expert advice in order to develop a safe, buildable and economical design.

A foundation is a structural member and supports a superstructure. Therefore, an awareness of the sources and nature

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of structural loads and the structure's tolerance of foundation movements and an understanding of ground–structure interactions is also needed. Finally, the foundations must be built economically and safely. Hence, a designer needs to have an appreciation of construction methods and equipment in order to develop a design that is practical and safe to build.

This list of attributes, which a foundation designer needs to possess, is rather intimidating. The author has not yet come across the god-like creature who possesses a perfect knowledge of all these topics. Therefore, first and foremost, the foundation designer must be prepared to ask questions and discuss these with other design and construction specialists

(e.g. geologists, structural and material engineers, specialist subcontractors). Good foundation design is usually the result of a multidisciplinary team effort, where two-way communications across the team occurs regularly and frequently.

52.2. Foundation types

There are two generic types of foundation: shallow and deep. Foundations developed on improved ground can be considered to be a hybrid of shallow and deep foundations, although ground improvement design requires additional considerations. The advantages and disadvantages of different foundation types are outlined in **Table 52.1**.

Foundation type	Advantages	Disadvantages
Pad/strip footing	<ol style="list-style-type: none"> (1) Simple to construct (2) Cheap and quick 	<ol style="list-style-type: none"> (1) Competent soils,^a need to be reasonably close to ground surface (typically less than 3–4 m) (2) If the groundwater table is above the base of the footing and there are permeable soils, then barriers or dewatering are needed during construction (3) Limited application if applied loads include large horizontal forces or overturning moments (4) Vulnerable to large differential settlements if applied loads vary significantly across structure or if ground conditions are heterogeneous (5) Interaction between adjacent footings, if closely spaced?
Raft foundations	<ol style="list-style-type: none"> (1) Simple to construct (2) Specialist equipment and subcontractors not required (3) If sufficient rigidity, then potential for differential settlement is significantly reduced (4) Can 'bridge' across local soft pockets of soil 	<ol style="list-style-type: none"> (1) As noted above (2) As noted above (3) Large area of excavation required, hence large amounts of spoil generated (particular problem if excavated soils are contaminated) (4) Depth of influence of significant increases in stress will be considerable. Will it affect underground infrastructure? Are weak layers present at depth? (5) Raft deformation needs to be carefully checked. Is movement acceptably small?
Shallow foundations generally	<ol style="list-style-type: none"> (1) Simplicity (2) Cheap if appropriate conditions 	<ol style="list-style-type: none"> (1) Inappropriate if site affected by 'global' ground movements, that may result in unacceptable differential movements^b (2) Excessive depth may be needed to locate foundation below seasonal changes in moisture content or frost penetration^c or, if close to rivers, potential scour depth (3) Inappropriate if desired footing depth would lead to undermining of existing foundations, utilities, roads, canals, railways, etc.
Piled foundations	<ol style="list-style-type: none"> (1) Large variety of pile types, diameters, depths are possible, so very large applied loads can be resisted (2) If near-surface soils are weak or of variable thickness then pile lengths can be readily modified to suit (3) If near-surface soils are contaminated then exposure can be minimised by appropriate choice of pile type (4) If site boundaries limit width of shallow foundations then piled foundations may be more appropriate (5) Horizontal and moment loads can be resisted (although a pile group may be more appropriate, rather than a single pile) 	<ol style="list-style-type: none"> (1) Can be relatively expensive (2) Construction will require specialist contractor input, hence construction sequence may become complex (3) Piling construction can be adversely affected by local variations in ground and groundwater conditions; technical and commercial implications? (4) Pile capacity can be significantly affected by construction method and equipment and timing of key activities (5) Costs and time to carry out pile testing (6) Pile construction may adversely impact adjacent structures, utilities, etc.
Caissons/shafts/barrettes	<ol style="list-style-type: none"> (1) Can provide extremely high-capacity foundations for 'special' structures (2) Can provide relatively high stiffness/capacity to resist large horizontal loads or overturning moments (3) Shafts, in appropriate circumstances, can provide high-capacity foundations in sites with limited plan area or headroom 	<ol style="list-style-type: none"> (1) May be complex or expensive to construct (2) Design and construction require expert input; these skills are usually in short supply (3) Verification of design assumptions may be challenging (4) Deformation behaviour requires careful assessment, may not be amenable to routine analysis methods

Table 52.1 Advantages and disadvantages of different foundation types (continued on next page)