ICE Manual of Geotechnical Engineering

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ICE Manual of Geotechnical Engineering

Second edition

Volume I
Geotechnical engineering principles, problematic soils and site investigation

Edited by

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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, FREng
ICE President, 2022–2023

The *ICE Manual of Geotechnical Engineering* is an essential reference document for experienced geo-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.

Michael Brown, John Burland, Tim Chapman, Kelvin Higgins, Hilary Skinner and David Toll

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Hilary Skinner (Editor)

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.

David Toll (Editor)

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, FREng, 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.

Professor John Burland (Editor and Section Editor)

Professor John Burland is Emeritus Professor of Soil Mechanics and Senior Research Investigator at Imperial College London. Born in the UK, Professor Burland was educated in South Africa and studied Civil Engineering at the University of the Witwatersrand. He returned to England in 1961 and worked with Ove Arup and Partners for a few years. After studying for his PhD at Cambridge University, John Burland joined the UK Building Research Station in 1966, became Head of the Geotechnics Division in 1972 and Assistant Director in 1979. In 1980 he was appointed to the Chair of Soil Mechanics at Imperial College London, before becoming Emeritus Professor and Senior Research Investigator there. In addition to being very active in teaching and research, John Burland has been responsible for advising on the design of many large ground engineering projects worldwide, including the underground car park at the Palace of Westminster and the foundations of the Queen Elizabeth II Conference Centre in London. He specialises in problems relating to the interaction between the ground and masonry buildings. He was London Underground's expert witness for the Parliamentary Select Committees on the Jubilee Line Extension underground railway and has advised on many geotechnical aspects of that project, including ensuring the stability of the Big Ben Clock Tower. He was a member of the international board of consultants advising on the stabilisation of the Metropolitan Cathedral of Mexico City and was a member of the Italian Prime Minister's Commission for stabilising the Leaning Tower of Pisa. He has received many awards and medals, including the Gold Medal for Engineering Excellence of the World Federation of Engineering Organisations and the Gold Medals of the UK Institution of Structural Engineers and of the UK Institution of Civil Engineers. In 1994 he was awarded the Kevin Nash Gold Medal of the International Society of Soil Mechanics and Geotechnical Engineering 'In recognition of outstanding services to ISSMGE, to

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.

Tim Chapman BE, MSc, DIC, CEng, FICE, FIEI, FREng (Editor)

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'.

Stuart Hardy MEng, ACGI, PhD, DIC, CEng, FICE (Section Editor)

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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Tony O'Brien is a Fellow of the Royal Academy of Engineering and a Fellow of the ICE. He is the Global Practice Leader for Geotechnics at Mott MacDonald and a Visiting Professor at the University of Southampton. He has provided technical leadership on several major projects across Europe, North America and the Asia-Pacific region and worked as an expert during litigation/dispute resolution. Tony has contributed to best practice guidance, including CIRIA Guide C791 on advanced numerical modelling, and recently published a book, *The Observational Method in Civil Engineering*, and contributed to several international ISSMGE committees.

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Mike Devriendt is Associate Director at Arup, London, and is a geotechnical and tunnelling engineer with over 25 years of experience. He is responsible for leading large multidisciplinary design teams on urban infrastructure projects such as Crossrail 2, HS2, Tideway and Crossrail, and a range of commercial and residential building projects. Mike specialises in working collaboratively with clients and contracting organisations to develop cost-effective and buildable designs. Mike is author of over 25 journal or conference papers. As a recognised technical expert, Mike regularly leads and contributes to national and international steering committees. He has been appointed to a number of industry-wide ICE and CIRIA roles and has been an expert panel member or author of geotechnical and tunnelling standards for BSI, CIRIA and HS2 Ltd. Mike has particular research interests in the practical application of new technologies in the field of monitoring and asset management. He has led a number of consulting commission and collaborative research projects with industrial partners such as UK Power Networks, HS1, National Highways and with academic partners such as the University of Cambridge, University of Oxford and University College London. As part of these projects Arup have provided consultancy advice and developed new techniques for application of photogrammetry, machine learning, laser and thermal scanning to achieve health and safety benefits and operational cost and programme savings associated with infrastructure monitoring and maintenance.

William Powrie (Section Editor)

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.*

John A Davis BSc, MSc, DIC, CGeol, EurGeol (Section Editor)

John A Davis is a Senior Partner at Geotechnical Consulting Group LLP. John has worked for contractor, consultant, client and government organisations. He has had two extended periods of secondment, one into London Underground to work on the potential effects of rising groundwater on below-ground assets, and another to the Crossrail client organisation where he was responsible for geotechnical matters in the eastern half of the project. He has interests in commercial management of ground risk and quaternary engineering geology. John is currently Chair of the Engineering Group of the Geological Society.

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Ian Jefferson is Deputy Head at the College of Engineering and Physical Sciences, University of Birmingham, UK and Professor of Geotechnical Engineering. He has research interests that span geotechnical engineering and engineering geology, addressing issues associated with geohazards and problematic soils, from assessments through modelling to mitigation, using both traditional and novel areolation techniques. Past Vice President (Northern Europe) of the International Association of Engineering Geology (2011–2015), he has some 30 years' experience working on several problematic soils, most notably collapsible and expansive soils. More recently he has focused on sustainable geotechnics and urban near-subsurface, serving on the Technical Committee TC 307 on Sustainable Geotechnics of the International Society of Soil Mechanics and Geotechnical Engineering. Recently he has led European-funded work, ARLI (Alternative Resource of Low Impact) supporting small and medium enterprises to develop new materials from waste streams, supporting the net-zero agenda. Since 2017 he has been Co-Director of the National Buried Infrastructure Facility, where he leads the work on geostructures and works with several industrial partners both in the UK and internationally. He has served on regional, national and international technical committees across both geotechnical engineering and engineering geology, including as a member of the ASCE Geo-institute's Engineering Geology and Site Characterization committee.

Section 1: Context

Section editors: **John B Burland and William Powrie**

Chapter 1

Introduction to Section 1

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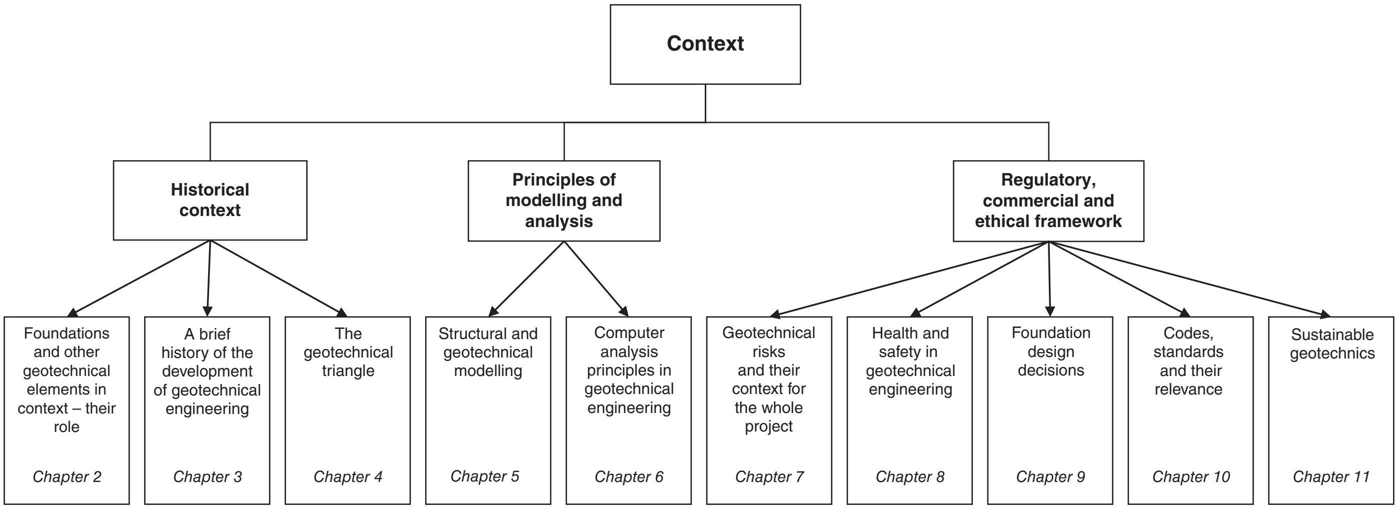

Figure 1.1 Layout of chapters in Section 1

Figure 1.1 outlines the layout and contents of Section 1 *Context*.

The first three parts of the section address the development of soil mechanics and geotechnical engineering as a distinct discipline over the past 80 years or so. Chapter 2 *Foundations and other geotechnical elements in context – their role* explains the importance of foundations and structures built in or of the ground within civil engineering and construction, and the need for a formal and holistic geotechnical engineering design process. Chapter 3 *A brief history of the development of geotechnical engineering* gives a history of the development of geotechnical engineering at the borderline between science and art, with the latter defined by Terzaghi in 1957 as 'mental processes leading to satisfactory results without the assistance of step-for-step logical reasoning'. This is reflected in the 'geotechnical triangle', described in Chapter 4 *The geotechnical triangle*, which emphasises the essential elements of successful geotechnical engineering as understanding the ground, material properties and relevant precedents (well-winnowed experience), connected by an appropriate model for analysis.

Chapters 5 *Structural and geotechnical modelling* and 6 *Computer analysis principles in geotechnical engineering* address some important principles of modelling and analysis in geotechnical engineering. Particular attention is paid in Chapter 6 *Computer analysis principles in geotechnical engineering* to computer methods, for which it is essential that an engineer has a sound understanding of the basis of the method of analysis, the influence of the material properties used and the shortcomings and limitations of the approach.

Finally, Chapters 7: *Geotechnical risks and their context for the whole project* to 11 *Sustainable geotechnics* discuss key aspects of the regulatory, commercial and ethical framework with which geotechnical engineering practice must comply, now and into the future. Chapter 9 *Foundation design decisions* emphasises that foundation engineering is a 'process' involving a number of interlinked operations, and design decisions need to take account of this. The other chapters address understanding and apportioning of geotechnical risk within a whole-project context (Chapter 7 *Geotechnical risks and their* *context for the whole project*); health and safety (Chapter 8 *Health and safety in geotechnical engineering*); current standards and codes of practice (Chapter 10 *Codes and standards and their relevance*); and sustainability (Chapter 11 *Sustainable geotechnics*). These issues are especially important, given that the place occupied by geotechnical engineering at the borderline between science and art means that risks are often more difficult to foresee and quantify than other areas of civil engineering, and the discipline does not lend itself to highly detailed codes of practice.

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Chapter 2

Foundations and other geotechnical elements in context – their role

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The purpose of this chapter is to describe the basic principles of geotechnical design and construction in the context of the whole project. At a given site the ground conditions have resulted from millions of years of natural geological processes (which are seldom simple) and have sometimes been modified by humans (e.g. by mining or many other processes). As a consequence there are always inherent uncertainties and risks, and the art of geotechnical engineering is to make informed allowance for these, in both design and construction. The key requirements for all geotechnical elements of a project are described. Emphasis is placed on the importance of constructive and positive interaction with professionals engaged in the many other contributing disciplines. The design life of the geotechnical elements is considered and the important concepts of geotechnical design and the construction cycle are introduced. Various managerial approaches to identifying the key elements of the complete design and construction process are described. The chapter concludes with a summary of the factors common to most geotechnical design and construction projects that are necessary for a successful outcome.

2.1. Geotechnical elements in the context of the rest of the whole structure

All built structures touch the ground in some way and hence all need some form of foundation. Other geotechnical elements include retaining walls and ground anchors. Sometimes they can be shallow (e.g. pad footings or gravity-retaining walls), other times they are deep (e.g. piles or embedded retaining walls). Often they rely on geotechnical processes such as ground improvement to produce a geotechnical element.

All foundations and other geotechnical elements have a number of characteristics that distinguish them from other parts of the structures that they support.

- They tend to be among the most heavily loaded elements in any structure.
- Their installation process is less amenable to factory-style production.
- Their capacity is very dependent on the ground of the site, which is always characterised by few observations and tests, and is normally very heterogeneous and may contain hazards that are difficult to foresee.
- Their capacity is strongly influenced by the method of construction and how well it is controlled.

Hence, the risk of failure tends to be significantly higher than that for other parts of the structure. The management of ground uncertainty is an important part of the design and construction process in order to produce elements that have the required degree of reliability.

A vital consideration in geotechnical design is the interaction of the structural element that is inserted into the ground with the ground itself – so-called ‘soil–structure interaction’. Structural loads are applied to the element and the ground resists – generally either by friction along the element, or by bearing of the element against the ground. Both of these resistances can occur vertically or horizontally, as shown in **Figure 2.1**. Normally ground stresses are maintained within failure limits, so the resulting displacements depend on the stiffness of both the element and the ground.

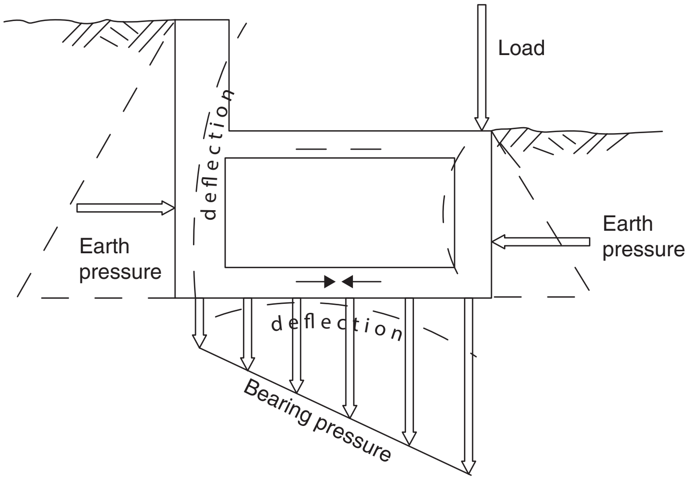

Figure 2.1 Soil–structure interaction

Loads can be imparted into foundations directly, as vertical or horizontal loads, or as imposed bending moments. They can also be imposed indirectly as displacements, which induce loads into the structural parts of the foundation. Eurocode 7 (BS EN 1997 – BSI, 2004, 2007b) treats these in a similar way by introducing the Newtonian concept of an 'action'.

Geotechnical elements are characterised by much higher degrees of uncertainty than other structural elements. The uncertainty is derived from

- the inevitable significant assumptions and idealisations that underlie the overall geotechnical design
- natural variability in the ground being modelled, often manifested by vast scatter in data points on graphs
- inherent variability in the construction processes, and their control, that are used to install the geotechnical elements and foundations, which may also have a profound effect on their eventual performance in service
- usual variability in the applied loads transmitted through a normally highly structurally indeterminate construction meaning that the actual loads on each foundation may be very uncertain
- the possibility of the construction and performance being heavily influenced by an unexpected feature of a site – for example a major geological discontinuity such as a sinkhole or a fault. It is not unusual for major construction problems to arise owing to adverse groundwater conditions.

All of these uncertainties mean that engineers who presume that their calculations are precise and predictable are deluded and may expose themselves to much more onerous load combinations than they could imagine. The wise geotechnical engineer should be humble and make prudent allowances for uncertainty. This is explained in more detail in Chapter 7 *Geotechnical risks and their context for the whole project*.

2.2. Key requirements for all geotechnical elements

2.2.1 General

All foundations or other geotechnical elements must fulfil a number of essential criteria.

- They must not fail, or else the structure they support will also fail. In terms of limit state design, failure by any mode is termed reaching or exceeding an 'ultimate' limit state, and may involve failure of a structural element or rupture along a soil–structure or a soil–soil interface.
- They must not move excessively or else the structure they support may become impaired or fail to operate as intended. In terms of limit state design, excessive deflection involves breaching a 'serviceability' limit state.
- They must last for as long as intended. Unlike many other building elements, foundations are hugely difficult to upgrade or repair, so their longevity will often dictate the life of the structure that they support.

2.2.2 Ultimate limit state modes of failure

There is a range of ways in which geotechnical structures can fail an ultimate limit state, and these are shown in **Figure 2.2**.

2.2.3 Serviceability limit state and displacements

Failure of a serviceability limit state is usually less serious than failure of an ultimate limit state, and is often repairable. It usually occurs when excessive displacements have taken place that impair the function of the structure. In addition to excessive movement, it also includes other forms of unacceptable tolerances, such as moisture penetration into basements. Examples are illustrated in **Figure 2.2**.

2.2.4 Design life and modes of deterioration

Design lives are covered in more detail in Section 2.4. Other than failures of a limit state, the life of a structure can be reached when

- it has become affected by material deterioration processes, such as corrosion of steel, carbonation of concrete or rotting or insect infestation of timber
- it has been subjected to physical processes, such as repeated loading cycles causing fatigue, or excessive damage from impacts
- it fails to meet new design or material standards and so offers a less than acceptable level of resistance against load, corrosion and so on.

2.3. Interaction with other professionals

2.3.1 General

The geotechnical engineer is seldom the professional solely in charge of a complete project – almost invariably the function sought of a new structure or facility goes beyond merely geotechnical considerations. Therefore, the role of a geotechnical engineer should be to support the wider design and construction process. They are likely to have most influence if the input complements the work of other professionals rather than seeking to dominate or failing to engage.

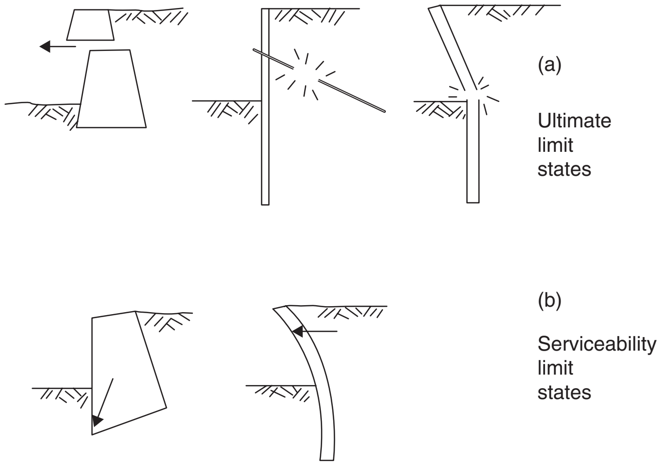

Figure 2.2 Limit state failures (Adapted from BS EN 1997)

The geotechnical engineer should be alive to the broader design process and any failures or gaps in those wider processes. The ICE (2018) report *In Plain Sight: Assuring the Whole-Life Safety of Infrastructure* highlighted a series of broad lessons that the construction industry and civil engineers should learn from the Grenfell Disaster – many projects have similar failings, so-called 'soft hazards' – and it is the responsibility of the professional to be alert to wider problems and ensure that the whole team react positively to resolve them.

2.3.2 General construction process

All project programmes involve controlled phases of input so that the optimum solution is devised with mutually consistent input from all members of the project team, through design procurement, implementation and commissioning. Once commissioned there is a need for maintenance, upgrades and repairs through the working life of the structure and finally decommissioning and sometimes reuse of the original elements in a fresh structure.

Client Best Practice Guide (ICE, 2009) provides a generalised approach for such inputs, based on the systems used for buildings (Royal Institute of British Architects, 2007 and updated in 2020) and the rail industry (Network Rail, 2007; previously known as the *Governance for Railway Investment Projects*, replaced in 2021 with *Project Acceleration in a Controlled Environment*), as well as guidance from the UK's former Office of Government Commerce (OGC) (now part of the Cabinet Office Efficiency and Reform Group). More detail on these processes is given in Section 2.5.

In the early stages there will be little certainty about the optimum solution, and many competing options will be considered and dismissed, often for reasons not obvious to individual members of the technical team. The design team can contribute best to this process if they understand the required function and the client's business drivers for the new structure or facility.

The early stages are also the period when it is easiest for the project to take on board geotechnical constraints and design and construction requirements. Hence, the geotechnical engineer is likely to have most success in integrating these requirements into the rest of the structure if they are identified early on, although this will often be in advance of the acquisition of data and completion of analyses. Therefore, experienced geotechnical input is valuable in these early stages and will often lead to a better solution, simpler design and construction processes and less costly subsequent geotechnical involvement.

The work of the geotechnical engineer is seldom completed in isolation. Normally there is much interaction with structural engineers. Sometimes the work of the geotechnical engineer is subsumed beneath that of the structural engineer. For simple structures this may be appropriate and sufficient, but for more complex geotechnical structures, or where the ground conditions are complex, it is likely that the geotechnical engineer will be better able to explain the particular issues directly to other members of the design team.

2.4. Design lives for geotechnical elements

Relevant design lives for structures are defined in Eurocode 'Basis of structural design' (BSI, 2010) and are generally distinguished according to whether the structure is a building or a piece of infrastructure. In its Table 2.1 it defines design life categories as follows.

- Category 1: Temporary structures, not including structures or parts of structures that can be dismantled with a view to being reused – 10 years.
- Category 2: Replaceable structural parts, such as gantry girders, bearings – 10–25 years (the UK National Annex to BS EN 1990:2002 modifies this to 10–30 years).
- Category 3: Agricultural and similar buildings – 15–30 years (modified in the UK to 15–25 years).
- Category 4: Building structures and other common structures – 50 years.
- Category 5: Monumental building structures, bridges and other civil engineering structures – 100 years (currently modified in the UK to 120 years to bring it into line with traditional National Highways bridge design life; it is possible that the UK may revert to 100 years if National Highways changes their guidance).

As foundations are difficult to repair or upgrade and as most structures last for longer than the period for which they were designed, allowing for a longer life is prudent.

Foundations are difficult and expensive to remove and so some consideration should be given to what will occur after the life expiry of the structure they support. This was addressed by the RuFUS (Reuse of Foundations on Urban Sites) project (see Butcher *et al*., 2006; Chapman *et al*., 2007) and in the paper *A Short Guide to Reusing Foundations* (Tayler, 2020). Where it is likely that a new structure with new foundations could become a major obstruction, the potential for future development of the site may be inhibited.

To prevent abandoned foundations from becoming an insidious form of ground contamination, the RuFUS project advocated that all foundations should be designed with the intention of allowing subsequent reuse. This mainly relates to the recording and saving of records so that the old foundations can be assessed by the future design team.

While most foundation and geotechnical elements are provided for 'permanent' elements that are required to persist for a normal structural life, sometimes foundations are required for shorter periods. These include the following.

- Interim structures, required for a significant life, perhaps 10 years.
- Contractor's 'temporary' works – structures that fulfil a temporary function during construction of a more significant structure, such as thrust blocks and crane bases. Sometimes a life of 1–2

years is specified. For these, Eurocode 7 Part 1 (BS EN 1997-1:2004; BSI, 2004) Clause 2.4.7.1(5) states 'Less severe values than those recommended in Annex A [for partial factors] may be used for temporary structures or transient design situations, where the likely consequences justify it'. This guidance is current at the time of writing and the next update of Eurocode 7 is due for publication in 2024.

- Demountable structures, such as scaffolding or temporary stands as may be required at sport or music venues, where a life of only perhaps weeks is required. The Institution of Structural Engineers (2017) guide, *Temporary Demountable Structures: Guidance on Procurement, Guidance and Use*, defines typical foundation concerns for such structures.

Design life can influence choice of factor of safety. However, it needs to be considered with the following points.

- The frequency with which the most onerous design load combination occurs – if it is very infrequent compared with the design life, some reduction in margin against failure may be possible. This may occur with 1-in-100-year wind or flood events or with 1-in-475-year seismic events.
- The consequences of failure – where the consequences are mild and do not threaten safety, then a lower factor may be permissible provided the economic consequences are judged and agreed as acceptable.

The design life also to some extent governs the measures required to limit deterioration of the foundation materials. Conventional structural design codes such as Eurocodes 2 (BS EN 1992; BSI, 2006) and 3 (BS EN 1993; BSI, 2007a) contain implicit requirements to ensure longevity of foundations; principally, crack width criteria for reinforced concrete, intended to limit the intrusion of air and water which then can come into contact with the reinforcing steel, and whose effect can be exacerbated by the presence of chloride ions from salt. Where potential corrosion processes will be slow compared with the foundation design life, it may be possible to relax these structural requirements for structures intended to have short lives, provided that code non-compliance is acceptable to the owner and any approver.

Temporary structures may sometimes have less onerous movement limits. Their nature may mean that larger movements are easy to accommodate; for instance, in temporary stands where shims and jacks can be used to compensate for differential foundation movements or where there are no rigid finishes that make obvious the effects of differential settlements.

2.5. Design in a time of climate and biodiversity emergency

It is now very clear that the planet is going through a period of unprecedented climate change, resource depletion and huge impacts on biodiversity – all caused by human activity, and the construction industry is responsible for a significant part of those effects. It is important that geotechnical designers (operating as part of a wider team) take into account

- a need for much greater circular economy so resources are used more sustainably
- as part of that, a much stronger emphasis on refurbishment of structures rather than new build, with reuse of foundations a major enabler for that
- a need to integrate better with nature
- a need to always reduce carbon, both capital and whole life, following the principles of PAS 2080 (BSI, 2023)
- much stronger emphasis on resilience – and potentially adaptation – to new climate conditions, for instance much higher sustained temperatures or much greater rainfall.

These are discussed in more detail in Chapter 11 *Sustainable geotechnics*.

2.6. The geotechnical design and construction cycle

Geotechnical design should be carried out in conjunction with the design of the whole structure, as explained in Section 2.1. Geotechnical design must always be carried out considering the source of the data and how the design will be implemented, with all three parts of this process being inextricably linked, as illustrated in **Figure 2.3**.

2.6.1 Project phases

All construction projects go through a number of distinct phases

- planning
- development
- implementation
- operation
- decommissioning.

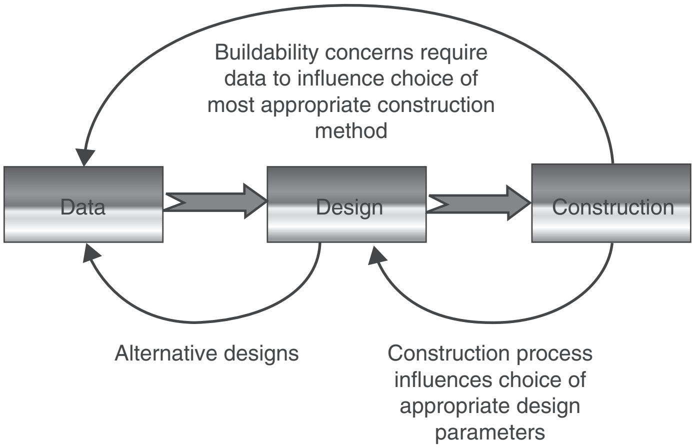

Figure 2.3 The geotechnical design and construction cycle