Urban Geoscience Report - Application of geotechnical and engineering geological data and information

Environmental Change Adaptation and Resilience Programme

Open Report OR/22/049

BRITISH GEOLOGICAL SURVEY

ENVIRONMENTAL CHANGE ADAPTATION AND RESILIENCE PROGRAMME

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Infographic showing city with geological cross sections and boreholes BGS©UKRI 2022

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Foreword

This report is published by the British Geological Survey Urban Geoscience Team as part of a series of reports to assess current opportunities and challenges in providing geological data, information, and knowledge to inform urban planning policy and sustainable development.

The reports focus on the value of geological data, and the knowledge and understanding applied to these data in urban areas for geohazards, construction and harnessing subsurface resource. Alongside, the reports describe the role of technology in characterising and visualising the shallow subsurface (the top 100 m below ground level), and how this has evolved in response to stakeholder needs. They also provide recommendations for how BGS data and science should develop to respond to future demands of urban geoscience stakeholders including academia, industry, policy makers, urban planners and the general public.

The reports in this series are as follows:

- Urban Geoscience Report - The value of geoscience data, information and knowledge for transport and linear infrastructure projects OR/21/065 (Bricker et al., 2022)
- Urban Geoscience Report - Capacity for 3D urban modelling OR/22/043 (Kearsey et al., 2022)
- Urban Geoscience Report - Application of geotechnical and engineering geological data and information OR/22/049

Further details of how BGS data and information are specifically used by stakeholders, and of the value, in general, of geoscience data and information to the construction sector, are presented in Bricker et al., (2022). Further details of 3D modelling, and in particular of 3D geological models in urban areas is also presented in Kearsey et al., (2022).

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Summary

GEOTECHNICAL AND ENGINEERING GEOLOGICAL DATA IS NEEDED NOW MORE THAN EVER TO SUPPORT SUSTAINABLE AND RESILIENT URBAN DEVELOPMENT

Geotechnical and engineering geological data and information is hugely important for understanding and managing the subsurface geosphere in urban centres and along the arteries that link them (roads, rail, waterways, and utilities), particularly because of the rapid growth of the world's urban population and the reciprocal relationship between urbanisation and climate change. According to the International Office for Migration (2015), by 2050 almost 70% of the world's population will live in urban areas. This increasing urban population will produce significant pressure on natural resources, energy consumption, waste production and carbon emissions, which will also further aggravate climate change. Intergovernmental organizations have explicitly sought to address this issue through their development agendas. For example, the Sustainable Development Goals (SDG), which were established by the United Nations General Assembly in 2015, have a dedicated goal to make cities and human settlements inclusive, safe, resilient, and sustainable. Moreover, the UN Habitat's National Urban Policy and the New Urban Agenda offer guidelines on the growth of cities until 2036 and UNISDR 2015 Sendai Framework for Disaster Risk Reduction contribute to the resilience of urban environments to natural disasters.

Geoscience can play a significant role in enhancing the sustainability and resilience of towns and cities by characterising the geological properties and processes within the urban subsurface, and ensuring this understanding is communicated to non-geoscience decision makers to ensure that inherent subsurface risks and benefits are understood and accounted for during all phases of urban development and management (Culshaw and Price, 2010; Dearman, 1991; De Mulder et al.,2001; Mielby et al., 2017; Lagesse et al., 2022; Legett, 1982*)*. While not the sole source of geoscience for this purpose, geotechnical and engineering geological data and information are a core component of the urban geoscience knowledgebase.

BGS has a long history of providing geotechnical and engineering geological information and data to support planning, construction and management of towns and cities, which dates to 1897 and the publication of 'Soils and subsoils from a sanitary point of view: with especial reference to London and its neighbourhood' (Woodward, 1897). This publication consisted of a memoir and accompanying geological map and is the first engineering geology publication produced by BGS, and perhaps the first in the UK. Further publications of geotechnical and engineering geological in literature and maps throughout the 1960s-1990s have demonstrated the importance of BGS outputs in this area and are described in this report. The timeline is shown in Figure 1.

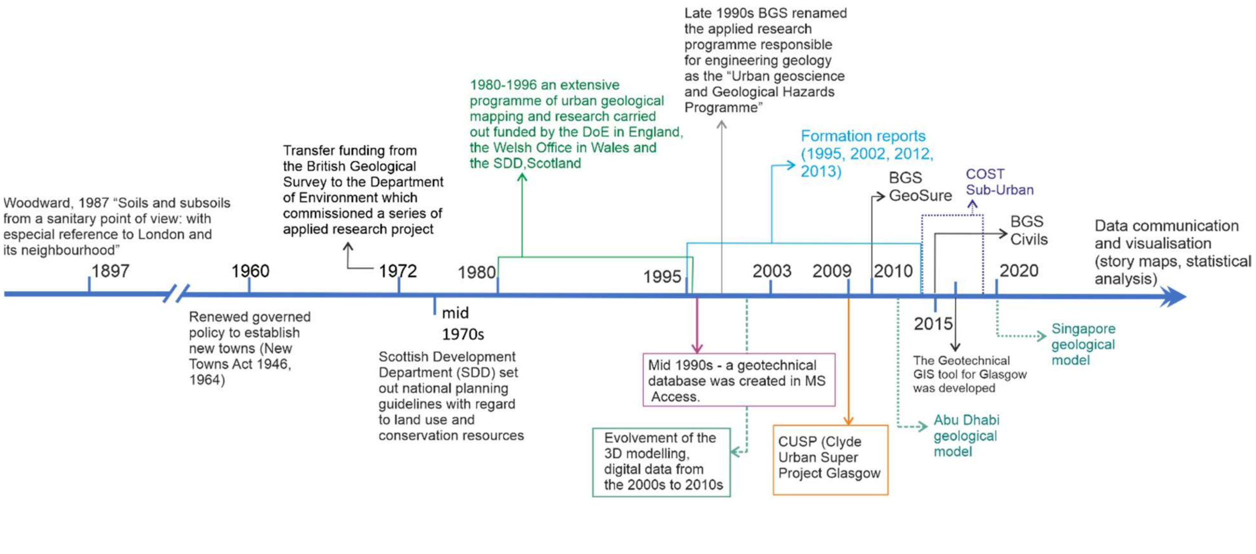

Figure 1 Timeline of urban-related engineering geology research programmes in the BGS.

The use, application, and presentation of geotechnical and engineering geological data, information and technologies has evolved significantly in response to the changing needs of the stakeholders over more than a century. Today's societal needs are now defined by the current trend of urban population growth in different cities and regions, recent advances in technology, and the UK Government priorities as set out in the National Infrastructure Strategy, and initiatives such as the Levelling Up agenda, Build Back Better and Net Zero. Thus, current needs for geoscience expertise are also different to those of the 1970's, 1980 and 1990s. With different stakeholders involved, it is important to consider a range of different needs, and level of geological understanding, so that data and information can be provided in the most appropriate formats.

URBAN STUDIES BETWEEN 1960-1990

The greatest concentration of urban geoscience studies undertaken by BGS, comprising 50 different studies, occurred in the 1980s and 1990s as part of a large-scale programme, funded by the Department of the Environment (DoE) (England), the Welsh Office (Wales) and the Scottish Development Department. The objective of these studies was to provide a geoscience basis for urban planning and development, and specifically to inform the decision-making of planners and developers, but also engineers and conservationists. To support this outcome, each of the reports was accompanied by a selection of thematic maps appropriate to the local geology, engineering geological considerations and planning needs. The Wigan and Bradford studies (Forster et al., 1995; Waters et al., 1996), which were the penultimate and final projects within the programme, were considered at the time to be the architypes for effective transfer of geological information to non-geologists (Smith & Ellison, 1999; Ellison et al., 2002; Forster et al., 2004).

The geotechnical data collected and generated by the urban geoscience studies of the 1980s and 1990s were originally stored in a series of flat file geotechnical datasets (paper and then spreadsheet): these data collections were found to be inefficient to use and difficult to manage. These impediments, coupled with recent technological advances and greater availability of personal computers and networking, prompted BGS to develop and populate a relational geotechnical database. In time this developed to become the BGS National Geotechnical Properties Database (NGPD), which became the foundation of many subsequent studies, and the continued population of the database a core ongoing activity (Self et al., 2012). The urban geoscience study reports and NGPD are key examples of how BGS manages and derives data and information to address urban issues.

TECHNOLOGY DRIVEN PARADIGM SHIFTS BETWEEN 1990 AND 2010

Throughout the 1990s to 2010s, data from the NGPD directly supported several national-scale programmes which, while not explicitly directed at urban centres, did produce a range of outputs that both incorporated and provided geotechnical and engineering geological data and information to inform planning and construction. These include:

- BGS formation study reports for the Gault Formation and Lias, Mercia Mudstone and Lambeth groups, which provide detailed information of the geotechnical properties and engineering considerations within these units (Forster et al., 1994; Hobbs et al., 2002, 2012; Entwisle et al., 2013).
- BGS GeoSure datasets, which are based on the 1:50,000 scale digital superficial and bedrock geology datasets (formerly known as DiGMapGB) and incorporate geotechnical and engineering geological data and information to produce hazards maps for landslides, shrink-sell clays, running sands, collapsible deposits, compressible deposits and soluble rocks (Lee and Doce, 2018).
- BGS Civils datasets, which utilise the digital geology datasets and geotechnical and engineering geological data and information, to characterise the geology in terms of specific engineering geological properties or civil engineering applications. The Civils datasets include bulking volume, ferrous corrosivity, discontinuities, engineered fill, excavatability, foundation conditions, strength, and sulphate/sulphide potential (Entwisle et al., 2015).

- 1:1,000,000 scale engineering geology maps of the UK, which were adapted from the 1:625 000 scale bedrock and superficial geology datasets and reattributed with engineering geological map units based on common geotechnical properties and behaviour. The maps are accompanied by an extended key that, for each engineering lithology type, provides an engineering geological description and implications for foundations, excavation, engineered fill, and site investigation (Dobbs et al., 2012).

In addition to the development of these national-scale outputs, further maturation of geospatial technologies, and BGS capability to use them, for example 3D geological modelling and the development of GIS tools, resulted in a range of new geoscience outputs to support urban development.

At the forefront of the technological advancement in the 2000s was the development of 3D geological models, which are of value in urban environments for subsurface planning and development. The development of the models themselves was also greatly facilitated by the availability of significant volumes of digitised borehole data, acquired during site investigations for the construction of new buildings and infrastructure, and the advent of a standardised format for the transfer of digital geotechnical data (AGS). The development of geological models quickly facilitated the development of 3D engineering geology models by providing a framework to attribute these volumes with geotechnical properties and behaviour. This in many ways echoed the way printed geology maps and GIS technology provided the framework for the development of thematic urban planning maps and the BGS GeoSure and Civils datasets. Initially 3D engineering models were restricted to bulk attribution of the geological unit volumes, but in the 2010s these models evolved to incorporate discrete geotechnical property data through numerical modelling approaches (Williams et al., 2018), and the integration of the built environment within the geological subsurface (Price et al., 2008).

Alongside, collaborations with other organisations have helped develop and advance the use of geotechnical and engineering geology data and information, e.g. COST European programme and CUSP. These programmes focussed specifically on the development of industry, government and research networks for sharing geoscience data, information and knowledge in urban areas (REF).

In parallel with the development of 3D engineering geology and geotechnical property models, BGS also created bespoke GIS tools (plugins) to support the development of geotechnical GIS for London and Glasgow (Entwisle et al., 2016). These tools enable geotechnical databases to be added to GIS and the geotechnical data visualised as pre-drawn cross-sections images and graphs, as well as some limited functionality to produce commonly used geotechnical data plots on the fly. Geotechnical GIS were the first attempt by BGS to enable the spatial visualisation and querying of large geotechnical datasets, within a single digital delivery platform, to support desk-based studies for urban planning and development. The development of web-based GIS delivery platforms has also been subsequently utilised by BGS to provide access to a digital version of the national-scale engineering geology maps. This web-based viewer also incorporated a simple query function to provide the supplementary information contained in the extended key for each of the engineering geological formations. The UK Engineering Geology Webviewer was recently decommissioned, but the data, including query function, have been retained and migrated to the onshore GeoIndex.

Between 2011-2012 the BGS undertook a 3D geological modelling project for the city of Abu Dhabi as part of the wider mapping project for the UAE (Farrant et al., 2012). As described in Section 5, the 3D geological model was attributed with grain size, strength/density as well as engineering class so that the information could be multi-purposed. Alongside, shallow geohazards were also assessed: the city is prone to subsidence (Kamali et al., 2021), which is in some part due to dissolution of gypsum because of aquifer recharge and water abstraction. The BGS were able to map the 3D distribution of over 500 occurrences of cavities (voids) recorded in boreholes, with some recording multiple downhole instances of cavities. Many of the cavities recorded were located where Quaternary deposits were thin or absent. The 3D geological model was essential for conveying information about the engineering challenges in Abu Dhabi and the associated geohazards.

CURRENT STATE-OF-THE-ART WITHIN BGS

Much of the experience and technical expertise gained in the last three decades by BGS has been synthesised and incorporated into a decade-long urban geoscience study of Singapore (Dodd et al., 2019, 2020; Gillespie et al., 2019; Leslie et al., 2019; Chua et al., 2020). At the outset, this programme sought to establish a robust geological framework using available borehole core and data collected as part of a nation-wide deep geological ground investigation. This not only resulted in the development of a new International Commission on Stratigraphy-compliant geological framework, 3D geological models and a geotechnical database, but also a much better understanding of the geology and the consequences for future urban development. To ensure that the new geological framework would be adopted, and that the new understanding would benefit the widest possible stakeholder community in Singapore, a series of outputs were developed to communicate the data and information derived from the study. This includes a geological memoir (Leslie et al., 2021a), interactive digital geological map (Leslie et al., 2021b), and practitioners' guide to the bedrock geology of Singapore (Gillespie et al., 2021).

A LOOK TO THE FUTURE

Current and future research and development in the BGS will explore how the assimilation of geotechnical and engineering geological data and information by users and stakeholders can be enhanced. This includes combining data alongside contextual information and narratives to enhance user experience, for example by using Esri story maps, which enables graphs, text, images, tables, and maps to be present in an interactive web-based format. The use of scripts, written using R and the programming language Python, are also being developed for automating statistical analysis and for generating tables and plots.

For BGS urban geoscience to remain relevant, it must continue to evolve and adapt in response to technology and society, but now must also contend with climate change and economic uncertainty. Based on the historical and contemporary examples presented in this report, and anticipated future changes and challenges, several key focus-areas are identified, and recommendations made for future urban geoscience research.

- Outputs from geotechnical and engineering geological data must be stakeholder-driven for them to be useful, useable and used. This will mean producing different outputs to suit different groups of stakeholders. Further BGS internal and external engagement is required, possibly facilitated through the Geospatial Commission activities or others, to identify which stakeholders need to be prioritised.
- The potential for BGS outputs (and services) to have an impact on urban geoscience problems is greatest when the data and information provided are targeted to address specific issues relevant to the strongest socio-economic and environmental needs, e.g. housing, critical infrastructure and climate change. Outputs should be limited to the shallow subsurface (250 metres below ground level) and scales of 1:10 000, or greater, to remain relevant in an urban environment.
- BGS must maintain its role as 'paradigm shifters' by continuing the innovation and adoption of new technology, such as the IoT, machine learning, and digital twins. However, BGS must also ensure that key geoscience data and information are also delivered using industry standard technologies and formats so that the wider stakeholder community can also benefit: technology must not become a barrier to communication.
- Multidisciplinary collaboration, within BGS and externally, is needed to provide holistic urban solutions: all future studies must integrate collaboration at the project concept and design stage.
- BGS must prioritise both data acquisition (both primary and from industry), and the sharing of these data with stakeholders under Q-FAIR data principles, which supports current government collaboration with the Geospatial Commission and Infrastructure and Projects Authority.

- Information and knowledge must be provided alongside geotechnical and engineering geological data to provide necessary context so that these data can realise their full value and potential.
- Baseline geology datasets must be invested in (particularly 1:10 000-scale geology maps and mapping of artificially modified ground) to both improve derived geotechnical and engineering geological data outputs and provide services that are fit for decision-making at the urban-scale.
- The BGS Civils and Geosure mapped datasets need to be turned into 3D geological modelling products to be more applicable to the urban subsurface. A shift away from vector-based modelling to voxelated modelling to allow multiple attributes and properties to occupy the same geographical space is one way of doing this. This will also help the transitioning of geotechnical and engineering geological data in the use of Smart City/Digital Twin developments.
- To improve upon and create new data, information and knowledge (e.g., new formation reports or improved urban geoscience reports), a sustained programme of funding over several years in collaboration with colleagues across the BGS and externally is required. This level of sustained funding for UK urban geoscience has not been in place for several years. The lack of investment will hold back progress and limit BGSs' impact in this discipline both nationally and internationally, where the BGS are considered thought leaders by peers in Europe and East and Southeast Asia.

The provision of geotechnical and engineering geological data and information has been a fundamental service provided by BGS since the 1960s. The modernisation and continuation of this will help address important UK government initiatives such as the Levelling Up Agenda, National Infrastructure Strategy, Build Back Better and Net Zero. This report provides examples of prominent outputs in this discipline by the BGS over the past 60 years, and how these outputs have evolved to ensure that the data and information provided remained meaningful and relevant in response to changing stakeholder needs and technological advances. BGS must continue to adapt these outputs to remain relevant and influential in the urban geoscience sphere.

1 Introduction

The generation and use of geotechnical and engineering geological data and information goes hand in hand with urban growth and development (including the links between urban centres through rail, road, and waterways). Today urban environments represent over 55% of the world's population and produce 80% of economic output; they also consume over 78% of the world's energy and produce more than 60% of greenhouse gas emissions and 50% of waste (Ellen MacArthur Foundation, 2017; World Bank, 2020; United Nations, 2022). Ever-increasing urbanisation means that the UN considers urban habitats to be critical for economic and social growth while also providing solutions that mitigate the effects of climate change and environmental degradation. Urbanisation is also exposing larger, and increasingly concentrated, populations to multiple geohazards: urbanisation is therefore also contributing to increasing risk. Consequently, the UN consider it vital that cities become the solutions to, rather than the cause of, today's global socio-economic and environmental challenges.

1.1 CURRENT SOCIO-ECONOMIC AND ENVIRONMENTAL DRIVERS

In 2020, the urban population of the UK was 84% and increasing at a linear rate of 0.27% per year (World Bank, 2022). Yet at the same time, urban land cover is only approximately 8% in the UK (EFTEC, 2017). Productivity within urban areas is also much higher in urban areas: it accounts for 84% of the Gross Value Added (GVA[1]) in the business economy to England and Wales and 67% in Scotland, and on average is 5% higher per worker in urban areas than rural areas (ONS, 2017). Within the UK, urban areas are therefore particularly concentrated and efficient, and critical to continued socio-economic development.

Regional growth and productivity within the UK are not evenly distributed. Seven city regions have over 40% of the UK population (Table 1), with many city regions also continuing to grow at a greater rate than elsewhere in the UK. Over the last 20 years Inner London had a growth rate of 27% and Outer London a growth rate of 19%. Outside of London, the population in cities increased by 16% overall, but with quite diverse rates: in Manchester and Nottingham the population grew by 30% and 25% respectively between 2001 and 2019, while at the same time Kingston upon Hull and Stoke-on-Trent only grew by 4% and 6% respectively (ONS, 2022).

City regions in England and cities in Scotland and Wales	Population in 2018	Population projection in 2040	Increase in %
Greater London	8,908,081	9,793,666	9.94
West Midlands	5,900,757	6,613,509	12.07
Greater Manchester	2,812,569	3,055,222	8.62
West Yorkshire	2,320,214	2,482,004	6.97
Nort East	2,657,909	2,746,961	3.35
Glasgow-Edinburgh	1,144,910	1,241,672	8.45
Cardiff*	364,200	≈ 400,700	10.02

Table 1 Population of the seven largest city regions in England and cities in Scotland and Wales in 2018 and projected population in 2040 (*Cardiff population projection to 2028) (Source: for England: www.ons.gov.uk; Scotland: www.nrscotland.gov.uk; Wales: www.gov.wales/

[1] The value of the amount of goods and services that have been produced, less the cost of all inputs and raw materials that are directly attributable to that production.

Productivity in England is greater in the south than in the midlands and north; within the southern region of England, productivity is greater in medium and large urban centres than in smaller urban centres (ONS, 2017). The higher productivity in the medium and larger urban centres in the south is a significant component of the overall higher productivities observed in the south compared to the rest of England. Furthermore, in some parts of the northwest of England the average GVA per worker in rural areas was found to be higher than in urban areas, indicating particularly low productivity within these urban centres. Addressing this regional disparity in growth and productivity has become a major priority of the current UK Government and one of the motivating factors for the Levelling Up agenda, which is a moral, social and economic government programme for spreading opportunities more equally across the UK (Department for Levelling Up, Housing and Communities, 2022). It identifies 20 regions for priority investment (Table 2).

Location for levelling up	Existing economic assets and strengths
Aberdeen	Oil and gas; life sciences; renewables and alternative energy
Glasgow-Edinburgh central belt	Life sciences; data, AI, fintech and robotics; strong university institutions
Northern Ireland	Cyber and fintech; health and life sciences, advanced manufacturing
North East	Automotive; advanced manufacturing and life sciences; universities and research centres
Tees Valley	Freeport Teesworks; advanced manufacturing catapult; low carbon energy and chemicals
West Yorkshire	Meditech – NHS England; universities of Leeds and Bradford; fintech
South Yorkshire	Energy and net zero research; University of Sheffield Advanced Manufacturing Research Centre and High Value Manufacturing Catapult; health and wellbeing
Humber Estuary	Freeport; offshore wind; energy intensive and process industries
Menai-Mersey-Dee	Freeport; manufacturing – Stanlow, Stellantis; vaccines research and delivery
Stoke and Staffordshire	Ceramics; advanced manufacturing; Keele University
Nottingham-Derby	Advanced manufacturing – Rolls Royce, Alstom and Toyota; University of Nottingham; East Midlands Freeport
Leicester and Leicestershire	Aerospace and satellite technology – National Space Centre; universities of Leicester and Loughborough; East Midlands Freeport
Cyber Valley (West England)	Cyber – GCHQ; skills and innovation; technology
East Anglia	Clean Growth; innovation assets and catapults; Freeport East
Western Gateway (Bristol-Swansea)	Aerospace – Airbus; semiconductors; universities of Bath, Bristol, Cardiff and Swansea
West Midlands CA	Automotive – JLR, WMG, Aston Martin; universities of Birmingham and Warwick; advanced manufacturing catapult
Thames Estuary	Clean energy/offshore wind; ports; logistics
Exeter M5 Growth Corridor	Aerospace and nuclear; universities of Exeter and Plymouth; marine autonomy
Solent	Port and maritime specialisms; trade; universities of Southampton, Portsmouth and Solent

Table 2 Twenty locations in the UK identified as potential priorities for investment and for harnessing existing economic assets for levelling up (Department for Levelling Up, Housing and Communities, 2022). In addition to the Levelling Up Agenda, the UK Government has also

announced several other initiatives and policies that directly affect urban development and management:

- Project SPEED (Swift, Pragmatic and Efficient Enhancement Delivery) seeks to significantly enhance the delivery of infrastructure through: reforming environmental regulations and the planning system; enabling the construction sector to be more productive, sustainable and competitive by making better use of data and modern construction methods; more effective decision-making, with greater emphasis on quality design, monitoring and evaluation; and more investment in skills for major project delivery (HM Treasury, 2020).
- The National Infrastructure Strategy is the UK Government's plan to address UK infrastructure needs over the next 30 years, whilst also helping to address regional socio-economic disparities, strengthening the Union, and achieving net zero emissions by 2050. The infrastructure identified by the report is very wide-ranging and includes: gigabit broadband; cycle and bus lanes; road and rail (including HS2); large-scale nuclear; ports infrastructure; green growth infrastructure (carbon capture and sequestration, hydrogen, offshore wind, heat pumps); and flood and coastal defences (HM Treasury, 2020).Build back better is the UK Government's plan for economic growth and focuses on three pillars of investment: high quality infrastructure to boost productivity and competitiveness; transforming Further Education to provide skills to succeed; and investment in research and development to support innovation (HM Treasury, 2021).
- The Net Zero Strategy: Build Back Greener sets out a ten-point plan for a green industrial revolution: advancing offshore wind; low carbon hydrogen; new and advanced nuclear power; zero emissions vehicles; green public transport, jet zero and green ships; greener buildings, carbon capture, usage, and storage; protecting the environment; and green finance and innovation (HM Government, 2021).
- The Environment Act 2021, mandates that all planning permissions granted in England (with a few exemptions) will have to deliver at least 10% biodiversity net gain from November 2023. This will be measured using Defra's biodiversity metric and habitats will need to be secured for at least 30 years. Alongside this is also a strengthened legal duty for public bodies to conserve and enhance biodiversity; biodiversity reporting requirements for local authorities; and mandatory Local Nature Recovery Strategies (LNRS).

1.2 REPORT SCOPE AND LAYOUT

Improving the way engineering geological data and information is ingested, managed, analysed, and presented has been a long-term objective of the BGS. The aim of this report is to provide an overview of evolution and current applications of geotechnical and engineering geological data and information to urban geological studies in BGS. It also makes recommendations for how BGS can both apply and communicate geotechnical and engineering geological data and information in future to respond to the socio-economic and environmental drivers, and thus meet urban geoscience stakeholder needs today and in future.

This report is not intended to provide an exhaustive review of every aspect of research and development undertaken by BGS with respect to geotechnical and engineering geological data and information, but rather to illustrate key concepts and changes using specific examples. Further information on the value of geoscience data and information for infrastructure is presented in Bricker et al., 2021 and on the development and future direction of 3D urban geology models in Kearsey et al., 2022.

This report describes the different methods and technologies applied to the presentation of geotechnical and engineering geological data and information within BGS, as follows:

- Section 2 presents a summary of the BGS National Geotechnical Properties Database (NGPD), which has become the foundation of much of BGS's past and current efforts in this field;
- Section 3 describes reports produced by BGS to support urban development, including the content and presentation of data and information;
- Section 4 describes the development of geotechnical and engineering geological maps;
- Section 5 describes the integration of geotechnical and engineering geological data and information within Geographical Information Systems (GIS), and the development of GIS tools for interrogating these data;
- Section 6 describes the use of geotechnical and engineering geological information within 3D geological models;
- Section 7 describes the current state-of-the-art application of geotechnical and engineering geological data and information within BGS, with specific examples provided of ongoing research and development;
- and Section 8 provides conclusions and recommendations for research and development within BGS based on future urban centre and stakeholder needs, anticipated technological developments, and the lessons learned from previous work by BGS.

2 Geotechnical and engineering geological data and information management

Geotechnical data collected and generated by BGS urban geoscience studies prior the mid-1980’s was stored in a series of flat file geotechnical datasets (paper and then spreadsheet): these data collections were found to be inefficient to use and difficult to manage. These impediments, coupled with technological advances and greater availability of personal computers and networking, prompted BGS to develop and populate a relational geotechnical database. In time this developed to become the BGS National Geotechnical Properties Database (NGPD), and continued population of the database a core ongoing activity with BGS (Self et al., 2012). In addition to supporting the BGS applied ‘urban’ mapping programme of the 1980s and 1990s (see section 3), the database also underpinned many other subsequent projects and outputs, including:

- BGS formation study reports (see section 3.2);
- BGS 1:1,000,000 scale engineering geology maps of the UK (see section 5.2.1);
- BGS Civils and GeoSure datasets (see section 5.1);
- 3D geological property models (see section 6);
- Current research on the Oxford-Cambridge Arc (see section 7.1);
- The East Birmingham Story Map (see section 7.2).

Today the NGPD contains in situ and laboratory test data from approximately 200,000 site investigation exploratory holes from across the whole of Great Britain. Sources of these data include clients, contractors and consultants within the civil engineering sector. Of these records, approximately 56,000 are currently identified as being confidential, with 50,000 of these records from a single source.

The database consists of 54 tables and 33 dictionary tables, which contain a range of geotechnical, geological, hydrogeological, geochemical and physical property data, and is broadly based on an AGS 3.1 data structure (see Appendix 1 for further details of records held in the NGPD). Further details about the structure and operation of the NGPD are presented in Self et al., (2012).

The data within the NGPD are not uniformly distributed but concentrated in urban areas and along the infrastructure corridors that connect them (Figure 2). The depth of data within the NGPD are also biased to the shallow subsurface, and rarely exceed 50 metres depth. This is however sufficient to support most building and infrastructure development projects in Great Britain.

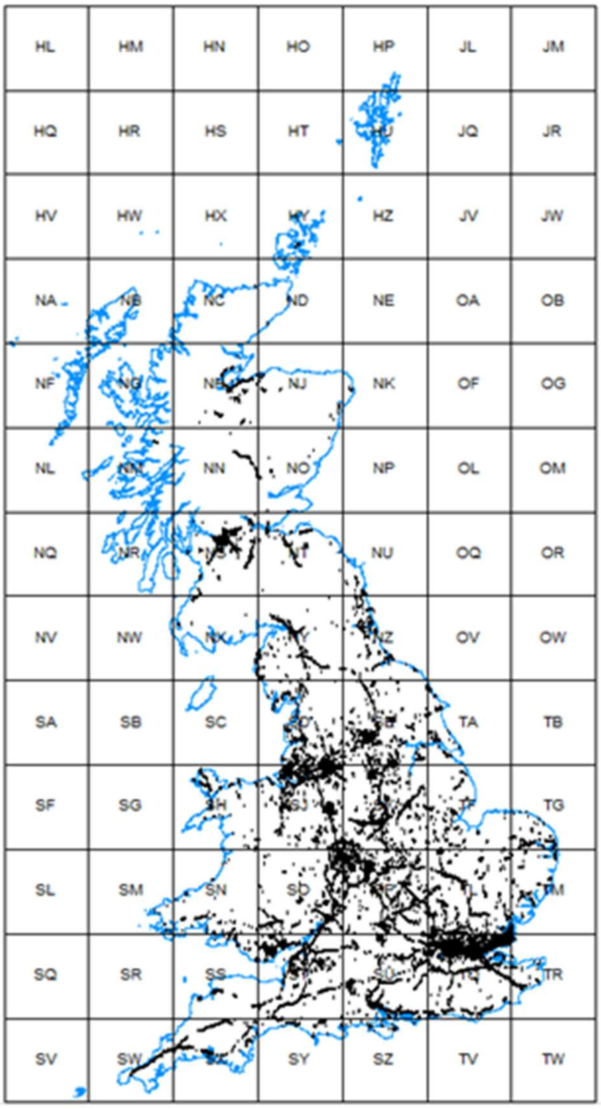

Figure 2 Distribution of all geotechnical data available at NGPD (as of November 2021).
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2.1 DATA ACCESSION AND QA

Historically, geotechnical data were manually digitised into the NGPD from paper, or pdf format, ground investigation reports. The records from approximately 65,000 exploratory holes have been entered in this way. More recently, AGS format ingestion systems have been used to semi-automate the process of data entry, which both reduces the time for data ingestion and reduces the risk of transcription errors. Due to the transition to digital accession, the proportion of AGS data within the database is also expected to increase proportionally in future.

Where possible, records held within the NGPD are attributed with lithology and stratigraphy. Typically, these attributes will be inherited from original data supplied by the BGS, and therefore represent third-party interpretation of the geology. Often lithology and stratigraphy will need to be converted by BGS into a valid BGS lexicon code as part of the ingestion process. If lithology or stratigraphy are not attributed, then these may be entered by a BGS geologist. Approximately 93% of the records in the NGPD are attributed with a stratigraphy code, though the proportion of these that have been independently validated by a BGS geologist is far less. Some clear errors within these data have also been recently identified within the LITHOSTRAT_CODE field, whereby geology codes entered are not consistent with geological descriptions or strength and consistency.

In addition to validating and entering lithology and stratigraphy, tables in the NGPD also contain check-constraints so no data considered to be invalid can be entered. This checks for duplicates, orphan records and values outside of a sensible range for the datatype (for example explicit limits, such as on grid-coordinates to ensure they plot within the UK using the British National Grid coordinate system; and checks on rationality, such as checking that plastic limit does not exceed liquid limit). Further checks are also run on the geology data before they can be loaded into the Borehole Geology Database (e.g., checking that lithological, stratigraphical attributions and layer interval descriptions within boreholes start at 0 m and end at the final borehole depth, and checking for gaps and overlaps in the intervals).

Boreholes entered within the NGPD are also accessioned to the Borehole Geology Database, and any stratigraphical interpretations made in the NGPD are periodically updated in the Borehole Geology Database, where they may sit alongside other interpretations of that borehole.

2.2 CURRENT APPLICATION OF THE NGPD

Within BGS, the NGPD is used predominantly for research that facilitates the planning, design and construction of buildings and infrastructure, and the mitigation of risk to these structures. Data from the NGPD are also used, in conjunction with the geology map of Great Britain (GeologyGB), to inform the development of applied and thematic geology datasets, such as BGS Civils and GeoSure (see section 5.1). The data, however, are not solely geotechnical, and therefore have the potential to be used more widely within BGS, particularly for research on regional geology, groundwater, soils, large-scale geohazards, renewable energy, energy storage, CCS and radioactive waste disposal.

Outside of BGS, the NGPD is currently used on an ad hoc basis by consultants and academics through the BGS enquires system, as the database is not accessible to external users. As a consequence of this, and legal constraints related to IPR and confidentiality, data are generally provided to external parties as:

i. non-parametric statistical data summaries, in a table format, for the geological units and properties of interest;
ii. raw data, excluding confidential data, are supplied for the units and properties within the area of interest in .xls format;
iii. and more recently data has been supplied to external users in AGS format using a newly developed in-house software tool, though this is still in alpha testing.

Generally, a nominal charged is applied to commercial users to cover the costs of querying the NGPD and preparing the data exported from it.

3 Reporting geotechnical and engineering geological data and information

The most productive period of urban geology research undertaken by BGS occurred in the 1980s and 1990s as part of an applied ‘urban’ mapping programme. This work was funded by the Department of Environment (DoE), the Welsh Office and the Scottish Development Department. Many of these studies were for urban areas within coalfields and sought to improve the availability of information for areas that might be liable to mining subsidence; other areas were selected on the basis of a broader range of geological characteristics and planning issues (Ellison et al., 2002). While this large-scale, decades-long, programme, which targeted over 50 urban areas, has never been replicated, smaller-scale studies, particularly to assess ground conditions, have continued in the UK for example Greater Manchester in 2021 (Arnhardt and Burke, 2021). Appendix 2 includes a list of urban geoscience studies undertaken by BGS in the UK and Figure 3 shows the geographical distribution of those studies.

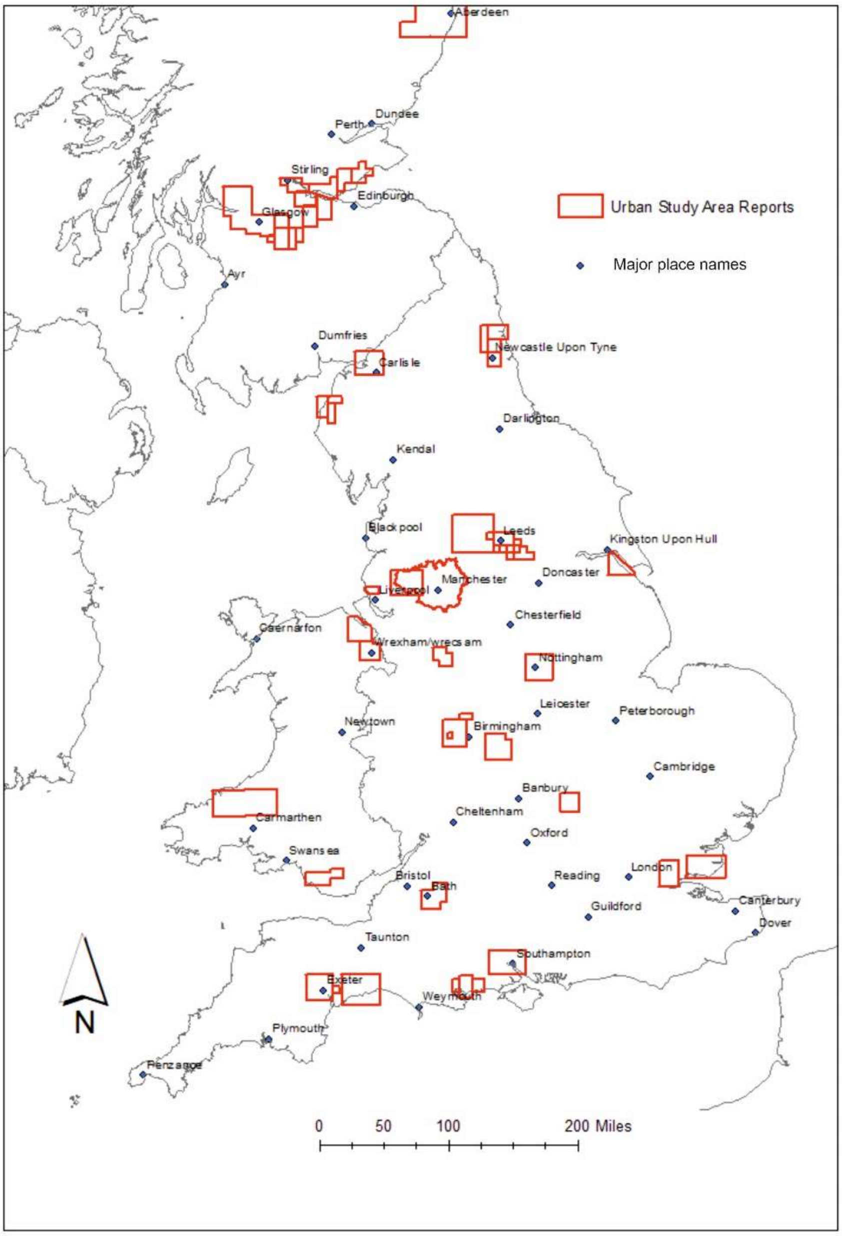


Figure 3 Location of urban geoscience study area reports produced by BGS. Contains Ordnance Survey data © Crown copyright and database right 2023

Other notable examples of geotechnical and engineering geological data and information reporting by BGS include the formation study reports, which were produced in the 1990s and 2000s and intersect many urban areas, and international commissioned research on the urban geology of Abu Dhabi (Farrant et al., 2012) and Singapore (see section 3.3).

3.1 UK URBAN GEOSCIENCE STUDY REPORTS

The objective of BGS urban geoscience reports is to provide a geoscience basis for urban planning and development, and specifically to inform the decision-making of planners and developers, but also engineers and conservationists. The Wigan and Bradford (Forster et al., 1995; Waters et al., 1996) studies were the penultimate and final projects of the 1980s – 1990s applied mapping programme. These reports were considered, at the time, to be the architypes for effective transfer of geological information to non-geologists, and in many respects defined that standard for both urban geoscience investigation and reporting for the decades to come (Ellison et al., 2002; Forster et al., 2004). The outputs from these studies were the culmination of knowledge acquired over the course of a decades-long research programme, available and reliable geological data, and maturation of GIS technology that enabled the data and knowledge to be synthesised and manipulated into a variety of user-friendly outputs.

UK urban geoscience study reports generally contain details of:

- geographical background;
- planning background: planning system, development plans, strategic planning issues (applied mapping reports only);
- geological information required for planning: local planning issues for which geological information is required (applied mapping reports only)
- geological background: description of bedrock, superficial and artificial deposits and structural geology;
- geological resources: minerals and aggregates (coals and construction materials), groundwater, sites amenable to specific use (e.g. waste disposal), geoheritage, soils;
- and engineering geology (ground conditions): geotechnical data, civil engineering considerations, geohazards, anthropogenic hazards (contamination, mining, etc) and hydrogeology.

Dedicated chapters are also often provided on specific geological issues of local interest, such as coal workings, slope instability, contamination and remediation, economic development, amongst others.

- geology and geography: background information for context and scene-setting;
- mineral resources: information on the extent of construction and energy resources, including sandstone, coal, fireclay, brick clay, sand and gravel, peat, and limestone;
- mining hazards: details on the areas of where underground mining is likely to have taken place, the location of associated shafts and adits, and the geological consequences of such workings and remedial measures;
- gas emission and leachates: details on the sources of gas emissions and identification of areas and lists remedial measures;
- water resources: information on surface water, groundwater water, water quality;
- engineering ground conditions: details/information on engineering properties of rocks and soils and assessment of ground conditions for construction;
- geohazards: provides information on the occurrence, within the study area, of geohazards such as slope instability, shrink-swell susceptibility, compressibility, running sand, and other geohazards.

Thirty-five of the BGS urban geoscience study reports were scanned and deposited on NERC Online Research Archive in 2015. The combined downloads since then exceed 40,000.

One of the objectives of the urban geoscience study reports is to describe the geotechnical characteristics of the main geological units, and to provide an assessment of ground conditions for structural foundations, excavatability and suitability for use as fill. In addition to providing engineering geological descriptions of units, a range of geotechnical data are also summarised by means of statistical analysis and presented using tables and graphical plots, such as scatterplots, extended box-and-whisker plots, line plots, stacked bar plots (see examples in Figure 4 and Figure 5).

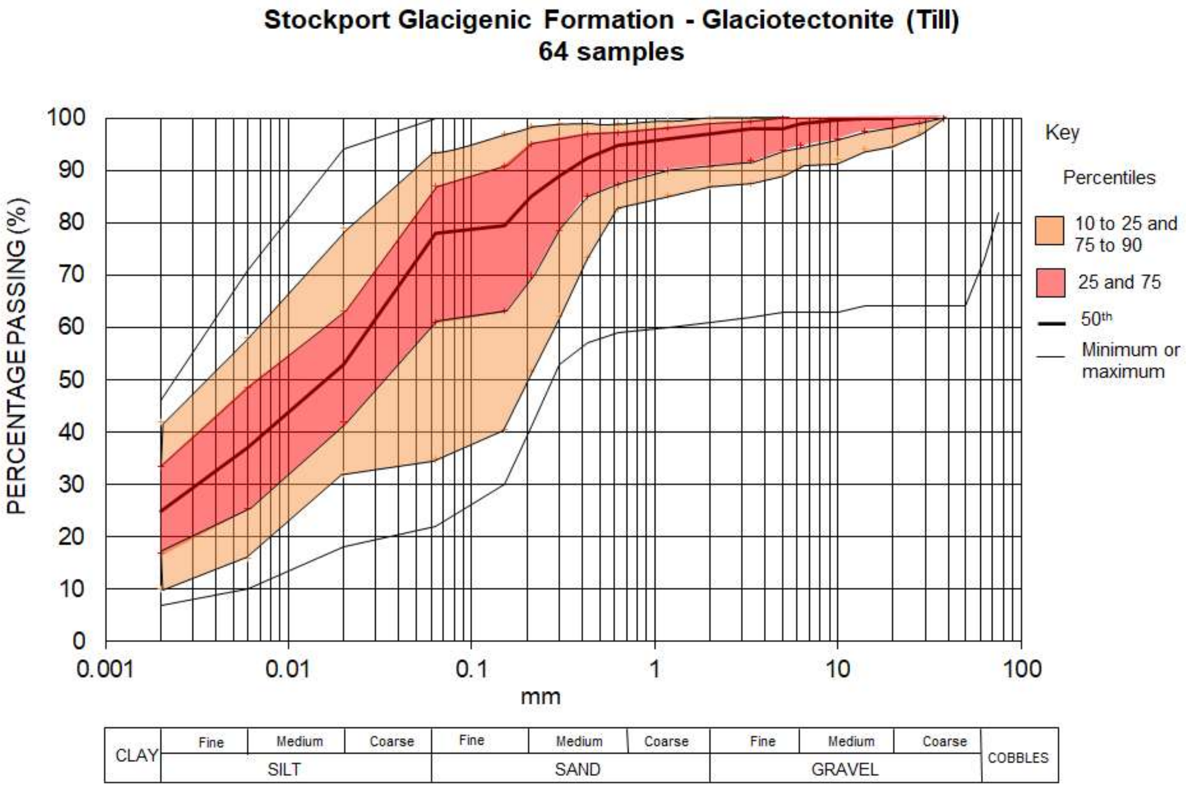


Figure 4 Example of plots of particle size distribution of Stockport Glacigenic Formation extracted from the urban geoscience study report of Greater Manchester (Arnhardt and Burke, 2021)

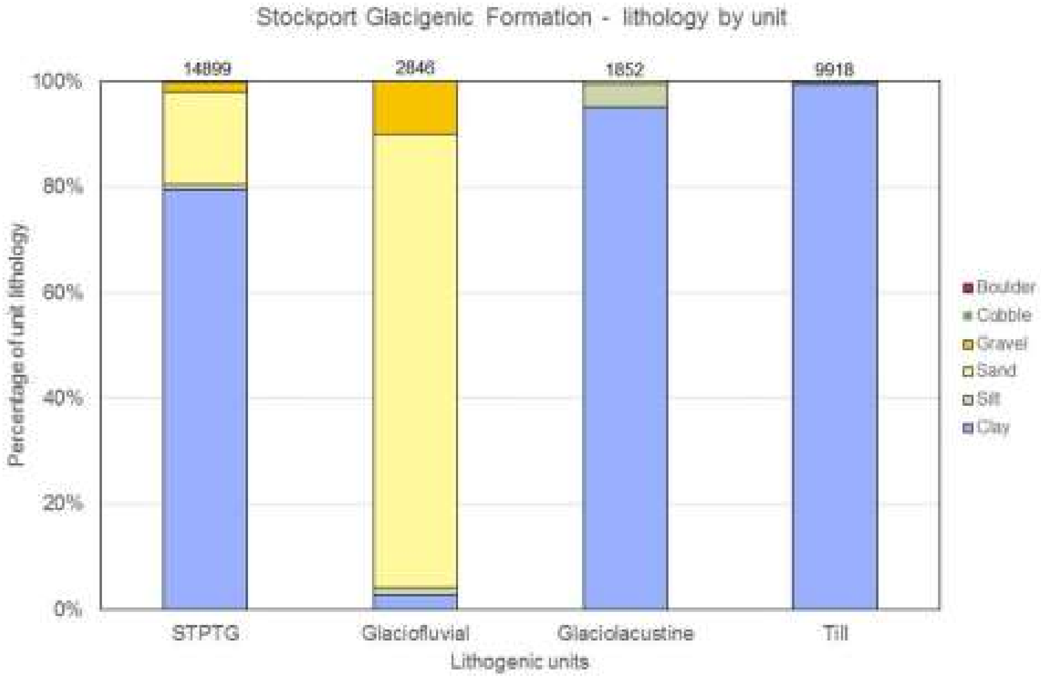


Figure 5 Example of plots of lithology of the Stockport Glacigenic Formation extracted from the urban geoscience study report Greater Manchester (Arnhardt and Burke, 2021)

Details of geological hazards present in the study area—such as slope stability, shrink-swell susceptibility, compressibility, and running sand are also provided. Descriptions of the nature of the geohazard processes and trigger mechanisms, indications of susceptible areas and remedial measures are provided, often with illustrations and photographic images that provide visual examples (as shown in Figure 6). Detailed maps showing geohazard likelihood and severity are also provided, often as supplementary maps (see section 4.3). Later iterations of BGS urban geoscience report include geohazards information extracted from BGS GeoSure products (see section 5.1.2; Arnhardt and Burke, 2021).

Figure 6 Example of geohazard image from the Bradford urban study report showing a landslip at East Morton (example of geohazard image from (Waters et al., 1996)

Geohazards associated with mining legacy (predominantly coal), including the history and methods of underground mining, as well as associated mine workings, its geological consequences, and remedial measures, are also included where relevant. These are principally shaft failures, which cause subsidence hollows, and issues related to rising mine water such as gas emissions, fault re-activation and subsidence. As with natural geohazards, images were used to provide visual examples of mining-related hazards (as shown in Figure 7).

Figure 7 Examples mining legacy image from the Bradford urban study report showing mining related subsidence at Baildon Moor (Waters et al., 1996)

3.2 FORMATION STUDY REPORTS

In addition to the urban geoscience study reports, the BGS formation study reports are also a notable example of the reporting of geotechnical and engineering geological data and information. These reports were produced to describe the main engineering characteristics of significant and problematic UK bedrock units, including the:

- Gault Clay (Forster et al., 1995);
- Mudstones of the Mercia Mudstone Group (Hobbs et al., 2002);
- Lias Group (Hobbs et al., 2012);
- and Lambeth Group (Entwisle et al., 2013).

These reports have a similar structure to the urban geoscience reports, and typically describe the geology, mineralogy, construction materials resources, geohazards and engineering considerations of the rocks and soils within the unit. As part of these studies, data from the NGPD were analysed and results presented within the formation study reports as tables and graphs. While not explicitly for urban areas, these geological units are found underlying several significant urban areas (Figure 8).

The formation study reports are used extensively by industry, with three of them ranked #1, #5 and #20 in the NERC Online Research Archive most downloaded items, and a combined total of 94,000 downloads (as of July 2022).

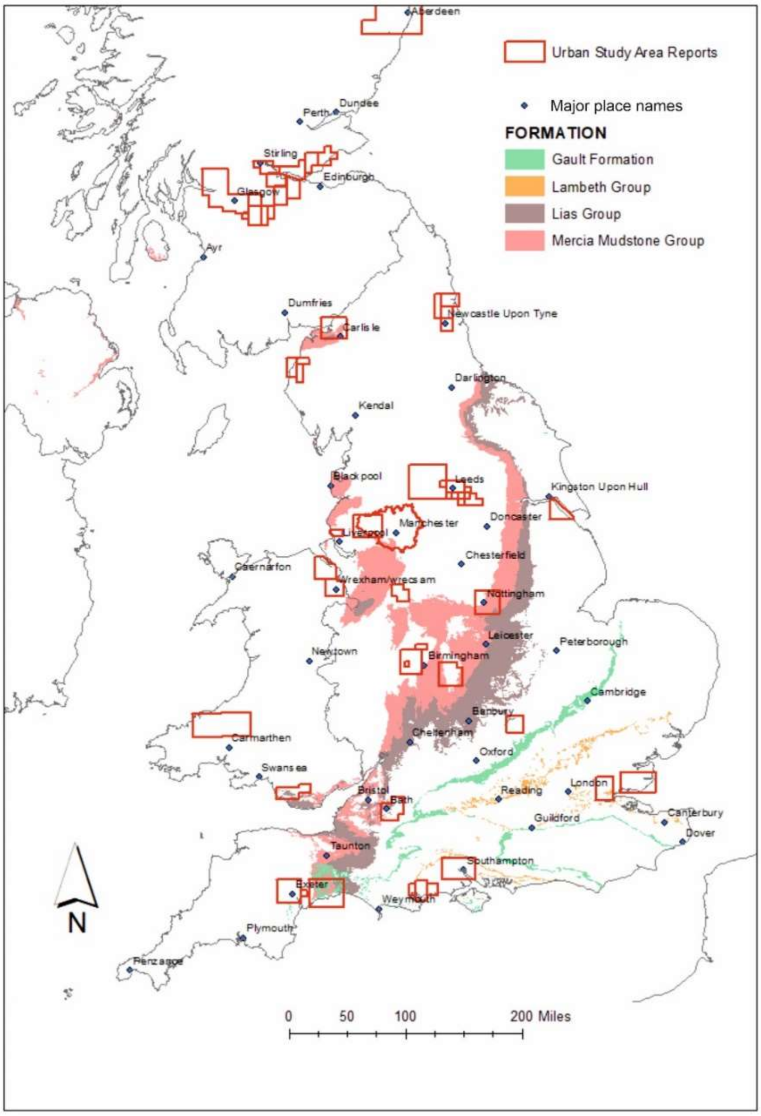


Figure 8 Map showing distribution of formation study geological units (outcrop only) reports alongside major urban areas and urban study report areas. Contains Ordnance Survey data © Crown copyright and database right 2023

Early published work on the geotechnical properties and classification of the formation is provided in most of the formation study reports. This typically includes weathering states, lithology, index properties, consolidation, strength and deformability, swelling, shrinkage and durability, compaction, permeability, geophysical properties, rock mass indices. In addition to the literature review, the collected geotechnical properties of the formations from the NGPD are analysed and summarised as discussed in section 3.1.

All four formation study reports provide detailed information on the engineering geology, including engineering geological descriptions for geological units, and information on ground conditions with implications for ground engineering activities. Table 3 provides an example from the Lambeth Group study report (Entwisle et al., 2013).

Table 3 Engineering geological descriptions and characteristics of the Woolwich Formation of the Lambeth group (Entwisle et al., 2013)

Formation	Unit	Lithology	Engineering Description	Foundations	Excavation	Engineered fill	Site investigation
Woolwich Formation	Upper Shelly Clay/Lower Shelly Clay	Shelly Clay	Firm to very stiff, often closely to extremely closely fissured, sometimes thinly to thickly bedded, generally dark grey sometimes mottled brownish grey shelly CLAY. Some beds, up to 1m thick, are almost entirely shells, locally weakly cemented	Shallow Foundations: Clay lithologies may be prone to shrink/swell movements that can be exacerbated by presence of trees, leaking drains and high-water tables. Presence of water-bearing sand bodies, beds or laminae may make foundation construction difficult. Water ingress may lead to reduced bearing capacity of clays. Piled Foundations: Lithological heterogeneity and presence of water bearing strata will dictate type, length and construction methods adopted. Continuity of strata across site may influence pile design where part of resistance is end-bearing. Presence of hard bands may prove an obstruction or offer a foundation solution for different pile designs.	Diggable. Strength contrasts between clay-dominant and shell dominant lithologies may lead to instability in excavations	Variability and relatively thin nature of each unit mean fill materials are likely to be composed of more than one unit and lithology. Acceptance criteria should be taken into account at planning, investigation and construction stages.	Important to determine groundwater conditions and lithological variability, particularly thickness and extent of shell bands. Sulphate/sulphide content.
	Laminated Beds	Clay, silts and sands	Variable, thinly interbedded succession of CLAY, SILT and SAND. Beds usually < 50 mm thick and typically laminated on a millimetre scale. Localised sand bodies (probable channels) up to about 4 m thick occur, particularly in SE London		Diggable. Usually water-bearing, giving rise to perched water tables and instability in excavations.		Important to determine presence of water bearing Laminated Beds of sand and silt and associated perched water tables; also, presence and extent of possible water bearing sand-filled channels.
	Upper Shelly Clay	Shelly sand (Generally in the east of London)	Medium dense to very dense, sometimes laminated, grey sometimes brown, occasionally with organic remains, silty, fine to medium, occasionally coarse SAND (representing infilled channels). Generally high sulphate and organic contents.		Diggable. Impersistent and often water-bearing, leading to unexpected water strikes and instability in excavations. Immediate support required		Important to determine position, extent and thickness of sand-filled channels and associated groundwater conditions.
	Upper Shelly Clay/Lower Shelly Clay	Shelly Mudstone and LIMESTONE (Limited to south and east London)	Weak generally thin but up to 300 mm thick beds of shelly MUDSTONE and strong dark grey LIMESTONE (Paludina limestone, Upper Shelly Clay)..		Digging, ripping or pneumatic tools may be required due to variable strengths. May be stable in excavation but dependant on hard band thickness, strength of surrounding strata and potential water ingress		Important to determine elevation, thickness, extent and strength of hard bands prior to construction.
	Lower Shelly Clay	Lignite (Mainly to south and east of London)	Firm to weak, sometimes thickly to thinly laminated, sometimes with extremely closely spaced fissures/fractures, dark brown or black, sometimes clayey or sandy LIGNITE. Sometimes with interbeds or thick laminations of black coal		Diggable, but trees and large roots preserved in situ may cause difficulties locally. Variable thickness, strength and close fracturing/jointing may result in instability in excavations. May be stable in short-term.	Unsuitable	Important to determine presence and extent of lignite bands associated with variable thicknesses and strengths.

3.3 SINGAPORE URBAN GEOLOGY PUBLICATIONS

This Singapore memoir (see section 3.3.1), practitioners' guide (see section 3.3.2) and geological map (see section 4.5) were produced to communicate and facilitate adoption of a radical new understanding of Singapore's geology. These publications are the final outputs a decade-long urban geoscience study of Singapore by BGS, based primarily on borehole core and data arising from a deep ground-investigation programme undertaken by the Building and Construction Authority of Singapore (BCA).

3.3.1 SINGAPORE GEOLOGY (2021): MEMOIR OF THE BEDROCK, SUPERFICIAL AND ENGINEERING GEOLOGY

The Singapore Memoir (Leslie et al., 2021a) was commissioned by BCA to formalise the new geological framework and consolidate the information contained in several papers published by BGS in a single volume (Dodd et al., 2019, 2020; Gillespie et al., 2019; Leitgeb et al., 2019; Leslie et al., 2019; Chua et al., 2020).

The memoir is subdivided into six sections that provide detailed information on the structural geology and sedimentary, igneous, superficial and artificial units and deposits. The final section also provides details on the engineering geology of Singapore. Rather unconventionally, the engineering geology section is not subdivided by geological unit, but rather by the key features of the geology that affect the variation in physical, chemical and mechanical properties of the subsurface and the potential for geological hazards and resources. This approach was taken in part due to the lithological heterogeneity of the units and extremely localised variation produced by deformation and alteration, and because the practitioners' guide summarised geotechnical properties by bedrock unit. This therefore allowed a more nuanced approach to be taken with the memoir and avoided significant repetition between the memoir and practitioners' guide.

The engineering geology section of the memoir details the:

- lithological variation within each geological unit, including the occurrence of fault-rock, xenoliths, tuffisite and dykes;
- discontinuities, including faults and fault zones, joints, veins and vein dissolution, karstic cavities, bedding and unconformities;
- alteration, including metamorphism and weathering;
- groundwater and hydrogeology;
- physical and mechanical properties;
- and engineering geological considerations.

The engineering geology section, and in particular the sections on lithological variation and physical and mechanical properties, make extensive use of graphs, including box-and-whisker and cross-correlation matrix plots, to show data distributions and geotechnical property relationships (Figure 9).

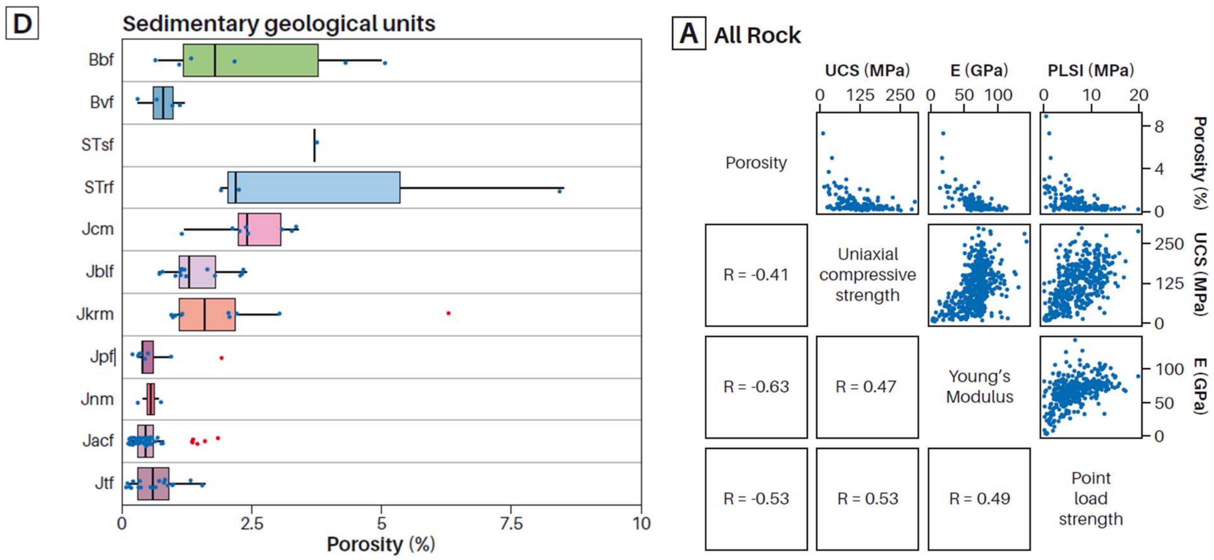


Figure 9 Examples of box-and-whisker and cross-correlation matrix plots used in the Singapore geology memoir. Reproduced from Gillespie et al., (2021) with permission. © 2021 Building and Construction Authority.

Appendix 2 of the memoir summarises geotechnical, geophysical and hydrogeological properties, subdivided by geological unit, lithology and weathering grade. The data are presented as likely minimum — likely maximum, median value [number of samples]. A nonparametric statistical approach was used to determine the likely minimum and maximum modified after Hallam (1990); whereby 0–9 data values, 0–100% of range; 10–19 data values, 25–75% of range; 20–59 data values, 10–90% of range; 60–99 data values 5–95% of range; 100–299 data values, 2–98% of range; and 300+ data values, 1–99% of range. This follows the convention for the presentation of extended box-and-whisker plots in the BGS formation studies reports (see section 3.2). For the most part the data are derived from the BCA deep ground-investigation, but where available data from published literature are also included and red-letter superscript-suffix included to identify the primary reference (Table 4**)**. These data are reported as they appeared in literature as ranges and or means.

Unit	Lithology	Weathering grade	Bulk density (Mg/m³)	Porosity (%)	UCS (MPa)	E (GPa)	Point load (MPa)	Tensile strength (MPa)
Jurong Group	mudstone	I	2.70-2.78, 2.74 [61]	0.4-1.1, 0.6 [12]	26.5-181.0, 85.4 [61]	43.2-84.0, 67.0 [61]	0.72-8.60, 4.74 [44] 3-12 (o, x) 4.85-13.91, 9.38 (j)	
		II	2.67-2.70, 2.68 [17]	1.3-3.4 [5]	27.2-104.0, 40.1 [17]	31.4-60.3, 50.5 [16]	0.38-4.97, 2.09 [22]	
		III	2.16-2.64 [2]		5.7-21.8 [2]	6.2-20.6 [2]	0.40-2.02 [3] 0.1-3 (o, x)	
		not stated	2.31-2.77 (e)		0.1-67 (e) 21-53, 34 (o, x)	0.01-38 (e) 33 (o, x)		

Table 4 Example of geotechnical properties presented in Appendix 2 of the Singapore geological memoir. Reproduced from Gillespie et al., (2021) with permission. © 2021 Building and Construction Authority.

Appendix 3 of the memoir summarises the engineering considerations, presented in Section 6, for each geological unit. This includes:

- foundation conditions;
- excavatability;
- stability of excavations and slopes;
- additional considerations for excavation of tunnels, shafts and caverns;
- material re-use;
- and ground investigation considerations.

A supplementary data folder was also produced to accompany the geological memoir. It contains data arising from the BCA deep ground-investigation programme, including laboratory rock test data, permeability data, rock quality designation (RQD) data, and sonic velocity data.

3.3.2 SINGAPORE GEOLOGY (2021): PRACTITIONERS' GUIDE TO THE BEDROCK GEOLOGY

A practitioners' guide was also developed to specifically help those engaged in ground investigation and ground engineering work in Singapore adopt and benefit from the new geological framework (Gillespie et al., 2021). The guide focuses exclusively on the bedrock units of Singapore as this was where most of the new data and understanding from the BCA deep ground-investigation was generated.

The main objectives of the guide are to ensure practitioners can:

- make consistent, accurate and precise observations of key geological features in borehole cores and outcrops;
- and use these observations to make informed and confident interpretations of the geology, including placing examined rock within the new geological framework.

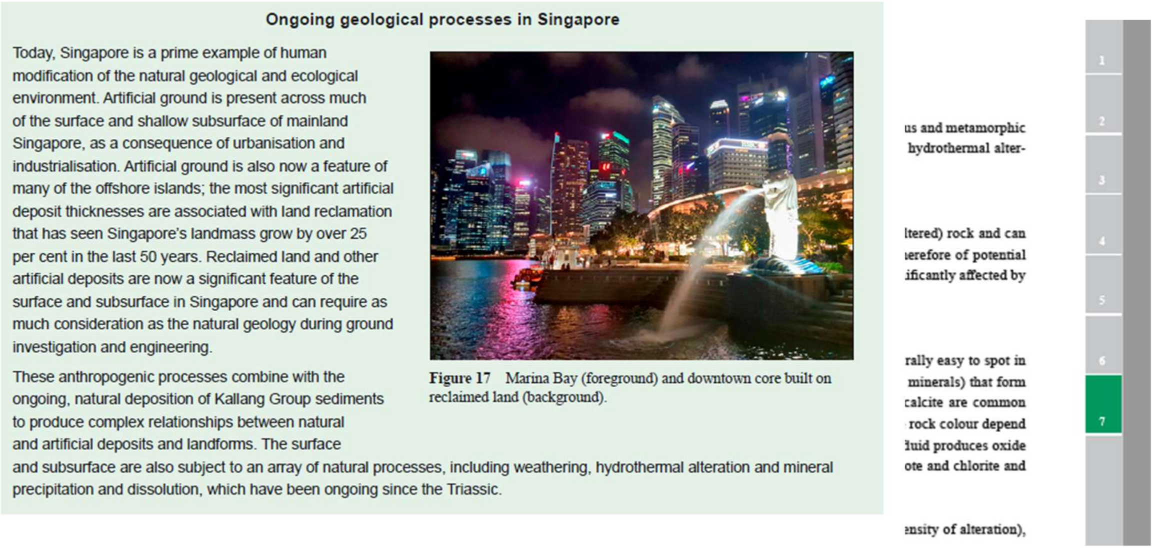
The guide is divided into two parts:

- Part 1 (Chapters 1 to 7) provides contextual information and methodological advice intended to help practitioners to identify, classify and describe key geological features, including a summary of the geological history and the rock-types, faults; and other features that can be found in the bedrock of Singapore;
- and Part 2 (Chapter 8) presents a summary of the key geological characteristics and geotechnical properties for each of the bedrock units of Singapore.

The volume is copiously illustrated with diagrams, infographics and example images to make it more accessible to those who are not native English speakers. Three appendices also provide additional information, including:

- tips for examining bedrock in borehole cores and outcrops;
- rock name terms used by BGS to log the BCA deep ground-investigation cores;
- and details of borehole core images obtained from stratotype and reference boreholes; which accompany the volume in a supplementary data folder.

The guide was produced as a digital publication, and to facilitate its use as a reference volume a coloured index was created that appears on every page to show the current chapter position and allow easy navigation to other chapters using embedded links (Figure 10). Green-coloured 'callout boxes' are also used throughout Part 1 of the guide to communicate self-contained pieces of information, which fulfil a number of different functions including highlighting important concepts, providing additional contextual information or definitions for geological terms used, and for signpost readers to further information outside the guide (Figure 10).



Ongoing geological processes in Singapore

Today, Singapore is a prime example of human modification of the natural geological and ecological environment. Artificial ground is present across much of the surface and shallow subsurface of mainland Singapore, as a consequence of urbanisation and industrialisation. Artificial ground is also now a feature of many of the offshore islands; the most significant artificial deposit thicknesses are associated with land reclamation that has seen Singapore's landmass grow by over 25 per cent in the last 50 years. Reclaimed land and other artificial deposits are now a significant feature of the surface and subsurface in Singapore and can require as much consideration as the natural geology during ground investigation and engineering.

These anthropogenic processes combine with the ongoing, natural deposition of Kallang Group sediments to produce complex relationships between natural and artificial deposits and landforms. The surface and subsurface are also subject to an array of natural processes, including weathering, hydrothermal alteration and mineral precipitation and dissolution, which have been ongoing since the Triassic.

Figure 17 Marina Bay (foreground) and downtown core built on reclaimed land (background).

Figure 10 Example of green 'callout box' (left) and coloured index tab (right) found along the right margin of each page in the Singapore Practitioners' Guide. Reproduced from Gillespie et al., (2021) with permission. © 2021 Building and Construction Authority.

The geotechnical and engineering geological data and information presented in Part 2 for each bedrock unit. This includes infographics showing where the unit occurs within the subsurface, the relative proportions of the main lithology-types encountered within boreholes that have intersected the unit, and the anticipated range and median strengths likely for weathering grades I – III (Figure 11). These infographics are based on those used for the engineering geological map flyover labels (see section 4.4) Tables also provide property summaries for the different lithology types by weathering grade, and also for rock mass properties by weathering grade (Figure 11). These data are the same as those in Appendix 2 of the geological memoir, and using the same format (see section 3.3.1), but are presented separately for each unit.

8.11.7 Geotechnical properties

Tuas Formation

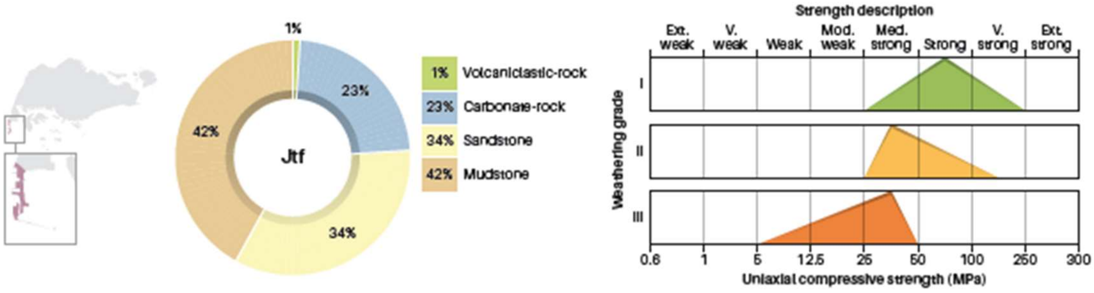


Figure 65 Map (left), dominant rock types (middle) and strength (right) for the Tuas Formation.

Table 17 Summary of intact rock properties for the Tuas Formation.

Lithology	W. grade	Bulk density (Mg/m^3)	Porosity (%)	UCS (MPa)	E (GPa)	Point load (MPa)	Tensile strength (MPa)
Mudstone	I	2.72–2.74 [6]	0.7–1.0 [2]	54.6–81.2 [6]	58.0–81.0 [6]	5.75 [5]	
	II	2.68–2.72 [2]		104.0–168.0 [2]	90.0–91.0 [2]	1.64–5.09 [3]	
Sandstone	I	2.68–2.71, 2.69 [13]	0.3–0.9 [7]	69.0–135.5, 87.4 [13]	57.5–73.5, 66.0 [13]	2.39–8.84 [5]	
	II	2.62–2.69 [5]	0.5–1.6 [4]	49.5–219.0 [5]	42.0–62.0 [5]	3.38–6.60, 4.46 [10]	
Carbonate-rock	I	2.70–2.73 [8]	0.1–0.3 [5]	59.2–132.0 [8]	60.0–85.0 [7]	1.88–5.16 [5]	10 [1]
	II	2.70 [1]	1.4 [1]	111.0 [1]	68.0 [1]	5.24 [1]	
All	I	2.68–2.73, 2.71 [27]	0.2–0.9, 0.3 [14]	57.4–135.2, 92.5 [27]	51.5–81.5, 65.0 [26]	2.52–6.71, 4.41 [15]	10 [1]
	II	2.62–2.72 [8]	0.5–1.6 [5]	49.5–219.0 [8]	42.0–91.0 [8]	2.40–5.90, 4.33 [15]	

Table 18 Summary of rock-mass properties for the Tuas Formation.

W. grade	P-wave velocity (m/s)	S-wave velocity (m/s)	Dynamic Poisson's ratio	Permeability (m/s)
I	3622–4545, 4167 [120]	1724–2273, 1961 [120]	0.32–0.38, 0.35 [120]	1.70×10^{-6} [1]
II	3448–4348, 3846 [103]	1472–2128, 1818 [103]	0.31–0.40, 0.36 [103]	$2.00 \times 10^{-8} – 2.30 \times 10^{-6}$ [3]
III	3125–3704, 3571 [39]	1199–1760, 1563 [39]	0.35–0.41, 0.37 [39]	
IV	3226–3333 [5]	1176–1299 [5]	0.40–0.42 [5]	
V	2632–3125 [6]	758–1124 [6]	0.43–0.45 [6]	

Figure 11 Extract of geotechnical properties section of the Singapore Practitioners' Guide showing combined used of infographics and tables to summarise the geotechnical properties of a single bedrock unit. Reproduced from Gillespie et al., (2021) with permission. © 2021 Building and Construction Authority.

4 Geotechnical and engineering geological data and information for geological maps

Traditionally, geological maps are attributed with lithostratigraphical (layered rocks) and lithodemic (intruded) units, based on common rock types, or a chronostratigraphical approach, based on common age. While this approach for presenting the geology is useful for geologists, without significant supplementary information, these maps can be only of limited use for informing planning, land use and development (Culshaw and Price, 2010; Dobbs et al., 2012). To address these shortcomings applied geology maps, including engineering geology, geotechnical, land use planning and construction suitability themed maps, have been developed to meet the challenge of making geological data and information more suited to land use planning, engineering design, building, construction and maintenance (Dearman, 1991). The main advantage of thematic maps is that they enable the communication of geological knowledge to non-geoscientists, while applied geology maps enable the communication of geological property data, information and knowledge between specialist geoscientists.

The nature of applied and thematic geology maps, and in particular the units used to attribute them, vary considerably according to scale and purpose. Some characterise the geology in terms of lithology and properties (more traditional engineering geology/geotechnical and hydrogeology maps), while thematic maps may address geological hazards and resources, or provide contextual information for specific applications, such as construction and land use planning. In some instances, these maps also depict how geology, or a property of it, varies with depth to inform excavation activities (Dearman, 1991; Dobbs et al., 2012).

The BGS has produced a range of applied and thematic geology maps, at different scales, to support urban planning, management and development. Many of these maps are outputs from urban geology projects funded by the DoE (and its successor departments) in England, the Welsh Office in Wales and the SDD in Scotland (see section 3; and Culshaw and Price, 2010). Importantly, these maps are also designed, almost universally, as an accompaniment to a memoir or other publication, which provides additional or necessary contextual information.

4.1 THE MAP OF THE SUB-SOILS OF THE COUNTRY AROUND LONDON

The map of the sub-soils of the country around London (Woodward, 1897), produced at a scale of 1: 253 440 (Figure 12), uses lithological units grouped into a Clayey series, Sandy series, Gravelly series and unspecified for Limestone (Chalk) and Marshland (alluvium). This map recognises the important role of grainsize in soil behaviour, and the relevance of this for applications such as foundations, drainage and sanitation. The memoir that it accompanies was specifically produced to communicate information to non-geoscience specialists on the geotechnical, hydrogeological and geo-environmental influences of geology on the building and construction of urban areas. It is the first engineering geology publication produced by BGS (Geological Survey of England and Wales) and also perhaps the first in the UK (Culshaw, 2004).

Figure 12 Map of the sub-soils of the country around London, from the 2nd edition of the Soils and subsoils from a sanitary point of view; with especial reference to London and its neighbourhood (Woodward, 1906). The first edition was hand colourised, and the second printed in colour.

4.2 THE GEOTECHNICAL PLANNING MAP OF THE UPPER FORTH ESTUARY

The geotechnical planning map of the upper Forth Estuary for heavy structures (Gostelow & Browne, 1986), produced at a scale of 1: 50 000 (Figure 13) uses six units to classify the ground ranging from very good for heavy foundations (zone A) to unpredictable (very poor to fair) (zone F). Units are also attributed with additional classification codes to indicate where assessment is based on limited geotechnical data, and also the class of materials present in the top 3 metres, and from 3 to 20 metres depth. A linked table provides additional information on potential foundation solutions, presumed allowable bearing capacity, and site investigation considerations. The map communicates specific and technical information for the surface and subsurface for foundations design, and also communicates a degree of confidence within this information. The map was produced as part of a study to assess the suitability of locations along the Firth of Forth and Cromarty Firth estuaries for heavy industry, primarily to support development of the petroleum industry in Scotland (Culshaw and Price, 2010).

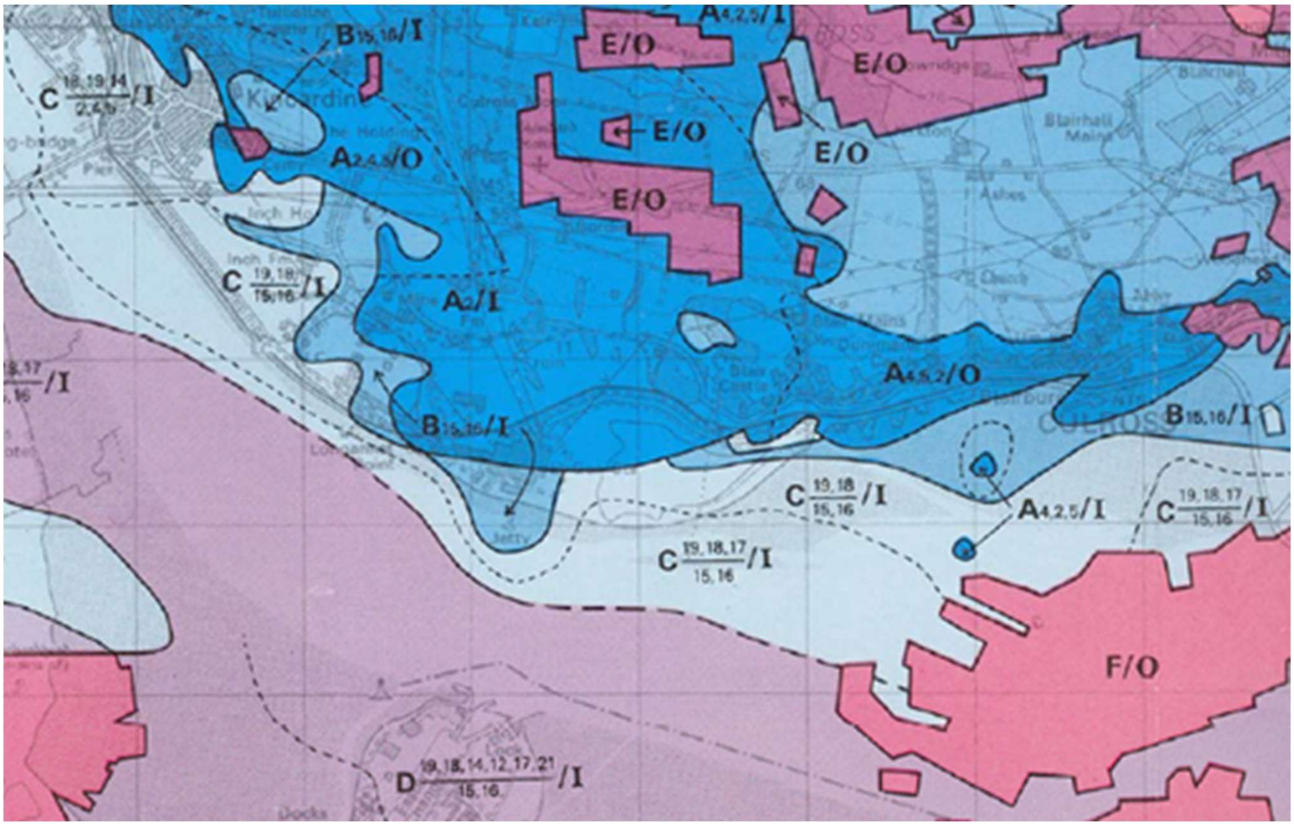


Figure 13 Extract from the geotechnical planning map of the upper Forth Estuary, Scotland, UK, for heavy structures (Gostelow & Browne 1986)

4.3 APPLIED GEOLOGY MAPS FOR PLANNING AND DEVELOPMENT IN WIGAN

A report on the geological background for planning and development in Wigan (Forster et al., 1995), is accompanied by a suite of maps produced at a scale of 1: 25 000. In addition to geology, applied maps also show the:

- distribution of boreholes, pits and site investigations,
- superficial deposit thickness,
- hydrogeology,
- mineral resources,
- distribution of made and worked ground,
- previous and present industrial uses,
- engineering geology,
- and shallow mining.

The engineering geology map uses ten units to show the primary rock- and soil-types: sandstone, mudstone, mixed cohesive/ non-cohesive soils, non-cohesive soils, organic soils and artificial deposits (Figure 14). The primary soil- and rock-types are further subdivided by strength and grain size to reflect their engineering geological behaviour. The map also uses a stripe system to provide information about the material at the surface and the subsurface (if another unit is present within the top 5 metres). Artificial deposits are represented using transparent hachuring to show where they occur, and what material is present below. The map is accompanied by an extended key providing an engineering geological description for each unit and the corresponding implications for foundations, excavations, engineering fill and slope stability.

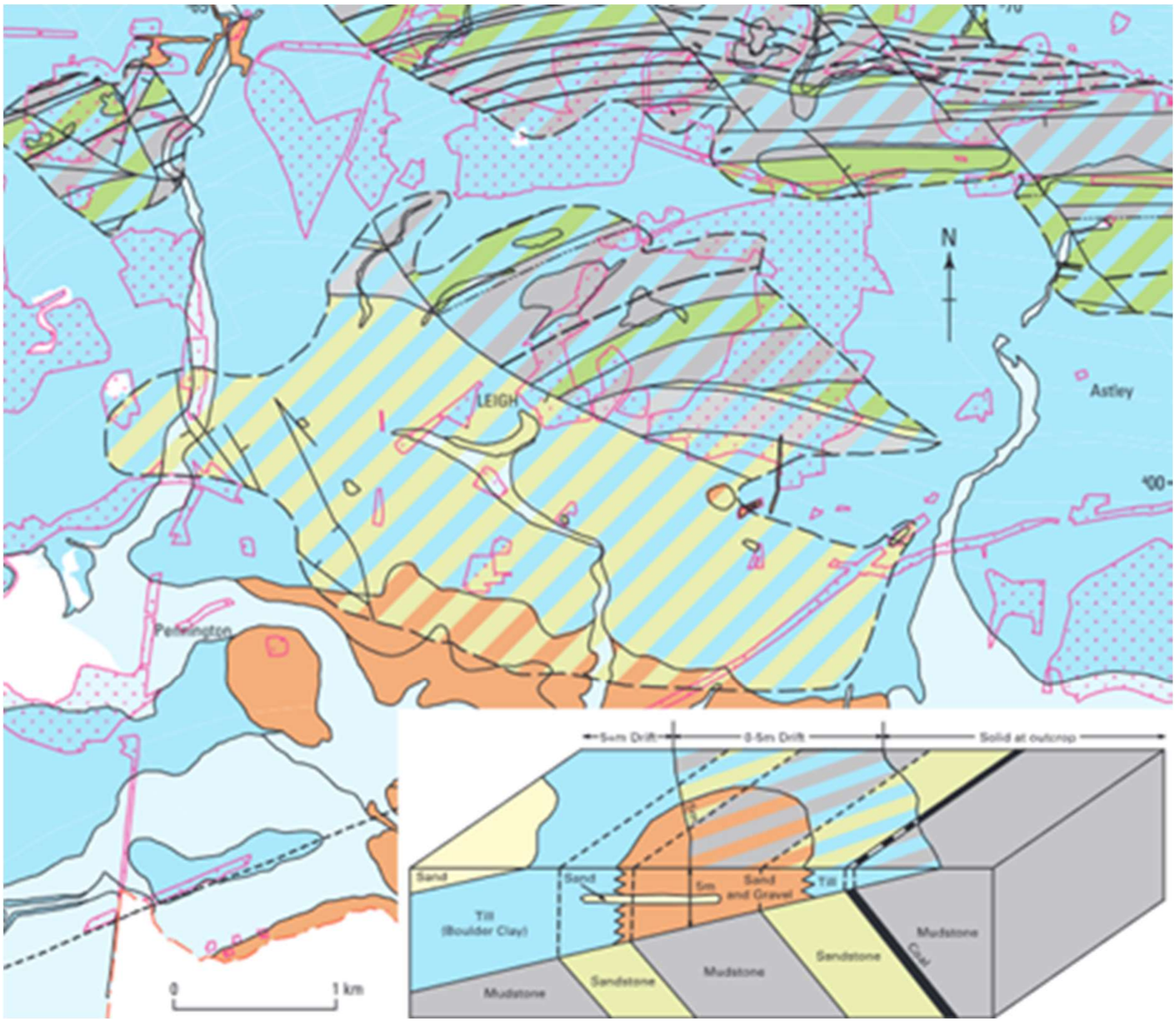


Figure 14 Extract from the engineering geology map of part of the Wigan area around Leigh (from Forster et al., 2004, fig.6)

A planning guidance map was also developed in consultation with local planners and developers. It uses ten units and three ornaments to show the distribution of abandoned shallow mines, potential for contaminated land and groundwater, mineral resources, major faults, and public water supply boreholes. These were considered to present the most significant geological problems affecting planning and development in the Wigan area.

4.4 SINGAPORE ENGINEERING GEOLOGY BEDROCK MAP IPDF AND PRINT MAPS

The engineering geological bedrock map of Singapore is available as an as a printed map, and as a layer within the Singapore Geology Interactive Map (Leslie et al., 2021b). The map has been produced at a scale of 1:50 000 and is attributed with fifteen engineering geological formations. These are a combination of seven principal geology-types and eight subordinate geological features (Figure 15). The units are also attributed with the typical strength ranges of fresh to moderately weathered rock (weathering grades I-III). Principal geology-types are based on common lithological assemblages and genetic origin, which control the overall properties, geohazards and resources present within each engineering geological formation. Subordinate geological features highlight the potential for considerable localised variation and/or present specific additional engineering geological considerations. The strength ranges of engineering geological formations are based primarily on data collected as part of BCA's deep ground-investigation programme, and where not available are estimated based on information available in published literature and BCA data.

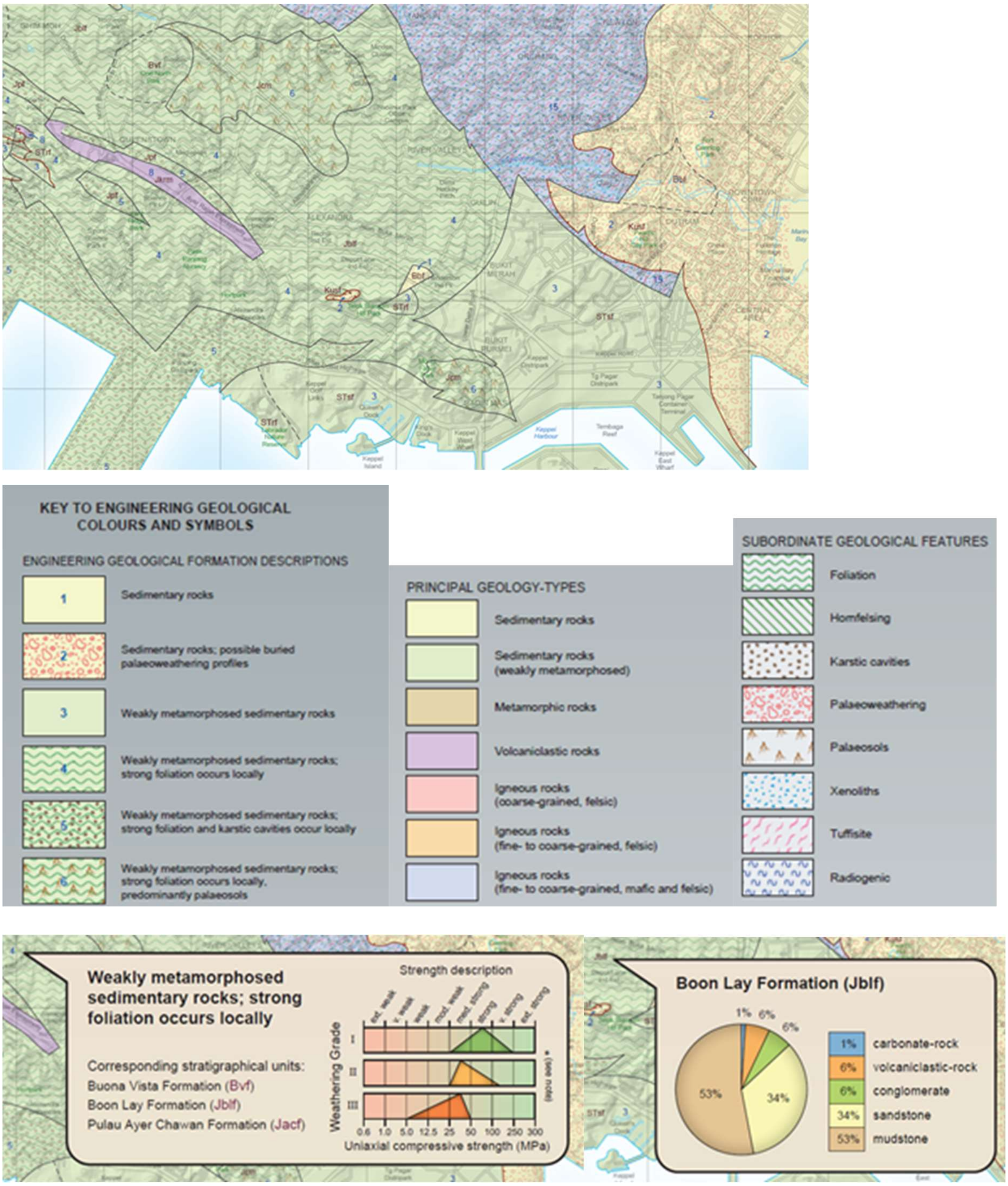


Figure 15 Extract from the Engineering Geology Bedrock Map of Singapore showing the map face (top); the Engineering Geological Formations and their component Principal Geology Type and Subordinate Geological Features (middle); and the flyover labels for both the engineering geology and bedrock units (bottom). Reproduced from Gillespie et al., (2021) with permission. ©2021 Building and Construction Authority.

Stratigraphical bedrock unit boundaries, and unit letter codes, are also retained on the engineering geological map to provide a direct link to the bedrock stratigraphy. Each stratigraphical unit is also further characterised in terms of the dominant lithology-types and relative proportions logged in BCA deep ground investigation boreholes or anticipated based on available outcrops and literature where this information is not available.

Infographics showing the typical strength ranges of the engineering geological formations, and the proportion of dominant lithology-types in each unit, are shown on the interactive map using flyover labels, which appear when the cursor hovers over the engineering geological formation map code or the bedrock unit short code respectively (Figure 15).

Within this interactive map are compilations, at 1:50 000 scale of the bedrock geology, superficial deposits, artificial deposits (reclaimed land only), and the engineering geology. The display of the geology can be configured in multiple ways along with the topography, elevation data and sheet grids as well as the various display enhancements provided.

User-defined map configurations can also be produced as A0 prints using the print function within the interactive map. These prints are fully annotated with appropriate marginalia that incorporates all the information found on a traditional printed geological map (e.g. keys and cross-section) as well as tables and graphs that summarise all the information contained in the flyover labels. For the engineering geology map, additional inset maps, diagrams, graphs and text boxes are also included to provide additional information about key geological features with engineering implications within the bedrock of Singapore (Figure 16), including:

- foliation (text boxes);
- hornfelsing (text boxes);
- karstic cavities (text boxes);
- palaeoweathering (text boxes);
- palaeosols (text boxes);
- tuffisite (text boxes);
- xenoliths (text boxes);
- radiogenic potential (text boxes);
- faulting (text boxes);
- weathering (modern) (text box and diagram);
- and groundwater (text boxes);
- simplified bedrock geology (small-scale map);
- Cenozoic and artificial deposits thickness (small-scale map);
- bedrock units -deposited, dominant lithology-types (stacked-bar chart);
- and bedrock units -intruded, dominant lithology-types (stacked-bar chart).

Four map configurations—bedrock, superficial, combined bedrock and superficial, and an engineering geology map—were also published in paper format to be sold alongside a printed version of the geological memoir.

The maps were developed to be used alongside the memoir and practitioners' guide, by those working in the civil engineering industry, and more widely in the planning and development sectors, to aid in the identification of the geological features and stratigraphical units present in Singapore, and to reduce the overall risk and cost of construction.

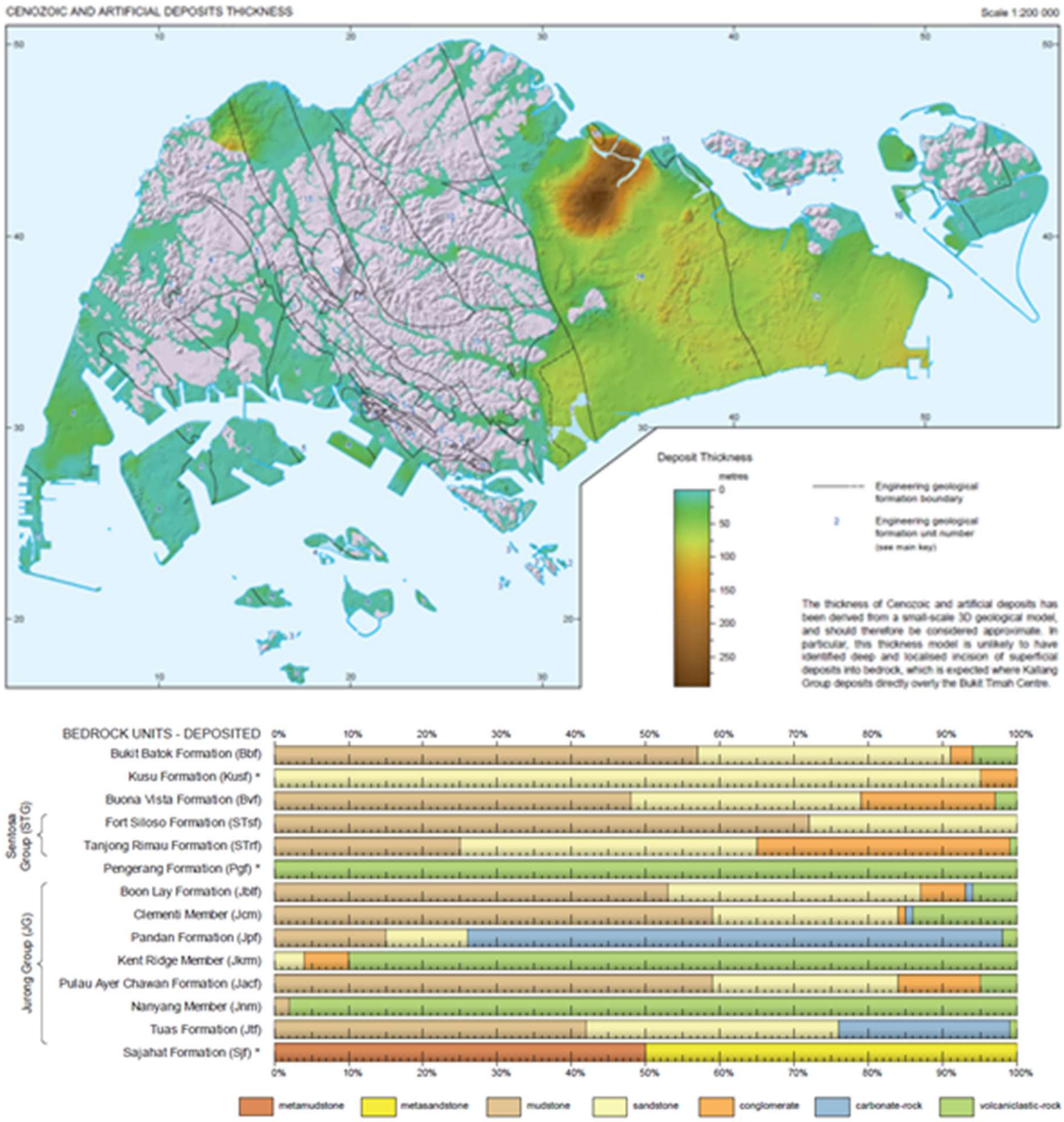


Figure 16 Example of inset map and figure from the Singapore Engineering Geology Bedrock Map showing the thickness of Cenozoic and Superficial deposits (top) and the proportion of dominant lithology-types recorded in the deposited (sedimentary and volcanic) bedrock units. Reproduced from Gillespie et al., (2021) with permission. ©2021 Building and Construction Authority.

5 Geotechnical and engineering geological data and information for GIS

GIS technology enables geoscience data and information to be synthesised and manipulated, with a wide variety of other disparate geospatial data, to produce new user-friendly maps and datasets. The versatility to programme new geospatial analysis tools also enables new ways of interrogating and displaying spatially organised data and information: GIS has become a fundamental tool for geoscience research including for geotechnical and engineering geological data and information analysis and provision.

5.1 GIS-DERIVED PRODUCTS

The ability to easily manipulate the digitised geological map polygons, and to integrate this with other data such as geotechnical data form the NGPD (see section 3), has enabled the derivation of a wide range of value-added geological map products. Principal amongst these are BGS GeoSure and BGS Civils. The objective of these products is to provide users with an indication of shallow ground conditions (top 2-4 m) and the potential implications for existing or proposed development. These products are used by a range of stakeholders for rapid identification of areas with potential problems, including regional planners, developers, insurers, homeowners, solicitors, local government.

5.1.1 BGS CIVILS

BGS Civils datasets provide information on ground conditions and civil engineering considerations, primarily for the near surface (top 2 m). Full details of the methodology used to produce individual datasets are presented in a series of internal BGS reports for each Civils dataset (Entwisle et al., 2015 and Lee et al., 2012, Entwisle et al., 2022). These datasets can be used to facilitate planning and development of buildings and infrastructure by providing generic assessments during the feasibility, planning and desk-study phase of projects.

The datasets use the 1:50 000 scale BGS GeologyGB (formerly DiGMapGB-Plus) dataset as a framework, reattributing these units with classes related to a specific 'civil' engineering themes (see Figure 17). Lithology type and variability are incorporated into the Civils classification schemes, but typically include:

- Parent Material Map V6 dataset;
- BGS National Geotechnical Properties Database;
- BGS Lexicon of Named Rock Units;
- BGS Map Sheet Explanations;
- BGS Sheet Memoirs;
- BGS GeoScenic;
- BGS and Geological Society Regional Guides;
- BGS Urban Planning Reports (Smith and Ellison,1999);
- BGS Engineering Geology Formation Study Reports;
- Site Investigation Records and Borehole Scans held in BGS archives;
- and BRITPITS (an abbreviation of British Pits, Cameron, 2011).

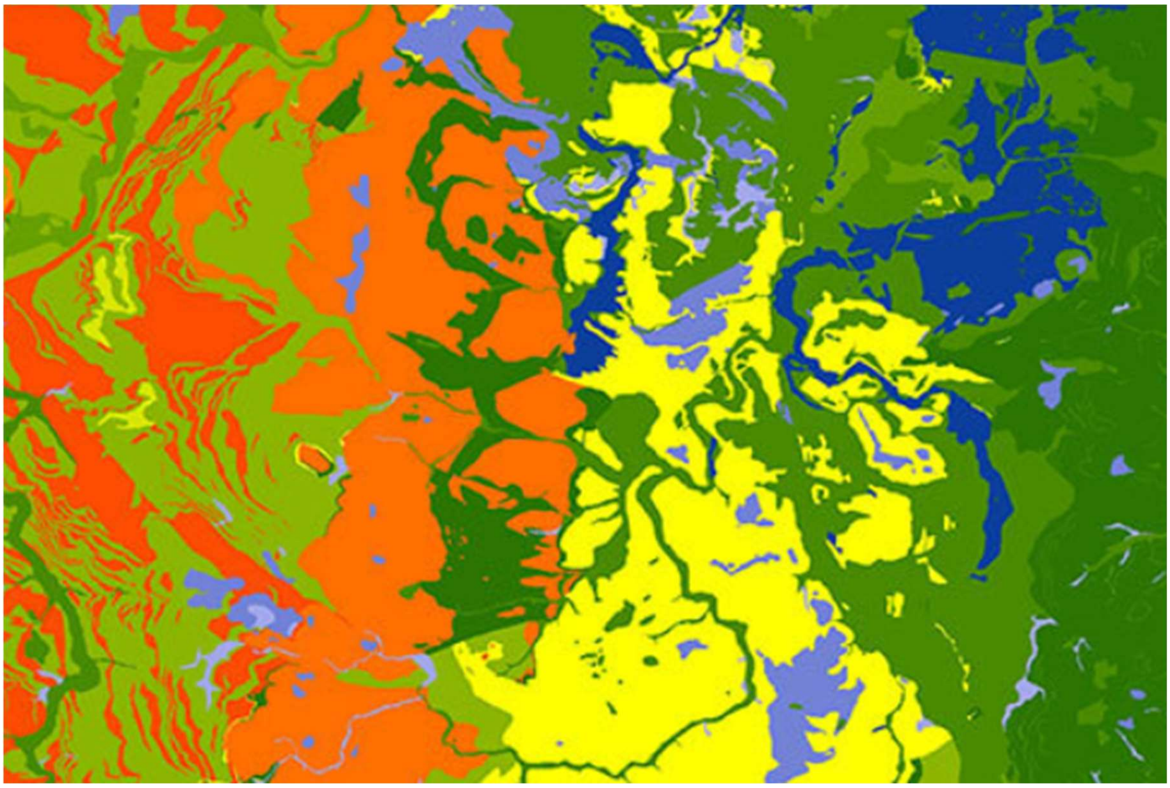


Figure 17 Example from the BGS Civils discontinuities sample dataset clearly showing the re-attributed geological map polygons underlying the dataset (https://www.bgs.ac.uk/datasets/bgs-civils-discontinuities/)

The data is presented in a GIS environment and comprises eight layers that provide national coverage for the whole of Great Britain at a scale of 1:50,000. These include:

EXCAVATABILITY

Excavations are used in civil engineering to dig cuttings, tunnels, quarries etc. Depending on material characteristics such as strength and mass characteristics, efficient and cost-effective excavation methods can be used. Four excavation requirements (hand tools, power tools, ripping, drill and blast), which are dependent on the ground properties, are presented in the dataset (Lee et al., 2012).

STRENGTH

Engineering strength of rocks and soils are provided as minimum, maximum and typical strengths using the BS5930 strength description (British Standards Institution, 2015). This tri-fold classification allows for the wide range of variation encountered within some stratigraphic units.

DISCONTINUITIES

This dataset provides information on engineering discontinuity types such as joints, faults, bedding fractures, cleavage fractures and incipient fractures.

SULPHATE AND SULPHIDE POTENTIAL

The presence of sulphide and sulphate can provide aggressive ground conditions and is important to consider in construction.

USE AS ENGINEERED FILL

Removal and disposal of unused material can be used as engineered fill in embankments, foundation pads and road bases. This dataset provides classification based on geological material, type, particle size, presence of sulphate and sulphide.

CORROSIVITY

Ferrous structures are prone to corrosion causing to failure. The dataset provides information on potential corrosive characteristics of a geological material. Scores of the following properties are used to assess corrosivity:

- Water content
- Redox status
- pH
- Sulphates/Sulphides
- Electrical resistivity

BULKING VOLUME

Changing volume of rock or soils can occur in the excavation and is named bulking volume is of importance in construction.

5.1.2 BGS GEOSURE

The BGS GeoSure product provides geological information to help planning decisions. It consists of six layers in GIS format to identify areas of potential hazard in Great Britain (Lee and Doce, 2018). The datasets are polygon (area) layers, which are described using a simple A to E potential hazard classification (A = Low, E = High; see Table 5). To produce the GeoSure natural ground stability data layers, the assessment of hazard is made by:

- identifying the factors that are involved in creating the hazard
- assessing which are thought to be present at each location
- assessing how significant they are thought to be at each location

The factors are then combined to estimate the level of hazard. The level of potential hazard does not mean that a damaging event is going to happen but is an indication of how many causative factors may be present and how severe they are thought to be. For example, in the case of the potential for slope instability, the factors are:

- The type of rock forming the slope
- The gradient of the slope
- The water level in the slope

More information about each of the layers is provides in the user guide (Lee and Doce, 2018).

Hazard rating	Advice for public	Advice for specialists
A — no indicators for compressible deposits identified	No actions required to avoid problems due to compressible deposits.	No special ground investigation required or increased construction costs or increased financial risk due to potential problems with compressible deposits.
B — very slight potential for compressible deposits to be present	No actions required to avoid problems due to compressible deposits	No special ground investigation required. Unlikely to be increased construction costs or increased financial risk due to potential problems with compressible deposits.
C — slight possibility of compressibility problems.	Take technical advice regarding settlement when planning extensions to existing property	New build — consider possibility of settlement during construction due to compressible deposits. Unlikely to be increase in construction costs due to potential compressibility problems. Existing property — no significant increase in insurance risk due to compressibility problems
D — significant potential for compressibility problems	Avoid large differential loadings of ground. Do not drain or dewater ground near the property without technical advice	New build — assess the variability and bearing capacity of the ground. May need special foundations to avoid excessive settlement during and after construction. Consider effects of groundwater changes. Extra construction costs are likely. Existing property — possible increase in insurance risk from compressibility if lowered groundwater levels drop due to drought or dewatering.
E — very significant potential for compressibility problems.	Avoid large differential loadings of ground. Do not drain or dewater ground near the property without technical advice.	New build — assess the variability and bearing capacity of the ground. Probably needs special foundations to avoid excessive settlement during and after construction. Consider effects of groundwater changes. Construction may not be possible at economic cost. Existing property — probable increase in insurance risk from compressibility due to drought or dewatering unless appropriate foundations are present

Table 5 Hazard ratings and advice for the BGS GeoSure products (https://www.bgs.ac.uk/datasets/bgs-geosure-compressible-ground/compressible-ground-property-hazard-information/)

BGS GeoSure includes the following layers:

COLLAPSIBLE DEPOSITS

Some soils may collapse when a load (such as a building or road traffic) is placed on them, especially if they become saturated. Such collapse may cause damage to overlying property or services.

COMPRESSIBLE GROUND

Some types of ground may contain layers of very weak materials like peat or some clays. These may compress if loaded by overlying structures, or if the groundwater level changes. This compression may result in depression of the ground surface, potentially disturbing foundations and services.

LANDSLIDES

Slope instability occurs when particular slope characteristics (such as geology, gradient, sources of water, drainage, or the actions of people) combine to make the slope unstable. Downslope movement of materials, such as a landslide or rockfall may cause damage, such as a loss of support to foundations or services or, in rare cases, impact damage to buildings.

RUNNING SAND

Some rocks and soils can contain loosely packed sandy layers that can become fluidised by water flowing through them. Such sands can 'run' (flow), potentially removing support from overlying buildings and causing damage

SHRINK SWELL

Swelling clays can change volume due to variation in water content, this can cause ground movement, particularly in the upper two metres of the ground that may affect many foundations. Ground moisture variations may be related to a number of factors, including weather variations, vegetation effects (particularly growth or removal of trees) and the activities of people. Such changes can affect building foundations, pipes or services.

SOLUBLE ROCKS

Ground dissolution occurs when certain types of rocks, containing layers of soluble material, get wet and the soluble material dissolves. This can cause underground cavities to develop. These cavities reduce support to the ground above and can lead to a collapse of overlying rocks.

5.2 GIS TOOLS AND APPLICATIONS

The wealth of data obtained from field and laboratory investigations are an excellent source but can cumbersome when contained solely in reports and databases. In this case, GIS can be a powerful tool to facilitate data and information searches, analysis and visualisation. To overcome many of these limitations, BGS has developed GIS tools and applications for data and information searches, geospatial data and information queries, and visualising geotechnical data and information as summary graphs. These tools and application have been developed at both national- and urban-scale, but principally to support land using planning decisions in urban areas.

5.2.1 ENGINEERING GEOLOGY MAP VIEWER

While not developed specifically to support urban development, the UK Engineering Geology maps did utilise many of the techniques and methodologies applied to the thematic maps of the urban geoscience studies of the 80s and 90s (see section 4).

The bedrock and superficial engineering geology maps of the United Kingdom (Dearman et al., 2011a, b), produced at a scale of 1: 1 000 000 (Figure 18), are adapted from the 1:625 000 scale bedrock and superficial geology maps (Dearman et al., 2011a, b). Each of the 243 lithostratigraphical bedrock units and 14 morphogenetic superficial deposits were separately assessed and reattributed with engineering geological map units. The engineering units comprise between one and four engineering lithology-types and use a stripe system to represent the relative proportion of each engineering lithology within the map unit (Dobbs et al., 2012). A total of twenty-two engineering geological units are used for the bedrock map and nine for the superficial map. An extended key was also produced for the maps that, for each engineering lithology type, provides an engineering geological description (British Standards Institution, 2015) and implications for foundations, excavation (Pettifer and Fookes, 1994), engineered fill (MCHW Vol. 1 Series 600), and site investigation (Dearman et al., 2011c).

The maps were initially published in paper format and as a digital pdf for download from the NERC Online Research Archive. Following this, a web-based engineering geology viewer was also developed that allowed users to query map units. The information within the extended key was integrated into the portal using a query function. This function used a pop-up box generate the text information from the extended key corresponding to the engineering lithology and theme selected using the index tabs at the top and base of the pop-up box. The viewer also showed the location of, and provided links to and references for, available BGS engineering geology publications including formation study reports, urban study reports and any other pertinent publications. The information contained in the engineering geology viewer has now been migrated to the onshore GeoIndex and is available alongside other freely available national-scale BGS datasets, with the functionality for displaying information within the extended key retained.

The purpose of these small-scale engineering geological maps and GIS is to present an overview of the engineering geology of the UK. The maps are particularly intended for those who are embarking on the study of engineering geology or who are in the early stages of their professional career, and to help increase the awareness of those in related professions as to the impact of geology on planning and development, and act as a reminder of the importance of engineering geology to reducing the risks associated with human interaction with the built and natural environment.

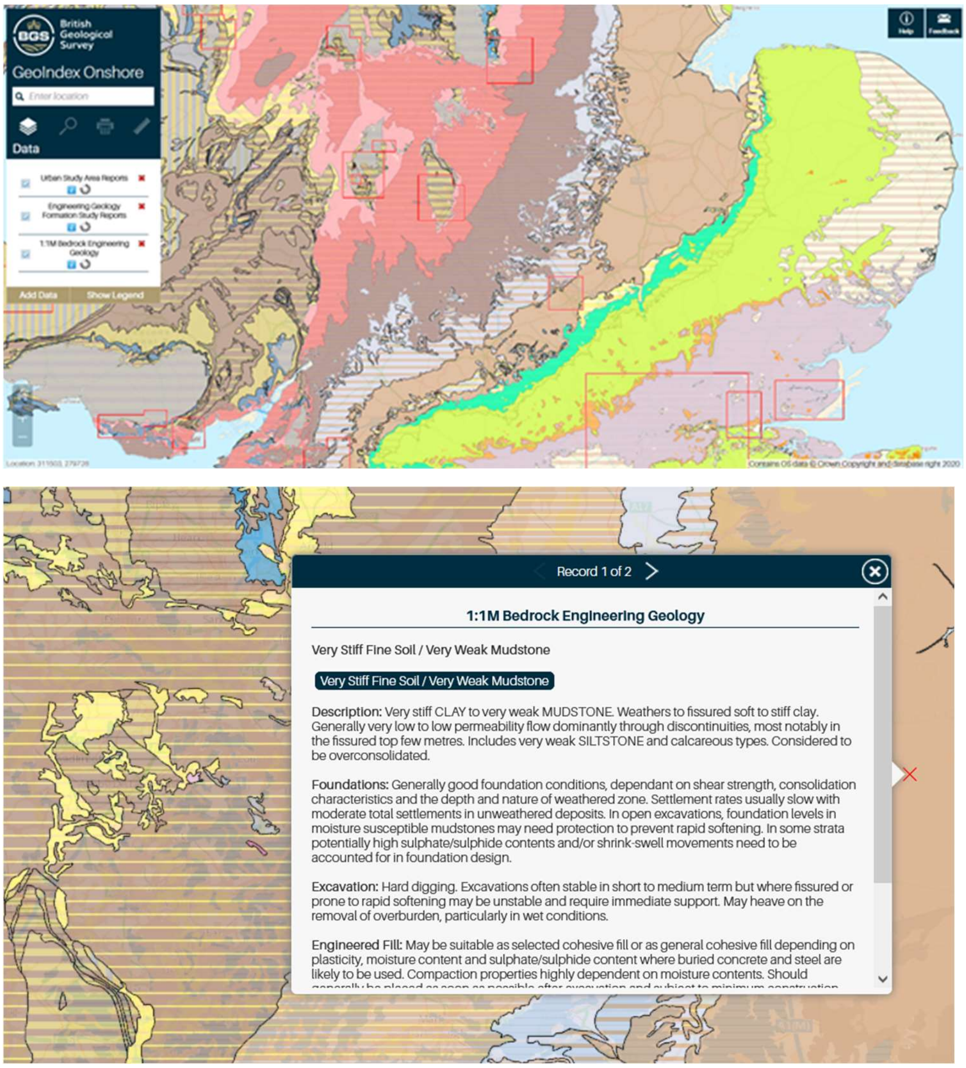


Figure 18 BGS onshore GeoIndex displaying UK Engineering Geology Bedrock and Superficial map layers overlain by the urban, highlighted in red, and formation study report areas, highlighted as transparent block-colours (top). Example of record generated using text from the extend key of the engineering geology maps when the query function is used in the GeoIndex on the engineering geology map layers (bottom). Contains OS data © Crown Copyright and database right 2020

5.2.2 GEOTECHNICAL GIS

A spatially defined geotechnical information system designed to provide geological and geotechnical data and information was developed for a 10 x 10 km square study area, which includes central and eastern Glasgow. The geotechnical GIS includes: the geology (bedrock, quaternary and artificial deposits and the thickness and depth of these deposits); a geotechnical and geo-environmental database; tools specifically developed to present these data; and underground mining hazard/the distribution of underground mining. The interface of the Geotechnical GIS Glasgow in shown in Figure 19 .

The data in the Glasgow Geotechnical GIS are presented in four main ways:

I. Geographical distribution of borehole data: show the location of all boreholes and pits provides details on the position and final depth and gives an overview of spatial data density.
II. Summary data plots: show the distribution of different geotechnical parameters, such as plasticity, particle size and SPT N-value, for a given geological unit.
III. Cross-sections: show geological interpretations overlain with borehole logs and in situ geotechnical test data that range in length from 1 km to over 5 km.
IV. User-created plots: show geotechnical data plots based on user defined criteria using data available within the Geotechnical GIS database.

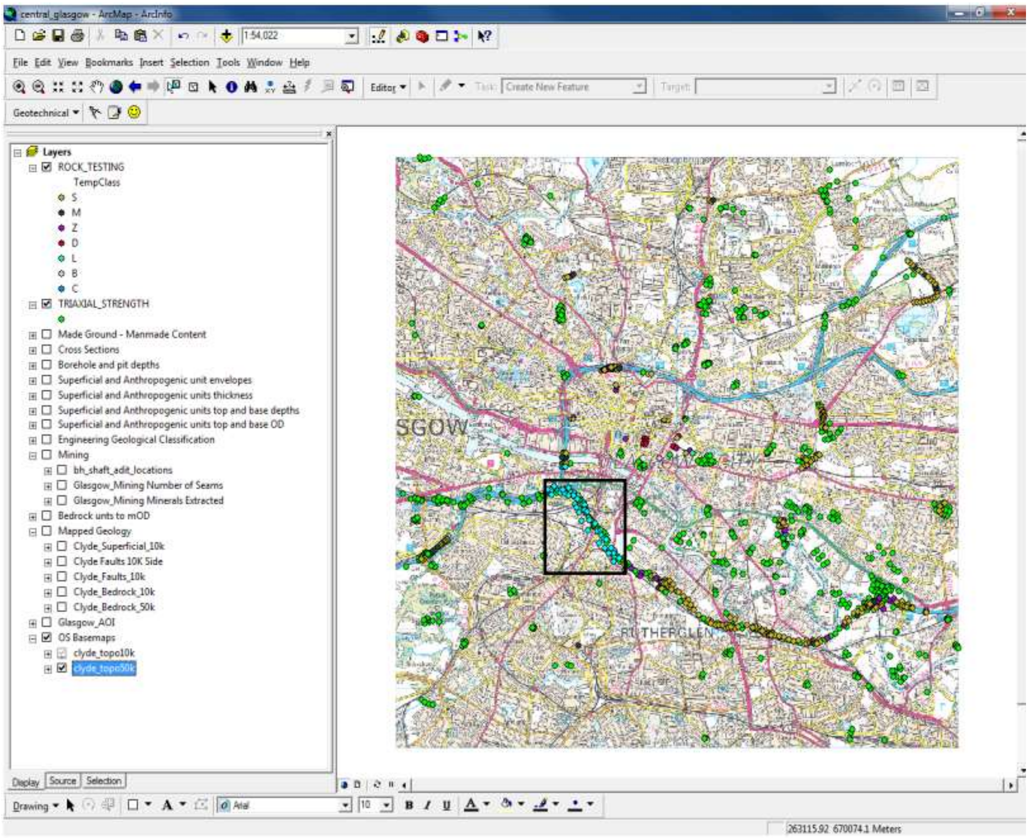


Figure 19 The interface of the Glasgow Geotechnical GIS showing geographical distribution of boreholes, background map and loaded shapefiles on the left-hand side of the ArcMap screen (from Entwisle et al., 2016, fig.15)

A geotechnical GIS tool was also developed for London and the Thames Gateway. The same methodology as in Glasgow but data for London is included such as a geodatabase, attributed with geotechnical data, and images of geotechnical summary plots stored as jpg files. It allows the user to view graphs and images by using ArcMap desktop. The Geotechnical GIS tool was initially developed using earlier versions of ArcGIS (3.3 to 9.3) but has not been updated to ArcGIS Pro versions of the software.

6 Geotechnical and engineering geological data and information for 3D geological modelling

The BGS has constructed a wide number of 3D geological models across the UK and overseas for the purposes of understanding the deep and in particular the shallow (< 100 m below ground level) ground conditions better (Gakis et al., 2016; Burke et al., 2014; Price et al., 2008). These models contain geological information concerning the geometries and relationships between the surface horizons and in some cases been re-purposed to become thematic models for hydrogeological modelling, geohazards and geotechnical applications (Terrington et al., 2019). There have been three different ways in which the BGS has created thematic geotechnical 3D models:

1. Inter-unit or bulk attributed thematic 3D geological models whereby a whole unit for a geological group, formation or member has had an overall property type applied to it, e.g., whether a rock is generally high strength or low strength.
2. Intra-unit thematic 3D geological models whereby the properties within a whole unit for a geological group, formation or member have been discretised for specific property, e.g., Volume Change Potential in the London Clay Formation.
3. Kriging and stochastic driven lithological modelling of geotechnical parameters, whereby the lithology provides the geotechnical variance and grouping of similar of objects to which properties can be applied.

In this section, the aim is to describe these different mechanisms of attributing 3D geological models with geotechnical attributes, giving examples of where these have been used.

6.1 INTER-UNIT/BULK ATTRIBUTED THEMATIC 3D GEOLOGICAL MODELS

3D engineering geological models tend to be of the shallow subsurface (<100 m below ground level) as much the infrastructure is usually within this domain (zone of human interaction). There are exceptions to this, for example tunnelling projects such as that for the Haweswater Aqueduct Resilience Programme that go to >200 m depth below ground level because of the topography. As a result of this, much of the GI (boreholes and shallow seismic survey data) will be in this shallower zone (top 20 m below ground level).

In the BGS, many of the shallow 3D geological models for the Quaternary and simpler layer cake bedrock as found in London (e.g. the London Clay Formation and Lambeth Group in London and the Thames Valley) are constructed using the GSI3D software from 2003 onwards (Kessler et al., 2009). The GSI3D software created surfaces of the geological unit extents in 3D using cross-sections and boreholes interpreted by the geologists and outcrops from geological maps. Subcrop extents are defined from the cross-section interpretation and joined with outcrop forming envelopes (complete outcrop and subcrop lateral extensions of the unit), thereby creating the 3D geometry of each unit. The outputs from the calculated GSI3D model gave a top surface, base surface, thickness and a shell (top and base plus a wall between them). These are attributed with the geological colours defined in the geological maps using a General Vertical Section (GVS) to define the super-positional order of each of the units. The GVS can also be attributed with different properties using additional columns in the GVS, and each unit could be re-coloured based on that attribute as shown in Figure 20. Figure 21 shows the 3D attributed model with the engineering properties described.

The 3D geological framework that the GSI3D model provides a structure into which additional qualitative physical property-based information for each modelled unit can be placed, analysed and reported. The integration of property-based information allows multiple thematic representations of the model to be derived, each addressing specific engineering geology or environmental applications which provides a powerful mechanism for knowledge transfer across different spectrums of stakeholders.

Model attribution with engineering properties, including strength or density data offers a predictive tool for rock strength, shrink-swell characteristics and compressibility; key factors in understanding and mitigating the ground constraints encountered in the London area and elsewhere.

Engineering Unit		Geological Unit	Characteristics	Engineering consideration
SOIL				
Organic		Peat	Very soft to firm, fibrous or amorphous dark brown, or black clayey PEAT occasionally woody or with layers of shells.	Highly compressible, even light foundation will be subject to variable and considerable settlement over long periods. Dewatering produces considerable and prolonged settlement. May produce acidic groundwater.
Mixed Soils	soft to stiff/ loose dense	Worked and Made Ground	Highly variable, very soft to stiff, uncompact to compact, loose to dense, CLAY, SILT, SAND, GRAVEL and COBBLE, may include man made materials. May be compacted.	Highly variable ground conditions, depending on content and whether it is engineered. May be contaminated. May produce explosive or noxious gasses.
	Stiff/ dense	Engineered Embankments	Highly variable generally stiff or dense compacted CLAY, SILT, SAND, GRAVEL, may include man made materials. Compacted	Mostly suitable for foundations depending on construction methods.
	Firm to hard/ dense to very dense/ weak	Lambeth Group and Harwich Formation	Highly variable lithologies, firm to hard CLAY occasional weak CLAYSTONE, compact SILT, dense to very dense SAND and/or flint GRAVEL, some shelly or SHELL beds, occasional weak limestone, occasionally organic. Lithological variation often unpredictable.	Generally good foundation material, however the lithological variability gives rise to variable groundwater conditions including lenticular water bearing sands. Variability provides difficult to very difficult tunnelling and deep excavation conditions. Fissuring in clays may affect the stability of cuttings.
Fine	Very soft to firm	Alluvium	Very soft to soft sometimes firm, sometimes laminated, often organic, sometimes with shelly CLAY. Top 2 to 3 metres may be firm to stiff due to desiccation.	Generally highly compressible, bearing capacities less than 100 kPa. Light foundation may be subject to variable and considerable settlement over long periods. Dewatering produces considerable and prolonged settlement.
	Uncompact /compact	Crayford Silt Ilford Silt Formations	Uncompact to compact often with vertical fissure, SILT or firm CLAY	Some parts have high porosity and open structure which may be prone to collapse on loading and wetting. Generally well drained, used in the manufacture of bricks (hence 'brickearth'), excellent agricultural land.
	Firm to very stiff	London Clay Formation	Firm to stiff becoming very stiff or hard at depth, near surface generally fissured, brown often with gypsum otherwise grey, CLAY sometimes compact SILT, occasionally dense to very dense SAND.	Near surface prone to shrink/swell affecting shallow foundations. Planting or removal of trees near buildings may exacerbate this. Depth of weathering and fissuring varies.
Coarse	Moderately dense to dense	Shepperton, Kempton Park, Taplow, Hackney and Lynch Hill Gravels Formations	Generally moderately dense to dense, sometimes very dense SAND or GRAVEL or mixture of the two, sometimes silty or clayey with local lenses of silt, clay or peat.	Generally good foundation condition. Excavations may require dewatering and are generally unstable. High water table in excavations may lead to running sand conditions.
	Very dense	Thanet Sand Formation	Very dense, slightly silty or clayey to silty to clayey fine SAND, with gravel to cobble flint at base (Bullhead Beds).	Generally high bearing capacity but may be lower near surface where weathered/cryoturbated. Requires dewatering in tunnelling and deeper excavation. Water pressures often artesian where this formation is below clay.
ROCK				
Chalk	Comminuted	Sleaford and Newhaven Formations	Comminuted to high density CHALK, variable weathering depth, sometimes karstic.	Depends on degree and depth of weathering and the presence of karst. Bearing capacity generally good where not highly weathered, however both bored and driven piles have little friction.

Figure 20 GVS attributed with geotechnical information (from Royse et al., 2009, Table 1).

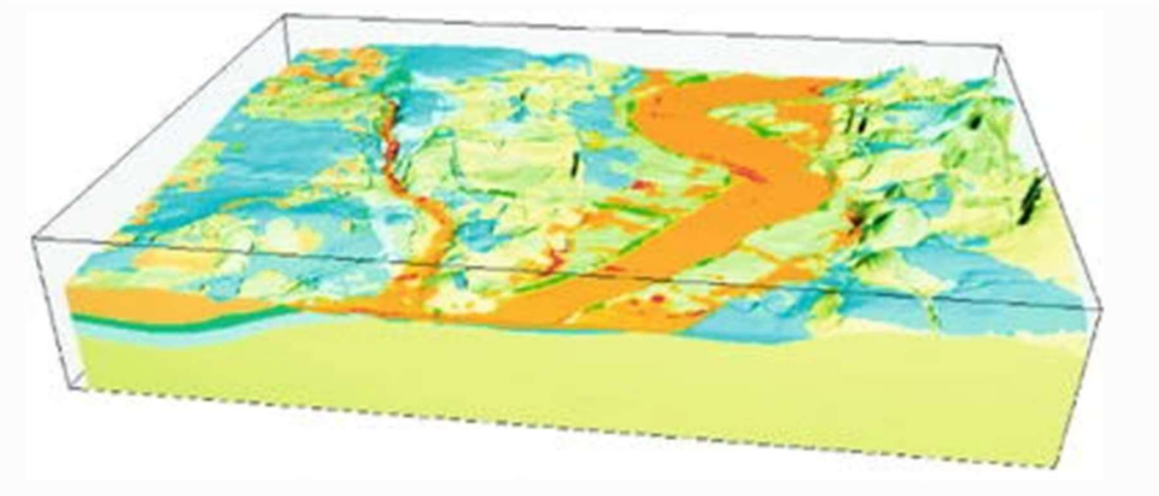


Figure 21 3D geological model of part of the Thames Gateway showing variation in compressibility. Areas of high compressibility are coloured in orange and red, variable compressibility coloured in light brown to green and areas of low compressibility are in blue to brown (from Royse et al., 2009, fig.5)

The bulk attribution of a 3D geological model has been applied in the main to TIN based models by using the GVS and legend to change the attribution of the model. However, there have been efforts by the BGS to translate these 3D visualisations into GIS formats using vector grids. These vector grids can be considered pseudo voxel models that can be analysed and visualised in 2D using GIS. This method involves creating a vector grid and applying several properties to each vector cell into its attribute table. This been implemented successfully for the Shrink Swell 3D data product (Jones and Hulbert, 2017). The Shrink Swell 3D layer is a regional hazard susceptibility map that identifies areas of potential shrink–swell hazard in three-dimensional space at intervals down to 20m using the London Lithoframe 50 geological model outputs (Burke et al., 2014).

Swelling clays can change volume due to variation in moisture, this can cause ground movement, particularly in the upper two metres of the ground, or where excavated and exposed, that may affect many foundations. Ground moisture variations may be related to a number of factors, including weather variations, vegetation effects (particularly growth or removal of trees) and the activities of people that might cause changes to the ground conditions. Such changes can affect building foundations, pipes or services.

The level of potential hazard does not mean that a damaging event is going to happen but is an indication of how many causative factors may be present and how severe they are thought to be. Thus, the hazard assessment method can be used to indicate how prone areas are to experiencing hazard events and of how frequently these hazard events might be expected to occur.

Use of this data can help manage land to its best advantage, safely and with the lower likelihood of financial loss. Shrink-Swell soils can have a damaging effect in tunnels and other underground spaces where specialist supports may be required; the 3D hazard map would help to identify areas for further investigation before construction begins. A depiction of the Shrink Swell 3D layer in ArcScene can be seen in Figure 22.

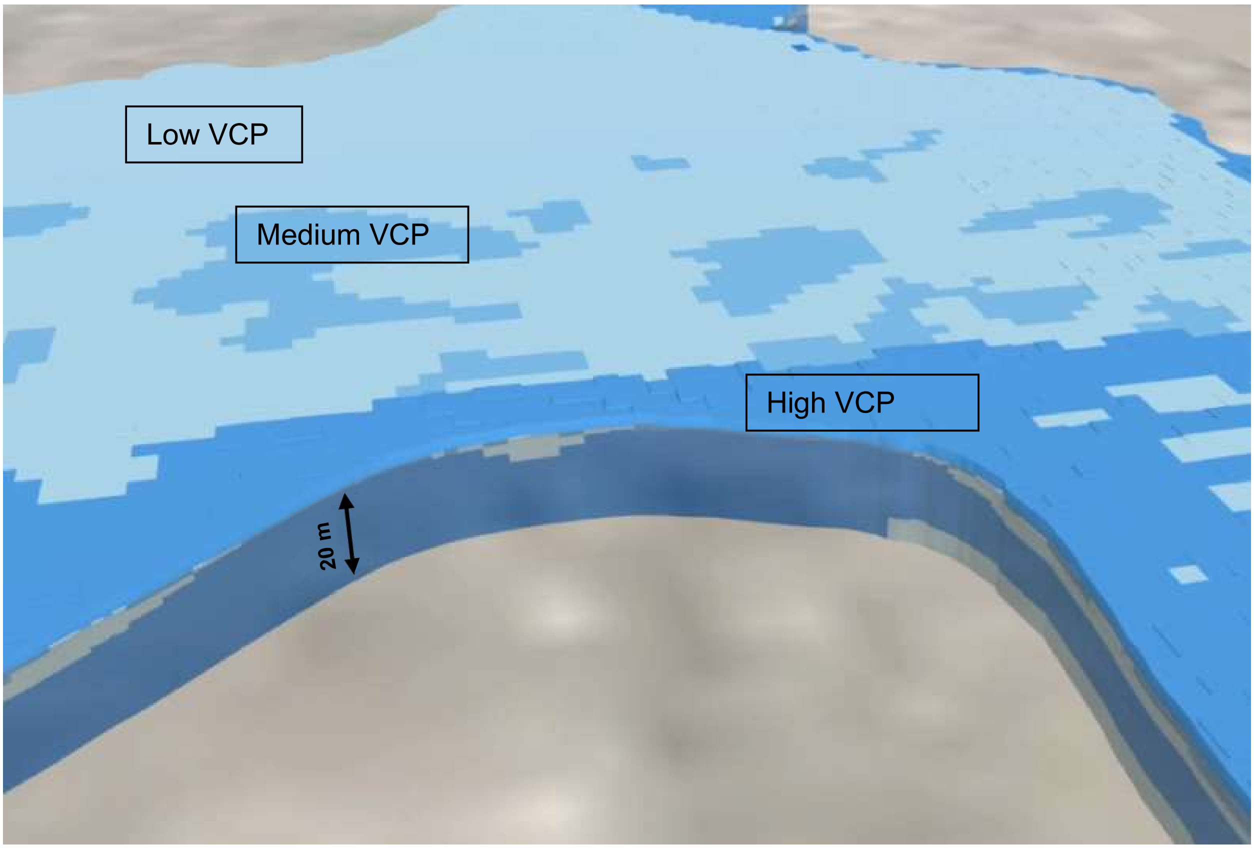


Figure 22. Example of the BGS Shrink Swell 3D layer in ArcGIS Pro. VCP – Volume Change Potential.

The geological 'Form' field is pivotal here. The 'Form' field is the unique code created by combining the BGS Lexicon code (LEX) and Rock Classification Scheme (RCS) codes, and is used as the key field to which other attributes can be joined. For example, the River Terrace Deposits is called RTD or RTDU (*U undifferentiated) in the BGS lexicon and the RCS code is XSV (X-equal, S – Sand, V – Gravel). An example of how the RCS differs at different depths for the same vector cell is shown in Figure 23 Using the RTD-XCV code, other attributes that describe geotechnical properties can be attached to each vector cell.

The dataset is split into 50 x 50 m grids and contains the following information per grid cell at intervals down to 20 m (0 m (surface geology), 1 m, 2 m, 3 m, 4 m, 5 m, 10 m, 15 m, 20 m.). This data layer provides information on the primary key 'Form' (Geological Formation – LEX-RCS code), the secondary key 'VCP' (Dominant Volume Change Potential) and the tertiary key 'Range' (Volume Change Potential Range). An example of the GIS output of the Shrink Swell clay product at surface (0 m) and at depth (5 m below ground level) for the Borough of Kensington and Chelsea is shown in Figure 24 , where the symbology of the layer can be changed by depth to show a different property distribution. As shown in Figure 23 and Figure 24, the clay type deposits have the greatest susceptibility to shrinking and swelling.

Foundation Conditions from the BGS Civils thematic dataset (Entwisle et al., 2015) uses the Parent Material Lithology code which can be translated into an RCS code to append geotechnical properties or descriptions as shown in Figure 25 (Terrington et al., 2019). This shows how each 2D vector cell can hold a bulk attribute at various elevation levels for use in GIS.

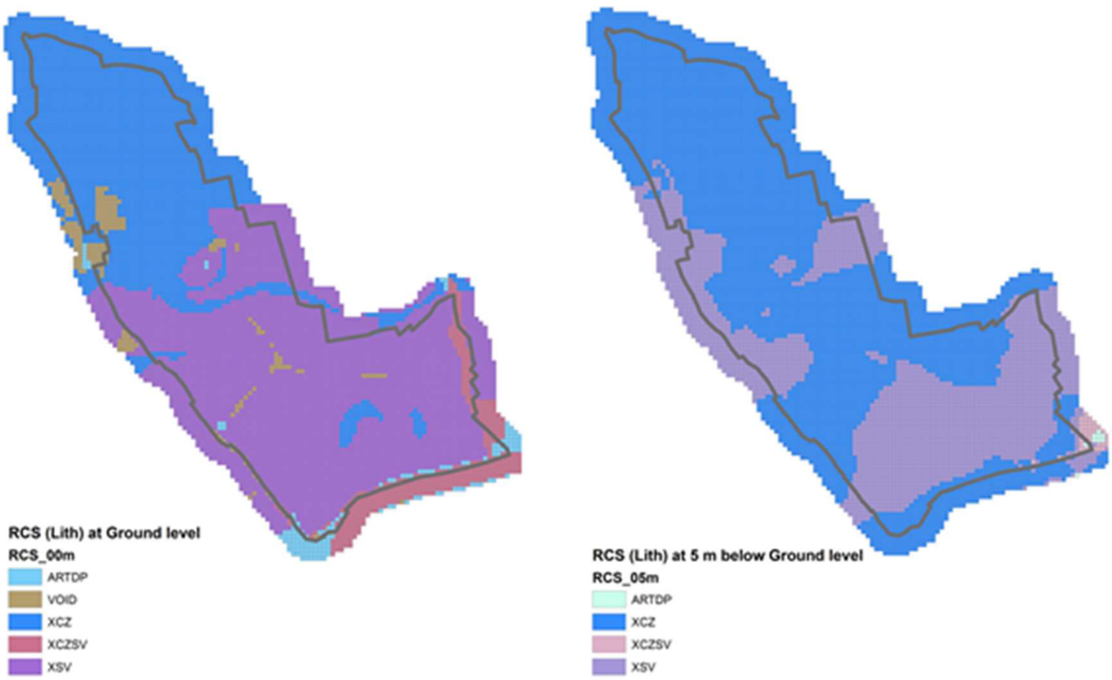


Figure 23 RCS codes applied to the Borough of Kensington and Chelsea vector grid at surface (0 m) and 5 m below surface. (C – Clay, Z – Silt, S – Sand, V – Gravel). (Terrington et al., 2019, fig 3)

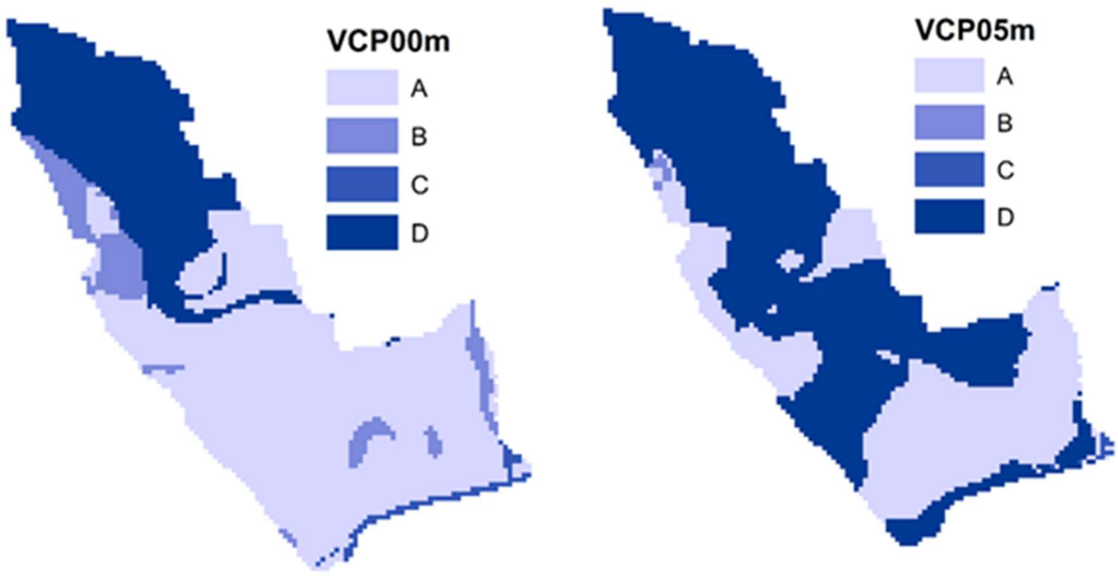


Figure 24 Volume Change Potential in the Borough of Kensington and Chelsea at surface (0 m) and 5 m below ground level. A – No or little susceptibility to shrinking and swelling to D – High susceptibility to shrinking and swelling. (Terrington et al., 2019, fig 4)

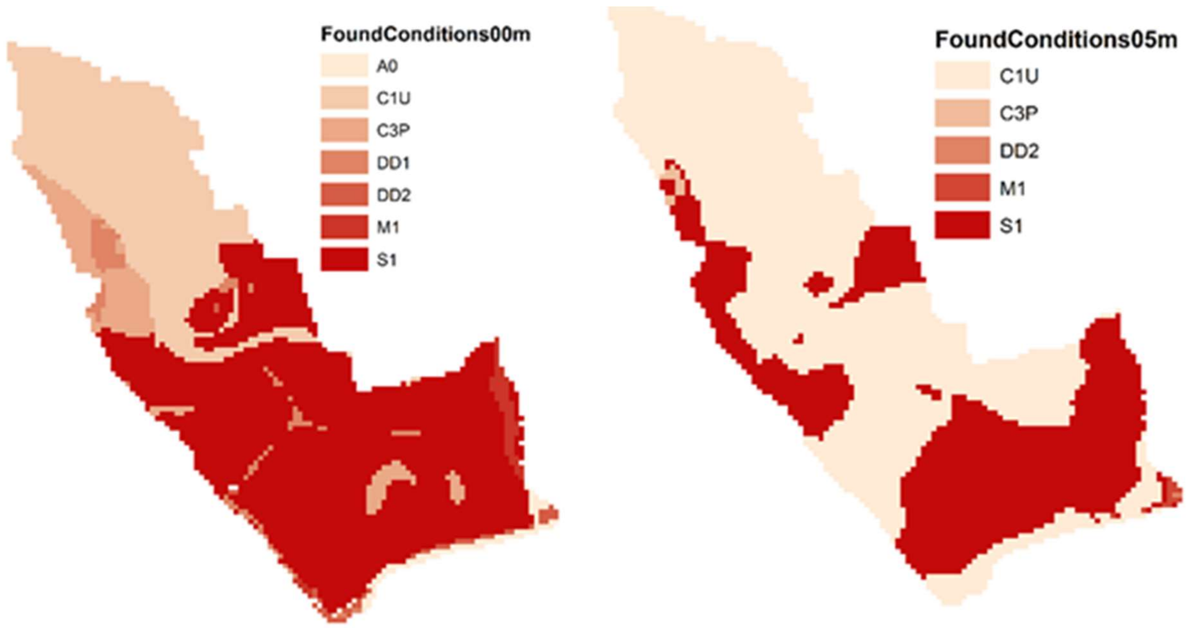


Figure 25 BGS Civils – Foundation conditions data (BGS Civils) applied to Shrink Swell 3D dataset. Codes describe ranges of foundations conditions. (Terrington et al., 2019, fig.5)

6.2 INTRA-UNIT THEMATIC 3D GEOLOGICAL MODELS

Although the vector grid as shown in section 6.1, allows the geology and subsequent properties to be mapped to them, this only allows bulk attributes to be mapped to individual cells at several depth slices and can be complex for GIS to handle depending on the size of the area. In a similar fashion, geostatistical techniques such as Inverse Distance Weighting (IDW) can be used at depth slices below ground level to interpolate geotechnical properties across a rasterised grid, a more efficient way of managing and analysing cell-based data. This technique has also been deployed on the BGS Shrink Swell dataset using plasticity values to inform on the Volume Change Potential (VCP) of a soil. The VCP is the relative change in volume to be expected with changes in soil moisture content and the subsequent shrinkage or swelling can cause major damage to structures above or below ground.

The IDW interpolative technique was applied to the London Basin dataset to determine whether any spatial trend in the plasticity of the London Clay was evident (Jones and Terrington, 2011). The IDW technique assumes that the weight of a value decreases as the distance increases from the prediction location. IDW techniques combine the notion of proximity whilst introducing gradual change based on the trend surface. The technique's principal weakness is that it makes no assessment of prediction errors, and it can produce a 'bulls-eye' effect around sample locations, especially where data samples are sparsely distributed. The number of nearest neighbour data points can be increased to lessen this effect.

To identify whether any directional trend existed in the Plasticity Index (I_P') values for the London Clay Formation, and the outcrop covering the London Basin was analysed (Figure 26), observing all available sample points, and ignoring variations with depth. However, some sizable gaps in the distribution of samples across the outcrop are likely to influence the interpolation model.

The resulting spatial analysis using the IDW interpolative technique showed that, although there are localised exceptions, possibly a result of the 'bulls-eye' effects of erroneous or isolated point data, the VCP tends to increase from the western part of the London Basin towards the east, and the mouth of the river Thames (Figure 27). The interpolation shows that in the central and eastern parts of the London Basin, the London Clay is more plastic than in the western part.

The method described above can also applied at different depth slices, like the vectorised grid described in Section 5.1, by sub-dividing the data by depth. However, beyond 5 m below ground level this method becomes limited by the sparsity of data available data at these depths – a general limitation of geotechnical boreholes, which in the NGPD average 8.9m depth and rarely exceed 50 m depth.

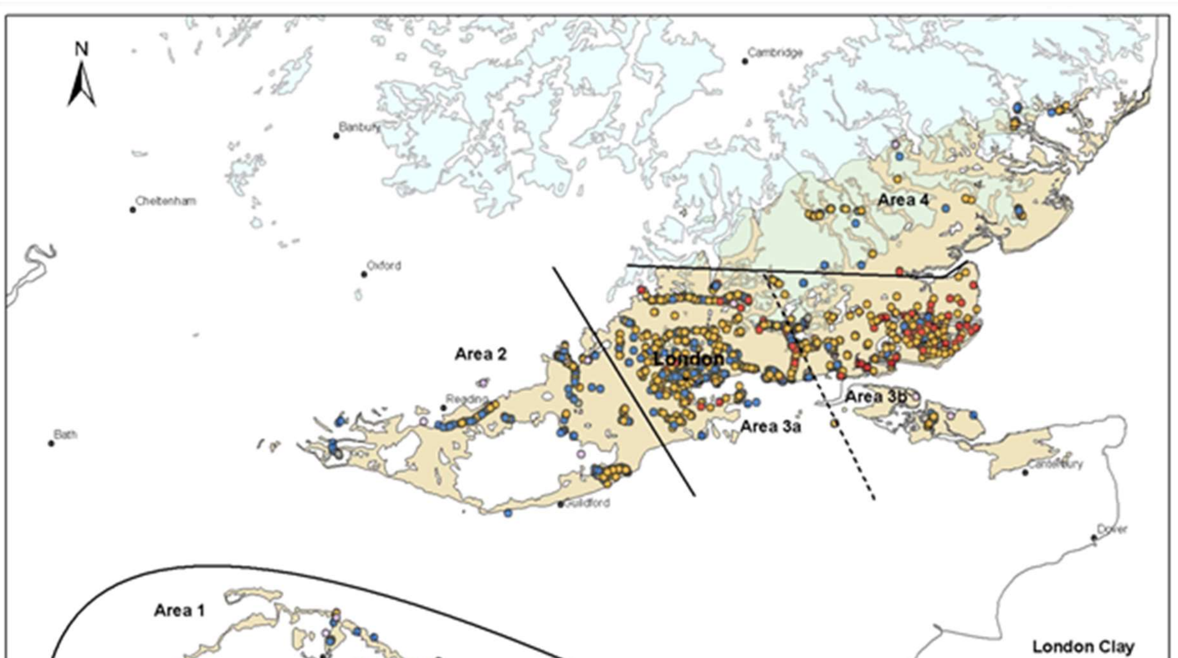


Figure 26 IDW interpolation for all samples point locations (from Jones and Terrington 2011, fig.4)

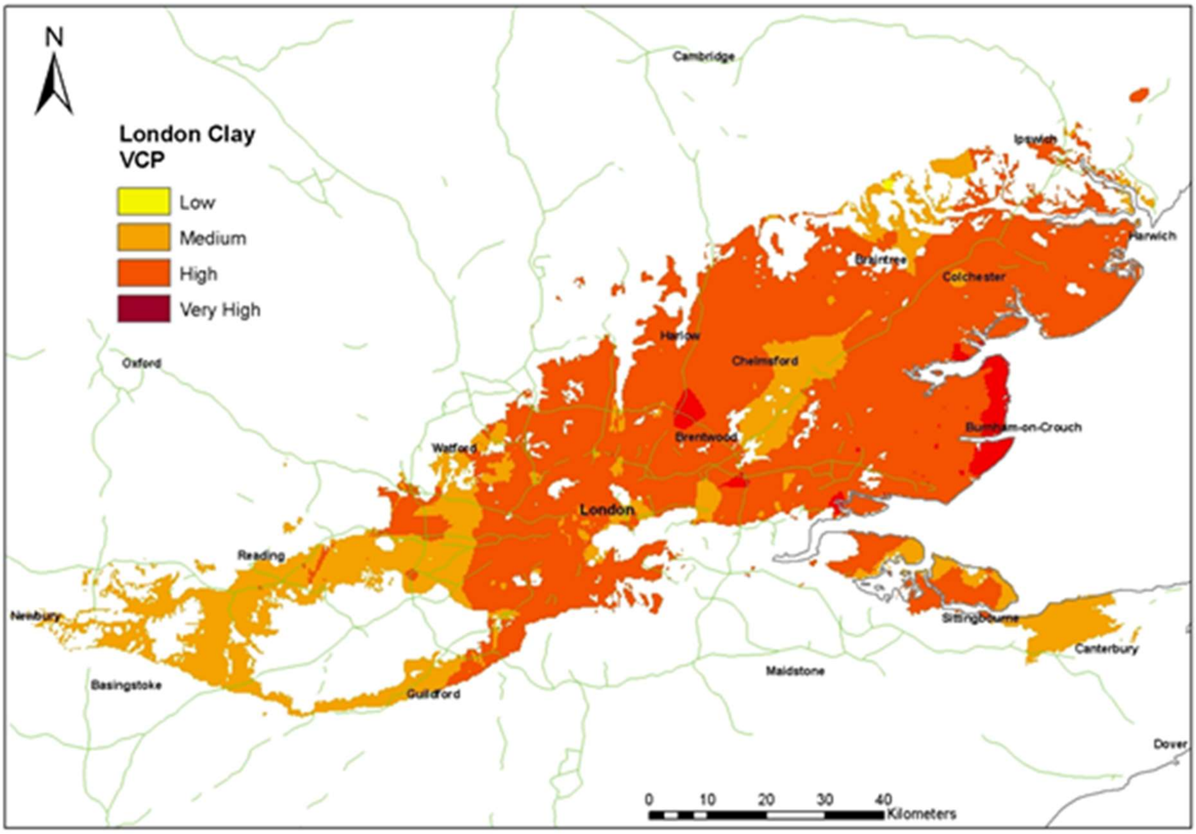


Figure 27 IDW interpolation for all samples using mean I_P' value at each sample location (from Jones and Terrington 2011, fig.9)

6.3 INTRA-FORMATIONAL VARIABILITY - VOXELATED ENGINEERING GEOLOGICAL MODELS

Discrete values (i.e. numeric intervals) can be used to model a property or several properties within a volume, typically using a voxel model (also known as voxel or block models). A voxel model is a 3-D regular or irregular grid consisting of volume elements called voxels, or cells which and be populated by XYZ-property and interpolated across in and XYZ direction to the empty cells. These values could be a geotechnical, geochemical or geophysical parameter, such as that shown in Figure 28.

There are a number of examples where the BGS has used this technique to model geotechnical properties such as Culshaw, 2004 where SPT 'N' Value data for glacial till in the Manchester/Salford (UK) area was voxelated to show intra-formational variability. Jones and Terrington (2011) used I_P' data to inform on the VCP inside a voxelated volume for the London Clay Formation which ranged from central London to the Thames Estuary (Figure 29). Typically, these have used Sequential Indicator Simulation or a form of kriging to model the variability of values across the volume using SKUA-GOCAD or Petrel.

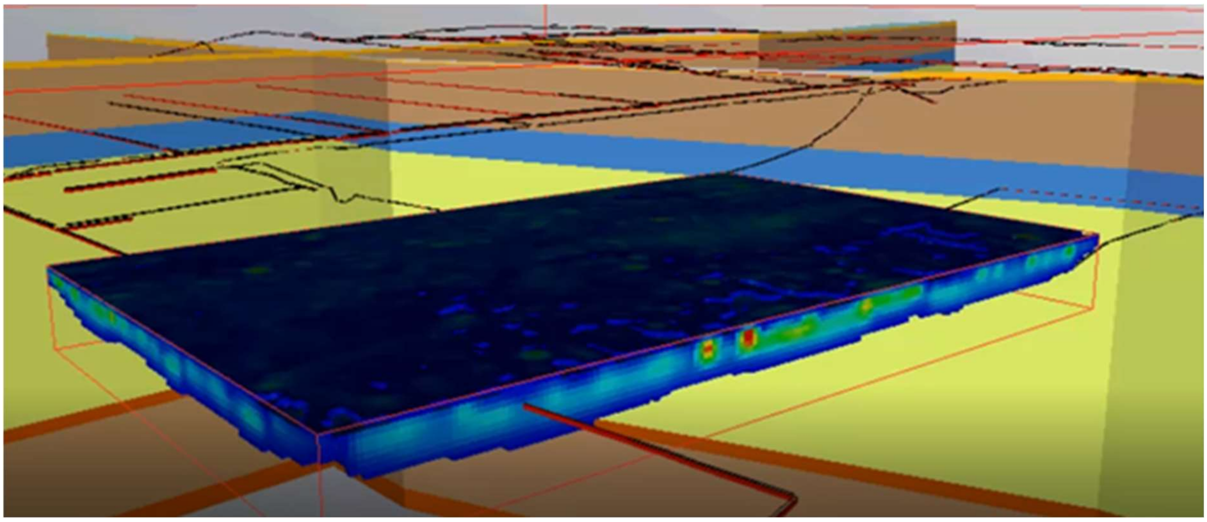


Figure 28 Example of a voxel model showing geophysical data with utility data and geological cross-sections.

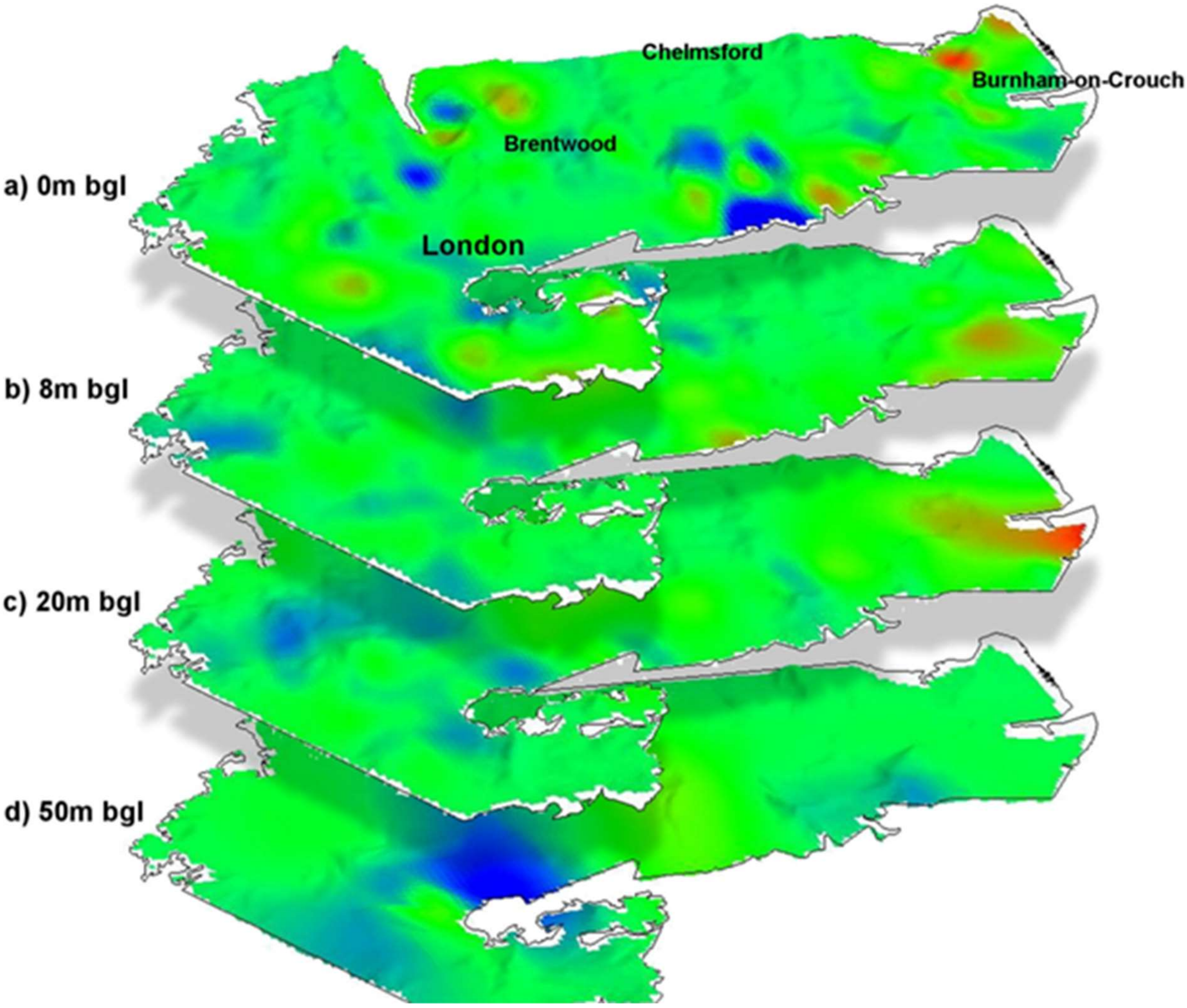


Figure 29 Layers showing surfaces at 0m, 8m, 20m and 50m below ground level (bgl). Blue-medium VCP, green-high VCP, yellow/red-very high VCP) (from Jones and Terrington 2011, fig.14)

6.4 LITHOLOGICAL PROPERTY 3D MODELLING OF GEOTECHNICAL PARAMETERS

The lithological of a rock unit helps to determine the stratigraphic interpretation of that unit, allowing for rock units to be classified into a hierarchy of members, formations and groups. Once these have been modelled into a classification such as the Lambeth Group, the variability within a stratigraphic interpretation cannot be quantified and hence the physical and geotechnical properties associated cannot be quantified either. Therefore, stratigraphic modelling may not always represent the full subsurface variability within each of these classes that is of direct relevance to end-users, such as ground engineers or groundwater modellers (Bianchi, 2015). The BGS has undertaken research into the modelling of the variability within the classes of rock units using lithofacies modelling in Glasgow and for the Chalk Group across eastern and southern England, explained further below.

Woods et al., (2015), constructed a high-resolution stratigraphical and physical property model of the Chalk Group of southern England. The model integrated bedrock mapping data for the Chalk, with structural data and interpretations of formational and sub-formational (marker-bed) stratigraphy in boreholes (predominantly from geophysical logs and cored boreholes) and outcrops. A range of simple facies data (e.g. hard chalk, hardground, marl, marly chalk) are digitised for the boreholes and outcrops using WellCad^{TM} software, interpreted directly from geophysical logs, core logs, borehole video logs, or outcrop logs. The results of this work are modelled in SKUA-GOCAD 2013.2 software, using statistical algorithms to project the likely distribution of physical property data. Many major civil engineering projects occur wholly or partly within the Chalk (e.g. Channel Tunnel, Cross-Rail). Understanding the nature of intra-formational variation in physical properties is key at two levels: 1) it potentially identifies broad geographical regions (domains) across which the physical properties of a unit might differ in one or more ways from adjacent regions; 2) it identifies local regions where a unit has atypical features. For engineering geology applications, understanding site specific variability within a geological formation is crucial, particularly the extent to which a given site conforms to or departs from the median predicted characteristics. Figure 30 shows an example from the Chalk Group kriged lithofacies 3D model, showing vertical slices through the voxel model with the boreholes used to inform it.

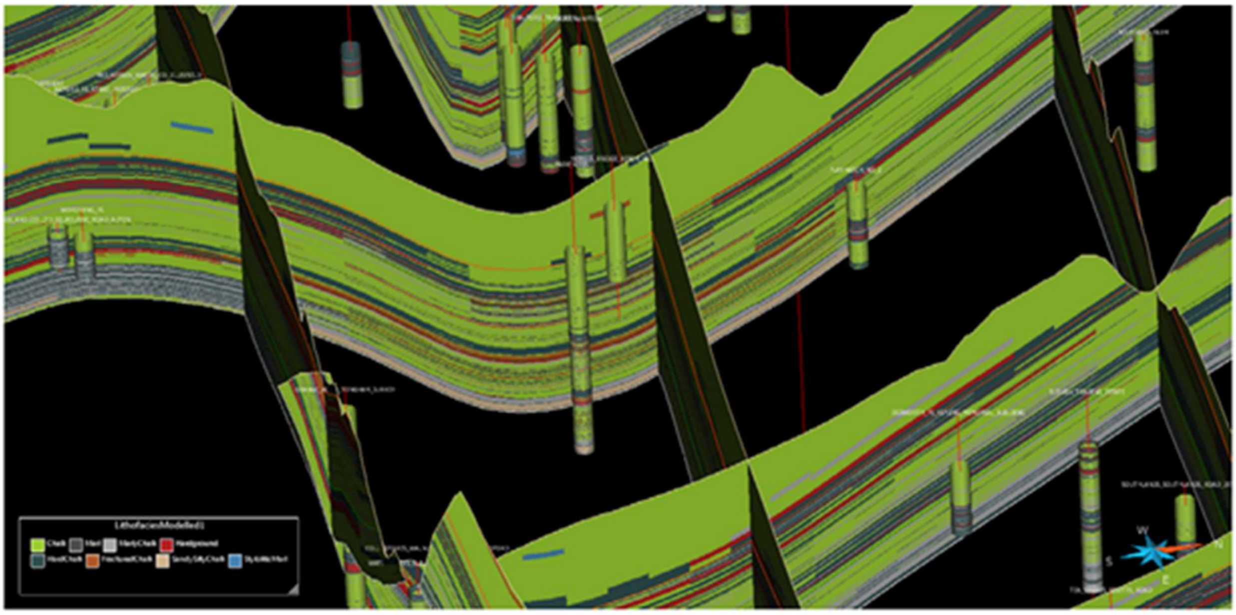


Figure 30 Well lithofacies data and selected grid sections through the modelled lithofacies. (Woods, et al., 2015)

In Glasgow area, this technique of breaking down the formations or members into their lithological components has been completed at a higher resolution in a smaller area (10 km by 10 km) compared to the Chalk lithofacies model described above which covers much of the southern and southeast England region. The Glasgow 3D geological model has had stochastic techniques applied, whereby many iterations of the model have been run to determine probability of occurrence of a lithological component (Kearsey et al., 2015). From a ground engineering perspective, it can highlight areas in the model that are data poor and may require further ground investigation

7 Current research on the application of geotechnical and engineering geological data and information

As of 2022, various visualization approaches have been piloted using statistical analysis of geotechnical and engineering geological data using data from the East-West railway, part of the Oxford-Cambridge Arc. In addition, communication tools, using ArcGIS StoryMaps for East Birmingham, have also been prototyped to improve the way in which geotechnical and engineering geological data is communicated and disseminated.

7.1 GEOTECHNICAL DATA PROCESSING AND VISUALISATION FOR OXFORD-CAMBRIDGE ARC

Ongoing research and development within BGS' Geotechnical Labs and Research team is exploring novel methods for processing and presenting geotechnical and engineering geological data and information. The Oxford-Cambridge Arc initiative has focussed on the development of an attributed geological route model along the East-West Railway route between Bicester and Milton Keynes and the development of semi-automated geotechnical and engineering geological data summaries for individual geological units. Both processes are using existing data held within the BGS databases and corporate datasets, including the Borehole Geology Database, NGPD, digital geology map, BGS GeoSure and Civils. While the current objective of this research is linear infrastructure, the processes developed, and lessons learned, are equally applicable to urban development.

7.1.1 EAST-WEST RAILWAY GEOLOGICAL ROUTE MODEL

The basis for the geological route model is a geological cross-section constructed along the East-West Railway line between Bicester and Milton Keynes using BGS Groundhog Desktop. The cross-section is attributed with lithostratigraphical bedrock units (sedimentary bedrock) and morphogenetic units (superficial deposits), which are used as the framework for further 'bulk attribution' (see section 5.1) of the cross-section with information about shallow geohazards and engineering considerations derived from the BGS GeoSure and Civils datasets. However, rather than re-attributing the individual cross-section layers with GeoSure and Civils categories, they are instead summarised as a series of coloured ribbons below the cross section (Figure 31).

This ribbon approach was chosen to display GeoSure and Civils data as it can summarise a wide range of geological information on a single page. Furthermore, this approach also addresses some inherent features of the GeoSure and Civils datasets that mean they are not universally suitable for bulk reattribution of cross-sections based on geological unit. In the first instance, many of the map units in GeoSure datasets are constrained by features other than geological units, such as slope aspect. There is therefore not always a direct correlation between geological map unit boundaries and GeoSure map unit boundaries. Second, both Geosure and Civils provide information about surface and shallow subsurface properties and processes: these are not always relevant or consistent with depth, and as such attributing a cross section, which is 80 metres deep in some places, with a single category may be misleading or nonsensical (e.g. strength can vary significantly between shallow weathered material and unweathered rock at depth).

Several other challenges and barriers were also identified during the construction of the geological route model. The complexity is dependent on the length of the route corridor considered, e.g. several/tens of kilometres in length would add additional complexity compared a corridor of one or two kilometres. For example, interpreting and presenting the geology (stratigraphy) is made more challenging when transitioning across geological map boundaries, which is more likely to occur with linear infrastructure, and particularly large-scale infrastructure of national importance. Adjoining geological maps can be of very different vintages, meaning that the stratigraphy across these maps may be inconsistent (e.g. current vs. obsolete units), the precision of the maps may be different (e.g. units mapped at member-level on one map, and formation-level on another map), and the geological unit boundaries may not be consistent at the map boundaries (e.g. due to different interpretations of the geology at the time of mapping). Furthermore, numerous examples were found of clearly erroneous stratigraphical interpretations within borehole and geotechnical data provided to BGS along the Bicester to Milton Keynes route. Given that so much of the data analyses and thematic dataset attribution is based on stratigraphy, and usually as one of the first steps, any error in these data will be propagated throughout any subsequent processes and outputs: ensuring the geological interpretation is as accurate as possible at the outset is critical to all subsequent applied geological endeavours!

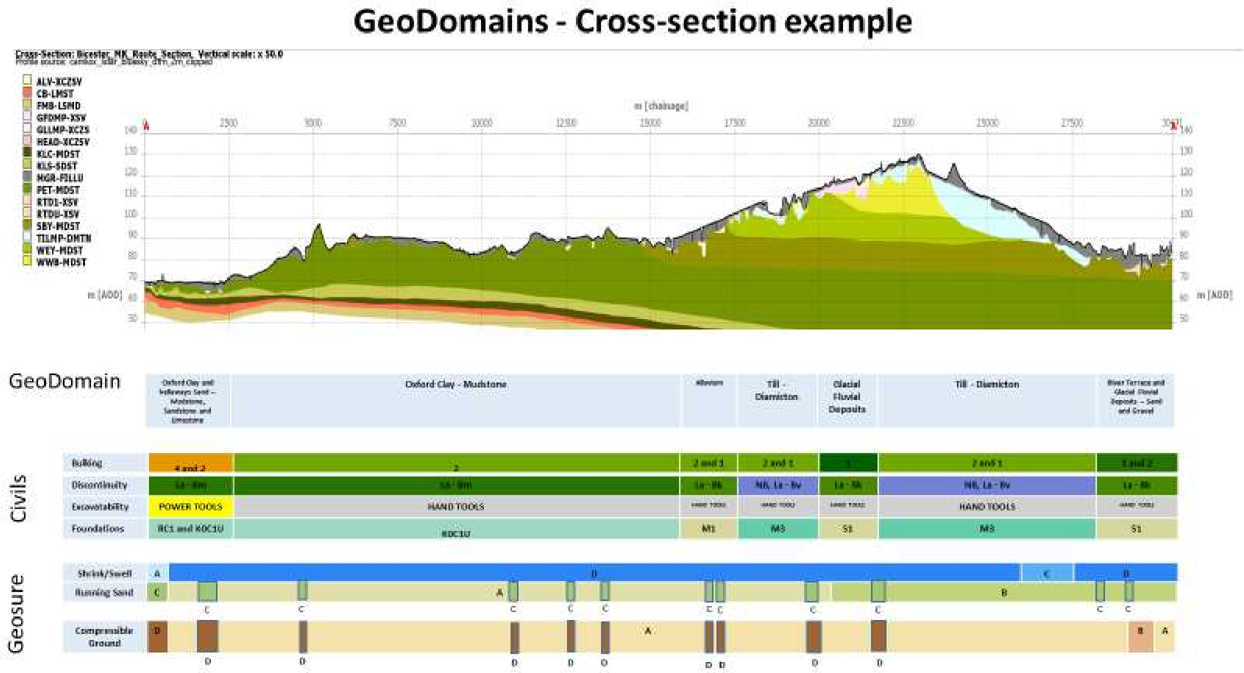


Figure 31 Bicester – Milton Keynes East-West Railway geological route model. Cross-section shows distribution of lithostratigraphical units (sedimentary bedrock) and the more recent strata such as alluvium and glacial deposits. (superficial deposits) at top with a series of coloured ribbons below representing different categories with a variety of BGS Civils and GeoSure datasets.

7.1.2 GEOTECHNICAL AND ENGINEERING GEOLOGICAL DATA SUMMARIES

A range of scripts have been developed in the programming language R to semi-automate the analysis and visualisation of geotechnical data extracted from the NGPD. Data for the Oxford-Cambridge Arc and Bicester to Milton Keynes section of the East-West Railway were used to test and validate the scripts. The scripts developed include processes for producing:

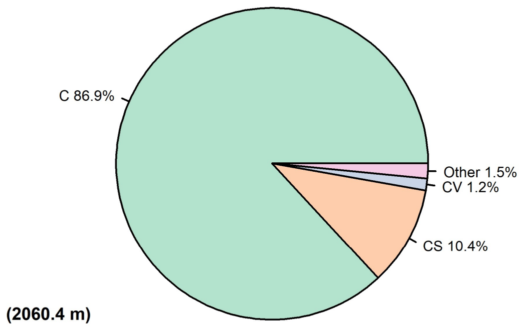
- statistical summaries from excel spreadsheets and .csv files, in particular non-parametric statistics, either for a range of different geotechnical properties for a single lithology-type or geological unit, or for a single geotechnical property for a range of different lithology-types or lithostratigraphical units (Table 6),
- extended box-and-whisker plots for single geotechnical properties for a range of different lithology-types or geological units, which is the traditional method used over the past 30 years by BGS for displaying geotechnical data,

- stacked bar charts for displaying the proportion of different soil and rock-types or strength/consistency recorded in borehole descriptions for a range of different geological units,
- pie charts for displaying the proportion of different soil- and rock-types recorded in borehole descriptions for single geological units (Figure 32),
- bar chart matrix plots for displaying the different strength and consistency recorded in borehole descriptions for single geological units, either at different depths (soils) or weathering grades (rocks) (Figure 33),
- and word clouds for visualising the engineering geological soil and rocks descriptions recorded in borehole logs (Figure 34).

	Natural Moisture Content %						
Geological unit	ALV	HEAD	ODT	OXC	WEY	SBY	PET
Number of samples	678	698	5101	2692	308	343	639
Minimum	6	3	1	3	2.6	8.4	6
0.5th percentile	9.4	7.6	7.9	8.4	8.4	14.7	13
2.5th percentile	12	10	11	14	15	16	15
10th percentile	17	15	14	19	18	20	19
25th percentile	22	19	15.6	22	20	22	23
50th percentile	28	23.8	18	25	22	25	26
75th percentile	41	29	20	29	25	28	30
90th percentile	59.3	35	24	34	28.3	32	35
97.5th percentile	100	46	29	39.8	33	37	40
99.5th percentile	145.2	79.2	35.5	47	40.0	42.2	43
Maximum	188	162	66	71	43	48	49

Table 6 Non-parametric statistical summary of Natural Moisture Content (%) for a range of geological units within the Oxford-Cambridge Arc region.

(ALV - Alluvium; HEAD – head; ODT – Oadby Till Formation; OXC – Oxford Clay Formation; WEY – Weymouth Member; SBY – Stewartby Member; PET – Peterborough Member)



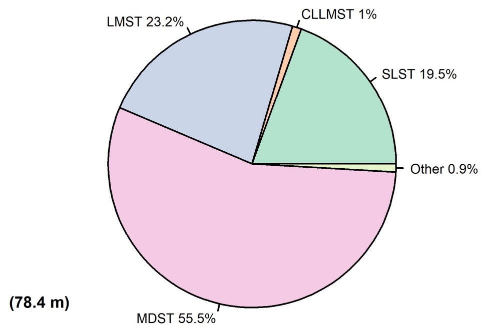


Figure 32 Pie charts showing the proportion of soil- (left) and rock-types (right) recorded in borehole descriptions of the Peterborough Member within the Oxford-Cambridge Arc. Total thickness logged is shown in brackets on the lower left of the pie chart. (C – clay; CS – sandy clay; CV – gravelly clay; MDST – mudstone; LMST – limestone; CLLMST – clayey limestone; SLST – Siltstone)

Figure 33 bar chart matrix plots displaying the stiffness/strength of fine soil recorded at different depth intervals in borehole descriptions of the Peterborough Member within the Oxford-Cambridge Arc. (SFTV – Very soft; SFT – Soft; FRM – Firm; STI – Stiff; STIV – Very stiff; WKE – Extremely weak)

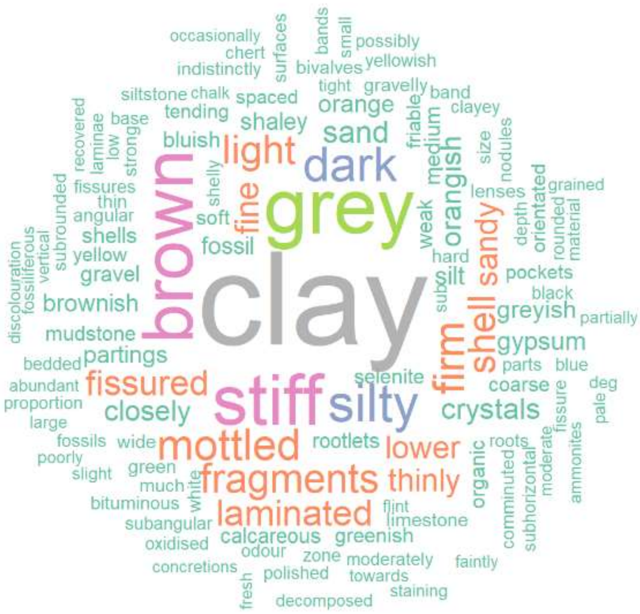


Figure 34 word clouds for visualising the engineering geological soil and rocks descriptions recorded in borehole logs of the Peterborough Member within the Oxford-Cambridge Arc region.

This typically includes grainsize of primary, secondary and tertiary components of soils or lithology-types, strength or consistency, colour, and discontinuities.

In addition to developing scripts, this project is also exploring the variation of geotechnical properties with depth, and whether more sophisticated regional property models can be developed to replace simple linear property-depth trends. One-dimensional property models for natural moisture content, standard penetration test (SPT) and undrained shear strength were produced using data for the Oxford Clay Formation from the Oxford-Cambridge Arc region using rolling window averages (median, mean, and mean of medians) on data sorted by sample depth. The results, for these properties at least, are relatively consistent and indicate that there are discrete zones in the subsurface with different property-depth trends (Figure 35), which appear broadly coincide with weathering grade described in the borehole geology descriptions and anticipated weathering depths in literature (Waltham, 2009; Hobbs et al., 2012). These models suggest that there is value in characterising and summarising geotechnical properties by depth or weathering grade to be better constrain data distribution within these zones and to establish more robust property-depth trends.

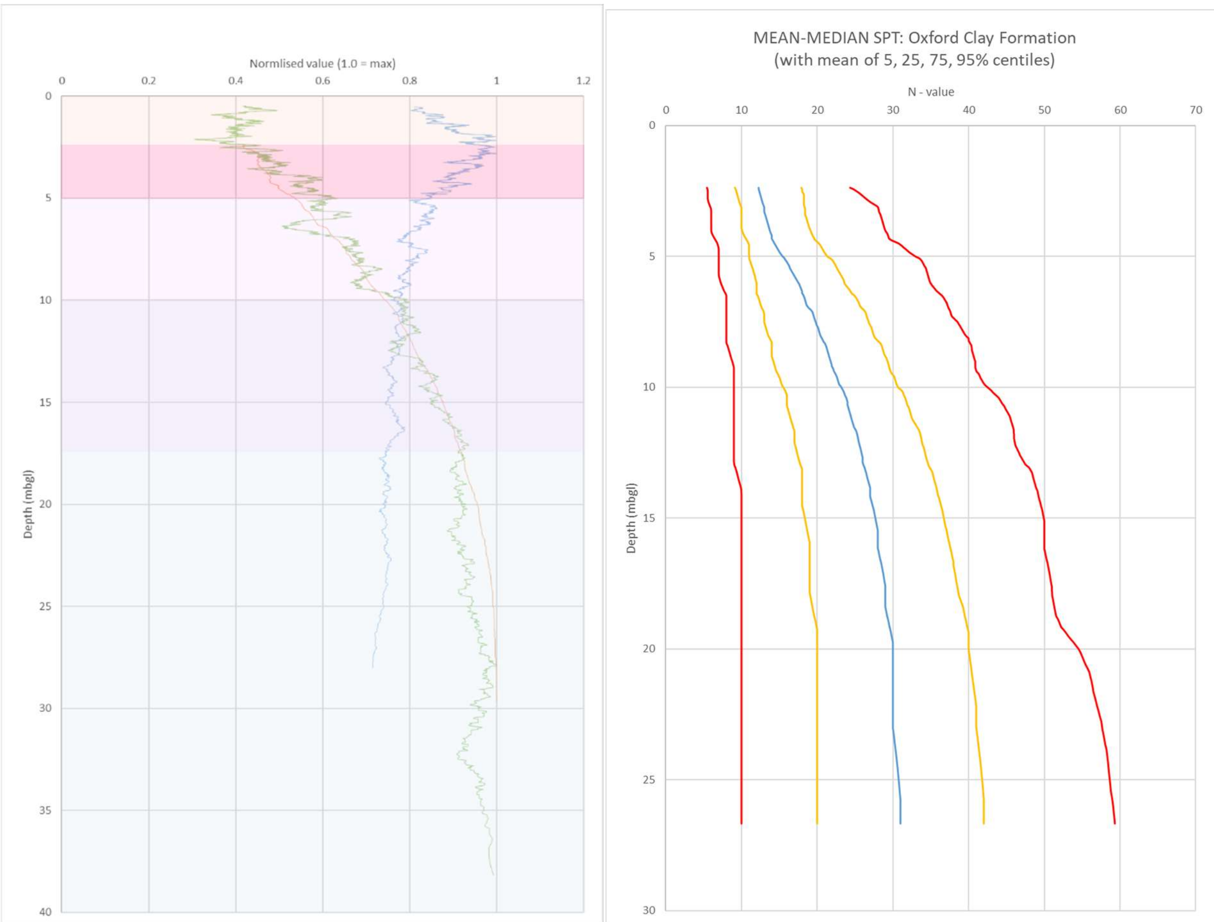


Figure 35 Left: One-dimensional property models for Oxford Clay Formation within the Oxford-Cambridge Arc. SPT (orange line), undrained shear strength (green line) and natural moisture content (blue line) with depth are based on a mean average 100-sample-rolling-window. All properties have been normalised by their maximum values for presentation purposes. Different coloured sections represent zones with different property-depth relationships. Right: One-dimensional property models showing variation in SPT with depth based on a mean of medians 100-sample-rolling-window (blue line) with 50% and 90% confidence intervals shown in yellow and red respectively.

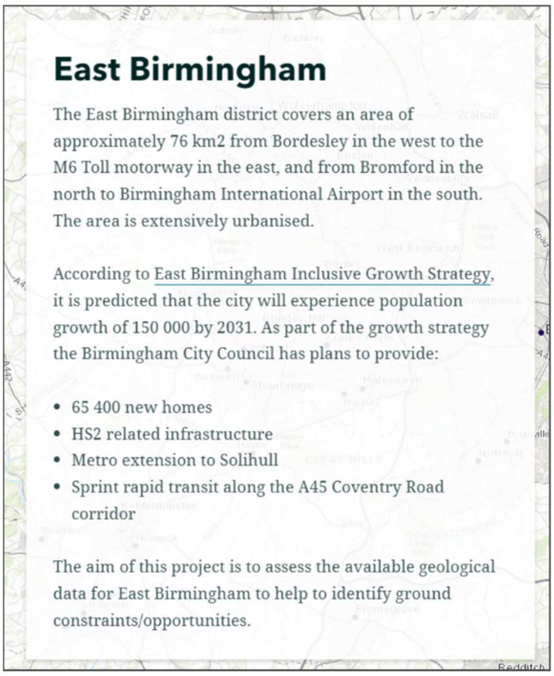
7.2 EAST BIRMINGHAM ARCGIS STORY MAP

Communication of geotechnical and engineering geological data and information to stakeholders is essential: using tools that engage them facilitates this task. Pre 1990s engineering reports and maps were produced as paper publications, and then as digital pdf files. Today, interactive digital tools, such as dynamic maps and videos, are increasingly used to facilitate more effective communication of data and information. One of these visualisation tools is the story map, which is a simple web application that allows dynamic maps to be accompanied by text, and multimedia content including images and embedded videos.

Currently, many providers offer story map services. At BGS, ArcGIS StoryMap applications are being used, which are hosted in the Esri cloud, to share information as a narrative text. As well as enabling users to visualise the data, contextual information is also provided that allows users to understand the data, and its applications and limitations. Knowledge, in addition to data and information, is therefore also communicated in a single output. The major advantages of using ArcGIS StoryMap are that they are easy to use, require no prior GIS proficiency or experience, nor any specialist software. However, design options are restricted to those available within the StoryMap builder.

BGS has compiled data and information for ground conditions for East Birmingham using an ArcGIS StoryMap. Figure 36 shows examples from the StoryMap showing how text, images and videos are embedded with background maps and shapefiles. The narrative text appears while scrolling, which is like browsing website. However, by clicking the expand button located on the upper right side on the map, the text disappears allowing the user to explore shapefiles and view a legend. Images and links can be also added to get further information.

The geotechnical data for the site were extracted from the NGPD, processed, and analysed. The contextual narrative text was then added to the story map alongside the summary graphs and tables inserted as jpg or png images. Examples showing the representation of geotechnical data and information are shown in Figure 36.



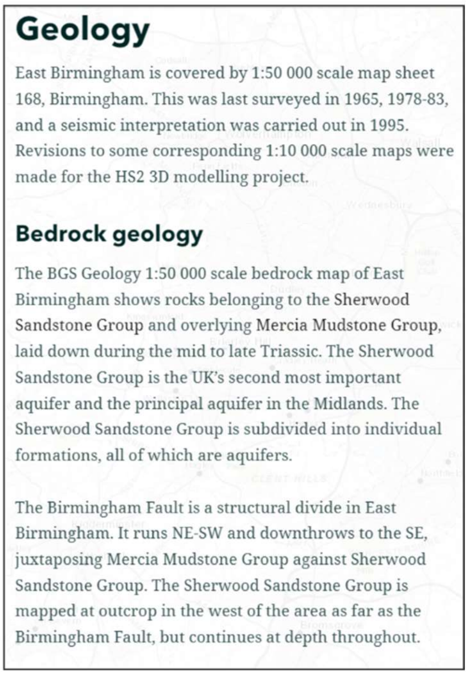
East Birmingham

The East Birmingham district covers an area of approximately 76 km2 from Bordesley in the west to the M6 Toll motorway in the east, and from Bromford in the north to Birmingham International Airport in the south. The area is extensively urbanised.

According to East Birmingham Inclusive Growth Strategy, it is predicted that the city will experience population growth of 150 000 by 2031. As part of the growth strategy the Birmingham City Council has plans to provide:

- 65 400 new homes
- HS2 related infrastructure
- Metro extension to Solihull
- Sprint rapid transit along the A45 Coventry Road corridor

The aim of this project is to assess the available geological data for East Birmingham to help to identify ground constraints/opportunities.



Geology

East Birmingham is covered by 1:50 000 scale map sheet 168, Birmingham. This was last surveyed in 1965, 1978-83, and a seismic interpretation was carried out in 1995. Revisions to some corresponding 1:10 000 scale maps were made for the HS2 3D modelling project.

Bedrock geology

The BGS Geology 1:50 000 scale bedrock map of East Birmingham shows rocks belonging to the Sherwood Sandstone Group and overlying Mercia Mudstone Group, laid down during the mid to late Triassic. The Sherwood Sandstone Group is the UK's second most important aquifer and the principal aquifer in the Midlands. The Sherwood Sandstone Group is subdivided into individual formations, all of which are aquifers.

The Birmingham Fault is a structural divide in East Birmingham. It runs NE-SW and downthrows to the SE, juxtaposing Mercia Mudstone Group against Sherwood Sandstone Group. The Sherwood Sandstone Group is mapped at outcrop in the west of the area as far as the Birmingham Fault, but continues at depth throughout.

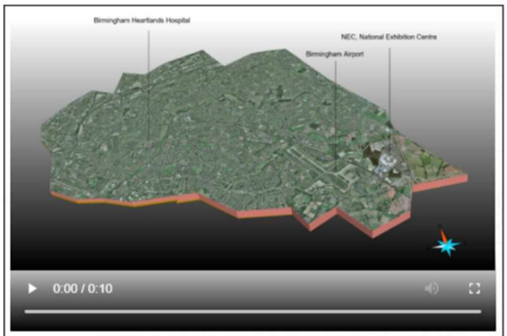


Fig.4 Overview of the 3D geological model of the area

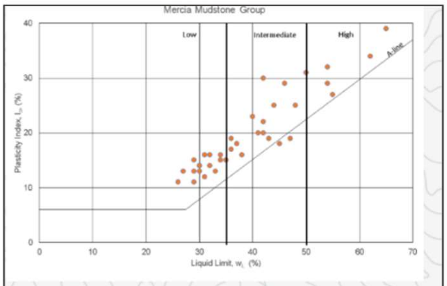


Fig. 18. Plasticity chart of Mercia Mudstone Group

Figure 36 Extracts from the ArcGIS StoryMap East Birmingham (background information, geology description, a 3D model of the area and a graph of a geotechnical test created using ArcGIS® by Esri. A background map (top left) and a world imagery on the 3D model (bottom left) contains the "World Topographic Map" and "World Imagery".

8 Discussion and Recommendations

For more than a century, BGS has provided data, information and knowledge about surface and subsurface geological properties and processes, and their implications for the construction and operation of buildings and infrastructure. Throughout this time, the research methods applied, and the outputs generated, have evolved to meet changing societal needs and to keep pace with technological change.

For BGS urban geoscience to remain relevant, it must continue to evolve and adapt in response to technology and society, but now must also contend with climate change and economic uncertainty. Based on the historical and contemporary examples presented in this report, and anticipated future changes and challenges, several key focus-areas are identified, and recommendations made for future urban geoscience research.

8.1 STAKEHOLDER-FOCUSED DATA, INFORMATION AND KNOWLEDGE SERVICES

For urban geoscience data and information to effectively contribute to the urban management process, they need to be both relevant and understandable to stakeholders. In the context of cities, this means addressing different socio-economic and environmental needs (see section 1.1), different industrial legacy and cultural heritage, and different geological conditions. In the context of stakeholders—which includes planners, developers, statutory consultees, consultants, contractors, asset managers, landowners, and the public—this means addressing very different needs and interests, but also different levels of geological literacy and technological capability.

Within the UK there will continue to be a need to support urban development, particularly in the fastest growing cities. Previously, the main considerations for development were economic viability, and specifically the location of potential geological hazards and exiting geological resources. However, now there is increasing emphasis on ensuring development is also socially inclusive and environmentally sustainable (see Section 1). Furthermore, in addition to development and redevelopment, there is a growing need to support the operation of existing buildings and infrastructure, which are becoming increasingly vulnerable to geohazards due to climate change.

One of the hallmarks of the urban geoscience study reports of the 1980s and 1990's was their focus on delivering locally relevant data and information in appropriate formats for stakeholders (see section 3.1). More recently, new examples of how BGS data and information could be presented, using data from the East-West rail route between Bicester and Milton Keynes, are shown in 7.1.1 , but further stakeholder engagement is required to optimise the presentation of this for end-users.

Research projects and services must be designed at the outset with the data and information end-users (geoscience stakeholders) in mind. In additional to novel formats for presenting data and information, more conventional formats will also still be required.

A one-size-fits-all approach, for either cities or stakeholders, will be less useful and useable, and thus less used. Data, information, and knowledge services must address individual city and stakeholder needs. BGS must produce different outputs to communicate the same information to different groups within cities, and, in some cases, wholly different outputs for different cities.

The potential for BGS outputs (and services) to have an impact on urban geoscience problems is greatest when the data and information provided are targeted to address specific issues relevant to the strongest socio-economic and environmental needs, e.g. housing, critical infrastructure and climate change. Outputs should be limited to the shallow subsurface (250 metres below ground level) and scales of 1:10 000, or greater, to remain relevant in an urban environment.

New methods of integrating geotechnical and engineering geological data and information with natural and social capital accounting systems need to be developed to help deliver socially inclusive and environmentally sustainable development.

8.2 PARADIGM SHIFT: TECHNOLOGICAL INNOVATION AND EARLY ADOPTION

Often technological change has prompted a step-change in how BGS geological data and information is managed, used and communicated: for example, the advent of personal computer and the development of the NGPD (see section 2), and GIS software and the development of BGS Civils and GeoSure (see section 5.1). BGS has frequently been at the forefront of technology innovation and adoption, which has directly benefited BGS's own research, for example using databases for national-scale formation study research (see section 3.2) and 3D modelling technology to create attributed and parameterised 3D geological models (see section 6).

The early-adopter role of BGS is especially significant for the wider geoscience community by helping it to overcome the 'paradigm paralysis' that can occur during the transition from one technology to another. By developing workflows and effectively demonstrating the viability of new technologies, and evidencing the beneficial outcomes, BGS has helped accelerate both the performance and awareness of new technology, and consequently the adoption of it by the wider geoscience community. For example, geotechnical databases, GIS and 3D modelling are now routinely used in the civil engineering industry, though years, and in some cases decades, after BGS pioneered the use of these technologies. It is however worth noting that this pioneering role can come at the expense of maintaining stakeholder engagement: industry and the public sector are often much slower to adopt new technologies until the perceived benefits of adoption are evident. For example, BGS has led the way in the use of lithofacies modelling, in Glasgow and London, but partners in industry are not yet able to use these outputs for their analysis or reporting.

Future technologies continue to emerge that will play a significant role in supporting future urban management. In particular the integration of the internet of things (IoT) with in situ ground monitoring; application of machine learning to Big Data analytics; and the integration of the geoscience data and information into Building Information Models (BIM) and City Information Models (CIM) for visualising and monitoring the built assets.

BGS must maintain its role as 'paradigm shifters' by continuing the innovation and adoption of new technology, such as the IoT, machine learning, and digital twins. However, BGS must also ensure that key geoscience data and information are also delivered using industry standard technologies and formats so that the wider stakeholder community can also benefit: technology must not become a barrier to communication.

8.3 MULTIDISCIPLINARY COLLABORATION

Urban geoscience is a much broader discipline than engineering geology and incorporates many other applied geoscience disciplines, including hydrogeology, geochemistry, geophysics, mineral resources and geological mapping and modelling. For geotechnical and engineering geological data and information to be effectively used, it needs to be integrated with other geoscience data and information and be complimentary.

One common feature of nearly all BGS urban geoscience study reports, is that while geotechnical and engineering geological data and information are a very significant component, they are not the sole component of these reports. For example, the applied 'urban' mapping reports of the 1980s and 1990s covered a range of topics, including geology, engineering geology, hydrogeology, mineral and aggregate resources, geohazards and industrial legacy (see sections 3.1 and 4.3). The success of these projects, and their value for stakeholders, is specifically attributed to the multidisciplinary nature of both the project teams involved, and of the project outputs (Smith and Ellison, 1999; Ellison et al., 2002; Forster et al., 2004). Likewise, the formation study reports of the 1990s and 2000s, which were very engineering geology focused, still included significant input from sedimentologists, structural geologists, mineralogists, hydrogeologists and geophysicists.

Multidisciplinary collaboration, within BGS and externally, is needed to provide holistic urban solutions: all future studies must integrate collaboration at the project concept and design stage.

This should include, as a minimum, geologists, 3D modellers, engineering geologists, hydrogeologists, geochemists, minerals and energy-resources (renewables) geoscientists, social scientists and informatics (IT professionals).

8.4 DATA ARE THE FOUNDATION OF KNOWLEDGE

Urban environments are rich in geological and geotechnical data due to the concentration of ground investigations for buildings and linear infrastructure. These ground investigation data have provided the foundation for BGS urban geoscience and engineering geology projects since the mid-1980s (see section 3). They are also a key resource for urban geological mapping and modelling, due both to the scarcity of geological outcrops in urban environments, and critically because they provide geological data from depth (see section 6 and Kearsey et al., 2022).

The strong demand for many BGS urban and formation studies reports (see section 3), is in part because they are geotechnical-data-rich. For some stakeholders (e.g., civil engineers), these data are used to augment their own site investigation data and help inform project specific decision-making: in this sense, the data often have greater value for some stakeholders than BGS interpretations of these data and information derived using them (e.g., geology maps and engineering geology, 3D geology and property models, and thematic datasets such as BGS Civils).

For the most part, geotechnical data held by the BGS have been donated by consultants, developers, and laboratories, and are now stored in the NGPD (see section 2). Currently, data from the NGPD are used on an ad hoc basis by consultants and academics through the BGS enquires system; within BGS, the data are also currently underutilised because of visibility and limited access routes. Data held in the NGPD are therefore neither easily findable, accessible, interoperable nor (re)suable (*c.f.* Geospatial Commission, 2022). The quality of data within the NGPD is also highly variable, due to age and provenance, and in some case hindered by non-systematic and erroneous attribution of some fields and tables, especially stratigraphy and lithology. It is also worth noting that data accessions are ongoing, which means new data are constantly available that may contradict existing information published by BGS (e.g., maps, reports and derived products).

Data are the foundation of knowledge. BGS must continue to maintain and populate the NGPD with new data: every year thousands of ground investigation boreholes are completed in the UK, and there are also decades of historic boreholes, including offshore, that have yet to be accessioned. There therefore remains significant opportunity to acquire additional geotechnical data, particularly in AGS format from industry stakeholders. Data acquisition should be prioritised in areas identified by UK government for strategic development.

Significant opportunities exist to enhance the impact of BGS geotechnical and engineering geological data with Stakeholders using Q-FAIR data principles, which also supports current government collaboration (GC, IPA) seeking to enhance the sharing of geotechnical data within industry. BGS should prioritise the development of an open-access web-based data portal for industry and academia to access raw NGPD data and summary statistics for UK rock and soil units. This could take the form of an interactive GIS with data-dashboard, which summarises key properties in the form of tables and graphs which enables data selection and export in CSV and AGS file formats. In the first instance this could be prioritise data considered to be of most value and use to industry, e.g., SPT, PSD, Atterberg limits, moisture content, density, and strength (cohesion, shear, UCS, tensile etc).

8.5 DATA ARE NOT ENOUGH!

Most geoscience stakeholders are not geoscientists, and even those that are will not all be engineering geologists. As such, 'raw' geotechnical and engineering geological data will be of very limited use to most stakeholders. Consequently, these data need to be translated into information and knowledge for them to be understandable and relevant, and thus be used by stakeholders for decision-making (see Figure 37). Furthermore, even for engineering geologists and geotechnical engineers, metadata are required to identify the provenance, quality, applications and limitations of the data.

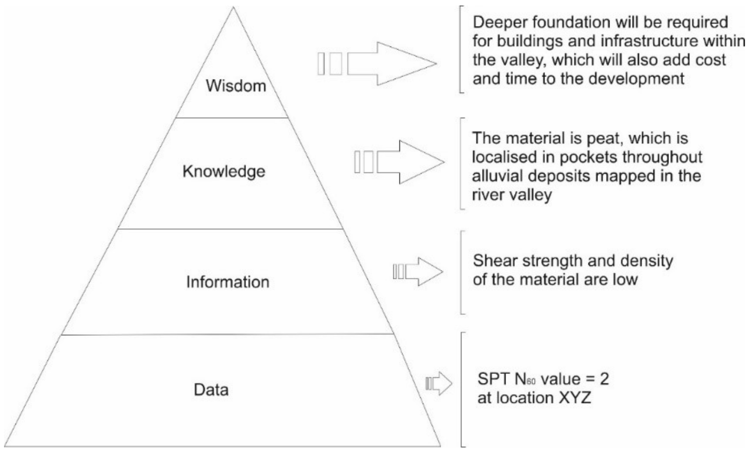


Figure 37 An example of using Information-Knowledge-Wisdom Pyramid for geotechnical and engineering geological data

Arguably, the strong demand for many BGS urban and formation studies reports is also because of the additional information and knowledge they provide (*c.f.* section 8.4), and therefore making them of use to geoscientists and non-geoscientist alike. For example, the urban and formation studies reports (see section 3) provide contextual information about the geology that helps relate variations in properties and behaviour to specific aspects of the geology, such as lithology, mineralogy, alteration, and micro- and macro-structure. The implications of the properties and behaviour for specific activities—such as construction, geohazard mitigation and resource management—is also provided, and therefore makes the local geology meaningful and relevant to urban management and construction.
In recent decades, some of the information and knowledge contained in traditional reports has become decoupled from the data as BGS transitioned from paper to digital outputs, and particularly to GIS datasets and 3D models. While these datasets and models are always accompanied by reports, they can be easily overlooked by users and thus necessary contextual information and knowledge may be lost. Though recently, one solution to this has though been identified with the introduction story maps, which provide information and knowledge alongside geospatial data in a single output (see section 7.2). The BGS Civils datasets is also a good example of a product that has potentially useful information embedded within it, but require additional contextual information, or a different presentation mechanism, to make these used more widely.

Data alone are not enough, they must be accompanied by, and translated into, information and knowledge to provide context and meaning so that they are applicable to all geoscience stakeholders. ArcGIS StoryMap is an example of a modern digital delivery mechanism that may supersede the map and memoir combination that served stakeholders so well in previous decades. Many existing datasets would benefit from further contextual information to facilitate greater understanding and application by stakeholders.

8.6 IT'S THE GEOLOGY, STUPID!

A robust geological framework is critical for the interpretation of geotechnical and engineering geological data, and particularly to enable the leap from knowing properties at discrete points within the subsurface—which are invariably multivariate, uncertain and unique, sparse, incomplete, and unevenly distributed (Phoon et al., 2019)—to predicting the properties of the ground between these points. Geological frameworks enable the variability of ground conditions to be spatially constrained by linking them to mappable geological units and their associated geological features (e.g. lithology, mineralogy, alteration, and micro- and macro-structure). For example, BGS geology map data are used as the basis for, or at least form a significant input to, the development of applied and thematic maps (see section 4), GIS-derived products (see section 5.1), and 3D models (see section 6). However, for geological maps and models to effectively support urban geoscience studies they need to be at scales relevant to stakeholder needs: at least 1:25,000 scale and preferably 1:10,000 scale, for which BGS does not have universal coverage.

The BGS formation study reports (see section 3.2) provide an enormous amount of useful information for the stakeholders in the civil engineering sector. This series could be expanded to include other geological units of interest such as the Oxford Clay Formation and UK till formations. These could be studied and reported by region or metropolitan area, or along major transport infrastructure corridors.

Anthropogenic influence on the evolution of the urban landscape, particularly of the shallow geosphere that makes up the foundation of our cities, is well known but poorly quantified geologically or geotechnically. Artificially Modified Ground (AMG) represents those areas where the ground has been significantly changed by human activity.

AMG was not consistently mapped by BGS until the 1980s although many urban areas are built on AMG and even the modern AMG mapping has focused primarily on mineral workings, industrial areas and transport routes. Therefore, AMG is an important but often underrepresented feature in geological maps and models (Aldiss et al., 2014; Ford et al., 2014).

Recent progress made by the British Geological Survey (BGS) and others around the world in this field has meant that AMG is increasingly mapped and modelled and is now regarded by many as an important deposit or excavation likened to natural geological processes (Bridge et al., 2005; Bridge et al., 2010; Burke, H F et al., 2014; Ellison et al., 2002; Price et al., 2012; Zalasiewicz et al., 2011).

Understanding the thickness, distribution and make-up of AMG will become increasingly important in urban areas and the research into the processes for doing this have been started (Terrington et al., 2019). 3D engineering geology models would go some way to identify and mitigate against hazards associated with AMG and integrating with the 3D ground model to plan for construction. As urban growth continues, the thickness and character of AMG will need to be better understood. BGS with others other organisations (e.g., the Ordnance Survey, engineering geology consultancies and local authorities) can improve the maps and 3D models of AMG to show the thickness and distribution of AMG in our cities, towns and the major links between these (e.g., railway embankments).

Geological frameworks are critical for translating geotechnical and engineering geological data and information into information and knowledge. BGS must continue to invest in its geological knowledge base, and in the provision of large-scale (i.e. 1:10,000) maps for urban areas that incorporate AMG. The availability of new geological data in urban centres provides good opportunities to revisit these datasets, even where they are already available, and would benefit from further collaboration with other relevant organisations (e.g., the Ordnance Survey and Historic England) to help identify and characterise AMG.

8.7 3D MODELLING FOR GEOTECHNICAL AND ENGINEERING GEOLOGY APPLICATIONS

3D modelling has always been a key element in urban environments, and particularly for engineering projects, and even when outputs were limited to two dimensions (see sections 4 and 5). Improved workflows and methodologies such as BIM (Building Information modelling) and the concept of Digital Twins, merging numerous environmental and built infrastructure datasets to simulate reality, means that the BGS geotechnical and engineering geology data will be the most relevant in these areas of innovation. Collaborating with the industry to find out how they use engineering geological and geotechnical data and information would benefit both stakeholders and the BGS.

Geotechnical property models moving to voxelated property models would be a great advantage as several properties could be attributed to the same voxel, e.g. TNO – GeoTOP (Stafleu et al., 2011). Both surface and subsurface data information could be portrayed in this way and form the beginnings of a 3D GeoLanduse map encompassing both the BGS Civils and

Geosure datasets whereby all the geotechnical and engineering geological data can be encapsulated in a single 3D model (Terrington et al., 2019). The GeoLanduse model is a 3D vector cell-based model that can be loaded into a GIS and interrogated per cell which can numerous depths and attributes associated using the same structure as the BGS 3D Shrink Swell product (Jones and Hulbert, 2017), but instead attributing with ground water levels and geotechnical and engineering parameters such as excavatability.

3D models of the geology, and the associated geotechnical parameters, are fundamental for the future management of the subsurface in urban areas. A BGS cross-cutting strategic programme of stakeholder engagement and 3D modelling is required to ensure that the modelling undertaken by the BGS is fit-for-purpose and relevant at the scales required for the infrastructure management and construction sectors, i.e. Digital Twins.

Appendix 1 Record of data stored in the National Geotechnical Properties Database (as of November 2021)

Database table	Description	Number of data records
BGS.GTCH_CNMT	Contaminant and chemical testing	5112810
BGS.GTCH_STCN	Static cone penetration test	2106811
BGS.GTCH_GEOL	Stratum descriptions	1011057
BGS.GTCH_SAMP	Sample reference information	851512
BGS.GTCH_PRTD	Pressuremeter test data	533818
BGS.GTCH_ISPT	Standard penetration test results	415382
BGS.GTCH_CLSS	Classification tests	381637
BGS.GTCH_HOLE	Hole information	197683
BGS.GTCH_CORE	Rotary core information	183626
BGS.GTCH_CONS	Consolidation test results – for each stage of test	120676
BGS.GTCH_GRAD	Particle size distribution analysis data	118922
BGS.GTCH_FRAC	Fracture spacing	104057
BGS.GTCH_DISC	Discontinuity data	96517
BGS.GTCH_PTLD	Point load tests	81704
BGS.GTCH_IVAN	In situ vane test	80655
BGS.GTCH_TRIG	Triaxial tests	80360
BGS.GTCH_WSTK	Water strike details	58756
BGS.GTCH_CDIA	Casing diameter by depth	47283
BGS.GTCH_WETH	Weathering grades	36052
BGS.GTCH_POBS	Piezometer readings	34751
BGS.GTCH_ROCK	Rock testing	26358
BGS.GTCH_CONG	Consolidation test – general results	20853
BGS.GTCH_CBRT	CBR test	14191
BGS.GTCH_CHLK_ENG	Chalk engineering properties	14069
BGS.GTCH_CMPG	Compaction tests – general	13529
BGS.GTCH_CHLK	Chalk tests	11382
BGS.GTCH_IPRM	In situ permeability test	9302
BGS.GTCH_CBRG	CBR test – general	8877
BGS.GTCH_PREF	Piezometer installation details)	8514
BGS.GTCH_PROJ	Project details	7765
BGS.GTCH_PROJ_DATA_ENTRY	Data entry details	7765
BGS.GTCH_MCVT	MCV test	6233
BGS.GTCH_VANE	Sample vane tests	6150

BGS.GTCH_ICBR	In situ CBR test	5887
BGS.GTCH_SHBG	Shear box testing – general	5651
BGS.GTCH_RWL	Rest water level data	4040
BGS.GTCH_PRTL	Pressuremeter test results, individual loops	3522
BGS.GTCH_IDEN	In situ density test	1858
BGS.GTCH_BRAZ	Rock Testing – Brazilian tensile strength results	1762
BGS.GTCH_PRTG	Pressuremeter test results, general	1467
BGS.GTCH_PUMP	Pumping test	1091
BGS.GTCH_SHRINKAGE	Shrinkage Tests	1032
BGS.GTCH_PTST	Laboratory permeability tests	931
BGS.GTCH_MODULUS	(Rock testing – Modulus related test results)	855
BGS.GTCH_SUCT	Suction tests	720
BGS.GTCH_SDI	Rock Testing – Slake Durability Index	531
BGS.GTCH_AGGREGATE	Rock Testing – Aggregate results	439
BGS.GTCH_RELD	Relative density test	318
BGS.GTCH_IRES	In situ resistivity test	186
BGS.GTCH_VELOCITY	Rock Testing – P-wave and S-Wave velocity measurements	146
BGS.GTCH_IRDX	In situ redox test	72
BGS.GTCH_SHORE	Rock Testing – Shore hardness	72
BGS.GTCH_FRST	Frost susceptibility	45
BGS.GTCH_IUCS	In situ UCS test	38

Appendix 2 List of BGS urban study reports

	Urban area	Report number
1	Poole - Bournemouth Area	WA/VG/84/005
2	Exeter Area	WN/91/16
3	Rothwell	WA/DM/84/001
4	Normanton	WA/DM/87/026
5	Morley	WA/DM/83/001
6	Oulton	WA/DM/85/003
7	South Humberside	WA/VG/83/7
8	Cramlington and Wide Open	WA/DM/85/014
9	Hurn - Christchurch	WA/VG/84/009
10	Ponteland - Morpeth Distict	WA/DM/86/006
11	Garforth - Castleford - Pontefract	WA/90/03
12	Corfe Mullen - Lytchett Minster	WA/VG/86/004
13	West Wiltshire and south-east Avon	WA/VG/85/008
14	Aldridge - Brownhills	WA/VG/84/001
15	Deeside (North Wales)	WA/88/002
16	Southampton	WO/87/002
17	Coventry	WA/89/029
18	Crosby - Bootle - Aintree	WA/VG/86/002
19	Workington - Maryport	WA/88/003
20	Dearham - Gilcrux	WA/89/070
21	Nottingham	WA/90/001
22	Wrexham	W/91/004
23	Morpeth - Bedlington - Ashington	WA/90/019
24	Stoke-on-Trent	WA/91/01
25	South-west Essex - M25 corridor	WA/91/28
26	Black Country	WA/92/033
27	Great Broughton - Lamplugh	WA/92/054
28	Leeds	WA/92/001
29	Wigan	WN/95/003
30	Bradford	WA/96/001
31	Brierley Hill	WA/91/062
32	South Essex	WN/EG/75/020
33	Afon Teifi	WA/97/035
34	Sidmouth	WN/98/001
35	Castleford	WA/DM/87/068
36	Milton Keynes	WN/EG/69/001
37	A74M and M6 Solway Area	IR/07/031
38	Aylesbeare, Devon	WA/DM/84/009
39	Bathgate	WA/89/019
40	Hamilton - Wishaw	WA/90/030
41	Stirling	WA/91/025
42	Dunfermline	WA/89/49
43	Livingston	WA/92/037

44	Falkirk - Grangemouth	WA/90/056
45	Fife: Cowdenbeath - Lochgelly	WA/85/001
46	Fife: Kirkcaldy	WA/88/032
47	Motherwell	WA/89/031
48	Hamilton - Wishaw	WA/90/030
49	Clyde Valley	WA/89/078
50	Aberdeen	WA/HI/86/001
51	Airdrie - Coatbridge	WA/LS/86/001
52	Morley - Rothwell - Castleford	WA/88/033
53	Newcastle upon Tyne and Gateshead	WA/DM/83/030
54	Bridgend	WA/VG/85/002
55	Greater Manchester	OR/20/033

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