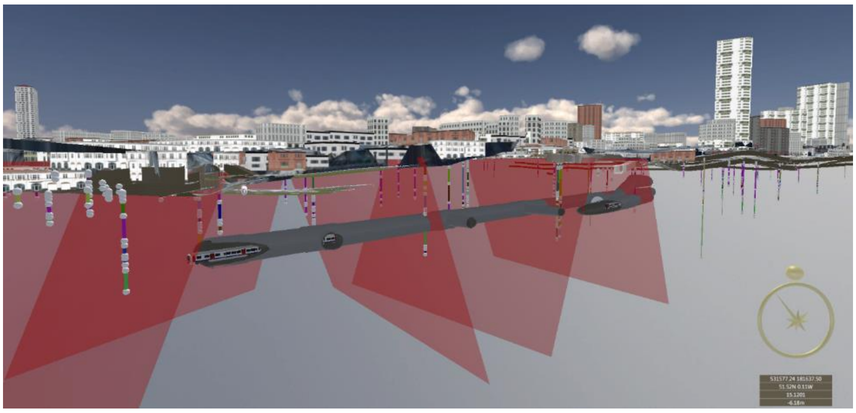
Urban Geoscience Report - The value of geoscience data, information and knowledge for transport and linear infrastructure projects

Environmental Change Adaptation and Resilience Programme

Open Report OR/21/065



BRITISH GEOLOGICAL SURVEY

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Geovisionary image showing the 3D model of Farringdon Station with newly identified faults. BGS © UKRI (2021)

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Urban Geoscience Report - The value of geoscience data, information and knowledge for transport and linear infrastructure projects

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Keyworth, Nottingham British Geological Survey 2022

BRITISH GEOLOGICAL SURVEY

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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 our urban geoscience stakeholders.

The reports in this series are as follows:

Urban Geoscience Report (this report) - The value of geoscience data, information and knowledge for transport and linear infrastructure projects OR/21/065

Urban Geoscience Report - Capacity for 3D urban modelling OR/22/043

Urban Geoscience Report - Geotechnical and engineering geological data and information for urban development at BGS OR/22/049

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New transport and urban infrastructure provision lies at the centre of UK government's Build Back Better campaign and the Levelling-Up Agenda, to deliver significant socio-economic value to local economies, through provision of jobs and supply contracts, and enhancing well-being through greater local access to services. This will comprise large scale investment in major infrastructure and construction projects like HS2, Crossrail, and major flood risk management programmes as well as the provision of housing and the rapid deployment of fibre and 5G. To maximise the value of investment in new infrastructure the UK Government has set targets for improved productivity, efficiency, and adoption of environment-sensitive principles in the construction sector with the introduction of 'Project Speed' and the 'Faster, Better, Greener' approach.

A number of recent initiatives have highlighted the value of subsurface data sharing to support construction and infrastructure development, and wider subsurface management. These include the Geospatial Commission's National Underground Asset Register; Dig-to-Share -an Infrastructure Industry Innovation Partnership project; Project Iceberg; and the EU Sub-Urban COST Action. These initiatives have been successful in bringing together public and private sector bodies to demonstrate the potential benefits arising from the deposition and (re-)use of geoscience data and information. Despite these successes the value of geological and geotechnical data throughout the infrastructure and construction lifecycle is still under appreciated, resulting in inefficiency and reduced productivity. It has been estimated that unforeseen ground conditions contribute to significant delays in 20-60% of transport and linear infrastructure developments, and budget overruns, typically over 10%, are recorded across the industry.

This report describes how geological data and knowledge is key to overcoming challenges associated with ground conditions and improving efficiency within planning and construction. Whilst the review is targeted to the transport and linear infrastructure sector, the observations on Ground Investigation (GI) data and geological data and support services are relevant to the broader construction lifecycle. Some of the wider social, economic and environmental benefits delivered when good GI and data management principles are applied are also highlighted. The report identifies the key datasets and services available from the BGS for those undertaking GI for new transport and linear infrastructure projects but more widely for those employed in construction and asset management. A number of cases studies are described which demonstrate the value of geological and geotechnical information for transport infrastructure, such as the Lower Thames Crossing, and Farringdon Station (CrossRail).

The key findings in this report are:

1. **Significant sums are being spent on new infrastructure in Great Britain, however only a fraction of this is being spent on GI and collection of geological data and information. Large amounts of data collected during GIs are not shared for onward use resulting in inefficiency and less targeted onward investigations**.
    - between 2013 and 2019 the proportion of GDP spent on new infrastructure in Great Britain increased by ~30% from 0.8% to 1.05% of GDP; a total of £23 billion in 2019 (ONS, 2021a)
    - GI and planning often takes up a large component of time on a project but only makes up about 0.05 –2% of total costs (UKessays 2018)
    - a conservative estimate of the annual cost of acquiring geological data and information for infrastructure alone would be £230 million per year
    - in relation to development of brownfield the BGS and, DEFRA estimate that £210m per year is spent unnecessarily on remediation due to poor ground investigation and unforeseen ground conditions in the UK (Brownfield briefing 2011)
    - it is estimated that currently 80% of historic GI data is missing from the BGS central archives. Based on an annual investment of £230m/y in GI this equates to a loss of data and knowledge to the UK economy of an estimated £184m/yr

2. **Lack of investment in GI and inefficient use of existing geological data is causing significant delay and overspend on infrastructure projects**.

   - 30%-50% of construction projects experience delays (Barron 2011), 17-20% experience significant delays (Chapman 2012)
   - Flyvjberg et al. (2003) found that cost overruns in 258 megaprojects (projects >$1Bn), averaged 45%, 34% and 20% for rail, bridges and tunnel, and road projects respectively, with an average across all classes of 28%; cost over runs also occurred in 90% of projects

3. **Access to geological information delivers value to infrastructure projects through, risk reduction, efficiency savings, informing decision-making processes, and knowledge creation.**
   The value derived from geological information is at its highest when:
      i. **the cost of using the information is low i.e. a public-good service,**
      ii. **there are no constraints on the use of the information,**
      iii. **decision-makers can act, at the right time, in response to learnings from the information. Particularly at the outset of a project where major decisions are made (e.g. route alignments)**
      iv. **the cost of making a wrong decision is high**

   - approximately 50 000 onshore boreholes are downloaded each month from the BGS GeoIndex open data portal (BGS Impact case study 2013). There are nearly 200 000 borehole scans available for the urban centres in the UK, of which only 29% of these boreholes have been digitised for stratigraphy in England, in Wales 44% have been digitised, while in Scotland it is 66%
   - access to subsurface data in the Netherlands via the 'BRO' register is expected to deliver significant benefits for the early stages of projects and could enable a reduction in subsurface-related failures of 2-5%. The projected net present value of BRO was estimated to be about €80 million in 2019 and rising to €130 million from 2028 onwards (Gates et al., 2021)

4. **Transport and linear infrastructure projects require high resolution geological data, and more so than most other construction projects. As such there is demand for value-added (income generating services) via data products or bespoke 3D geological modelling services.**

   - over a 3-year period (between 2017-2020), infrastructure/transport/construction licenses accounted for 58% (£2.52 million) of all data licences, which was by far the largest proportion of all licences paid by sector. The BGS Civils and BGS Geosure datasets are the two most licensed thematic, data products by this sector, alongside traditional geological maps (1:10 000 scale)
   - use of 3D urban geology models and pre-existing geological borehole records is estimated to lead to at least a 10% efficiency saving in drilling for GI
   - the cost of 3D modelling in central London was estimated to be one tenth of the cost of additional GI (Aldiss et al 2012)

5. **There is substantial cross-industry support for improved data sharing and digital systems to enhance the value derived from geological data and information.**

   - the Geospatial Commission's (GC) 'Call for Evidence' appeals for improvements in linked environment-built modelling; transitioning to 3D datasets and data systems; improving data accuracy and data standards, and; geospatial upskilling.
   - an Infrastructure and Projects Authority (IPA)-GC-BGS cross-industry engagement workshop identified the following areas to enhance the value of GI data:
      - raise data confidence levels.
      - engage financial and legal representatives to facilitate the principles of data sharing and address any privacy or security concerns
      - implement and enforce contractual obligations for data-sharing
      - provide incentives for, or demonstrate the value of, developers submitting GI data

    - communicate whether it is fit for purpose
    - embed conversations on GI data sharing in wider government open data policy and construction policy and technology e.g. Building Information Models
- mechanisms that enable data to be combined with expert knowledge are key to successful transport and linear infrastructure projects
- harnessing the convergence of technologies, data sharing initiatives, and gathering data intelligence from different sectors will be the key advancement for transport and linear infrastructure

As described above, better sharing of geoscience data and in particular GI data, and the application and conveying of the knowledge from these types of data is directly relevant to national initiatives for transport and linear infrastructure projects such as the Union Connectivity Review and Project Speed.

The BGS has long been the custodian, thought leader and knowledge broker for geological data either through research and development (reports/papers/presentations), informatics (value added open source or licensed data), or through bespoke commissions whereby regional knowledge is applied at national to local scales. This report summarises the BGS development of data and knowledge for transport and linear infrastructure projects and how it aligns with the national initiatives mentioned. The report contains the following:

- an overview challenges faced by transport and linear infrastructure projects in relation to geological and Ground Investigation (GI) data
- a description of the BGS data, services and technology of relevance for transport and linear infrastructure projects
- analysing which BGS data is primarily used by transport and linear infrastructure projects
- BGS case studies of transport and linear infrastructure projects, including a description of the project, the challenges involved, the role that BGS played and the short and long-term benefits
- looking at the case for future intervention and potential advancements in this area

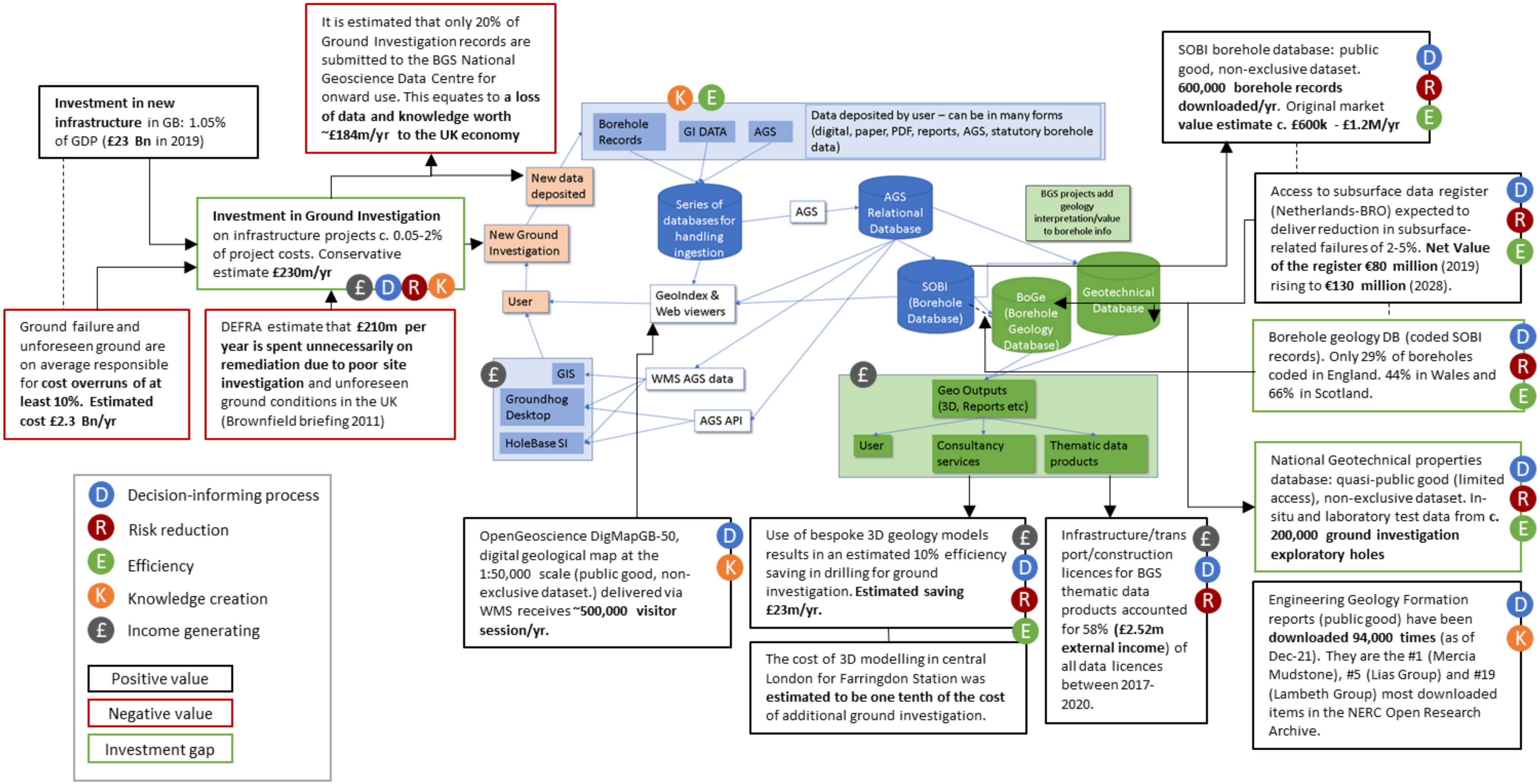

Figure 1. Schematic summary highlighting the value of geological and geotechnical data to the infrastructure sector. BGS © UKRI 2021

1 Introduction

As of 2022, there are currently several major projects under development that primarily involve transport and linear infrastructure across the UK including:

- HS2 – a multi-phased high-speed rail development spanning from London to Birmingham and Manchester. For more information, see https://www.hs2.org.uk/;
- Lower Thames Crossing – Major road and tunnel development for east London region. For more information, see https://nationalhighways.co.uk/our-work/lower-thames-crossing/;
- CrossRail 2 - Underground development for London. For more information, see https://crossrail2.co.uk/;
- Oxford-Cambridge Arc – a multi-development of the transport arc between Cambridge and Oxford including road and rail. For more information, see https://placebuilder.io/futureofthearc# & https://www.gov.uk/government/publications/oxford-cambridge-arc/oxford-cambridge-arc.

A wider review of transport and linear infrastructure across the UK was undertaken by the UK Government which was called the 'Union Connectivity Review'. The objectives of this was to assess current transport connectivity within and between the nations of the UK and to make recommendations that will maximise economic potential and improve quality of life (Union Connectivity Review – Final Report – November 2021). The review intended to deliver a series of substantive recommendations that seek to address inequalities in connectivity and economic potential in England, Scotland, Wales, and Northern Ireland. A key emerging recommendation from the Union Connectivity Review was the possible development of a new UK Strategic Transport Network – UKNET, which would be a strategic transport network for the whole of the United Kingdom, with the commitment of funding to improve the network, particularly parts that are not performing well. This would build on the top-down assessment approach taken to define the Trans-European Transport Network devised to support the European Single Market through improved connectivity and the closure of gaps in existing cross-border transport networks.

The development of a UK equivalent could support better assessment of transport routes and investment decisions, better management of the flow of people and goods between nations and improved partnership working between the UK government and devolved administrations. Two recommendations through the Union Connectivity Review are:

- plan improvements to the network using multimodal corridors, which should be reviewed regularly and appraised on a wider economic basis to support government objectives such as Levelling Up, Build Back Better and Net Zero;
- and gather data on a UK wide basis to support decision making relating to the network.

The Union Connectivity Review also identified the need for UK-wide data sharing to support improved transport planning and operations. Alongside this, a complementary initiative called Project Speed was also set up by the UK government in February 2021. The framework for Project Speed is made up of three accelerators:

- streamline governance and decision making (early sight of geological data and contextual information to help analyse and make early often important decisions concerning the construction)
- speed up planning decisions (display and visualise geological data in context with other data such as built environment data)
- design a variety of options (for scenario development, cost-benefit analysis and assessment of risk, e.g. geohazards)

This shows that there is an ongoing need for value added geoscience data and knowledge across the UK for transport and linear infrastructure projects. These types of projects tend to be complex, multi-disciplinary and involve and connect many partners and stakeholders throughout the construction lifecycle and beyond. These projects have the added complexity that they go under, through and over a wide range of natural environments (geological soil and bedrock, artificial ground or water courses) and artificial assets (buildings, utilities, road and rail networks). For both the natural environment and artificial assets, unforeseen ground conditions are a particular issue. To address this, particularly in the natural subsurface environment, observational data and information are combined with conceptual knowledge to produce a ground model of the reality as early as possible in the project timeline (preferably at the outset of a project) to predict conditions, and inform decision-making, ahead of investigation, design and construction. The model should be updated periodically with new findings, including 'as encountered' ground conditions. An overview of engineering geology ground models is provided by Parry et al., (2004).

In major transport and linear infrastructure projects (i.e. those projects arranged along a corridor between two or more places, e.g. HS2) the geology can significantly vary horizontally and vertically along any given route. As opposed to a single site (e.g. a large high-rise building) where you are you dealing with geological complexity over a limited spatial area, transport and linear infrastructure projects will have multiple geological relationships to deal with including transitioning between different types of geology (e.g. superficial deposits to bedrock), multiple geological structures (e.g. faults and folds), geohazards such as scour hollows, karstic environments, compressible ground, and the hydrogeological, geotechnical and geochemical considerations for the construction and management of the infrastructure asset over its lifecycle. Using the geology of London as an example, Lee and Graham (2020) summarised many specific civil engineering challenges associated with the different geology types, and appended to this the BGS data and services available to help mitigate against these issues (**Appendix 1**). For example, faulting is highlighted as a particular hazard to civil engineering projects. Faulting can cause significant spatial variations in geotechnical properties such that simple lithological models cannot confidently be used to inform the ground model (Royse et al., 2012). In terms of specific civil engineering challenges, faults can radically alter localised groundwater flows which can cause problems during dewatering.

Ground condition issues can be further complicated in areas where the subsurface has already been developed (e.g. CrossRail – London), and where significant thicknesses of artificially modified ground can cause unforeseen issues due to their variable nature, and physical obstructions such as basement facilities, utilities and existing tunnels cause logistical issues such as access. Data and knowledge are key for minimising the impact of unforeseen ground conditions, and this report highlights the role that the BGS, as a national geological survey organisation, plays in providing both data and knowledge, and also how the long-term management and re-purposing of data deposited at the BGS can be of use to all in the future.

In addition to the challenges associated with ground conditions, predicted environmental changes (e.g. urban heating, sea-level rise, increased frequency of extreme weather events) pose a significant threat to transport and linear infrastructure assets. The Intergovernmental Panel for Climate Change has stated with a high degree of confidence, that global climate warming is likely to reach 1.5˚C between 2030 and 2052 if warming continues at current rates (International Panel for Climate Change, 2018). An independent report, commissioned by the London Assembly and published in 2019 (Russell, 2019), identified five key climatic 'risks' related to climate-driven hazards interacting with the urban environment: (1) hotter, drier, summers; (2) milder, wetter winters; (3) changing rainfall patterns with more abrupt rainfall events; (4) more frequent extremes in weather that are either prolonged or severe; and (5) sea-level rise with potential for an increased frequency of North Sea storm surges. These risks are likely to significantly impact transport and linear infrastructure (Russell, 2019). Russell (2019) outlined the potential impact of climate change on transport infrastructure in London:

- 50% of central London underground stations are at risk from a 1 in 30-year surface flood event
- 125km (11%) of roads are at risk from a 1 in 30-year surface flood event

The BGS has undertaken studies in these areas (Harrison 2010 and 2012), looking at the impact of climate change on the different geological domains that will be affected by these (e.g. shrinking and swelling of the London Clay Formation), and have created a number of free and commercial datasets to help predict the effects of climate change to mitigate against the impact on transport and linear infrastructure and transport (e.g. the BGS GeoClimate: shrink–swell national datasets).

Understanding where there could be an increased risk of subsidence means suitable engineered structures can be put into place to cope with this risk.

Further datasets that are useful for informing the potential susceptibility of linear infrastructure and transport assets to geohazards are discussed and listed in **Section 3**.

There are a number of reasons why transport and linear infrastructure projects are important to UK communities, not least the many economic and social value issues that can be addressed. The use and re-use of data has been highlighted in several of the United Nations Sustainable Development Goals – SDGs (Paris Accord COP21), which are directly linked to ground engineering and construction. These encompass the pressing issues of sustainability, to be addressed holistically on the social, environmental and economic fronts. Delivery of sustainable infrastructure does not just underpin SDG 9: industry, innovation and infrastructure but is also a critical component of many other SDGs including:

- SDG 6: clean water and sanitation;
- SDG 7: affordable and clean energy;
- SDG 11: sustainable cities and communities;
- SDG 12: responsible consumption and production;
- and SDG 13: climate action.

This shows that the engineering and construction industry are a key partner in the global effort to achieve the SDGs by developing sustainable infrastructure projects, especially in developing countries (Fei, 2021; Lagesse et al., 2022). The SDGs highlight the impact that transport and linear infrastructure projects and indirectly the data and information generated can have on the wider social value on the communities that they effect. Fei (2020) suggests that governments across the globe should use the construction industry as drivers in developing the right policies and regulations. Construction organisations should collaborate with government agencies, industry peers and policymakers to integrate the SDGs into long-term business strategies, while the construction industry can contribute to the realisation of all the SDGs.

This is supported by Dobson et al., (2020), who states that transport and linear infrastructure projects can help address local socio-economic issues and inequalities; create jobs for previously unemployed people; provide opportunities for Small and Medium Enterprises (SMEs); and ultimately increase the quality of life of people involved in, or impacted by, an infrastructure project. Therefore, the benefits that an infrastructure project can generate are not limited to the basic physical function of an asset such as an aqueduct or motorway. This is highlighted by the Thames Tideway Tunnel project, a 25 km super sewer through London to protect the River Thames from sewerage contamination. A range of initiatives to improve the social and financial value of the project were realised which included:

- engagements with charities and volunteers to improving awareness on the impact that humans have on the River Thames by 95%
- employment opportunities and initiatives for SMEs and apprenticeships from wide ranging backgrounds including those with convictions
- and environmental considerations - transporting tunnel spoil by rivers rather than roads avoiding 200,000 two-way HGV movements

Subsequent sections of this report aim to build an evaluation of the benefits of geological data and information, targeted to the transport and linear infrastructure sector. Considering both the cost of inadequate geological appraisal and the value of geological data and services the report contains the following sections:

Section 2: An overview challenges faced by transport and linear infrastructure projects in relation to geological and Ground Investigation (GI) data

Section 3 and 4: An overview of the BGS data, services and technology of relevance for transport and linear infrastructure projects

Section 5: Analysing which BGS data is primarily used by transport and linear infrastructure projects.

Section 6: BGS case studies of transport and linear infrastructure projects, including a description of the project, the challenges involved, the role that BGS played and the short and long-term benefits

Section 7: Looking at the case for future intervention

2 An overview challenges faced by transport and linear infrastructure projects in relation to geological and ground investigation data

GI often takes up a large component of time on a project but only makes up about 0.05 – 0.2% for buildings, 0.2% – 1.5% for roads/rail and 1% for dams of the total cost of the project (UKessays 2018), and even less if the lifetime building costs are considered (Gates et al., 2021). However, the benefits are rarely appreciated, or quantifiable, unless the data and information are found to be deficient. This is especially so when unforeseen ground conditions are encountered, or major failures occur, such as the Cologne Archive collapse due to underground metro construction (Fuchs, 2014), and Glendoe tunnel collapse (Hencher, 2019) – see **Section 6.1**. In both cases, further GI including desk-based study would have reduced the risk of these collapses occurring, saving lives in the case of the Cologne Archive tunnel collapse, and many millions of euro and significant programme overruns for both.

Barron, (2011) suggest that 30%-50% of projects experience delays due to unforeseen ground conditions while Chapman (2012) concluded that *significant delays* due to ground conditions probably occur in 17-20% of UK Projects. Industry reports ground problems that result in:

- 50% over-run (greater than 1 month)
- costly resolution, claims and litigation
- increased project risk & overspend
- increased investigations for unforeseen ground conditions

The exact costs associated with these problems are difficult to ascertain, but with respect to development of brownfield land DEFRA estimate that £210m per year is spent unnecessarily on remediation due to poor GI and unforeseen ground conditions in the UK (Brownfield Briefing, Anon, 2011). The following sections provide more detail on the costs and delays associated with building and construction of which transport and linear infrastructure is a major component.

2.1 SOCIO-ECONOMIC IMPACTS OF THE INFRASTRUCTURE INVESTMENT GAP

'Without the necessary infrastructure—from transport systems to electricity grids and water pipelines—economies cannot meet their full growth potential and economic and human development suffers… failure to meet infrastructure needs will stifle growth in GDP and employment' (Dobbs et al., 2013)

In 2013 the McKinsey Global Institute estimated that at least $3.2 trillion per year of investment was required globally up to 2030 to maintain current infrastructure levels with expected growth: 60% more than had been spent in the previous 18 years, and equivalent to 3.5% of anticipated global GDP. Furthermore, these costs did not account for the additional investment required to make infrastructure more resilient to the effects of climate change or higher building costs required to lessen the impact of construction on the climate and environment (Dobbs et al., 2013).

Between 2013 and 2019 the proportion of GDP spent on new infrastructure in Great Britain increased by ~30% from 0.8% to 1.05% of GDP; a total of £23 billion in 2019 (ONS, 2021a). This however, is significantly less than the proportions of both total and additional investment (relative to global GDP) that the McKinsey Global Institute estimate are required to maintain parity; it is also significantly less than the EU average of 2.6% per year (Dobbs et al., 2013), and less than the UK average growth in GDP of 1.9% during that period (ONS, 2021b). The value of the UK's existing infrastructure assets is also lagging behind many other developed and developing economies, including India, China, South Africa, Poland Spain, Italy, Germany, Canada, the US and Japan (Dobbs et al., 2013). This historic low-level of investment in infrastructure was recognised by the 2018 National Infrastructure Assessment, which concluded that '*much of the country's infrastructure has not kept pace with population growth, demand and advances in technology. The UK must [start] running to stand still*' (NIC, 2018).

Despite the UK government recognising the findings of the 2018 National Infrastructure Assessment, and developing a thirty-year National Infrastructure Strategy, the National

Infrastructure Commission's fiscal remit is set to be maintained between 1.1 and 1.2% of GDP for at least the next year to address spending deficits caused by the Covid-19 pandemic (HM Treasury, 2020). The prospect of this proportion of spend increasing in future is further hindered by increasing national debt, which was more than 100% of GDP at the end of January 2021 (ONS, 2021c), well above the reference value of 60% set out in the protocol on the excessive deficit procedure within the Maastricht Treaty (ONS, 2014). There is therefore a substantial risk within the UK that a lack of infrastructure funding will have a detrimental effect on social and economic growth unless alternative mechanisms are sought to reduce the infrastructure gap.

2.2 ADDRESSING THE INFRASTRUCTURE GAP WITH GEOLOGICAL INFORMATION

The challenge of increasing infrastructure spending when there is pressure to reduce national spending is a global problem, and one that the McKinsey Global Institute concludes is best addressed by increasing productivity within the construction sector by up to 60%. Dobbs et al., (2013) propose that this can be achieved by: i) making better choices about projects to execute; ii) enhancing project delivery; and iii) making existing infrastructure more efficient. While not the sole solution to increasing productivity within the construction sector, geological data and information can, and in many cases already does, make a significant contribution to enabling and enhancing decision-making throughout the whole lifecycle of construction projects. However, it is arguably in the initial stages of the project lifecycle, during feasibility and design, where geological data and information can be of greatest value. It is also in this early stage of the project cycle where there is the greatest potential to reduce overall project costs.

Globally construction projects across all infrastructure classes are plagued by time and cost overruns (Chapman 2012; Gates et al., 2021). For example:

- Barbosa et al. (2017) found that large projects typically take 20% longer to finish than scheduled, and are up to 80% percent over budget
- a survey of 106 projects found that 69% of construction projects were more than 10% of their original budget (KPGM, 2015)
- Van Staveren (2006) estimates the cost of project failure to be 5-13% of annual €70Bn construction expenditure in the Netherlands
- Wannick (2006) identifies 14 major tunnel failures between 1994 and 2003 that resulted in $600 million in losses, with repair costs exceeding the original construction costs.
- Flyvjberg et al., (2003) found that cost overruns in 258 megaprojects (projects >$1Bn), averaged 45%, 34% and 20% for rail, bridges and tunnel, and road projects respectively, with an average across all classes of 28%; cost over runs also occurred in 90% of projects.
- the National Audit Office (2001) reported that 73% of public construction projects were delivered late
- a study of 71 hydroelectric power projects around the world by Hoek and Palmieri (1998) found the average cost to be 27% higher than originally estimated and took on average 28% longer than estimated to be complete

Within the UK this tendency for project cost and programme escalation was so great that explicit adjustments for 'optimism bias' were introduced to 'The Green Book' in 2003 to address systematic underestimation of costs and programme and the overestimation of benefits (Mott MacDonald 2002; HM Treasury, 2003; Flyvjberg, 2014).

Although a myriad of political, economic, legal, technical and environmental factors have been identified as contributing to cost and time overruns (Mott MacDonald; HM Treasury, 2003; Flyvjberg et al., 2003; Creedy et al., 2010; Flyvjberg, 2014), there is ample evidence to demonstrate that unforeseen ground conditions and ground failure (i.e. a lack of true understanding of the ground and it's properties) are significant contributory factors, and do not appear to have diminished over time (Littlejohn et al., 1994; Fookes, 1997; Chapman, 2012).

2.3 THE COST OF UNFORESEEN GROUND CONDITIONS

The interconnected nature of many of the factors identified as causing time and cost overruns means that if can be difficult to identify and isolate specific causes (Flyvjberg et al., 2003; Creedy et al., 2010; Flyvjberg 2014). In the case of unforeseen ground conditions this can be particularly challenging because it can affect programme, design, and final performance, and is also frequently cause for litigation. Several studies of a range of different construction project and activities do however suggest that ground failure and unforeseen ground are on average responsible for cost overruns of at least 10%. For example:

- a review of 5000 industrial building projects in the UK in 1983 found that 50% overran; a representative sample of these found that 37% of these (19% total) were attributed to ground problems (NEDO, 1983)
- a review of 8000 commercial building projects in 1988 found that 66% of projects overran; a representative sample of these found that 50% of these (33% total) were attributed to unforeseen ground conditions (NEDO, 1988)
- a study of ten UK highway construction projects found final costs on average to be 35% above the tender sum, and in half of these inadequate GI or GI interpretation was identified as a cause (Littlejohn et al., 1994)
- an assessment of 87 projects by the United States National Committee on Tunnelling Technology found that claims for unforeseen ground conditions occurred in 60% of projects, resulting in overall 12% cost increase (Gould, 1995)
- Brandl (2004) found that 80-85% of all building failures and damages are related to ground conditions
- Chapman and Marcetteau (2004) found that 33% of UK construction projects are significantly delayed, and 50% of those delays are caused by problems in the ground.
- the Dutch Piling Federation assess their own failure costs to be 10% of their turnover (Van Staveren, 2006)

It is also important to note that for many of the studies cited, the cost of unforeseen ground conditions and ground failure will only relate to the cost of design alteration and delay in construction works and will not include any additional legal costs associated with deciding who will pay for the additional works due. Furthermore, as the burden of additional costs frequently falls upon the contractor, the full cost of unforeseen ground conditions may also not be included as a cost overrun unless the project owner also shares the burden of additional costs. It is therefore reasonable to assume that the overall cost of unforeseen ground conditions and ground failure may be significantly higher than 10%.

2.4 CALCULATING THE VALUE OF GEOLOGICAL INFORMATION FOR INFRASTRUCTURE PROJECTS

Häggquist and Söderholm (2015) in their review of the economic value of geological information highlight that whilst calculating the cost of obtaining geological data and information is relatively straight forward, understanding the benefits or value of geological data is less tangible. The authors make an important observation that much geological data and information is collected and maintained by national government-funded geological survey organisations. Geological information is generated and enhanced by strategic investment, the value of the data and information accrues with time over the longer-term, it is not projectized and subject to formal economic cases or cost-benefit analysis as is routine for national infrastructure projects. Calculating the value of geological information is further complicated as it does not have a traditional market value, data and information are often provided as a public good service and is non-rivalry in nature. This means that the information can be (re)used multiple times by multiple users, often without charge.

In the Netherlands, new legislation (2015) mandated that subsurface data acquired with public funds (e.g. for national infrastructure) had to be submitted into a central repository 'Basisregistratie Ondergrond' (BRO) and all public bodies must consult the 'BRO' when making decisions that impact the subsurface. The investment in the BRO was subject to a societal cost-benefit analysis and in-depth financial analysis. It concluded that BRO would deliver significant benefits for the early stages of projects and could enable a reduction in subsurface-related failures of 2-5% (Gates et al., 2021). The projected net present value of BRO was estimated to be about €80 million in 2019 and rising to €130 million from 2028 onwards (Gates et al., 2021). These benefits were considered to be an underestimate since only national-scale infrastructure investment was considered.

Depending on the operating model of government-funded geological survey organisations three dimensions of geological information value can be described:

- non-rivalry / non-exclusive value: data can be (re)used multiple times by multiple users, the value of data does not diminish significantly with time and data-use is not subject to restrictions. It is a public good asset but not readily assessed against economic markets. Examples include, borehole records (non-digitised) and geological maps
- quasi-public good: geological data is collected and analysed by national government-funded geological survey organisations, or third-party organisations but its use and/or value is restricted by licensing, IPR, accessibility, usability, interoperability, user-expertise
- income generation: geological data and information is used for the purpose of securing direct and indirect income. Geological expertise is used to provide value-added data services, examples include, 3D geological model development, data products e.g. engineering conditions, and geo-reports. The income may be generated directly by the geological survey organisation or by third-parties. The income value is restricted by the user's willingness-to-pay and the availability of competing, alternative products and services provided by other organisations

Whilst the range of benefits delivered by geological information is varied, there are a number of over-arching ways in which the value or benefit is realised. These are outlined below and also characterised for the case studies presented in **Section 6**.

- **Decision-informing process**: Decisions are made and action is taken in response to the geological information that is available. For transport and linear infrastructure this might include for example, decisions about the routing of the infrastructure network, design of monitoring networks, design of the road or tunnel, or selection of tools for the tunnel boring machine. Aldiss (2012) reported an estimated cost-saving of £90,000 by providing access to a 3D geology model for central London and therefore reducing the need for targeted boreholes to a third of the original estimate. The benefits of 3D geology models to refine drilling during GI was also report in Gates et al., (2021), noting a reduction in GI boreholes of around 10%.
- **Risk reduction**: The availability of geological information reduces uncertainty with respect to ground conditions and likely occurrence of geological hazards. This might be expected to lead to safer construction, reduced liability, reduced need for additional surveys, reduced disruption to project delivery.
- **Efficiency**: Efficiency benefits go hand-in-hand with decision-informing benefits and risk reduction, the accumulation being an anticipated saving in time and costs. These benefits might be realised through a reduced need for additional surveys or remedial measures but efficiencies could equally be realised from improved access to digital geological data outputs. For example, having access to boreholes that have already been digitised by a geologist. Significant savings are reported by Gates et al., (2021), where the project 3D geological model has allowed live updates to the conceptual ground model and decisions about the design of new or relocated boreholes to be made in near-real time.
- **Knowledge-creation**: The process of collecting geological information and completing geological assessments for construction and infrastructure projects, generates new geological knowledge and enhances the geologist's skills and experience. These benefits are maximised when the geological knowledge is collected for new locations and where the data and skills are retained or transferred to enable future use (Gates et al., 2021).

Häggquist and Söderholm (2015) note that the value derived from geological information is at its highest when:

(i) the cost of using the information is low (public-good service),
(ii) there are no constraints on the use of the information (non-exclusive; FAIR-compliant - Findable, Accessible, Interoperable and Reusable),

(iii) decision-makers can act, at the right time, in response to learnings from the information, (e.g. to inform design of transport infrastructure),

(iv) the cost of making a wrong decision is high (e.g. risk of tunnel collapse, subsidence, karst amongst others)

It is further observed by MacLeamy (2004) that the value of geological data is highest at the outset of a project when the cost implications of design change are lowest and potential for efficiency savings are highest.

Calculating the total or true value of the geological information and data to infrastructure projects is a near impossible task because geology can contribute to decision making and risk mitigation throughout the whole lifecycle of a construction project. It may contribute to design or risk mitigation that ultimately ensures that a project is technically and financially viable, and therefore completed in the first instance. During operation it may inform the protection, maintenance and upgrade of infrastructure, and thus ensures the continued use of the asset. In both cases, the value of the geological data and information will often go unnoticed as it has essentially ensured that the project is either completed as planned, or continues to operate as intended. Paradoxically the value of geological information and data is often only apparent when it is lacking and results in cost or time overruns.

In crude terms an attempt can be made to calculate the value by first estimating the cost of acquiring geological data and information during GI. The cost of GI varies significantly between projects, ranging from between approximately 0.05 and 5% of the total project cost, but it is typically between 0.1 to 2% (Rowe, 1972; Fookes, 1997; Waltham, 2003). Given that that cost of GI for infrastructure projects is typically higher than for buildings (Rowe, 1972), then a value of 1% of total project costs would be reasonably conservative estimate. The total value of new construction work in GB in 2019 was £119 billion, with £23 billion spent on infrastructure (ONS, 2021a) then a conservative estimate of the annual cost of acquiring geological data and information for infrastructure alone would be £230 million per year. The value of the data and information to infrastructure is though far greater than this but, for the reasons outlined above, is nearly impossible to calculate. It is also worth adding that despite this estimated investment of £230 million per year in GI, it is still not enough to address geoscience knowledge and data deficits that result in unforeseen ground conditions and ground failure. The value of geological data and information therefore has the potential to be significantly greater if in GI investment was increased and sharing of legacy data was increased or became mandatory requirement. Increasing the investment in GI is unlikely to happen soon, however, sharing and re-suing of GI data could offset these costs significantly.

Based on the range of values provided for cost overruns and, where these have been calculated, the proportion of the overruns that have been attributed to ground conditions, it would seem reasonable to make a conservative estimate that overall cost of failure due to ground conditions in UK to be about 10% of annual construction spend. If the total value of new infrastructure and construction projects in the UK is estimated at £23 billion, then a conservative estimate of the additional potential value of geological data and information would be £2.3 billion per year, ten times the amount that is currently spent on GI.

Furthermore, reducing the overall cost of infrastructure construction by this amount would also make a significant impact on addressing the infrastructure gap, which is critical to maintaining our current rates of economic and social growth. Therefore geological data and information is not just of high value, but is in fact a critical component off all progressive social and environmental endeavours.

3 BGS data and services for transport and linear infrastructure projects

Data and knowledge about the data is a key component of the BGS mission, which is to provide impartial and independent geoscience advice and data. The BGS is the custodian of over one million boreholes in GB and provides a sustainable borehole management system for the long-term storage and management for GI boreholes and ancillary data (e.g. geotechnical data). A key example is the use and re-use of GI borehole data by the BGS and how this can be up value added and multi-purposed. It is estimated that currently 80% of historic GI data is missing from BGS archives, based on an annual investment of £230m/y in GI this equates to a loss of data and knowledge to the UK economy of an estimated £184m/yr.

Not only is there the sustainable use of the data, the data and information associated can be re-purposed for many different projects. To raise the awareness of borehole re-use the BGS have initiated two projects, to improve the sharing of data where the BGS acts a sole repository for these.

Dig to Share (2018 - 2020) - a collaboration between the BGS, Atkins and Morgan Sindall to:

- unlock GI data.
- create a fully digital sustainable workflow accessible to the whole industry utilizing existing BGS systems
- identify blockers and facilitate solutions across the supply chain
- develop a “Super User” community around open data and create a self-perpetuating model for data sharing. There are currently 50 members of this network
- target of releasing borehole records as open AGS data – over 40 000 have been released to date (Dec-2021)

The 2nd project is the Big Borehole Dig (2020 onwards) – A BGS led citizen-science initiative to help improve the availability and accessibility of borehole data for all users. This is a continuation of the Dig to Share project. These activities aim to promote the sharing of data whereby the BGS can facilitate the sharing of the data using the online Deposited Data system through the National Geoscience Data Centre.

Alongside these initiatives, there are future working practices to ensure that the long-term use and re-use of data are safe guarded. Wilkinson et al., (2016) describes the FAIR Data Principles, whereby data is Findable, Accessible, Interoperable and Reusable, not only by individual users, but also enhancing the ability of machines to automatically find and deduce relationships in the data. These principles have been developed to incorporate ‘Quality’ so becoming Q-FAIR, ensuring data is fit-for-purpose, an approach being delivered by the Geospatial Commission in the UK (Irving, 2021), The BGS is part of the Geo6 within the Geospatial Commission, and is working with the other Geo6 partners (who are the Ordnance Survey, Coal Authority, HM Land Registry, UK Hydrographic Office and the Valuation Office Agency), to improve on the following:

- data discoverability – assessing and improving access to current data sets
- linked identifiers – supporting users to bring different data together in valuable new ways.
- licensing – working towards simple, common licensing terms to increase data use
- enhancing core data assets – using third party data to improve the quality of data and make its collection more efficient

This will be key to transport and linear infrastructure projects, reducing costs, improving lives and providing a sustainable long-term knowledge base from which to learn and apply in other sectors.

As the national custodian of geoscience data, the BGS holds a wealth of data and information that is useful for transport and linear infrastructure projects and practical applications which are highlighted in the following sections.

3.1 1:10 000 GEOLOGICAL MAPS (BGS GEOLOGY 10K)

The BGS has developed 1:10 000 scale map coverage of the geology for large parts of the GB, particularly for the major urban centres. The geological areas (or polygons) are labelled or attributed with a name based on their lithostratigraphic, chronostratigraphic or lithodemic nomenclature and their composition (rock type or lithology). This information is arranged in (up to) four themes as available:

- bedrock geology
- superficial deposits
- mass movement
- artificial ground
- faults and other linear features (available in a separate theme)

Geology maps are the foundation for many other types of earth science-related maps and are of potential use to a wide range of users, but for transport and linear infrastructure it provides the necessary resolution for these types of projects that require local detail. A map showing the distribution of the 1:10 000 geological maps is shown in **Figure 2**. Finer resolution is possible using 3D geological modelling techniques for areas rich with borehole data, e.g. Glasgow and London (see **Section 3.4**). The OpenGeoscience BGS Geology 50, digital geological map at the 1:50 000 scale delivered via Web Map Services receives >40 000 visitor sessions per month (BGS Impact Case study - 2013).

Figure 2. BGS 1:10 000 geological map coverage. BGS © UKRI 2021

3.2 BOREHOLE LOGS AND RECORDS

GeoIndex is a public-good, non-exclusive data portal, offering free (at point of access), direct, online access to the National Geoscience Data Centre's (NGDC) collection of over a million onshore scanned boreholes, shafts and well records.

https://www.bgs.ac.uk/map-viewers/geoindex-onshore/

Boreholes range from one centimetre to fifteen kilometres long. They have been drilled for a range of purposes. Most of the boreholes between 1 m and 50 m have been drilled for GI. Those that drill down to depth of several hundred metres below the surface were drilled for groundwater, mineral (including coal) and scientific reasons. Those boreholes deeper than a 1 km were mostly drilled for hydrocarbon protectivity. Borehole records are produced from a geologist's or surveyor's observations of the rock core extracted from the ground, or interpretation of geophysical logs, and typically include locality and lithological descriptions with depth and thickness. These often vary depending on the purpose that the borehole was drilled for and may use different and conflicting classification schemes. Geophysical logs may also be noted from on-site measurements.

Scans of the non-confidential borehole records can be accessed freely from the BGS Geoindex map viewer. Additionally, borehole records which have been digitally transcribed into the BGS held databases can also be licensed. Approximately 50 000 onshore boreholes are downloaded each month (BGS Impact case study - 2013).

Of the borehole records that the BGS hold, 197 969 boreholes are within urban centres. A large proportion of these borehole records have been interpreted (digitised) by the BGS, recording the litho-stratigraphic units down the borehole. These digitised boreholes form a quasi-public good dataset, available upon request and subject to licensing conditions. The extent to which these have been digitised varies considerable across towns and cities in the UK. In Glasgow the percentage of digitised boreholes is as high as 79%, Greater London 51%, Cardiff 46%, whereas for Birmingham it is 29%, Sheffield 12%, Newcastle 10%. In England only 29% of these boreholes have been stratigraphic digitised, in Wales 44% have been digitised, while in Scotland it is 66% (**Figure 3**).

There are two notable spikes in the number of boreholes digitised into the BGS BoreholeGeology database. The first in 2004 and 2005 was during the BGS Digital Geoscience Model Programme (DGSM), where there was concentrated effort of several geologists to interpret and digitise borehole data for the base of the superficial deposits to inform the BGS National Superficial thickness Model (Lawley and Garcia, 2009). The second spike in 2016, was where there was a mass ascension of several other databases into the BGS BoreholeGeology database. Alongside the geological map, digitised borehole data is a key dataset for understanding the relationships and geometries of the geological units in the subsurface particularly in urban centres where there is limited geological outcrop because of the veneer of artificially modified ground (e.g. tarmac, concrete, and foundations of buildings). 3D geological models are often the solution used to show the conceptual understanding of the geology in urban centres (described in more detail by Kearsey et al, 2021), and are directly applicable for transport and linear infrastructure projects as shown in the case studies (**Section 6**).

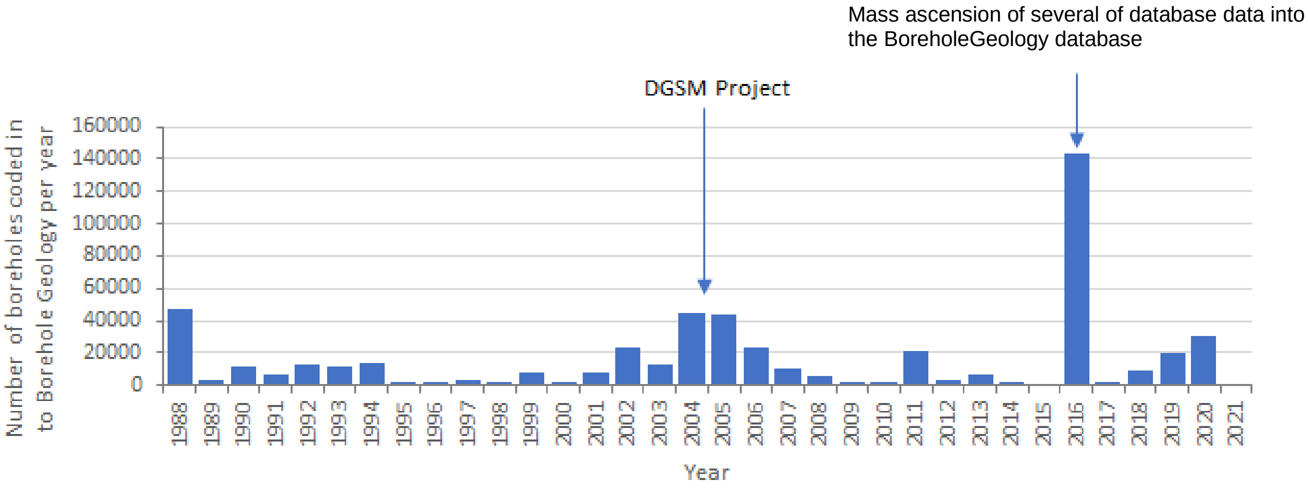

Figure 3. Number of borehole logs digitised into the BGS BoreholeGeology database – UK. BGS © UKRI 2021

3.3 BGS NATIONAL GEOTECHNICAL DATABASE

The BGS manages the national geotechnical database, also known as the National Geotechnical Properties Database (NGPD), which contains in situ and laboratory test data from approximately 200,000 GI exploratory holes from across the UK. Sources of these data include clients, contractors and consultants within the civil engineering sector, and data produced by the BGS in-house laboratories (described in more detail by Dobbs et al, 2021).

The database consists of 54 tables and 33 dictionary tables (Self et al., 2012), which contain a range of geotechnical, geological, hydrogeological, geochemistry and physical property data. The data are not uniformly distributed, but predominantly concentrated in urban areas and along infrastructure corridors. 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 infrastructure development projects in Great Britain.

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 the BGS into a valid BGS lexicon code (BGS, 2020) 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 lithostratigraphy code.

Within the BGS, the NGPD is used almost exclusively 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 BGS Geology maps, to inform the development of applied and thematic geology datasets, such as the BGS Civils and Geosure datasets. Outside of the BGS, the NGPD is currently used on an ad hoc basis by consultants and academics through the BGS enquires system. Non-parametric statistical data summaries are typically provided for the geological unit and properties of interest; occasionally non-confidential raw data are supplied to the enquirer in excel format. Geotechnical data summaries derived from the database, also form important components of four engineering geology reports for the Mercia Mudstone Group, Lias Formation, Lambeth Group and Gault Formation, which are used extensively by the civil engineering industry (see **Section 3.6.1**). The NGPD has significant potential to be further utilised on a more systematic basis as 'Big Indirect Dataset' (*c.f.* Phoon, 2020) to support the planning and interpretation of GI by the civil engineering industry.

3.4 3D GEOLOGICAL MODELS

3D geological models characterise the changes in depth of the rocks and soils in the subsurface, providing sophisticated insights for geological understanding. These models are increasingly being used to enable decision making and support advanced analysis for ground conditions, groundwater systems, resource assessments and subsurface storage.

A review of the economic case for the use of 3D geological models to characterise subsurface conditions is provided by Gates et al., 2021 but in summary the benefits of 3D geological modelling for infrastructure projects are as follows:

- early-identification of ground conditions, providing opportunities for risk reduction, preparation of competitive bids with reduced optimism bias, and more accurate Geotechnical Baseline Reports (GBRs)
- development of a shared digital conceptual ground model to maximise knowledge transference
- identification of data-poor areas allowing more targeted design of GI borehole drilling and sampling and reduced uncertainty. 10% reduction in borehole drilling estimated from existing projects
- near-real time updates to the conceptual ground model following GI, quick-time assessment of ground conditions for the design of additional or relocated drilling
- improved selection of construction methods, tool selection, earthworks planning and infrastructure design

The 3D geological models are available at scales ranging from regional (1:250 000) to local (1:10 000) and cover a range of urban areas, infrastructure corridors, catchments and geological basin areas. Gridded surfaces from the BGS LithoFrame models are available for licencing.

https://www.bgs.ac.uk/geology-projects/geology-3d/

Further to this, the BGS have released of set of Urban Interactive Models via the GeoIndex (Onshore) that present a range of options for the user to interrogate 3D geological model data using borehole, cross-section, and horizontal slice prognosis from the gridded outputs of the 3D geological model (**Figure 4**). These are primally aimed at pre-GI desk-based studies where the user can gain knowledge about the potential ground conditions and make decisions where best to target GI.

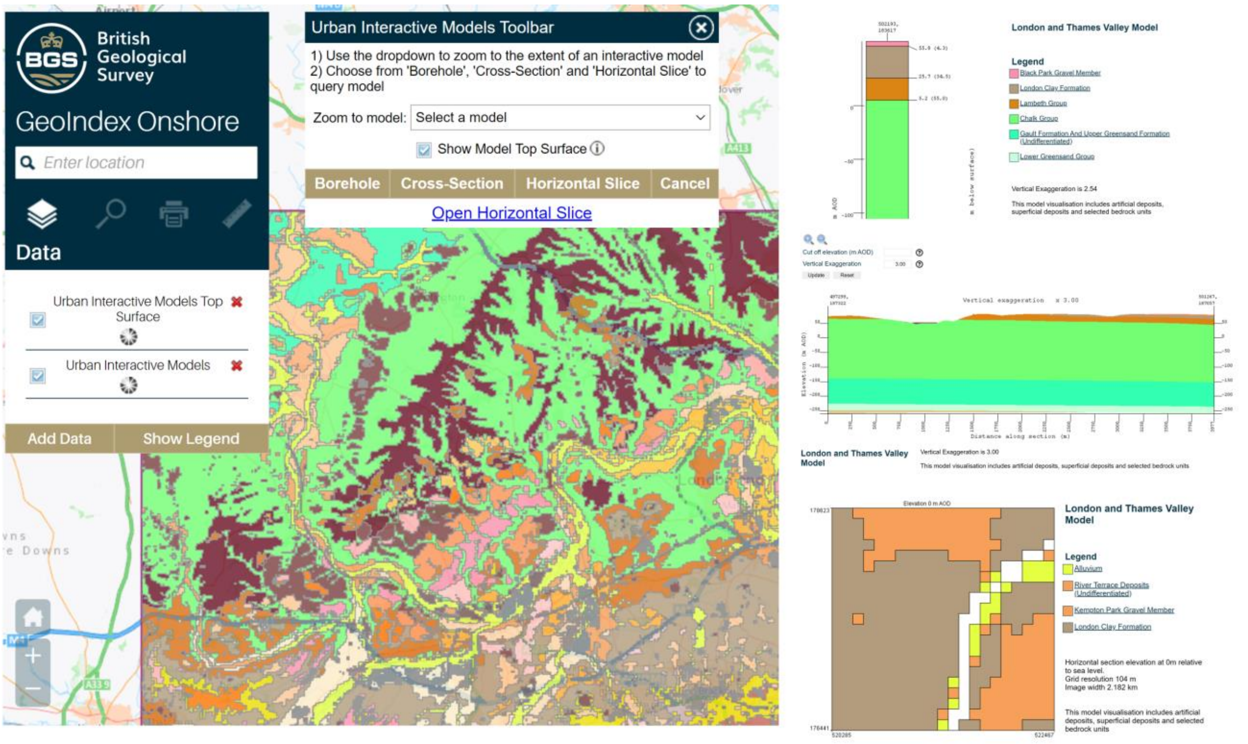

Figure 4. Urban 3D Models Tool – London. Contains OS data © Crown Copyright and database right 2020 and BGS © UKRI 2021

3.5 THEMATIC/DERIVED DATASETS

The BGS Civils dataset is a suite of national maps of engineering properties based on geological data and the digital BGS Geology 1:50 000 maps.

It comprises eight layers which are

- bulking volume
- corrosivity (ferrous)
- discontinuities
- engineered fill
- excavatability
- foundation conditions
- strength
- sulfate/sulfide

The primary goal of the product is to provide the key engineering characteristics of the geology of GB to professional users who need simple and rapid access to such information. The user of this data might be planning pipeline routes avoiding difficult ground conditions, calculating tender costs for trench excavation or you might need knowledge of ground properties in order to plan your daily activities.

Alongside the BGS Civils datasets, the BGS GeoSure national datasets provide geological information about potential ground movement or subsidence that can help planning decisions. BGS GeoSure data gives you information about:

- collapsible deposits
- compressible ground
- landslides
- running sand
- shrink–swell
- soluble rocks

The data is provided as GIS shapefiles that are available to licence individually or as a bundle to meet user own requirements.

3.6 BGS ENGINEERING EOLOGICAL STUDY SERIES

The BGS engineering geological study series provides domain characterisations and information on the distribution of geotechnical properties and the regional variation of these properties within particular geological formations across the UK.

These studies have assessed in detail the engineering geological characteristics, mineralogy, industrial applications, geological hazard potential, physical properties and behaviour of the formations.

All geotechnical data from these studies are stored in the National Geotechnical Properties Database (see **Section 3.3**). The work on the Mercia Mudstone and Lambeth groups complements reports published by the Construction Industry Research and Information Association (CIRIA). Three of these reports, for the Mercia Mudstone, Lias and Lambeth groups, are ranked respectively #1, #5 and #19 in NORA's most downloaded items and have a combined total of 94,000 downloads as of December 2021.

The BGS study series includes:

- Gault Formation
- Mercia Mudstone Group
- Lambeth Group
- Lias Group

3.6.1 References for the engineering geology formation reports

Lambeth Group:

ENTWISLE, D.C., HOBBS, P.R.N., NORTHMORE, K.J., JONES, L.D., ELLISON, R.A., CRIPPS, A.C., SKIPPER, J., SELF, S.J., & MEAKIN, J.L. 2005. Engineering geology of UK rocks and soils: Lambeth Group. British Geological Survey Internal Report IR/05/006

Gault Clay:

FORSTER, A., HOBBS, P.R.N., CRIPPS, A.C., ENTWISTLE, D.C., FENWICK, S.M., RAINES, M.R., HALLAM, J.R., JONES, L.D., SELF, S.J. & MEAKIN, J.L. 1994. Engineering geology of British rocks and soils: Gault Clay. British Geological Survey Internal Report, WN/94/31.

Lias Group:

HOBBS, P.R.N., ENTWISTLE, D.C., NORTHMORE, K.J., SUMBLER, M.G., JONES, L.D., KEMP, S.J., SELF, S.J., BARRON, M. & MEAKIN, J.L. 2005. The engineering geology of UK Rocks & Soils: The Lias Group. British Geological Survey Internal Report, IR/05/008, 137 pp.

Mercia Mudstone Group:

HOBBS, P.R.N., HALLAM, J.R., FORSTER, A., ENTWISTLE, D.C., JONES, L.D., CRIPPS, A.C., NORTHMORE, K.J., SELF, S.J. & MEAKIN, J.L. 2001. Engineering geology of British Rocks & Soils: Mudstones of the Mercia Mudstone Group. British Geological Survey Internal Report, RR/01/002, 106 pp

4 BGS software applications for use in transport and linear infrastructure

The BGS has developed a number of software applications that can be purposed for transport and linear infrastructure projects. Those that are most relevant have been described below.

4.1 BGS-SIGMA

System for Integrated Geoscience MApping (BGS·SIGMA); an integrated toolkit for digital geological data capture and mapping, which enables the assembly, capture, interrogation and visualisation of geological information as well as the delivery of digital products and services (**Figure 5** (Smith and Lawrie, 2017)). This can be used in conjunction with GIS based software such as ArcGIS Desktop and Pro, Groundhog Desktop and GeoVisionary to provide a full mapping and modelling solution in any environmental setting (Westhead et al, 2013).

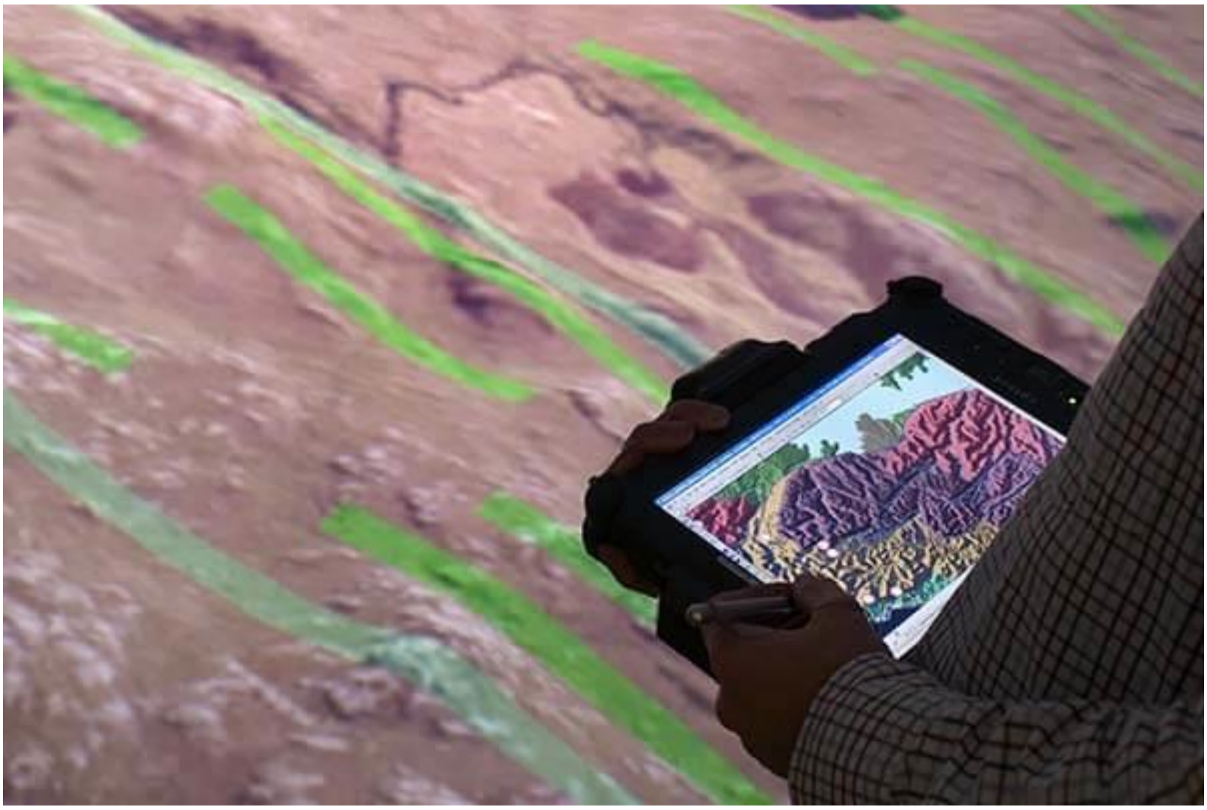

Figure 5. BGS·SIGMA operating with 3D visualisation software – GeoVisionary. BGS © UKRI 2021.

4.2 GEOVISIONARY

The BGS in collaboration with Virtalis have developed sophisticated 3D virtual reality visualisation software called GeoVisionary (**Figure 6**) which enables the user to visualise a plethora of data such as:

- historical geological maps and literature including information on coal seams, faults, dykes and joints
- boreholes – lithogical and geophysical either vertical and deviated. Includes lithostratigraphical interpretation
- existing 3D geological cross-sections and modelled surfaces/volumes including voxel models

- 2D and 3D geophysical surveys
- mapped data capture such as bedrock dips and strikes
- Parameterized volume models showing geotechnical and geophysical properties
- bathymetry/Terrain data - from high regional (0.25 cm) surveys to regional scale (100 m plus) surveys
- Earth observation data

Originally developed for virtual field mapping (e.g. landscape feature mapping and checking using high resolution terrain models), GeoVisionary has a wide range of applications such as for Virtual Field Reconnaissance which can be used to plan field work and do risk assessments, knowledge exchange through collaborative working by providing realistic visualisations of data including the terrain/bathymetry models, assets and all other types of geoscience data at its native resolution (Hughes et al, 2017).

GeoVisionary can also integrate CAD data of buildings and infrastructure, multiscale combinations of bathymetry/terrain data, animated movements of objects (e.g. vehicles), point clouds from terrestrial or airborne LiDAR (Light Detection and Ranging for high resolution ground measurement), and sensor data to provide real-time data. GeoVisionary has the capability to provide the visualisation functionality for Digital Twins/Environmental Digital Twins as it is able to visualise any type of data from the natural or built environment at its native resolution in 3D.

A number of tools have been developed to investigate the data held within GeoVisionary ad add digitisation or interpretation akin to the tools you find in a typical GIS and indeed these interpretations can be exported from GeoVisionary to GIS systems for further analysis. GeoVisionary has been used directly for linear infrastructure projects (Omar et al, 2020) and the advantages of having such a system is that the full lifecycle of the linear asset development from the GI, installation, management, decommissioning and post use of above and below ground space can be visualised and analysed in detail as a group. In summary these include:

- holistic approach to linear route assessment—being able to integrate all types of data formats into one environment for analysis and the communication to colleagues, partners and stakeholders
- planning—exploration of different route options for optimisation of cost/risk
- management—risk assessment scenarios using GPS tracking on vehicles and sensor networks to provide continual environmental monitoring, e.g. groundwater levels, flood risks and landslide hazards

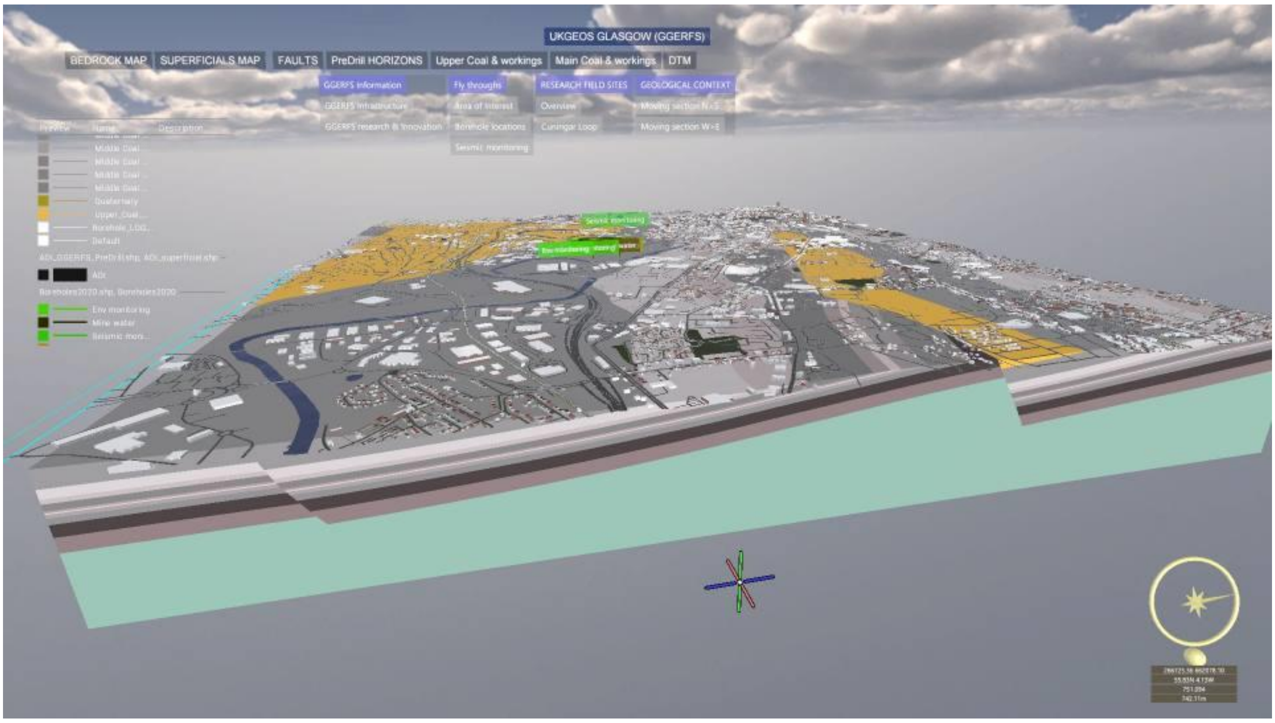

Figure 6. GeoVisionary - Glasgow UK GeoObservatory - Image from GeoVisionary. BGS © UKRI 2021.

4.3 GROUNDHOG DESKTOP

Groundhog Desktop is a software tool developed and made available by the BGS and used for geological data interpretation and 3D geological modelling. During 2022, all functionally will be provided as an Open software. Groundhog Desktop is a key part of the BGS's work to develop 3D models of the UK subsurface. The software has been designed with the shallow subsurface in mind from conceptual site models (CSM) to geotechnical investigation.

https://www.bgs.ac.uk/technologies/software/groundhog/

BGS Groundhog Desktop has been used directly to construct 3D geological models for urban environments and transport and linear infrastructure projects (see **Section 6.4** – Lower Thames Crossing). There are a number of tools available within BGS Groundhog Desktop that are useful for primary surveys for transport and linear infrastructure projects. These include:

- interpretation and presentation of borehole data
- generation cross-sections using simple drawing tools
- geological map drawing
- visualisation objects in 3D space such as boreholes and cross-sections (**Figure 7**)
- graphical object integration and scenario based conceptual site models
- build 3D geological models (**Figure 8**) using a variety of data and 3D model rules (e.g. thickness ranges), for superficial deposits and simple bedrock stratigraphic contacts

The BGS Groundhog Desktop software can be used with other sophisticated modelling software to construct complex 3D geological engineering models (Ojala et al., 2021).

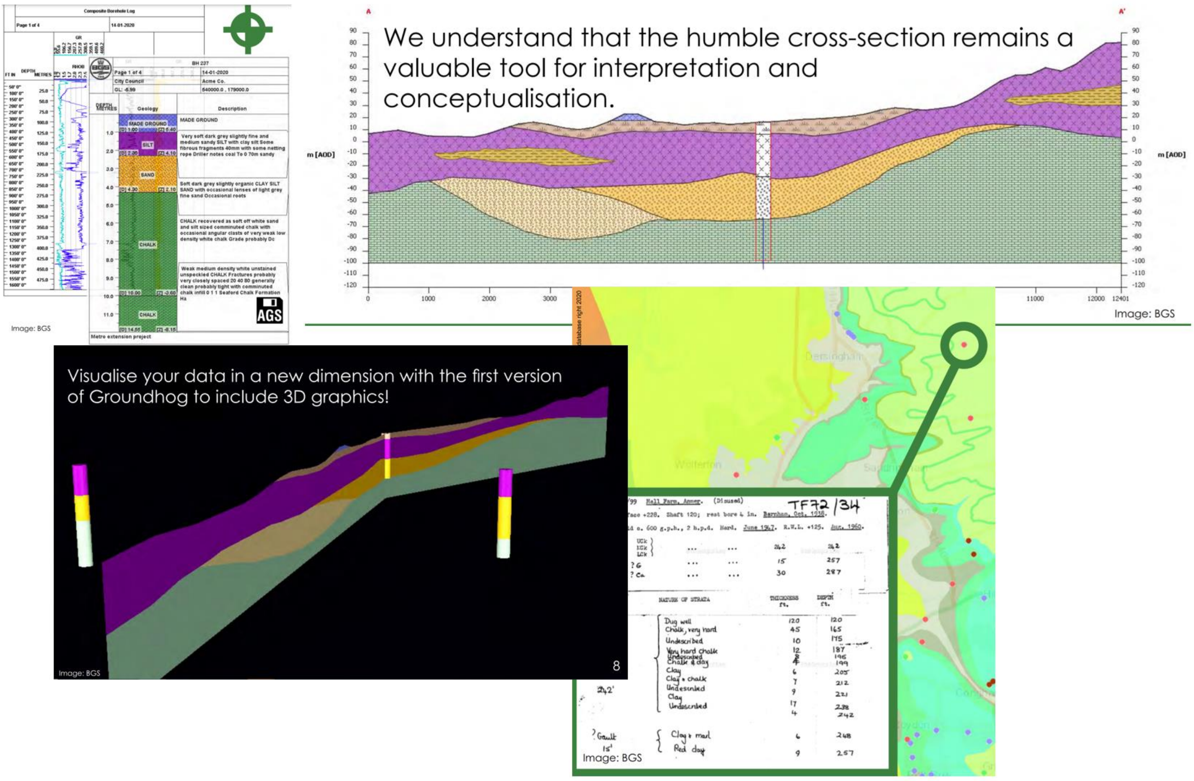

Figure 7. Groundhog Desktop – cross-section and borehole visualisation. BGS © UKRI 2021

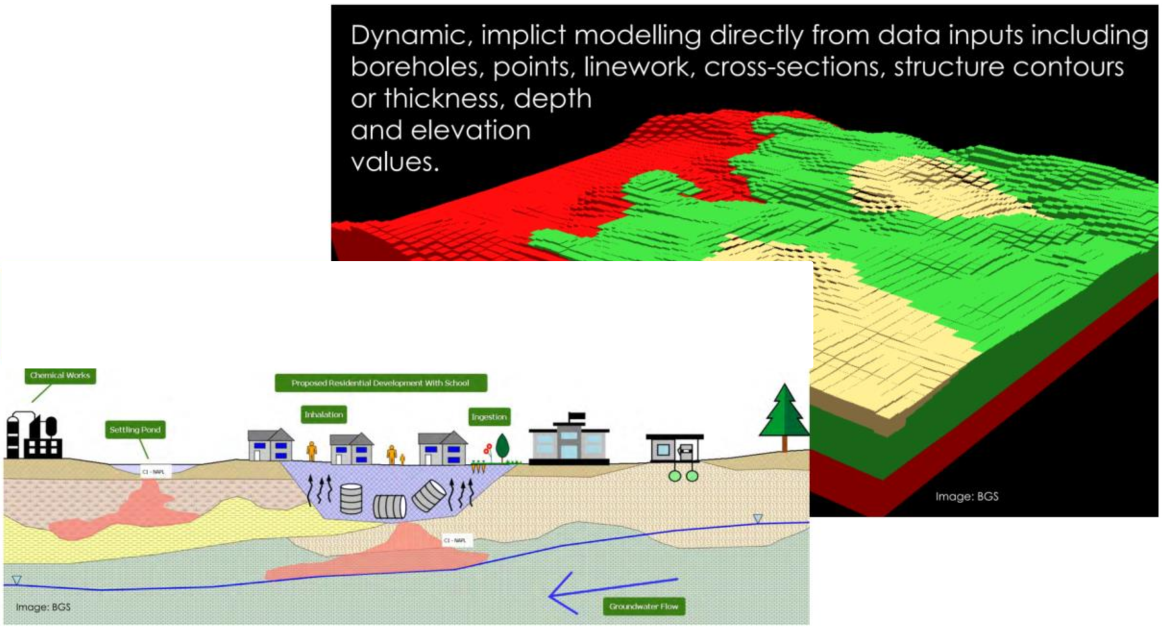

Figure 8. Groundhog Desktop – graphic integration into cross-section and 3D geological model. BGS © UKRI 2021

4.3.1 BGS Groundhog Desktop downloads – 2020

As shown in **Figure 9** the largest proportion of those downloading Groundhog Desktop are those from the engineering sector (Infrastructure/Construction/Transport) which fits with the aim of the software from a development perspective being designed for use in Conceptual Site Models and GI, closely followed by academia (31%). This implies that there is a need for a low-cost software for infrastructure be it in the planning, interpretation or implementation phase, and that those who work in this sector are early adopters of modern technology particularly for SMEs who may not have the capacity or resource to fund licenses for the mainstream software vendors in this area.

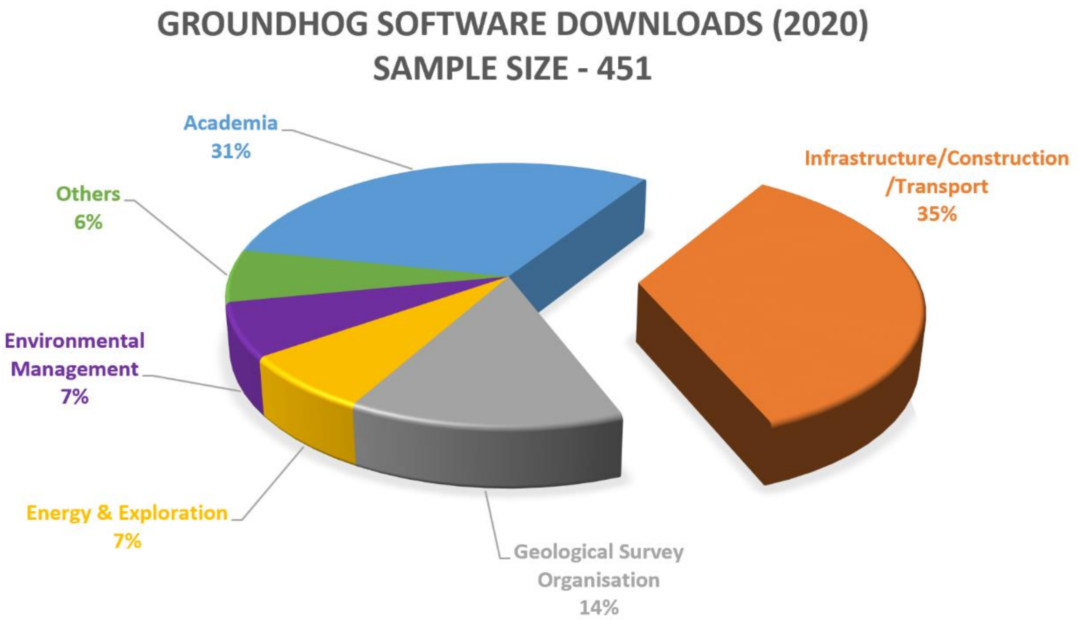

Figure 9. Groundhog Downloads – 2020/2021. BGS © UKRI 2021

5 Comparison of BGS data and applications trends by sector

5.1.1 Overview

In this section, the uses and data trends concerning the various sectors and organisations that access and license BGS data are described and analysed, and how transport and linear infrastructure differs from other sectors.

5.1.2 Dataset licenses - BGS

Over a 3-year period (between 2017-2020), transport, construction and linear infrastructure licenses accounted for 58% (£2.52 million) of all data licenses which was by far the largest proportion of all licences paid by sector (**Figure 10**). The next nearest licensees of the BGS data were the water and environmental management sector who accounted for 27% of all data licenses (£1.19 million). This indicates that the transport, construction and linear infrastructure sector has by far the highest need for ground model data, and this is probably due to the:

- costs associated with GI and construction are greater than those associated with other sectors (see **Section 2**)
- costs associated with unforeseen ground conditions – risks, failures and liability
- the availability / relevance of GI data from the BGS

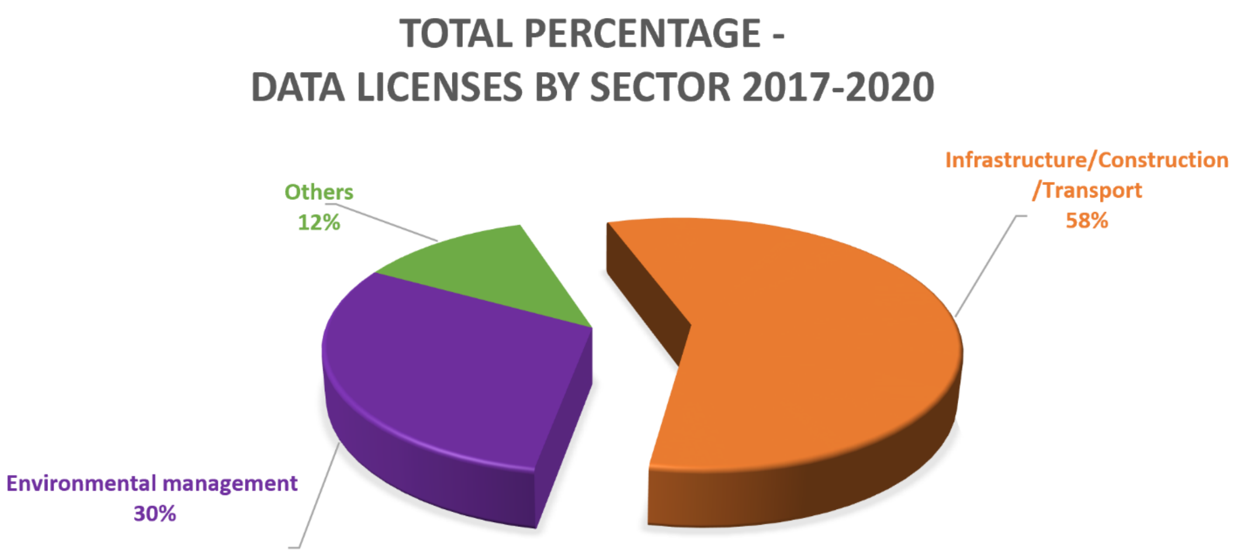

Figure 10. Data licenses by sector (Licenses are based on circa. £4.4 million over the 2017-2020 period). BGS © UKRI 2021

5.1.3 Total licence sales by BGS product

The three sectors with the highest number of licences for BGS data have been sub-selected and compared by BGS product type. The BGS products were:

- BGS Geology 1:10 000 maps
- BGS Geology 1:50 000 maps
- BGS Civils (see **Section 3.5**)
- BGS Geosure (see **Section 3.5**)

Infrastructure/construction/transport account for the highest proportion of the BGS Geology 1:10 000 maps licenses which indicates that there is a need for higher resolution data in that sector (**Figure 11**). This sector also takes in a larger proportion of BGS Civils and Geosure data, which indicates that the work undertaken is linked to geohazard risk analysis and uncertainty. In the other two sectors (Water Management/Environmental Protection and Local Government), by far the largest proportion of data was for the BGS Geology 1:50 000 maps (**Figure 12**). These sectors have a regional focus, therefore the higher resolution BGS Geology 1:10 000 map data will be unavailable for some of their area of interest, particularly if the areas are rural rather than urban. Conversely, the BGS Geology 1:50 000 maps have national coverage and because of this has an increased consistency between map sheets so for transport and linear infrastructure projects that cover a wide area including both urban and rural (e.g. HS2), the BGS Geology 1:50 000 maps are probably the most used.

This shows that transport and linear infrastructure projects need high resolution geoscience data to fulfil their requirements of de-risking and improving confidence for the ground conditions and ground model. The need for higher resolution data (and if possible in 3D) was also highlighted in the Geospatial Commission 'Call for Evidence' – responses document (published in 2019).

The key points relating to geology and use of the subsurface from this document are shown below:

- accuracy/precision is more important now than ever. There is a want and need for higher resolution data to be made open (e.g. BGS Geology 1:10 000 maps)
- disconnect between infrastructure or built asset and natural environment

Other keys points raised from the Geospatial Commission 'Call for Evidence' relate to advanced technology requirements, many of which are to do with how stakeholders interact with data and the interoperability of that data:

- need for all data to be in 3D rather than 2D.
- use of Augmented Reality (AR) and Virtual Reality (VR) in the construction industry is widely used – need more use with natural environment data
- geospatial data tailored to suit outputs and dissemination. Upskilling and software/hardware updates required for Local Government who are not able to incorporate 3D data
- aspiration for the UK standards to be aligned with commonly used world-wide standards and vice-versa (INSPIRE, AGS, OGC)
- future look - real-time data immersed in a 3D environment

The BGS has a dedicated user experience team that are looking to improve the use of geoscience data, and in tandem a 3D visualisation systems team which have developed several immersive VR techniques for improving the way the surface and subsurface environments are mapped and interrogated though Virtual Field Reconnaissance – VFR (Hughes et al, 2017). See **Section 4.2** for more information.

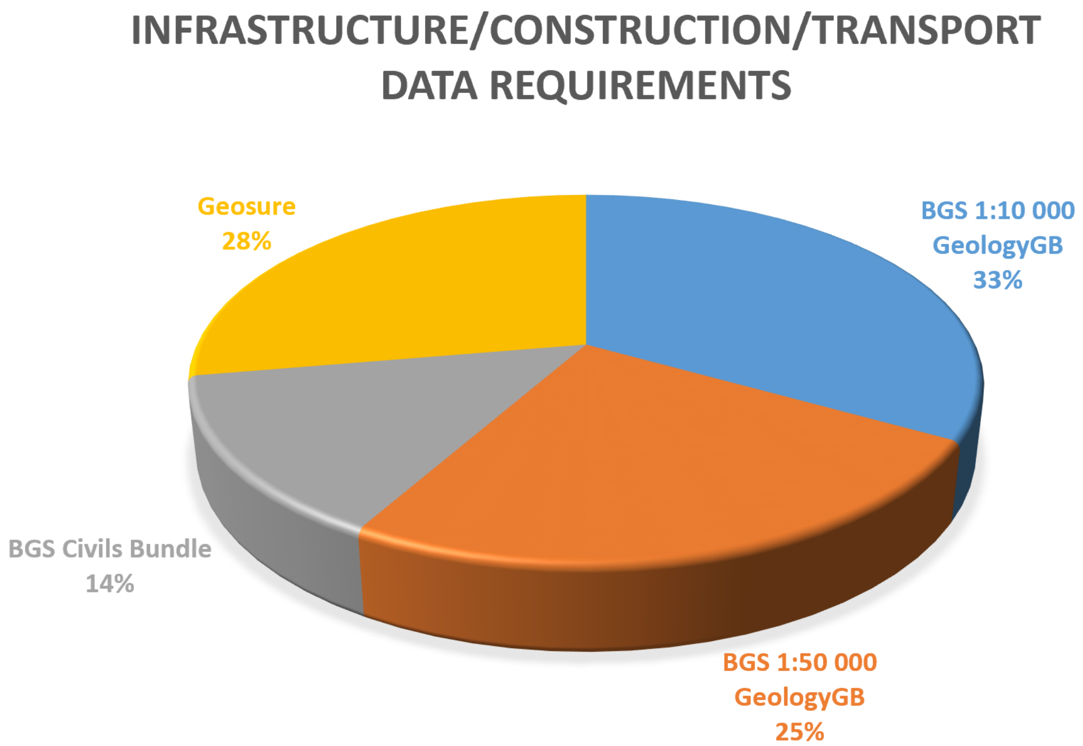

Figure 11. BGS dataset use by transport, linear infrastructure and construction sector. BGS © UKRI 2021

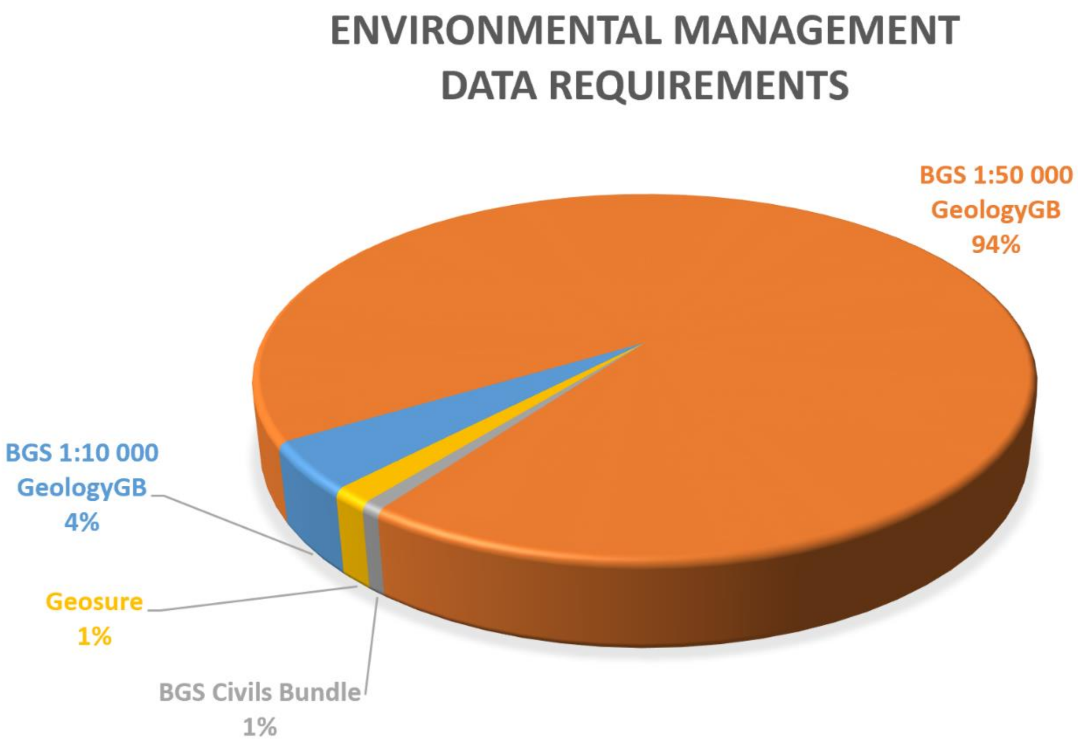

Figure 12. BGS dataset use by environmental management sector. BGS © UKRI 2021

6 BGS case studies of transport and linear infrastructure projects

The BGS has undertaken many different types of investigations for transport and linear infrastructure, often using a mixture of BGS data, understanding of the data, knowledge of the geology (including the structure and material properties) and applying that data and knowledge often in a 3D geological model. The aim is to better understand the subsurface structures, geometries and relationships between these and their impact on the built environment or the impact of the infrastructure asset on the natural environment.

Following, are examples where the BGS has collaborated with industry to help identify areas of uncertainty or risk at an early stage and underpin the decision-making process of subsequent GI, or re-purposed the 3D geological model for a different intended use. Or in the case of the Glendoe hydroelectric scheme case study, the aim was analyse and describe the nuisances of bedrock geology and the application of this understanding alongside the data.

For new infrastructure development this could help optimise the investment into GI and also reduce down-the-line costs associated with 'unexpected' ground conditions during construction, so the outputs could be a contribution to a geotechnical baseline and GI report. For existing infrastructure, the project focus would be on managing the asset by identifying areas of potential susceptibility to the asset from the subsurface environment or assessing where asset failure may impact on the surrounding natural and built environment. The case studies cover the following:

- Glendoe hydroelectric scheme – benefits of geological data and knowledge application for fault characterisation in light of a tunnel collapse
- Farringdon station (CrossRail) – cyclical 3D geological model development and collaboration
- Leeds-York railway – Building Information Model development for high resolution design and hazard assessment
- Lower Thames Crossing - a novel multi-disciplined approach to characterise the geology and hazards associated at surface and tunnel depths
- Monmouthshire and Brecon Canal – targeted risk mitigation
- HS2 (Assessing potential for Natural contamination in excavated materials) – re-purposing of the 3D geological model for application to a different discipline

6.1 GLENDOE HYDROELECTRIC SCHEME – CHARACTERISATION OF FAULT ROCK DURING TUNNEL DESIGN AND CONSTRUCTION

6.1.1 What is it?

The Scottish and Southern Energy's (SSE) Glendoe Hydroelectric Scheme is a multi-million-pound project in the Scottish Highlands that involved the construction of 6.2 km of pressured water tunnel through Precambrian basement rock. The 5 m diameter tunnel, cut at depths of 350-250 m below the surface, connects an aqueduct-fed reservoir to a 100MW turbine situated near to the shores of Loch Ness (**Figure 13**). Opened by the Queen in June 2009, it was at the time the longest unlined tunnel in the UK and the first time a Tunnel Boring Machine (TBM) method, instead of traditional cut and blast method, was used to construct a pressured headrace tunnel cutting through a complex geology of high-grade metamorphic rocks cut by several large fault structures. Driven by the move towards decarbonisation the project marked a resurgent interest in developing Scotland's remaining large hydro power generation potential around the area of the Great Glen Fault. The site operates on a stop-restart system providing additional energy into the national grid during times of peak demand and generating significant income for SSE.

Within a few months of operation significant reductions in power output were noted and in August 2009 these culminated in a major collapse and complete blockage of the tunnel. The blockage, located in the upper sections of the headrace tunnel and spatially linked to a significant strike-slip fault (the Conagleann Fault Zone), effectively put the operation out of action for 3 years whilst a by-pass tunnel was constructed and finally brought back online in 2012.

6.1.2 Challenges

The geology at Glendoe is complex and formed of recrystallised and poly-deformed metamorphic rocks displaced by several large strike-slip faults with multiple movement histories. Whilst the hard crystalline and relatively dry nature of the Precambrian geology facilitated steady progress with tunnelling and confidence in the unlined design, the key geological concerns were the fracture and fault systems cutting the tunnel at high angles. These faults included a low angle inclined thrust structure in the tailrace tunnel and several steep-to vertical strike-slip faults forming a flower structure on unknown extent and expression in the host rocks of the headrace tunnel. In all cases the faults represent zones of potential weakness containing crushed rock fragments, clays and carbonate and sulphide mineralisation indicating a history of repeated movement and acting as pathways for infiltrating fluids.

In this context, the spatial extent and recognition of erodible or durable rock associated with faulting is key to engineering solutions during tunnelling and choice of support. Strike-slip faults typically contain braided strands of intensely faulted rock separated by relatively unaffected rock and can lead to problems of identification of the zone intense deformation in the fault core and the lateral extent of the zone of fault-affected rock (or damage zone). In the case of mica-rich metamorphic strata failure to recognise and differentiate the micro-fragmentation by repeated fault movements to produce units of fine-grained fragmentary rock (cataclasite) and mineralised veins from the background foliated mica-schist can lead to underestimates of the nature and risk posed by faulted rock.

6.1.3 BGS role

During initial construction BGS geologists were able to access the head- and tailrace tunnels and rock exposures at the dam plinth and aqueduct trenches to record and update the geological map for the area. At this stage, the problematic Conagleann Fault Zone was not observed, but hidden behind a veneer of shotcrete. Post-collapse BGS geologists were contracted in to inspect the accessible tunnel and to work with the contractors and drilling teams to assist with understanding of the local geology and type of faulting, to inform the siting of boreholes, complete rapid core logging on-site and the interpretation of fault rock fabrics. Careful logging of core and 3D modelling of the fault network allowed correlation of mapped surface geological features with fractures and faults observed in the tunnel and an estimate of the extent of faulting (**Figure 14**). Engineering logs whilst recording crucial observations, these can be mis-interpreted by engineers, and in this case the difference between 'mica schist' that formed as a result of deformation and metamorphism of the host semipelitc rock and 'mica schist' that formed as a result of repeated fault movements was not recognised. This led to an underestimate of the extent and nature of weakened fault-affected rock. Thus, during the construction of the by-pass tunnel BGS geologists were continuously on site to provide advice and geological interpretation of core as it encountered the Conagleann Fault Zone.

In the ensuing legal case BGS was contracted as an expert witness and provided detailed analysis and responses including construction of a 3D geological model to counter claims that the fault structure that triggered the collapse was offset and therefore not observed. The expert work culminated in 5 days cross examination in court including demonstration of the geology and 3D modelling of the fault structure (**Figure 15**).

6.1.4 Benefits to the project

The benefits of insight and knowledge brought to the project by the BGS geologists and the understanding provided through the 3D geological modelling to the Glendoe project were significant. Not only in the provision of advice and understanding of strike-slip faults but also in the detailed geological interpretation to inform the recovery of tunnel operations with routing and construction of the by-pass tunnel solution.

BGS also provided key input to the subsequent legal action providing expert witness input and presenting in court for the first time an interactive 3D model. In 2017 The Court of Session in

Scotland issued the verdict that the contractor was not liable for the collapse in the upper part of the tunnel and therefore not required to compensate the pursuant SSE for the subsequent repair costs. This was contested and in 2018 SSE won an appeal to recover repair costs with the judges voting in favour to allow a claim for £107.6 million of recovery repair costs and £1 million for business losses.

As noted in the judge's findings the contractors involved had failed to identify a fault that presented a threat to the tunnel stability, and this represented a failure to understand the nature of the faulting. As a result, further work on the development of new hydro-schemes in the vicinity of the Great Glen Fault have utilised BGS geological expertise at the design and planning stages and currently are working closely with contractors in the development of the new Coire Glas Pumped Storage Scheme.

6.1.5 Realised knowledge and capability development

In a recent review Brox (2020) notes that many of the major recent collapses in the tunnelling networks of hydro schemes are due typically to design errors due to the incomplete identification of weak geological zones during excavation.

Therefore, the adoption of a more complete understanding of fault-related weak zones and their expression in a tunnel is important for the specification of shotcrete for long-term stability and support of major geological faults. This is key for power schemes where internal water pressure oscillates during operation with increased risk of erosion and saturation of the weakened rock behind the shotcrete lining.

The close collaboration and complimentary approaches of the consultant engineers and the BGS expert geologists has been of key benefit to the recovery of the Glendoe Hydroelectric Scheme and has application to other tunnelling and infrastructure projects intersecting major fault structures. Understanding the added value of shared borehole logging to assess the geometry of fracture systems from a geological and engineering perspective and developing the use of 3D models that link surface and subsurface data permits a shared understanding and visualisation of the geology both prior to and during construction.

6.1.6 Value assessment

Table 1 shows the value gained from the Glendoe hydroelectric scheme project.

Table 1 Value assessment - Glendoe hydroelectric scheme. BGS © UKRI 2021

Value category	**Derived value**
Decision informing process (action taken in response to data and information)	The BGS were able to identify the root cause of the tunnel failure, and quantify the extent of the fault zone, using a 3D model construction Inherent understanding of geological processes contributing to a greater knowledge of geological structure than could be derived from a geological map or model alone
Risk reduction	A shared understanding between the geologists and engineers of the logs, mapping and 3D model prior to and during construction mitigates against further tunnel failure.
Efficiency	BGS involved at design and planning phase to improve confidence of interpretation

Value category	Derived value
Knowledge-creation	Increased competence (geological modelling, BIM workflows, tunnelling method) Developed understanding of the engineer's perspectives and ensuing legal action that was undertaken.
Non-rival; quasi-public data goods generation	Knowledge gain of the Conagleann Fault Zone

6.1.7 Links and references

Glendoe: in the footsteps of the 'Hydro Boys' - International Water Power (waterpowermagazine.com) - https://www.waterpowermagazine.com/features/featureglendoe-in-the-footsteps-of-the-hydro-boys

Rock falls shut down Glendoe power plant (tunneltalk.com) - https://www.tunneltalk.com/Glendoe-Aug09-Rockfall-shutdown.php

Brox D 2019, Hydropower tunnel failures - risks and causes, In. Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art. Taylor and Francis 2019. ISBN 9780429424441

Figure 13. Location and example of Headrace tunnel of the Glendoe Hydroelectric Scheme. BGS © UKRI 2021

Figure 14. Example of faulted core from the Glendoe hydroelectric scheme. BGS © UKRI 2021.

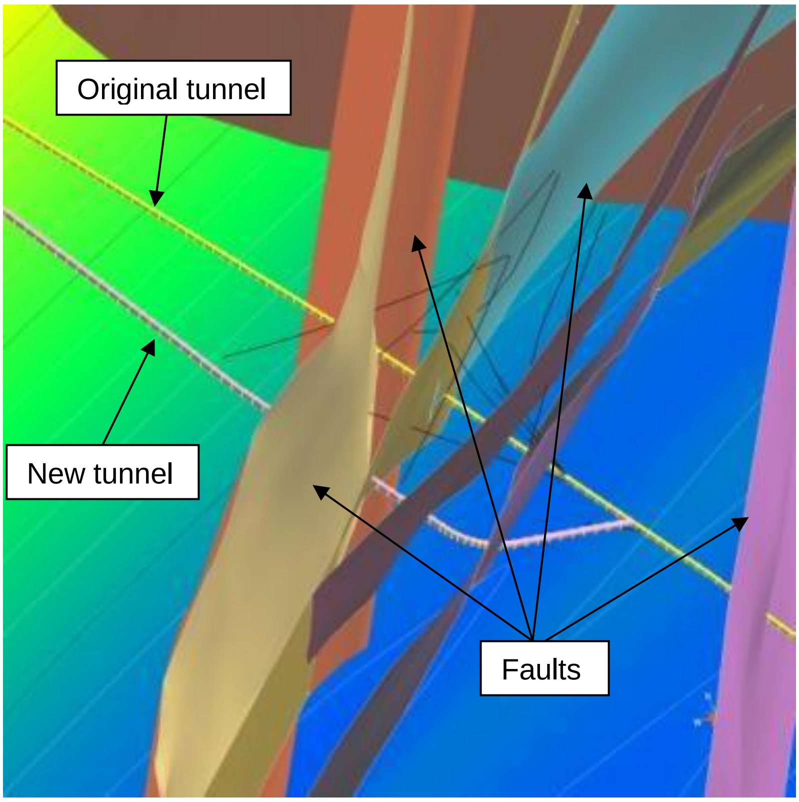

Figure 15. 3D geological model of the Conagleann fault zone at Glendoe. BGS © UKRI 2021.

6.2 FARRINGDON STATION (CROSSRAIL) – CYCLICAL 3D GEOLOGICAL MODELLING FOR TUNNELLING WORKS (2009 ONWARDS)

6.2.1 What is it?

Farringdon station (borough of Islington, London) is one of the major transfer hubs as part of the multi-billion-pound CrossRail project with the construction of a west to east suburban passenger service through central London on the Elizabeth line. Farringdon station will be one of the busiest in the UK, connecting with Thameslink and the London Underground to provide links with outer London, the Home Counties, the City, Canary Wharf and three of London's five airports.

6.2.2 Challenges

As opposed to many other parts of the CrossRail project where the major bedrock geological unit is the London Clay, in the Farringdon station area the construction is mainly through the Lambeth Group. This is a complex heterogeneous unit with both vertically and laterally variable sequences of clay, some silty or sandy, with some sands and gravel. Farringdon Station required a state-of-the-art geotechnical approach to manage the risk related to the open face, spray concrete lining (SCL) tunnelling. The main issues were the location (including the geometry orientation) of the faults and the potential deterioration of the mechanical soil properties close to the faults and water seepages associated with these, and the water bearing sand lenses within the Lambeth Group, which can cause severe issues with the construction and SCL of the tunnel if not mitigated for (Gakis et al., 2016).

6.2.3 BGS role

The BGS produced a 3D geological model in 2009 (Aldiss et al., 2012) and then supported specialist tunnel contractors who did 'live' updates of the 3D geological model using tunnel excavation data and observations to help understand the location and proximity of the faults and sand lenses (**Figure 16**).

6.2.4 Benefits to the project

The benefits of the having an evolving 3D geological model were considerable. In the pre-construction phase, the 3D geological model produced by the BGS, and the support given, assisted in the identification of areas where additional investigation was required.

During the construction phase, the continually updated 3D geological model was essential in the support for additional design changes as parts of the SCL tunnels were redesigned and where the construction environment allowed it, a reduction in lining thickness could be achieved (supported by detailed knowledge of the geotechnical conditions). During this phase, a cycle of risk reduction was implemented using in-tunnel probing to validate the 3D geological model. Actual data was fed back into the model, reducing both risk and increasing the level of knowledge and confidence.

The increased understanding of the geology and geotechnical conditions provided the following key benefits:

- it supported a 70% reduction of in-tunnel probing from that originally planned
- the 3D geological model was used to optimise the direction of additional in-tunnel probing and depressurisation wells in 3D space
- supported more efficient SCL design for 5 additional tunnels including two 9.5 m wide tunnels without a pilot and 5 openings without additional reinforcement or thickening.
- the 3D geological model was a key component in the risk mapping along the route and the geotechnical risk management framework as part of the site supervision workflow.

6.2.5 Realised knowledge and capability development

Farringdon station provided a real-world example whereby geological data and knowledge is no longer transitioned and archived in a one-way system. It followed the principals of Building Information Modelling (BIM) where the model is an evolving entity and feedback mechanisms were enabled to ensure that the BGS became the custodian of the evolved 3D geological model. This was an exemplar around the UK and the world of how geological survey organisations and geotechnical/engineering consultancies can work together to safeguard geological knowledge and data for future generations.

6.2.6 Value assessment

Table 2 shows the value gained from the Farringdon Station project.

Table 2 Value assessment - Farringdon station (CrossRail). BGS © UKRI 2021

Value category	Derived value
Decision informing process (action taken in response to data and information)	Identification of areas where additional investigation was required and enabled DSP/BFK to perform an initial geotechnical risk mapping for the tunnelling works. Alternations to monitoring boreholes. Optimisation of tunnel probing surveys and depressurisation wells. Alterations to SCL-design
Risk reduction	In-tunnel probing used to validate 3D model to increase confidence in geological model and lower onward risk.
Efficiency	70% reduction in tunnel probing Reduction in pilot drilling Reduced need for additional tunnel reinforcement or thickening of tunnel liner.
Knowledge-creation	Identification and geological characterisation of geological faults, sand lenses and water seepages. Increased competence (geological modelling, BIM workflows, tunnelling method)
Non-rival; quasi-public data goods generation	Generation of over 50 digitised and interpreted boreholes from the BGS archive and a 3D geological model for submission into the National Geoscience Data Centre and National Geological Model for non-exclusive re-use. 3D model re-use subject to data licensing.

6.2.7 Links and references

Aldiss, D.T.; Black, M.G.; Entwisle, D.C.; Page, D.P.; Terrington, R.L. 2012 Benefits of a 3D geological model for major tunnelling works : an example from Farringdon, east-central London, UK. Quarterly Journal of Engineering Geology and Hydrogeology, 45 (4). 405-414. https://doi.org/10.1144/qjegh2011-066

Gakis, Angelos; Cabrero, Paula; Entwisle, David; Kessler, Holger. 2016 3D geological model of the completed Farringdon underground railway station. In: Black, Mike, (ed.) Crossrail Project, infrastructure, design and construction. Volume 3. London, UK, Thomas Telford Limited and Crossrail 2016, 431-446.

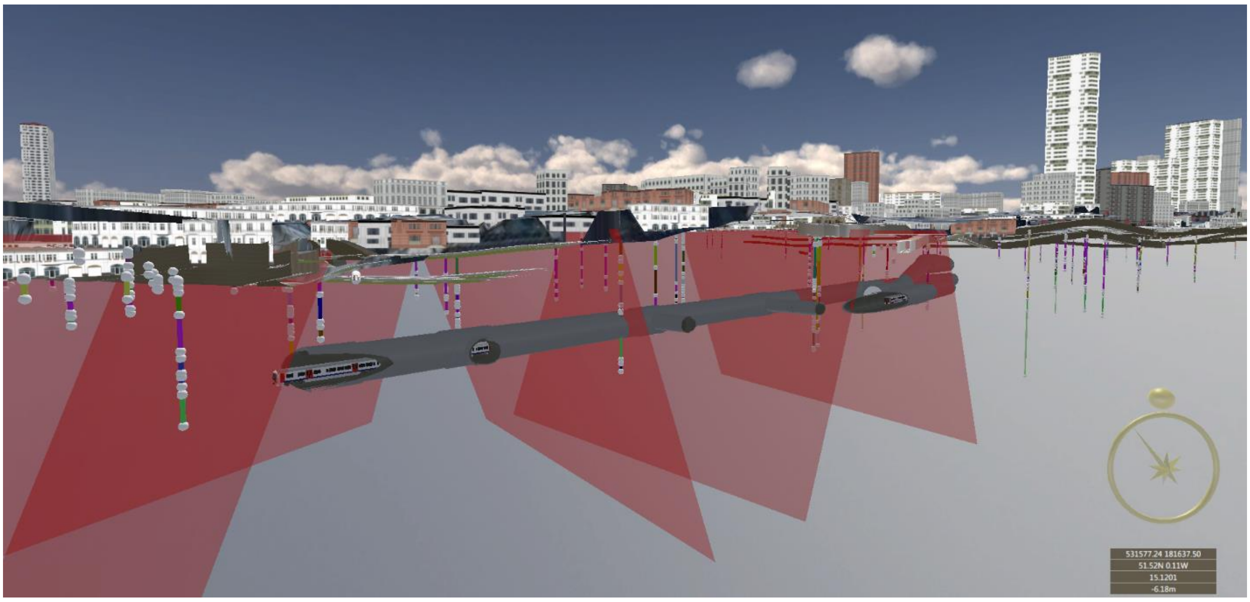

Figure 16. Farringdon Station with newly identified faults during the 3D geological modelling process - Image from GeoVisionary. BGS © UKRI 2021

6.3 LEEDS-YORK RAILWAY – TATA STEEL PROJECTS (IN COLLABORATION WITH TECHNICAL SOLUTIONS IN PARTNERSHIPS - TSP)

6.3.1 What is it?

The Leeds-York railway line opened in 1869 and runs eastwards from Leeds to Micklefield, where the line curves north-east, crossing the River Wharfe on the Tadcaster Viaduct and approaches York from the south-west. In preparation for electrifying the line and upgrading the track to run faster trains, the BGS was commissioned to construct a detailed 3D geological model along 28km of the route from Leeds to Colton, approximately 9 km south of York. The model was used to identify areas where intrusive GIs are needed along the route, and to inform the selection of deep or shallow foundations to support masts that carry overhead electrical cables.

6.3.2 Challenges

The geology along the route, and therefore the ground conditions, is variable. Carboniferous Pennine Coal Measures Group consisting of mudstone, siltstone and sandstone with worked coal seams underlie the Leeds area; Permian Zechstein Group dolomitic limestone and evaporite-rich mudstones underlie the central part of the route; and Triassic evaporite-rich mudstones and the Sherwood Sandstone Group are present in the north towards York. In the northern part of the route the bedrock is concealed beneath a thick and complex sequence of glacial sediments and modern floodplain deposits.

The client was particularly interested in the depth of weathering in the bedrock units because it affects the engineering strength of the rock and the stability of exposed rock in cuttings. The Cadeby Formation, for example, is composed of dolomitic limestone and weathers to calcareous clay. The depth of weathering governs the depth of piling needed to support the masts that carry the overhead electrical cables. It was also important for the client to know where dissolution of evaporites and mining of coal seams have occurred because of the risk of subsidence.

Understanding the distributions, 3D geometries and weathering profiles of the geological units enabled the client to assess the ground conditions at the design stage along the route and provide a more accurate cost estimation to electrify the line.

6.3.3 BGS role

To enable the client to assess the ground conditions along the route the Coal Measures are modelled as separate units to show individual coal seams, sandstones and beds of siltstone/mudstone. This level of detail in the geological succession is based on BGS Geology 1:10 000 scale maps and borehole logs and included 29 faults.

A 25cm cell size Digital Terrain Model (DTM) of the railway line capped the 3D geological model. The level of detail in this DTM enabled the extent of embankments along the line to be captured in a GIS as made ground, which increased the accuracy of the model.

A bedrock weathering profile was constructed in the model to inform potential foundation design along the route. The engineering properties of the bedrock and superficial geological units along the route were also assessed using geological descriptions in the borehole logs to flag up potential issues such as weak horizons and gypsum beds.

Another geological consideration in the foundation design is subsidence. One cause of subsidence is coal mining where the route is underlain by Pennine Coal Measures Group rocks. Representing individual coal seams in the model enables the client to see the depth and extent of these workings and displacements across geological faults. The model also shows the distribution of units that are prone to subsidence from dissolution. and a location map of sink holes was produced. These are associated with three named anhydrite units and gypsum bearing mudstones in the middle section of the route.

6.3.4 Benefits to the project

The geological model was delivered in CAD format in 'Snake Grid' projection for integration with the client's Building Information Management (BIM) system. 3D pdfs were also provided to enable the client to view the geological model without the need for any specialist software. The modelled weathering profile and detailed bedrock and superficial geological model enabled the client to directly relate the above ground infrastructure to the geology below the ground. Together with an accompanying report explaining the engineering geology and the location of karst subsidence and mine workings, this enabled the client to plan the depth required for mast foundations and highlight areas where intrusive GI is needed.

6.3.5 Realised knowledge and capability development

The delivery of 3D geological models in CAD format and integration with BIM systems enables the below ground geology to be represented alongside above ground infrastructure. Although the upgrade to the Leeds-York railway line did not go ahead, this innovative method can be applied to future construction projects to highlight any potentially difficult ground conditions at an early stage (**Figure 17**).

6.3.6 Value assessment

Table 3 shows the value gained from the Leeds-York railway project.

Table 3 Value assessment - Leeds-York railway project. BGS © UKRI 2021

Value category	Derived value
Decision informing process (action taken in response to data and information)	Identification of areas where intrusive GIs were needed along the route. Weathering profiles generated to inform GI and depth of foundations required. Geohazard assessment – summary of mine workings, karstic areas and potential zones of dissolution Engineering assessment of boreholes to identify gypsum and weak horizons.
Risk reduction	3D model geometries with weathering profiles and geohazard assessment enabling targeted GI.
Efficiency	Reduction in intrusive GI Improved design of foundations and piling depth required. BIM compatible 3D model outputs for client software
Knowledge-creation	Identification and geological characterisation of geological faults, geometries and thickness of key horizons with weathering information Increased competence (geological modelling, BIM workflows, geohazard assessment for infrastructure)
Non-rival; quasi-public data goods generation	Generation of over 100 digitised and interpreted boreholes from the BGS archive and a 3D geological model for submission into the National Geoscience Data Centre and National Geological Model for non-exclusive re-use. 3D model re-use subject to data licensing.

6.3.7 Links and References

Burke, H.F.; Hughes, L.; Wakefield, O.J.W.; Entwisle, D.C.; Waters, C.N.; Myers, A.; Thorpe, S.; Terrington, R.; Kessler, H.; Horabin, C.. 2015 A 3D geological model for B90745 North Trans Pennine Electrification East between Leeds and York. Nottingham, UK, British Geological Survey, 28pp. (CR/15/004N)

Kessler, Holger; McArdle, Gerard; Burke, Helen; Entwisle, Dave. 2017 Applications of digital ground models to support the maintenance and upgrading of rail infrastructure. [Speech] In: Ground Related Risk to Transportation Infrastructure, London, UK, 26-27 Oct 2017.

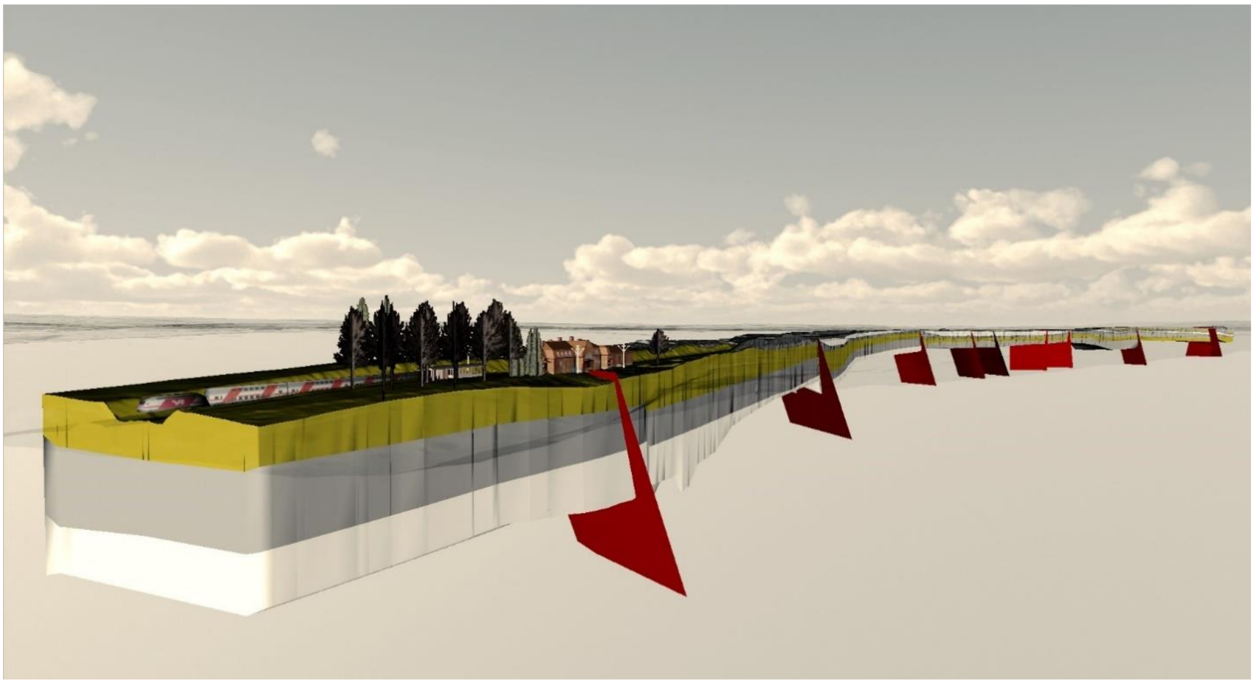

Figure 17. Leeds to York 3D geological model with linear infrastructure - Image from GeoVisionary. BGS © UKRI 2021

6.4 LOWER THAMES CROSSING - AN ENHANCED GEOLOGICAL CHARACTERISATION FOR PREDICTING GROUND CONDITIONS

The BGS would like to thank the following for their contribution to the Lower Thames Crossing Case study:

James Codd – Principal Geotechnical Advisor (National Highways)

Cedric Allenou – Ground Engineering Lead (Lower Thames Crossing project)

6.4.1 What is it?

The Lower Thames Crossing (LTC) is a multi-billion-pound project commissioned by National Highways (formerly Highways England), which includes the development of 23 km of motorway connecting the M2/A2, A13 and M25, including two 4 km tunnels (each will be 16.4 m diameter) in the area of the Thames Estuary. Around 50 new bridges and viaducts are proposed to be constructed. This will benefit the area by doubling the road capacity, alleviating the pressure on the Dartford Crossing, and generating billions of pounds additional economic benefits through investment and business opportunities.

6.4.2 Challenges

The variable geology and wide spatial extent of the LTC scheme pose multiple geotechnical challenges. Accurately predicting ground conditions is critical for overcoming these issues and for optimising the design of the scheme.

Preliminary GI demonstrated significant parts of the LTC scheme cut through flinty chalk. Information on the likely proportion of flints, their size, morphology and distribution informed several technical aspects, such as considerations regarding the Tunnel-Boring Machine (TBM) and slurry treatment plants. Identifying the precise stratigraphical level of the tunnel proved very valuable in assessing the amount of flint present and their impact on tunnelling equipment.

Ascertaining the precise stratigraphy was also important for assessing the behaviour of excavated chalk in earthworks, which can be prone to puttying, and determining fracture style. Conjugate fractures, susceptible to wedge failures in tunnels and cuttings, are common in the marl-rich lower Seaford and upper Lewes Nodular Chalk formations. Vertical fractures are common in the upper part of the Seaford Chalk.

Other geological hazards included lithological heterogeneity within the Lambeth Group, the depth to the Palaeogene-Chalk unconformity, and the possibility of old chalk mines (deneholes). Of particular concern was the depth to rockhead in the Thames Estuary where the chalk is covered by a variable thickness of river terrace gravels, peat and alluvium. Identifying, quantifying and mitigating all these hazards prior to detailed design and construction was deemed to be a very beneficial exercise to undertake.

6.4.3 BGS role

The challenges posed above necessitated a collaborative approach between the BGS and the LTC project team. Many linear route investigations focus on logging and correlating boreholes. In chalk successions, flint bands are often missed in borehole logs because the drill passes between individual widely spaced nodules, or because they shatter resulting in core-loss. Engineering logs often miss crucial information for correlating chalk stratigraphy. This leads to erroneous correlations and an under-appreciation of flint content. A second challenge is constraining the spatial variability in the depth to rockhead and the Cretaceous-Palaeogene unconformity along the route.

Two innovative approaches were used to overcome these issues. The high reflectance contrast between chalk and flint enabled the BGS us to use laser scans of quarry faces to quantify the spatial and stratigraphical distribution of flints. The data was calibrated by manual flint measurements and placed into stratigraphical context using biostratigraphy. By scanning, logging and correlating multiple localities across the Thames Estuary region, a quantitative high-resolution flint stratigraphy was constructed.

Novel passive seismic geophysical surveys ('Tromino') were used to identify rockhead and the base-Palaeogene surface across the LTC route corridor, calibrated using borehole logs. The small, portable nature of the equipment and rapid data acquisition enabled to survey rapidly and reliably, including areas where traditional invasive SI methods were not possible.

The laser scanning, Tromino data and borehole logs formed the basis of a high-resolution 3D geological model, resolved down to individual flint bands and marl seams. The resolution and wide spatial extent of the model represents a significant improvement on existing solutions, enabling quantitative estimates of flint volumes to be calculated.

6.4.4 Benefits to the project

The benefits of the development for the overall project delivery were considerable. They included the cost-effective collection of a large amount of project-specific ground information in a very short timeframe and with minimal impact on landowners, the increased confidence in the existing ground model (refinement, confirmation or alteration of data), and the provision of project-specific information for considerations associated with tunnelling-related equipment (e.g. TBM, slurry treatment plant). This augmented the intrusive GI, increasing the confidence of predicting the likely ground conditions for the tunnel and transport infrastructure.

A particular benefit of the Tromino methodology is the lightweight, portable and non-intrusive nature of the equipment. This allowed the geology to be characterised beneath sites where access constraints for invasive investigations such as drilling were challenging. As the passive seismic method involves a simple walk over survey, landowner access constraints and problems were minimised. The rapid data acquisition meant that the BGS were able to constrain the depth to the base of the Palaeogene strata across the whole LTC corridor quickly and more cost effectively compared to intrusive drilling. The spatial coverage was also far more extensive with a greater density of data points, giving confidence in the interpretation.

6.4.5 Realised knowledge and capability development

The adoption of new innovative methods of data collection and their incorporation into the construction of a high-resolution 3D geological model sets an example that can be applied to other infrastructure schemes, not just those in the Chalk Group. The routine use of passive seismic surveys and laser scanning has the potential to speed up the GI phase while at the same time improving the level of detail available for constructing quantitative ground engineering models.

Using laser scanning and section logging to quantify flint content and characterise rock properties has been a particular benefit for the LTC project. The same approach can be used in other chalk-hosted infrastructure schemes across northern Europe. Moreover, the same methodology can be used in other geological settings, particularly heterogeneous, variable strength rock units such as breccias, conglomerates and variably bedded siliciclastic and carbonate sequences.

The development of 3D ground models using data acquired from field mapping, passive seismic surveys and laser scanning, coupled with GI data, can be applied in many other geological settings, both prior to and during construction. Laser scanning of exposed faces during construction offers the chance to update geological models in real time.

The methodology has wider implications outside the engineering sector. A similar approach can also be used in the water industry, where groundwater flow is often influenced by bedrock lithology including flint bands, and superficial deposits. Improved groundwater modelling also has implications for understanding groundwater conditions into engineering schemes such as the LTC and HS2 (**Figure 18**).

6.4.6 Value assessment

Table 4 shows the value gained from the Lower Thames Crossing project.

Table 4 Value assessment - Lower Thames Crossing. BGS © UKRI 2021

Value category	Derived value
Decision informing process (action taken in response to data and information)	Flint quantification and statistical variance in 3D for TBM planning and design. Geohazard assessment – summary of mine workings/deneholes, karstic areas and potential zones of dissolution Passive seismic survey data acquisition using Tromino for rockhead model horizon – infrastructure planning and foundation design for bridges, motorway and tunnel portals.
Risk reduction	Non-intrusive GI methods in hazardous areas (Tromino and laser scanning) Statistical assessment of flints for TBM design
Efficiency	Rapid acquisition of subsurface data to identify the rockhead interface using Tromino. Flint analogues from laser scanning outcrops leading to a reduction of GI required. BIM compatible 3D model outputs for client software
Knowledge-creation	Identification and geological characterisation of geological faults, geometries and thickness of key horizons High resolution flint appraisal for the Upper Chalk formations Increased competence (geological modelling, BIM workflows, geohazard assessment for infrastructure)
Non-rival; quasi-public data goods generation	Generation of over 30 digitised and interpreted boreholes from the BGS borehole archive and a 3D geological model for submission into the National Geoscience Data Centre and National Geological Model for non-exclusive re-use. 3D model re-use subject to data licensing.

6.4.7 Links and references

https://highwaysengland.co.uk/our-work/lower-thames-crossing/

https://www.tunneltalk.com/UK-11Nov20-Procurement-begins-for-UK-Lower-Thames-Crossing.php

(Shortlisted for the Ground Engineering Awards UK for Technical Excellence – 2020)

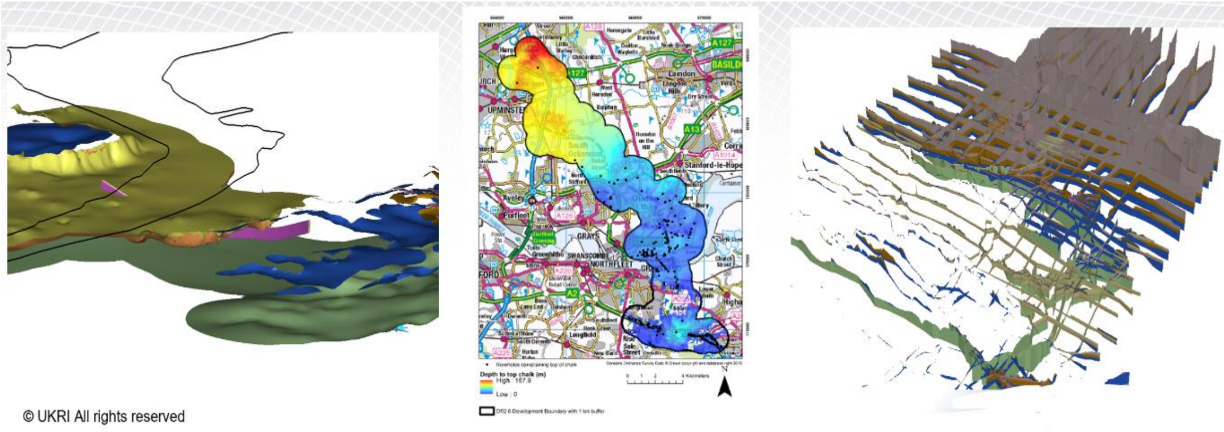

Figure 18. Example visualisations from 3D geological model of the Lower Thames Crossing area Left – 3D surface horizons, centre – contour map from 3D geological model, right cross-sections correlated for 3D geological model construction. BGS © UKRI 2021

6.5 MONMOUTHSHIRE AND BRECON CANAL – BRITISH WATERWAYS

6.5.1 What is it?

The Monmouthshire and Brecon Canal in Wales runs for much of its course within the valley of the River Usk and through the Brecon Beacons National Park and stretches 35 miles (56 km) along its length. The canal descends from its origin at Brecon where it lies at approximately 130 m elevation and through a series of locks along its route it gradually falls to less than 100 m elevation at Pontypool. Constructed in the late 1790s, it carried much of the raw materials of coal and iron that were derived from the South Wales Coalfield. The northern section of the canal, between Pontypool and Brecon, is still in use today under the management of British Waterways and it is estimated by British Waterways that the canal contributes £17m per year to the tourism economy, plus securing almost 400 full time jobs.

6.5.2 Challenges

The canal has been driven through a complex and variable Bedrock and Quaternary sequence. The canal alignment, from Crickhowell southwards, follows the contours of the hills forming the eastern edge of the South Wales Coalfield. Bedrock to the west of the canal comprises interbedded mudstone, siltstone, coal and sandstone belonging to the Middle Coal Measures Formation. Beneath the route of the canal, and to the north and east, bedrock comprises mudstones, siltstones and sandstones of the Lower Old Red Sandstone Group. Quaternary deposits with a relatively high level of variability are present throughout the length of the canal and comprise a mixed sequence of glacigenic, glaciofluvial and fluvial deposits.

In October 2007, there was a breach of the Mon-Brec canal when part of the canal bank near Gilwern collapsed, causing several houses to be evacuated and a road closure for several days. Subsequently, the whole of the canal was drained for geotechnical inspection along a 16 mile (26 km) stretch identifying 90 leaks, which were repaired at a cost of £8.5 million. A further £7.5 million was estimated to secure the long-term future of the canal.

The challenge was to understand the geometries, distributions and relationships between the various geological units that the canal goes through to understand the hydrogeological nature between these and prevent geotechnical failures such as further breaches and help identify areas where leakages could occur.

6.5.3 BGS role

The BGS developed a 3D geological model of the superficial and bedrock geology beneath the Mon-Brec canal. The depth of the model focused on the shallow subsurface to around 20-30 m below the base of the canal and within 100 m either side of the canal extent along its length.

The objectives were:

- to create a 3D geological model showing the distribution, thickness and elevation of geological units beneath the canal using borehole data (both from existing BGS database and those supplied from British Waterways), geological maps and a high-resolution digital terrain model (2 m LiDAR supplied by British Waterways).
- to identify which geological units have a direct hydrogeological link with the canal base.
- to better understand the composition and location of artificial embankments.

Using a high-resolution LiDAR digital terrain model presented challenges itself concerning software capacity, so the model was split into several sections to ensure that surface features (e.g. artificial embankments) were modelled to the highest resolution possible.

The BGS also gave a full geological summary of the origin and composition of all the units along the length of the canal to help understand the hydrogeological properties of those units and relationship between them.

6.5.4 Benefits to the project

The BGS were able to define the lithological composition in a number of zones along the canal including the bedrock types that are underneath the canal itself. These included dividing the embankments on the basis of interpreted lithology into clay dominant and sand dominant units. It was found that the lithological composition of embankment fill is generally constrained by the underlying geology and is generally sandy except in the embankments near Llanhamlach, between Gilwern and Llanvoist and in the Pontypool area. The thickness, geometry and locations of these were presented in a series of map outputs which can be used by British Waterways to target further remediation of the canal to prevent future breaches and leakages (**Figure 19**).

6.5.5 Realised knowledge and capability development

The BGS used novel methods to integrate a high resolution DTM (2 m cell size) along the entire length of the canal to provide a realistic representation of the ground surface of the canal structure. This approach provides British Waterways with a long-term resource that can be used to support future planning and GI. Potentially, this could save British Waterways significant costs by being able to target repairs and sharing this knowledge and insight.

6.5.6 Value assessment

Table 5 shows the value gained from the Monmouthshire and Brecon canal project.

Table 5 Value assessment - Monmouthshire and Brecon canal. BGS © UKRI 2021

Value category	Derived value
Decision informing process (action taken in response to data and information)	Lithological composition identification and zonation of the Mon-Brec canal for remediation planning Hydrogeological 3D characterisation for potential leakage and canal failure
Risk reduction	Desk based study of canal, limiting need for field survey
Efficiency	BIM compatible 3D model outputs for client software
Knowledge-creation	Identification and geological characterisation of geometries and thickness of key horizons High resolution flint appraisal for the Upper Chalk formations Increased competence (geological modelling, BIM workflows, geohazard assessment for infrastructure)
Non-rival; quasi-public data goods generation	Generation of >50 digitised boreholes and a 3D geological model for submission into the National Geoscience Data Centre and National Geological Model for non-exclusive re-use. 3D model re-use subject to data licensing.

6.5.7 Links and references

1- http://news.bbc.co.uk/1/hi/wales/7969952.stm

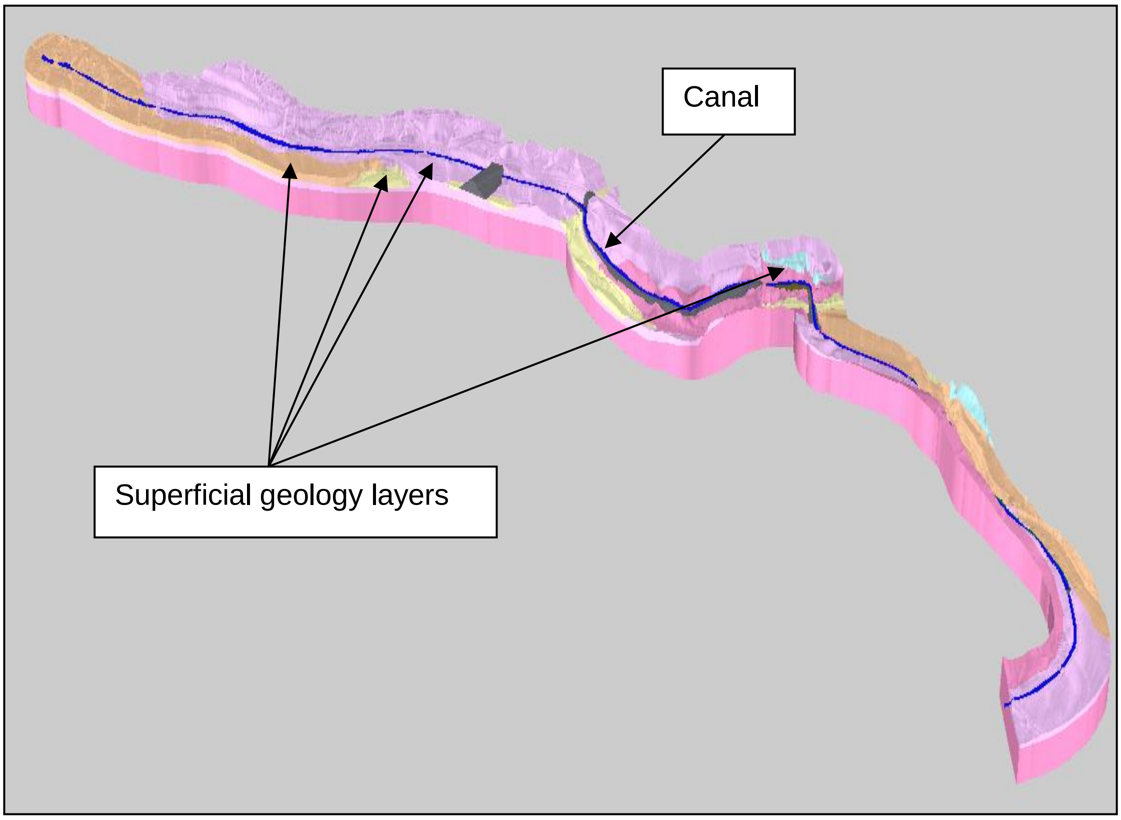

Figure 19. Mon-Brec Canal 3D geological model. BGS © UKRI 2021.

6.6 HS2 - ASSESSING POTENTIAL FOR NATURAL CONTAMINATION IN EXCAVATED MATERIALS

6.6.1 What is it?

HS2 is a high-speed railway linking up London to the Midlands and beyond. The construction of the new railway is split into three phases – Phase One linking London and the West Midlands; Phase 2a linking the West Midlands and the North via Crewe; and Phase 2b completing the railway to Manchester and Leeds.

6.6.2 Challenges

Natural contamination is determined as the natural state of the geological unit, and these geological units can be grouped into domains if a geological unit shares common characteristics with another geological unit, e.g. two clay units. An assessment was needed to consider the baseline properties (geochemistry and potentially toxic metals), reactivity on mixing different domain units, their weathering and mobility characteristics, and their leaching/retardation potential. The spatial distributions of the geological domains were determined from the 3D geological models developed by the BGS along the route of the HS2 (Phase 1 only). Changes that might occur due to disturbance, storage or waterlogging were also considered, as well as reference to the Contaminated Land: Applications in Real Environments (Cl:aire) code of practice.

6.6.3 BGS role

The BGS has constructed several 3D geological models along the route of HS2 Phase 1 in anticipation for the need for geological information about the spatial distribution of the units occurring in the vicinity of the proposed route. These models generally form a 5 km buffer around the proposed route and go to depths of 30 m below OD. Artificially Modified Ground (e.g. Made Ground), Superficial and Bedrock units have been modelled in 3D, the scale of which varies but are generally suitable from 1:10 000 in some areas to 1:100 000 where there is limited data availability.

Using the 3D geological models developed, the BGS undertook an assessment of natural contamination in excavated materials to determine the potential for naturally occurring contamination within the rocks and deposits along the phase 1 route. The study employed a team of experts to assess the likely contaminant 'activity' for a range of chemicals and metals. The study analysed a range of geological datasets, databases of geochemical analyses and borehole data. This analysis was carried out both vertically and laterally with respect to the proposed alignment of the track.

6.6.4 Benefits to the project

The result is a detailed assessment of natural contamination in excavated materials relevant to the proposed track alignment. Spatial information is provided for the current ground-level conditions, the proposed track-level conditions, and for the geological units encountered above and below proposed track-level, which will be encountered in those areas where the track lies within cuttings or tunnels. A simple to use GIS workspace was constructed to show this data in a four map-layer order to provide rapid assessments of potential natural contamination scenarios, these included:

Map1: Ground-level conditions

Map 2: Geological units encountered ABOVE proposed track-level

Map 3: Track-level conditions

Map 4: Geological units encountered BELOW proposed track-level

6.6.5 Realised knowledge and capability development

The HS2 natural contamination study showed how 3D geological models can be re-purposed and re-used, using an in-depth knowledge of the geochemical composition of the geology along the HS2 alignment, and potential geochemical reactions that may occur when porting and depositing the material through construction. This showed that 3D geological models and outputs modelled by the BGS geologists provide an easy mechanism for knowledge transfer in a digital format (**Figure 20**).

6.6.6 Value assessment

Table 6 shows the value gained from the HS2 geochemical project.

Table 6 Value assessment – HS2 geochemical project. BGS © UKRI 2021

Value category	Derived value
Decision informing process (action taken in response to data and information)	Detailed assessment of natural contamination in excavated materials relevant to the proposed track alignment,
Risk reduction	Desk based 3D study of the HS2 route with added value attribution of the geological units
Efficiency	Readily available GIS output of multi-attributed 3D geological model
Knowledge-creation	Knowledge and technical methodology application of key rock types that are potentially susceptible to naturally occurring contamination within the rocks and deposits along the HS2 alignment
Non-rival; quasi-public data goods generation	Knowledge and technical development of geochemistry data attribution in 3D geological models, 3D model re-use subject to data licensing.

6.6.7 Links and References

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Thompson, J. 2017. GSI3D model metadata report for HS2 Area 4 (Thorpe Mandeville to Ladbroke). British Geological Survey open report OR/15/035. http://nora.nerc.ac.uk/id/eprint/512705/

Wakefield, O. J. W. and Barron, A. J. M., 2017. Model metadata report for HS2 Area 6 (Cubbington to Hampton in Arden). British Geological Survey open report OR/15/044. http://nora.nerc.ac.uk/id/eprint/519286/

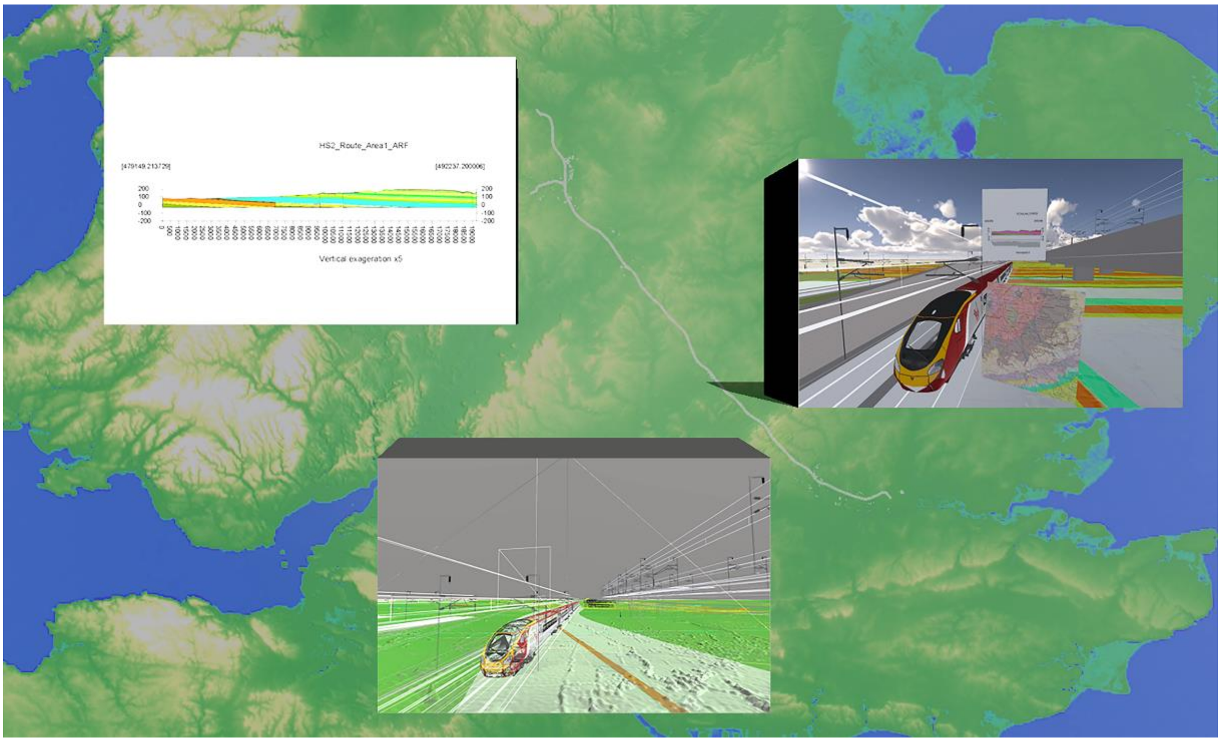

Figure 20. HS2 alignment and 3D geological model images. BGS © UKRI 2021.

7 Future intervention and developments

7.1 OVERVIEW

This section describes the case for future intervention in transport and linear infrastructure projects, and a look at some of the new developments that could impact this sector.

7.2 STRATEGIC CASE FOR FUTURE INTERVENTION

The rationale for further intervention to enhance the value derived from urban geological and geotechnical data is governed by a combination of policy drivers and industry need. Initiatives with the Geospatial Commission (GC) and the Infrastructure and Projects Authority (IPA) serve to identify these needs and opportunities with respect to GI data.

The GC is an expert committee within the Cabinet Office established to maximise the value of geospatial data and help to grow the UK's digital economy. Working with private and public sectors the overarching objectives of the GC are to increase economic growth and improve social and environmental outcomes, including setting cross-cutting geospatial strategy, policy and data standards, and by improving accessibility, interoperability and quality of data.

At their inception, the GC conducted a 'Call for Evidence' (Response document published in 2019) to gather information from stakeholders about geospatial priorities and set the agenda for their Geospatial Strategy. The evidence suggested improvements in linked environment-built modelling; transitioning to 3D datasets and data systems; improving data accuracy and data standards, and; geospatial upskilling. Barriers, both technological and cultural, and high-resolution data availability are also mentioned in the GC – 'Call for Evidence' Response document. The BGS have done much to bridge these issues (e.g. **Section 6** – Case Studies), however there is still more work to be done in each of the areas above.

The Geospatial Commission's Strategic Priorities for 2019-2020 identified the challenges of data management, particularly underground asset data, across the Infrastructure and Construction Sectors. In consultation with key stakeholders, the Geospatial Commission undertook a research exercise to understand the market, business needs and existing exemplars of good underground data management in the UK and internationally. Projects of note on this topic include, the North East Underground Infrastructure Hub (NEUIH); Project Iceberg; Dig-to-Share; EU COST Sub-Urban; and AGSi. In April 2019, as a result of this research exercise, the Geospatial Commission announced a £3.9m investment for two pilot projects in the Northeast of England and London to evaluate the benefits of a National Underground Asset Register (NUAR). These two pilot projects focus on specific use cases related to strike avoidance and improved efficiency of planning utility excavations, and provide learnings, evidence and recommendations to inform a planned national implementation. Additional use cases for an underground asset register and better subsurface data use were identified by the GC during the research exercise and were subsequently evaluated by the Project Iceberg team (Freeborough et al., 2019); higher priority applications of subsurface data included street works coordination; urban development; underground space use; utilities maintenance, and; resilience planning (including flood risk).

The IPA lies at the centre of government's 'Build Back Better' campaign. The IPA is the government's centre of expertise for infrastructure and major projects (e.g. transport, housing, defence), including projects delivered by the private sector, to be set up for success and to be capable of delivering value for money outcomes in line with government priorities (IPA Mandate Report 2021). The IPA is responsible for delivering the UK's pipeline of infrastructure projects and forms part of the Infrastructure Delivery Taskforce that will deliver 'Project Speed' a cross-government initiative to significantly reduce the time it takes to develop, design and deliver vital infrastructure projects.

Aligned to these policy and project initiatives and drawing together the collective public-private expertise, the IPA, GC and BGS convened a group of cross-industry representatives to consider the business case for intervention with respect to the sharing and increased re-use of GI data. Industry representative reached consensus on four improvement areas, these being:

- culture of data sharing
- confidence in data quality
- improved access to the data
- ensuring usability of the data

In addition, there was support for greater consideration of legal risk and liability management, and communication of data standards, and alongside the BGS in helping organisations and users of this data, interpret it and understand it.

The value of GI data, the benefits of data sharing and the effectiveness of existing data systems were also discussed by industry representatives (**Table 7**)

Table 7 The benefits delivered through sharing of GI data. BGS © UKRI 2021

Benefit	Value
More targeted GI, which leads to time and cost efficiencies in addition to reduction in environmental impact	Efficiency; Social value
Informs early-decision making in projects prior to the commissioning of new GI, allows more robust business case, facilitates project financing and better design/planning decisions	Decision-informing process; Risk reduction
Enables better management of risk for projects	Risk reduction
Delivers time efficiencies/productivity on projects e.g. streamlined access to (digitised) borehole logs.	Efficiency
Encourages uptake of data standards and improvements in data quality over time	Knowledge-creation (public good); Risk reduction
Improved understanding of regional geological setting beyond site boundaries	Knowledge-creation (public good);
Validation of the ground model	Knowledge-creation; Risk reduction
Enables development of a shared ground model supporting cross-project communication	Knowledge-creation; Efficiency
Encourages the development of geological data services and enables secondary data products and models	Non-rivalry, public good. Income generation
Increased opportunities for research (e.g. increased geological knowledge) and innovation (e.g. enhanced geospatial technology)	Knowledge-creation; Non-rivalry, public good

Opportunities to enhance the value derived from GI data:

- raise data confidence levels
- engage financial and legal representatives to facilitate the principles of data sharing and address any privacy or security concerns
- improve the interface between clients, consultants and contractors
- implement and enforce contractual obligations for data-sharing
- provide incentives for, or demonstrate the value of, developers submitting GI data
- communicate what the data is useful for and whether it is fit for purpose

- embed conversations on GI data sharing in wider government open data policy and construction policy and technology e.g. Building Information Models

7.3 TECHNOLOGY AND STANDARDS

A number of formats and standards exist for geospatial data for linear infrastructure project, often technology driven by the likes of Autodesk and Bentley MicroStation. Several standards that are gaining momentum for the use of geoscience data are being produced by the Open Geospatial Consortium:

GeoSciML - a data model and data transfer standard for geological data - from basic map data to complex relational geological databases.

MUDDI - Model for Underground Data Definition and Integration. This will involve mappings to/from other models for geospatial data that represent underground infrastructure assets and characterize the underground environment that contains those assets.

glTF/ 3D tiles - designed for streaming and rendering massive 3D geospatial content such as Photogrammetry, 3D Buildings, BIM/CAD, Instanced Features, and Point Clouds.

The challenge for the application of these standards is the adoption by industry to make them an accepted standard format that are used regularly across a broad range of geoscience areas and not become an academic exercise. In addition, these standards and associated data will only be adopted by industry only if industry can see the benefits and GI has a strong (economic foundation) business case

Alongside the standards mentioned above, the Open Geospatial Consortium (OGC) are also developing a suite of APIs to spatially enable web content for all sorts of environmental uses. For example, the SensorThings API provides an open, geospatial-enabled and unified way to interconnect the Internet of Things (IoT) devices, data, and applications over the Web.

Technology is also key driver of providing novel solutions in the way in which geospatial data is consumed, interpreted and understood. Two abstract concepts that were announced in 2021 were the Nvidia Omniverse and Facebook metaverse. These concepts take the idea of a Digital Twin to a new level, whereby an interconnected, interactive digital world is created in which virtual simulations of entire cities can be run and even simulations beyond the laws of physics can be carried out, delivering a vision beyond a Smart City Digital Twin (Hurtado and Gomez, 2021). These will enable many users to be able to see, analyse and immerse themselves in this VR environment at the same time, enabling quicker more dynamic knowledge exchange and communication. This is partially down to a convergence of technologies where once these used to be developed independently, and were mostly disconnected or unrelated, they are either catching up with each other or people are working out how to use these tools together seamlessly and for the better. These include but are not exclusive to the following:

- LiDAR and UAVs
- cloud processing and storage
- Digital Twin software advances
- sensors/telemetry
- big data computing, Machine Learning and Artificial Intelligence
- visualisation using Virtual Reality and Augmented Reality hardware and software

Much of the focus for smart cities and Digital Twins (DTs) has been on physical artificial infrastructure, for example buildings, roads, rail, tunnels, utilities, and the movements of people within these environments i.e. a DT for the built environment. Less focus has been attributed to the natural environment (specifically the subsurface) and the interaction between the natural and artificial environment, mainly because the technologies mentioned above have been developed for the built environment, The concept of an Environmental Digital Twin (EDT) is starting to gather pace (Bauer et al 2021, Blair 2021) and in some respects the parts to this are already in place using Earth observation data, weather models, laser scans and sensors, and bringing these together will be the key to unlocking their potential, a geospatial data convergence to go alongside the technologies convergence described above.

How we connect the DT for the Built Environment with above surface EDT and below surface EDT, which are at differing scales of resolution and precision, will determine how successful the idea of a Smart City Digital twin will be, particularly concerning the use of renewable energy and the sustainable use of subsurface resource.

The convergence of these technologies such as those mentioned above, sustainable working practices concerning the use of data, and the knowledge that can be applied to these types of data means that the BGS are at the forefront of being to deliver an exceptional service to transport and linear infrastructure projects and projects in associated sectors.

8 Summary

Geoscience data is and will become even more important to transport and linear infrastructure projects. In summary:

- significant sums are being spent on new infrastructure in Great Britain, however only a fraction of this is being spent on GI and collection of geological data and information. Large amounts of data collected during GIs are not shared for onward use resulting in inefficiency and less targeted onward investigations. A lack of investment in GI and inefficient use of existing geological data is causing significant delay and overspend on infrastructure projects (see **Section 2**)
- access to geological information delivers value to infrastructure projects through, risk reduction, efficiency savings, informing decision-making processes, and knowledge creation (see **Sections 3, 4** and **5**)
- transport and linear infrastructure projects require high resolution geological data, and more so than most other construction projects. As such there is demand for value-added (income generating services) via data products or bespoke 3D geological modelling services (see **Section 6**)
- there is substantial cross-industry support for improved data sharing and digital systems to enhance the value derived from geological data and information (see **Sections 3** and **7**)
- technology advancements will increasingly push the use, re-use and development of geoscience data with other types of data (e.g. built environment data) for decision making (see **Section 7)**

Appendix 1

Table 8 The primary geology-related civil engineering considerations in London (Lee and Graham 2020). BGS © UKRI 2021

Geology	Civil-engineering challenges	BGS data/Service
Anthropogenic geology	Unknown thickness and composition can cause uneven consolidation and compaction; potential contamination issues.	Enhanced mapping techniques (Terrington et al., 2015) and quantification of anthropogenic material (Terrington et al., 2018)
Drift-filled hollows	Over deepened hollows that extend into bedrock and are infilled with superficial deposits; can give rise to highly localised and unpredictable ground conditions.	Drift-filled hollows database (internal)– contact enquiries@bgs.ac.uk Hazard susceptibility mapping of drift-filled hollows (Banks et al., 2015)
River Terrace Deposits	Thickness can be variable, and presence of clays and peats can also be variable giving rise to compressible and compactable ground conditions.	London and Thames Valley model Burke et al., 2014 and Mathers et al., 2014.
Clay-with-Flints	Flint content and distribution; unpredictable obstacles for GI and wear on plant and tyres.	London and Thames Valley model Burke et al., 2014 and Mathers et al., 2014.
London Clay Formation	Joints and fissures within clay-rich horizons (B2 and A3) can fail when stress is relieved during excavation; silt and clay partings (A3) can store and transmit water; claystones (throughout the London Clay but especially in B2) up to 0.4m thickness can cause obstacles when drilling, piling, tunnelling and deep excavations; high shrink-swell susceptibility.	London and Thames Valley model Burke et al. (2014) and Mathers et al. (2014) BGS GeoSure shrink–swell 3D for London and Thames Valley https://www.bgs.ac.uk/datasets/bgs-geosure-shrink-swell-3d-for-london-and-thames-valley/
Lambeth Group	Vertical and horizontal facies variability cause challenging ground conditions for civil engineering; sand bodies within the Lambeth Group are conduits for irregular groundwater flow and can lead to instability of the tunnel face and ingress of water / running sand.	Farringdon Station: Aldiss et al. (2012), Gakis et al. (2016)
Thanet Sand Formation	Dewatering performance linked to vertical variations in particle size.	London and Thames Valley model Burke et al. (2014) and Mathers et al. (2014)

Geology	Civil-engineering challenges	BGS data/Service
Chalk Group	Dewatering performance and engineering properties linked to diagenetic and tectonic history; key features being stratigraphic variations in the presence of marl horizons, joints (and infills), stiffness and compressibility); flint horizons can also form obstacles to drilling to increased wear on tunnelling equipment and tyres.	Royse 2008, 2012. The London Chalk model Newell, 2018. Implicit modelling of Chalk properties.

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