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3D ground-use optimisation for sustainable urban development planning: A case-study from Earls Court, London, UK



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ABSTRACT

By 2050, almost 70% of the world's population will live in towns and cities. This places increasing pressure on land to support development whilst minimising environmental impact and providing long-term sustainability. Prior knowledge of the ground at the planning and development stage is needed to assess its suitability to meet planned subsurface uses and avoid subsurface conflicts at an early stage of design.

This research tested the development and application of a 3D engineering geological model and its spatial integration with 2D (hydro)geological datasets to support sustainable development decision-making at Earls Court, London, UK. The 3D engineering geological model consists of seven geological layers extending from Made Ground to the top surface of the Chalk Group. The 3D geological model, and 2D datasets derived from it, are combined with 2D geospatial datasets of urban underground space (UUS) indicators to identify potential uses of urban underground space based on its suitability to do so. This is complimented by a qualitative assessment of the potential subsurface interactions between UUS indicator uses and their implications for delivering the sustainability and energy objectives specified in the Earls Court masterplan.

Infiltration sustainable drainage systems (SuDS), ground source heat potential and foundation condition potential were chosen as suitable UUS indicators against which to test the outputs of the methodology. Infiltration SuDS potential was assessed using nationally-available (hydro)geological 2D GIS datasets. Ground source heat potential was assessed using national-available 2D datasets and estimates of thermal properties of each geological layer revealed by the 3D geological model. Potentially suitable foundation conditions were assessed using density data from existing ground investigations and depth of suitable geological layers derived from the 3D geological model.

The results reveal constraints for the development of rapid infiltration SuDS but opportunities for bespoke design that considers the thickness of overlying permeable sand and gravel. It identifies the susceptibility of the London Clay Formation to potential volume change and ground movement based on an assessment of its plasticity. Closed-loop ground source heat pump opportunities exist depending on site-specific thermal and hydraulic properties and heat exchange design. Opportunities for the use of the Kempton Park Gravel Member for ground source heating and cooling and combined use of thermal regulation and pile design via thermopiles are identified. A qualitative assessment of potential benefits and conflicts between UUS indicator uses reveals that the Kempton Park Gravel Member and London Clay Formation are likely to have the highest, relative, UUS value.

The results demonstrate that there is potential to modify the energy and sustainability components of the Earls Court masterplan prior to invasive ground investigation and development. It is further suggested that this approach can be used to compliment research-tested, semi-qualitative means of valuing UUS indicators. The implications of the methodology for mainstreaming UUS into city masterplans is also assessed. It is concluded that opportunities now exist for the integrated 3D and 2D spatial assessment of UUS indicators into city-scale masterplans.

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1. Introduction: research context and objectives

Cities provide opportunities for economic growth, cultural and social development and scientific and technological innovation. Yet they have often developed without coordination and integration of the mutual benefits that could be provided by using urban underground space (UUS), often to the detriment or exclusion of other potential city functions (Parriaux et al., 2004). Given that 60% of the area expected to be urbanised by 2030 has yet to be built (World Economic Forum, 2016) there is significant opportunity to influence future city planning and design using subsurface engineering geological ground models as a component part of a UUS management system. For future city development to be sustainable and resilient to change, an integrated approach that crosses disciplines and facilitates desirable urban futures while minimising the likelihood of undesirable ones is required (Lombardi et al., 2012; Price et al., 2016).

UUS contains natural geological, hydrogeological and geothermal resources and ecosystem services below the ground that provide space, materials, energy and water to support city development, transportation and utility provision (Bobylev, 2009; Li et al., 2012, 2013b; Sterling et al., 2012). They are referred to here as geo-assets. Historical top-down city development, focused on single-uses for underground space, or without consideration of the potential interactions between underground space uses, has resulted in a complex and hidden underground that has evolved without strategic coordination (Fig. 1). The efficient use of land above and below the ground (Evans et al., 2009) is one of many factors that define the sustainability and metabolism of a city. Evans et al (2009) identified multiple ground uses at depths < 50 m below ground level including foundations, utilities and transport. This illustrates the requirement for a relatively shallow zone of the urban subsurface to support multiple urban development needs. Although it is not routinely considered as such, UUS is a component part of urban ecosystem functionality (Sterling et al., 2012). The functions it can provide are summarised in Table 1 following the ecosystem function classification of the UK National Ecosystem Assessment (UK National Ecosystem Assessment, 2014).

In response to a greater awareness of planning for subsurface uses many cities have adopted dedicated subsurface master plans. Cities and countries including Singapore (Zhou and Zhao, 2016), Hong Kong (Arup, 2009; Wallace and Ng, 2016), Montreal (Paul et al., 2002; Li et al., 2012) Tokyo (Kishii, 2016), Helsinki (Vähäaho, 2016) and Paris have developed urban underground space plans for city development based on the recognition of subsurface space potential (Paul et al., 2002; Li et al., 2012). Despite the importance of UUS and its benefits to masterplanning, it is not routinely adopted. Further, existing masterplans do not routinely consider multiple uses, benefits and interactions of potential future uses based on the geological suitability of the ground (Bobylev, 2009; Admiraal and Cornaro, 2016).

Optimal use of UUS requires knowledge of the physical, chemical and biological characteristics of the subsurface and then consideration of the potential interactions between multiple existing and future uses (Li et al., 2016). For the sustainable development of the ground to become part of routine site development and masterplanning, knowledge of ground suitability, potential ground-use interactions and its relationship to wider city-scale UUS capacity is required (Griffioen et al., 2014). This approach permits the characterisation of geo-assets as a component part of urban ecosystem function and developing knowledge of the natural capital on which cities are founded (UK National Ecosystem Assessment, 2014). Strategic assessment of the natural capital and ecosystem services delivered by UUS has not yet been undertaken in the UK.

Four major classes of geo-assets are critical to support the provision of ecosystem services in the built environment; space, construction materials, energy and groundwater (Parriaux et al., 2004; Sterling et al., 2012; Li et al., 2013a, 2013b). These classes have been proposed as UUS indicators to enable quantitative measurement of city resilience and



Fig. 1. Conceptual model of subsurface development in a mature urban environment. Subsurface development includes groundwater abstraction, ground source heating and cooling, subsurface mineral working, transport and utility infrastructure, and deep basements from Price et al. (2016). Reproduced with the permission of the British Geological Survey ©NERC. All rights Reserved.

Table 1

Urban underground benefits for development and their ecosystem classification (modified after de Mulder et al., 2012). Ecosystem classification modified after Corvalan et al. (2005) and Rawlins et al. (2015).

Urban underground development benefits	Ecosystem classification
Source of natural resources (geologically-derived aggregate and fill, groundwater, geothermal)	Provisioning, regulating and platform/carrier
Storage and transport of materials (solid, liquid, gas)	Platform/carrier
Space for public and commercial use, space for green infrastructure	Platform/carrier
Geotechnical medium for foundation design and construction	Platform/carrier
Component in life-support systems (e.g. air and water regulation through soils)	Regulating
Archive of archaeological and geological heritage	Cultural

sustainability (Bobylev, 2016). City-scale geological characterisation in 2D and preferably 3D, provides a fundamental framework for the assessment of UUS and its suitability to deliver ecosystem service function (Sterling et al., 2012; Li et al., 2016). Spatial GIS mapping of underground resources forms part of an urban underground management system referred to as the ‘Deep City Method’ (Li et al., 2013a, 2013b). This methodology has been tested for cities in Switzerland and China.

The method considers space, materials, energy and groundwater and applies qualitative scores against and between them to qualify supply and interpreted quality of each subsurface resource. This method has been further developed to apply 2D spatial mapping techniques to visualise and quantify underground resource potential in San Antonio, Texas (Doyle, 2016). The methodology used by Doyle maps and classifies geological layers into families of characteristics (geotypes) which are then used to qualitatively assess their suitability for each of the four resource classes corresponding to space, materials, energy and groundwater at depths between 0–15 m and 15–30 m below ground level. Suitability is based on expert judgement to which numerical scores are assigned based on the Analytic Hierarchy Process (Saaty, 1990) developed as part of the Deep City Method. Pairwise comparison between each geotype and its suitability for each specified resource use is expressed as a ratio scale of suitability and presented as a 2D map visualisation.

The provision of geological data and information in 3D is therefore a central requirement of mainstreaming UUS into a city's masterplan (Parriaux et al., 2004; Bobylev, 2009). Despite the increasing technological developments that allow digital 2D and 3D characterisation of the subsurface and the development of 3D UUS as promoted by Bobylev (2009), Sterling et al. (2012) and Li et al. (2012), the application of 3D ground information to UUS planning is not yet widely accepted. Case studies that describe the potential benefits for optimised use of the ground using 3D geological models for examples are lacking in the literature.

This paper presents an example case study that aims to illustrate how a methodology that combines the development of a site-scale 3D engineering geological model with nationally available 2D digital hydrogeological and geothermal datasets to create a qualitative 3D UUS framework for underground geo-assets at a large development site-scale to inform pre-development design and construction. The case study is illustrated using a 3D engineering geological model, ground source heat potential and surface water infiltration to illustrate how a combined approach could address the UUS indicators of space, water and energy described by Li et al. (2013a), Sterling et al. (2012), Doyle (2016) and Bobylev (2016).

Information about UUS indicators needs to be easy to capture, reliable, regularly updated and possible to integrate with both the planning and construction sectors (Mielby et al., 2017). The methodology applied in this case study helps to bridge the gap between city-scale geospatial mapping used to support land use planning, and site-scale ground models developed to inform project design and construction. At the site-scale Building Information Modelling (BIM) practices are utilised by the construction sector to generate and manage digital information about the physical characteristics and functions of buildings and facilitate the sharing of data and models. This BIM principal is being further developed to include digital representations of subsurface structures and ground properties. At the same urban planners are transitioning from the use of 2D GIS data management to the application of 3D city models and flexible local planning which utilises dynamic city data. For both the construction and planning sectors, the aim is to maximise data accessibility, facilitate common standards for data-sharing and encourage transparency in decision-making. The case study presented here combines BIM concepts with digital city-planning frameworks by utilising a 3D digital workflow that encourages the transfer and integration of multiple datasets between public and private-sector companies. In doing so, city-scale geospatial maps and used in combination with site specific data to determine variable and sustainable uses of the UUS.

The purpose of integrating 3D geological data is to provide a 3D digital background to the development of a site during planning and before ground investigation in support of design. It is not intended to replace detailed ground investigation or site-specific considerations that can only be identified during invasive site appraisal.

1.1. 3D geological models as an underground UUS indicator

To date, geological consideration of the ground below cities at a regional or national scale has focused on the avoidance of geohazards (e.g. Walsby, 2008; Foster et al., 2012). This is supported at the site-scale by desk studies and ground investigations to derive geotechnical parameters for design. Urban geological data and information has been used in support of environmental decision-making and planning in the UK and is described by Ellison et al. (1998) for over fifty towns and cities. The development of applied geological information for city preservation and resilience is described by Culshaw and Price (2011). They showed that use of geological information evolved from single-use applications including avoidance of mine workings and provision of drinking water to the consideration of multiple uses in any one place. While geohazards are a material planning consideration, there is now an opportunity to integrate underground planning beyond that of the avoidance of geohazards.

A conceptual ground model is a fundamental part of ground investigation and site development. Its value in ground engineering for the identification of suitable engineering soil and rock types, their thickness and geometry is well established (Dearman and Fookes, 1974; Fookes, 1997; Brunnsden, 2002; Griffiths et al., 2012). The construction of city-scale deterministic 3D geological models to support urban development planning was described by Culshaw (2005). The potential offered by 3D geological models to support urban development planning was facilitated by the development of national-scale digital geotechnical and geological databases alongside development of relevant 3D modelling software and methods (Kessler et al., 2009; Van Der Meulen et al., 2013). The software and methods were developed with the intention of supplementing the development of conceptual ground models prior to, and not to replace, ground and laboratory investigations.

Deterministic 3D geological models are represented by the change in elevation and shape of the tops and bases of geological layers. Deterministic 3D geological models are typically constructed in steps by correlation of downhole geological information recorded in boreholes, creation of cross-sections and interpolation of correlated points. 3D geological models created in this way have been constructed for cities including London (Burke et al., 2014; Mathers et al., 2014), Glasgow (Campbell et al., 2010), Manchester (Price et al., 2010) and regionally, in parts of the Netherlands (Van Der Meulen et al., 2013) and Germany (Neber et al., 2006). Deterministic models built in this way are qualitative and subjective in areas of low data density. They offer the advantage of ease of use and the ability to influence geological interpretation based on implicit geological knowledge.

In addition to geological layers represented as their top and base elevations, geological layers can be represented as regular shapes of different dimensions known as voxels. Voxels allow stochastic models to be generated where the presence of a geological layer and its physical properties can be statistically derived by probabilistic modelling (Kearsey et al., 2015). Stochastic models are quantitative and objective; based on statistical probability of occurrence of a given geological layer or a specified physical property (e.g. grain size, permeability, density). The choice of geological modelling approach is influenced by geological complexity, cost, data type, time and application. Deterministic models have been proven to be widely applicable to geological modelling in the shallow subsurface (< 100 m below ground level) where geological layers are typically engineering soils or weak rocks and complexity related to geological folding and faulting is low.

Deterministic 3D geological models have been applied to single-resolution environmental and geotechnical problems in the UK. For example, 3D geological models have been used in city-scale (Lelliott et al., 2006) and regional (Neber et al., 2006; Van Der Meulen et al., 2013) aquifer recharge and vulnerability assessments. A site-scale 3D geological model was used to inform ground investigation and tunnel design as part of the UK's Crossrail 1 project at Farringdon, London (Aldiss

et al., 2012). In Bergen, Norway, anthropogenic deposits including archaeological deposits have been included in 3D geological models to enable the assessment of buried heritage preservation potential (de Beer et al., 2012). There are no examples in the UK where 3D geological models have been directly used to inform strategic urban plans, nor are there examples of their use to solve multiple solutions to ground characterisation. For those examples where 3D geological models have been used for single-solution problems, it is often the derived 2D outputs that are used rather than the 3D geological model data itself. This is an important consideration in the future development of a 3D UUS as it suggests that although 3D geological models may be used for visualisation, their direct use could be from their derived 2D map outputs.

1.2. Surface water infiltration as an underground UUS indicator

Infiltration sustainable drainage systems (SuDS) provide one means of mitigating the effects of excess rainfall beyond the capacity of conventional drainage systems and can therefore improve city-resilience to surface water flooding. Engineering SuDS are designed to mimic natural drainage and so manage water where it falls. By mimicking natural drainage, infiltration SuDS can mitigate the effects of excess surface water by reducing flow rates and volume, reducing reliance on piped drainage, while providing amenity value (Woods-Ballard et al., 2007). They can therefore be considered a factor in providing sustainability in urban areas and could further be considered a UUS indicator in the sense of Bobylev (2016). Infiltration SuDS including soakaways and permeable paving can attenuate surface water flow and volume by using the infiltration capacity of the subsurface. Subsurface factors controlling infiltration potential include permeability of bedrock and/or superficial deposits and depth to groundwater. Infiltration potential is measured at a site using an invasive infiltration test. The development of the British Geological Survey's (BGS) national infiltration SuDS dataset (Dearden et al., 2013) provides an opportunity to inform preliminary information on the suitability of infiltration SuDS during planning. The SuDS dataset does not replace infiltration testing but provides relevant information on ground compatibility for infiltration SuDS based on the presence of constraints to infiltration, drainage potential, geohazards and groundwater protection.

1.3. Geothermal properties as underground UUS indicators

Ground source heat pumps can be used to extract heat from the ground via a circulating refrigerant fluid and heat exchanger system (Banks, 2009). They can provide a low carbon option for building heating and/or cooling. They may be closed or open loop systems and installed horizontally or vertically. Horizontal systems are closed and often buried in shallow trenches to a depth of ~1.5 m (Busby, 2016). Vertical system may be open or closed loop systems requiring circulating water transported via a heat exchanger to distribute heat. If open loop systems are used, they make use of groundwater in subsurface aquifers either to distribute or store heat for future use.

The suitability of the ground to support the use of shallow ground source heat pumps is dependent on its thermal and hydrogeological properties and requires a relevant conceptual geological model (Busby et al., 2009). Ground to a depth of ~15 m is influenced by seasonal fluctuations in temperature. At ~15 m depth the ground temperature is equal to the mean annual air temperature. At depths below about 15 m, temperatures are affected by the heat conducted upwards from the subsurface. In the UK this creates an increase in temperature with depth of $2.8\text{ }^{\circ}\text{C}/100\text{ m}^{-1}$ (Busby et al., 2011). This geothermal gradient varies depending on the type of rock and their thermal properties. In addition, groundwater movement can create warmer conditions by transporting heat from depth or cooler conditions by transporting cool water from the surface.

Installers of ground source heat pump schemes are required to be certified by the Microgeneration Certification Scheme (MCS) and to

adhere to the Microgeneration Installation Standard: MIS 3005 (https://www.gshp.org.uk/pdf/MIS_3005_Heat_Pump_Systems.pdf).

Installers of open loop systems may also have to abide by regulations relating to the abstraction and discharge of water, determined by the Environment Agency in England, Natural Resources Wales in Wales and the Scottish Environment Protection Agency in Scotland. When designing a closed loop system it is necessary to make an estimate of the thermal conductivity of the ground and for non-domestic systems this is often accomplished with a Thermal Response Test (TRT). The test comprises creating a closed loop borehole and monitoring the temperature evolution from the inlet and outlet temperatures due to the injection of heat at a constant rate for around 50 h (e.g. Banks et al., 2013). The results of the TRT are the average thermal conductivity for the geological strata intersected by the borehole and the borehole thermal resistance. To date, conflicts between GSHP schemes has not been a major issue due to the small number of installations in the UK (although see Fry (2009) for open loop cooling scheme interference in London). Heat (and cooling) are not licensed in the UK and so it is left to planning authorities and water regulators to try and avoid interference problems between GSHP schemes.

1.4. Research objectives

The objectives of the research are to:

- Develop a 3D engineering geological ground model beneath the Earls Court development area using subsurface 1D, 2D and 3D geological and geotechnical data and information;
- Use the 3D geological model and associated geologically-based Geographic Information Systems (GIS) datasets for surface water infiltration and ground source heat potential to assess the suitability of the ground to meet proposed sustainable development land-uses in the Earls Court masterplan;
- To undertake a qualitative spatial comparison of ground compatibility and intended land-uses to identify potential subsurface ground-use opportunities and conflicts;
- To investigate a future land-use optimisation methodology that identifies the most suitable use of the ground based on its physical properties to support integrated and sustainable urban planning.

2. Site area

Capital & Counties Properties Ltd (Capco) Earls Court development site in London, UK was chosen to test the application of a 3D engineering geological ground model to support sustainable development planning in an urban context. The area was chosen as demolition works are underway at the time of writing in preparation for development, guided by the site's masterplan. The availability of subsurface, geological ground information provides an opportunity to undertake a spatial assessment of the elements of the masterplan whose successful implementation relies on compatible ground conditions for its implementation.

2.1. Site description

The site is located on the north bank of the River Thames and the elevation of the ground varies between 5 and ~8 m above Ordnance Datum (aOD), falling to ~3 m aOD; coincident with railway cuttings in the valley of Counter's Creek. The Earl's Court development area is divided into two planning zones corresponding to the Royal Borough of Kensington and Chelsea (RBKC) and the London Borough of Hammersmith and Fulham (LBHF). The development area is shown in Fig. 2 and covers a total of $320 \times 10^3\text{ m}^2$. The development will comprise mixed retail, residential, education, commercial, open space and below ground basement construction for car parking.

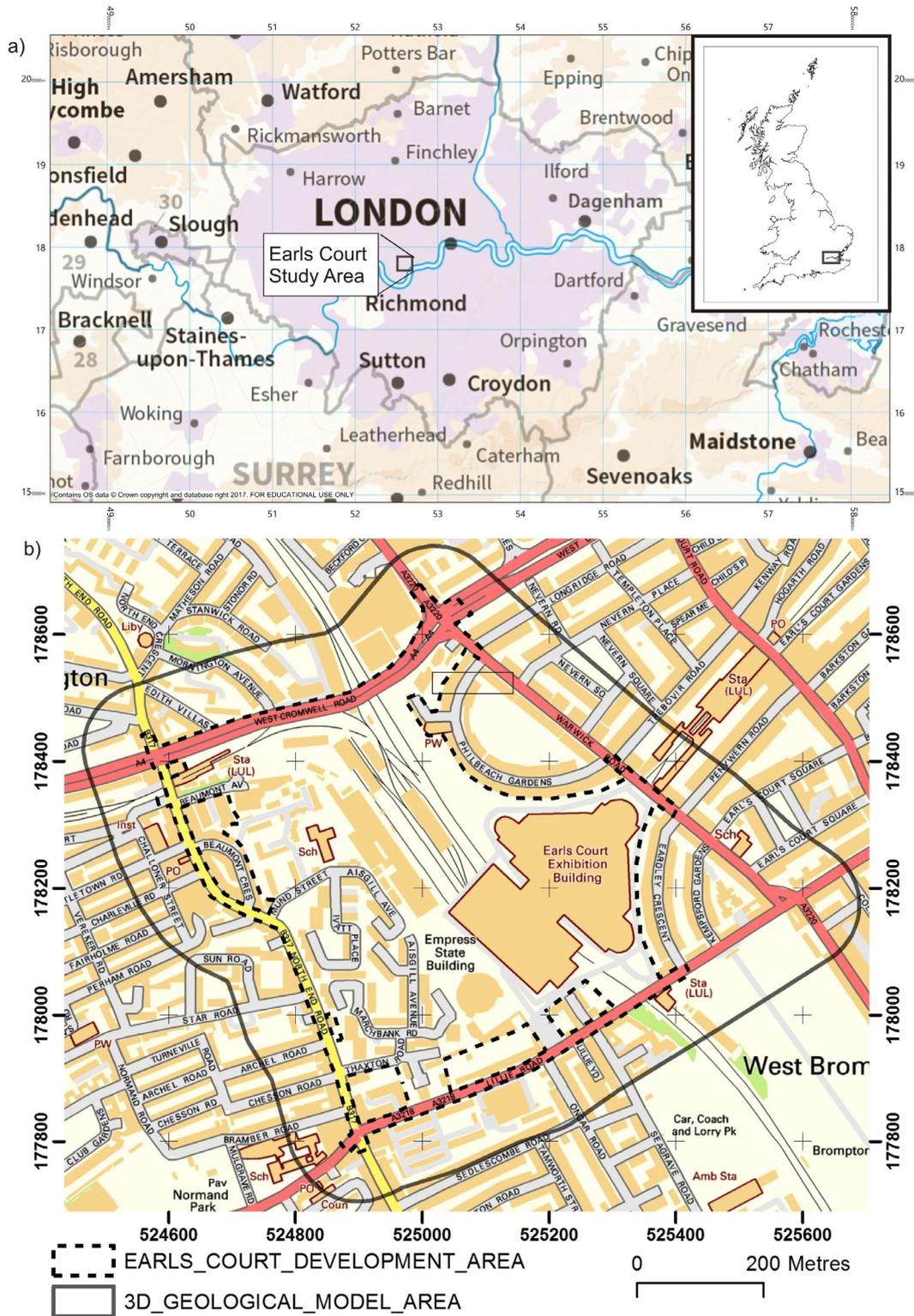


Fig. 2. Site location in Great Britain (a) and study area plan (b). British National Grid graticule. © Crown Copyright and Database Right [2017]. Ordnance Survey Digimap licence.

2.2. Earls Court masterplan

The Earls Court masterplan comprises documents that form part of the planning application submitted by EC Properties following the original design specification of Farrells architects (DP9, 2011; Farrells and Patel Taylor, 2011). A conceptual design based around four villages and a highstreet with individual districts connected by open, green

transport corridors forms the basis of the masterplan. The design objectives and the overall vision for the development are summarised in Farrells and Patel Taylor (2011).

The masterplan sets out wide-ranging principles for design of the development. Sustainability, low-carbon living, ecological diversity and human well-being are core elements of the initial design brief and the proposed development plan (DP9, 2011). The role of UUS is not

Table 2
 Engineering Geological classification of geological units interpreted to be present beneath the Earls Court site. Geological succession based on Ellison et al. (2004), Pantelidou and Simpson (2011) and Entwisle et al. (2013).

Engineering Unit	Geological Unit	Engineering Class	Characteristics	Engineering consideration
Soils Mixed soils	Very soft to stiff/ loose to dense	1	Highly variable, very soft to stiff CLAY, uncompact to compact SILT, loose to dense, SAND and GRAVEL and COBBLES including man-made materials of clinker, ashes, bricks, timber, glass metal and concrete	Highly variable ground conditions depending on content and whether it is engineered. May be contaminated. May produce explosive or noxious gases. Includes World War II high explosive bomb damage debris
	Firm to hard/ dense to very dense	2	Highly variable lithologies firm to hard CLAY, some ROCK, compact SILT, dense to very dense SAND and/or flint GRAVEL, sandy CLAY. Some shells and shelly beds, occasional calcareous nodules, occasionally organic. Lithological variation often unpredictable. Occasionally fissured	Generally good foundation material but lithological variability gives rise to variable groundwater conditions including water-bearing sands. Variability provides difficult to very difficult tunnelling and deep excavation conditions. Fissuring in clays may affect stability of cuttings. Where sand is dominant water pressures in the Thanet Sand Formation are often artesian where it is confined beneath overlying London Clay Formation. Pressurised, deoxygenated gas in Lambeth Group
Fine	Very soft to firm	3	Very soft to soft, sometimes firm, often organic CLAY with some SILT and SAND and occasional GRAVEL. Top 2–3 m may be firm to stiff as a result of desiccation	Generally compressible with bearing capacities < 100 kPa. Light foundation may be subject to variable and considerable settlement over long periods without sufficient engineering design. Dewatering produces considerable and prolonged settlement
Coarse	Firm to very stiff/hard	4	Firm to stiff becoming very stiff or hard at depth, generally fissured, brown in upper part otherwise grey CLAY and SILT, silty CLAY and clayey SILT occasional SAND, GRAVEL in upper weathered zone. Occasionally weakly-laminated. Common shell fragments, often pyritised, micaceous, gypsum and pyrite in weathered zone, occasional calcareous nodules. SILT common on fissures. Some wood fragments, occasionally present as lignite	Near-surface prone to shrink-swell behaviour affecting shallow foundations. Planting or removal of trees and surface water infiltration without engineering design, near buildings may exacerbate this. Depth of weathering and fissuring varies. Commonly brecciated. Potential effects of heaving into excavations
	Very dense to dense	5	Generally very dense to dense, sometimes loose sandy GRAVEL and gravelly SAND, sometimes clayey or silty in the upper part with local lenses of silt, clay or peat	Generally good foundation conditions. Excavations may require dewatering and are generally unstable. High water table in excavations may lead to running sand conditions

specifically addressed expect to identify the maximum depth of development below ground level. All other masterplan criteria are explicitly above ground.

The masterplan identifies environmental and sustainability goals as part of a series of planning measures to achieve the safe and efficient use of land within the development. One of five public realm strands relates to the delivery of a sustainable environment. This strand incorporates ecology and biodiversity, reduction of urban heat island effect, food production and pollution abatement. It also identifies goals to mitigate and adapt to climate change including the management of surface water. The implementation of sustainable drainage systems (SuDS) including permeable paving and infiltration basins are planned with an emphasis on increasing infiltration to the ground by managing flow rate and volume at source through surface water storage and attenuation.

A supplementary energy strategy for Earls Court identifies multiple options for heating, cooling and power generation (Lea, 2011). The preferred option is for the installation of a combined heat and power (CHP) district heating system. Based on an assessment of low yields within the underlying chalk aquifer, the report authors concluded that the ground is not suitable for the installation of ground source heat systems.

3. Methodology

The combined 3D and 2D methodology was developed to test the application of a 3D engineering geological model against three UUS indicators corresponding to materials, water and energy to be consistent with three high-level UUS indicators identified by Sterling et al. (2012) and Li et al. (2012). In this methodology, the suitability of the ground for foundations (materials), infiltration SuDS (water) and ground source heat potential (energy) are chosen as representative examples of UUS use for masterplanning.

The methodology comprises six steps:

1. Geological and geotechnical classification of individual geological layers beneath the site from published reports and 1:10 000 digital 2D geological map data;
2. Geological interpretation, classification and digitisation of 1D downhole geological and geotechnical data from existing ground investigation data and deterministic 3D geological modelling using SubsurfaceViewerMX;
3. Estimation of ground thermal properties from published 1:250 000 scale 2D geological maps and records of ground and air temperatures;
4. Spatial assessment of 2D infiltration SuDS detailed dataset based on a compilation of 24 national-scale datasets;
5. Spatial analysis of ground-use options for surface water infiltration, ground source heat potential and foundation conditions, based on the results of 3D geological modelling and 2D spatial analysis;
6. Comparison of ground use options against the Earls Court masterplan.

The methodology excludes consideration of site-specific design criteria as they rely on ground investigation and laboratory-derived design parameters. The intention of this methodology is to use readily available sources of data and information to inform decision-making prior to design-based ground investigation and laboratory testing. It also excludes an analysis of the presence, distribution and condition of existing utility and transport infrastructure including parts of London Underground.

3.1. Geological and geotechnical classification

Ground conditions beneath the site can be described initially in terms of their geological and geotechnical properties. The relationship

between geotechnical properties and geological units can be achieved using lithostratigraphy (Northmore et al., 2011). Lithostratigraphy provides a means to correlate and group together similar geological layers based on their similar composition, relative age and geological history. Lithostratigraphy therefore provides a fundamental basis for the assessment of geological ground conditions beneath a site. The variability and distribution of lithostratigraphical geological units can be assessed from 2D geological maps. The geological succession above the top of the Chalk Group beneath the site is interpreted from geological maps and the results of 3D geological modelling described in Section 4.1. Geotechnical data was compiled where it was available from borehole records or ground investigation reports. These results have been combined with geotechnical data including soil consistency, density, particle size and plasticity to establish a qualitative engineering geological classification following the methodology of Royse et al. (2009) and Dobbs et al. (2012) (Table 2).

3.2. 3D geological modelling

A 3D digital geological framework model of London, UK has been developed by the BGS (Burke et al., 2014; Mathers et al., 2014). The geological model was constructed at a scale equivalent to 1:50 000 scale 2D geological maps and comprises bedrock, superficial (Quaternary) deposits and artificial ground. It was constructed using GSI3D modelling software using the modelling procedures described by Kessler et al. (2009). Existing geological data derived from ground investigation boreholes were digitised using the method described by Burke et al. (2014). In total 7172 boreholes were considered during the construction of the geological model. In common with other geological models in urban areas, the density distribution of boreholes is uneven. As a result, the density of boreholes as control data influences the qualitative assessment of uncertainty of the geological model. In areas of lower control data density, uncertainty is generally greater than those with a high density of control data. If changes in thickness or elevation of a geological unit with distance is low, its geological complexity is considered low and fewer control points will be needed, thus offsetting the need for a greater number of borehole control points.

The London LithoFrame50 geological model provided a regional assessment of likely ground conditions beneath Earls Court. The density of digitised boreholes considered in the LithoFrame50 model, in addition to cross-section spacing > 1 km, meant that there was insufficient model coverage when applied at the development site-scale. To attempt to mitigate this uncertainty and make use of additional ground investigation data, a higher resolution 3D geological ground model of the Earls Court development site was constructed using SubsurfaceViewerMX, version 6.0.25.

3.2.1. 3D geological modelling methodology

SubsurfaceViewerMX requires geological data to be digitised and processed into software-specific file formats. The files and their metadata are presented in Table 3.

3.2.1.1. Borehole digitisation. The SubsurfaceViewerMX modelling methodology requires subsurface geological data in the form of depths below ground level of points corresponding to the top and base of each geological unit that has been intersected during borehole drilling or trial pit excavation. Records of historical boreholes and trial pits were selected and digitised from scanned PDF records. Non-confidential, publicly accessible records were accessed from the BGS Single Onshore Borehole Index, via the BGS Geology of Britain Map Viewer. These data were supplemented by borehole records derived from Concept Site Investigations (2014). The number and maximum depth of drilling of the boreholes considered is shown in Fig. 3.

Borehole index data recording names, geographic location in cartesian, x, y coordinates of the British National Grid and start height elevation relative to m aOD at the time of drilling were digitised.

Table 3
Data source files for 3D geological modelling using SubsurfaceViewerMX.

SubsurfaceViewerMX file	Metadata
Digital Terrain Model (DTM)	Ordnance Survey (OS) 1:10 000 scale OS Terrain 5 dataset. 5 m post resolution, 1.5 m root mean square error (RMSE) for elevation data in urban areas. Converted from ASCII to TIN format. © Crown Copyright and Database Right [2016]. Ordnance Survey Digimap licence
Bedrock, superficial and artificial ground geology	British Geological Survey (BGS) DigMap50 dataset (1:50 000 scale). ESRI shapefile format. Contains public sector information licensed under the Open Government Licence v3.0
Borehole Index file	Boreholes interpreted and digitised from BGS Single Onshore Borehole Index. ESRI shapefile format. Start height elevation data in metres above ordnance datum (m aOD), recorded from boreholes or where missing derived from OS Terrain 5 data. Contains public sector information licensed under the Open Government Licence v3.0
Borehole Geology file	Boreholes interpreted and digitised in part using scanned PDF images accessed from the BGS Geology of Britain Viewer, March and April 2016
Generalised Vertical Section file	Constructed using the stratigraphical scheme described in Burke et al. (2014) , Mathers et al. (2014) and Ellison et al. (2004)
Model legend file	Derived and updated from BGS LithoFrame50 3D geological model
Topographic mapping	OS street view accessed March 2016. Raster GRID format © Crown Copyright and Database Right [2016]. Ordnance Survey Digimap licence

Geological data derived from borehole records were digitised using the lithological coding scheme of [Cooper, Kessler and Ford \(2006\)](#), based on the scheme in [Table 2](#). Lithostratigraphical names for geological units were derived from the BGS Lexicon of Named Rock Units and [Burke et al. \(2014\)](#), [Mathers et al. \(2014\)](#) and [Ellison et al. \(2004\)](#). 96 borehole records were digitised.

3.2.1.2. Geological profile construction. The construction of a grid of intersecting geological ground profiles provides the geological framework with which to construct a 3D geological model using SubsurfaceViewerMX. 96 borehole records were considered to create 22 intersecting northwest-southeast and northeast-southwest geological profile sections spaced ~50 m apart ([Fig. 4](#)). The Ordnance Survey Terrain 5 digital terrain model (DTM) was used to represent the existing ground surface and so cap the ground profiles.

Each geological unit above the top surface of the Chalk Group (equivalent to the base of the Thanet Sand Formation) was digitally correlated between borehole records in turn using the engineering geological scheme presented in [Table 2](#). Nodes were placed during correlation at borehole intersections using an iterative density sufficient to define the geometry and stratigraphical relationships of each geological unit. Each node is automatically attributed with geological unit, elevation (metres above OD) and geographic position in terms of

easting and northing. Digital surfaces exported from the BGS London LithoFrame50 geological model were imported in GOCAD™ .ts format and referenced during profile construction.

Boreholes deeper than 10 m were prioritised for inclusion in the profiles to provide the best opportunity for the greatest number of geological unit intersections. Boreholes were correlated based on their geographic position and recorded or DTM-derived start height elevations. 34% of the boreholes considered used start height elevations derived from the DTM. The elevations of the boreholes were compared to the DTM during modelling to assess the influence of anthropogenic changes in ground surface elevation since the date of drilling. Where borehole start heights occurred below the DTM and whose start height elevation was interpreted to be accurate, anthropogenic ground level increase was inferred and Made Ground was interpreted. Conversely, anthropogenic ground lowering through excavation was interpreted where boreholes occurred above the DTM and their position and start height elevation were accurate.

3.2.1.3. Distribution of geological units. The surface and subsurface distribution of each geological unit was interpreted using the relative position of nodes on geological profiles. The distribution of each geological unit was defined in turn with reference to units above and below. Geological map data from DigMapGB10, was used to interpret

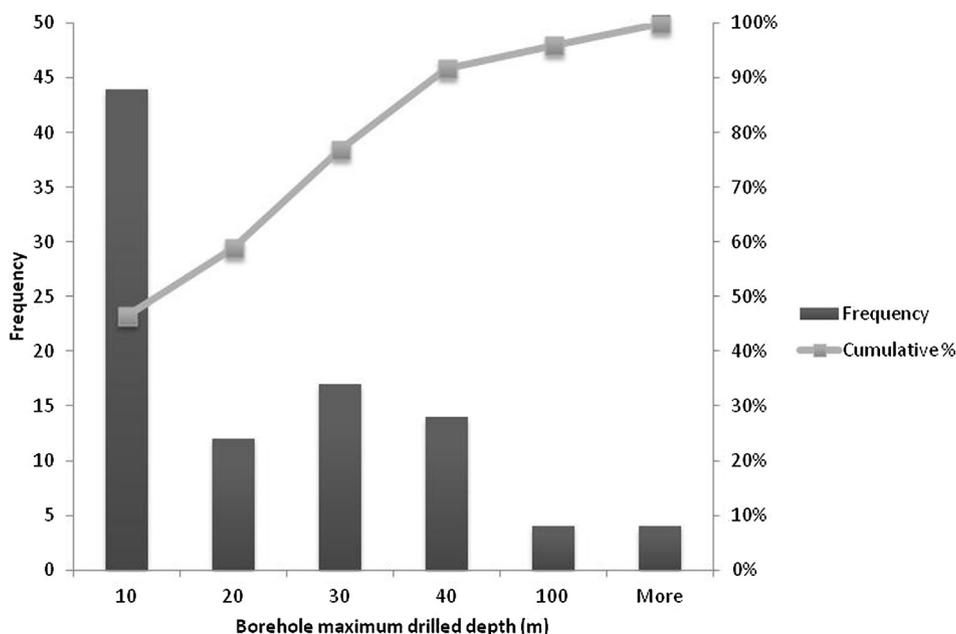


Fig. 3. Maximum depth of drilling and frequency distribution for boreholes considered in the Earls Court 3D geological model.

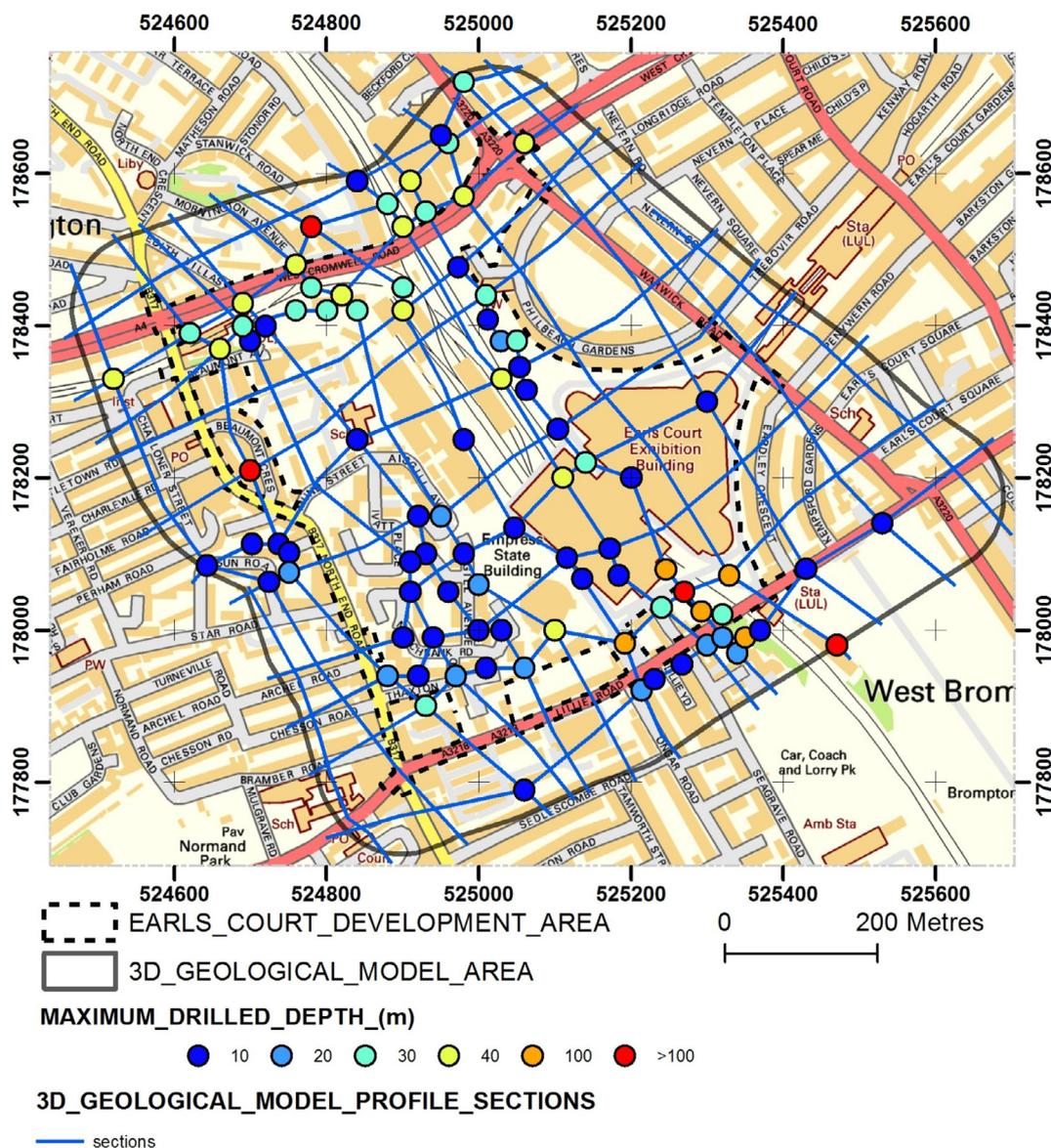


Fig. 4. Location and orientation of geological profile sections in Earls Court used for 3D geological modelling. Boreholes classified according to maximum drilled depth (metres below ground level). Geological Map Data © NERC 2017. © Crown Copyright and Database Right [2017]. Ordnance Survey Digimap licence.

the distribution of surface layers. The distribution of subsurface layers was determined by their combined correlation extent shown on geological profiles.

3.2.1.4. *Geological model calculation.* Nodes representing each geological unit in addition to their surface and subsurface distribution were used to calculate the geological model. The option to refine Triangular Irregular Networks (TINs) was selected and a minimum thickness of 0.5 m was chosen. The resulting geological model is defined in terms of a stack of triangulated irregular network (TIN) grids representing the base and top of each unit. Each geological unit was exported from the model in ASCII and ESRI grid format.

3.3. *Ground source heat potential*

The temperature of the ground determines the temperature gradient within the collector loops of ground source heat pumps. Surface ground temperatures are determined by the air temperature and are influenced by daily and seasonal variations (Busby et al., 2009). Mean site temperature was estimated using a model based on the 30-year station

averages published on the UK Meteorological Office (UKMO) web site (www.metoffice.gov.uk). The annual temperature variation is transmitted into the soil layer, but rapidly reduces in amplitude (Busby et al., 2009). The annual temperature variation at 3.5 m depth will be about one quarter that at the surface. Soil temperatures at depth have been estimated using a soil diffusivity of $0.05 \text{ m}^2 \text{ day}^{-1}$. At depths below about 15 m temperatures are affected by the small amount of heat conducted upwards from the subsurface. In the UK this creates an increase of temperature with depth that has an average value of $2.6 \text{ }^\circ\text{C per } 100 \text{ m}$ (Busby et al., 2009). This geothermal gradient will vary depending upon the nature of the rocks and their thermal properties. In addition, moving groundwater can create warmer regions by transporting heat from depth; or cooler regions when cold water flows down from near the ground surface. Estimates of the temperatures at 100 and 200 m depths have been made from an estimate of the local heat flow and the thermal conductivity of the bedrock geology shown on the 1:250 000 scale geological map. Anomalies caused by flowing groundwater have not been included.

The rate at which heat is exchanged between the collector loop of a ground source heat pump and the ground is determined mainly by the

thermal properties of the earth. Thermal conductivity is the capacity of a material to conduct heat, while thermal diffusivity describes the rate at which heat is conducted. For a horizontal loop system in a trench, the properties of superficial deposits are important whilst for a vertical loop system, bedrock properties are important.

Thermal conductivity varies by a factor of more than two ($1.5\text{--}3.5\text{ W m}^{-1}\text{ K}^{-1}$) for the range of common rocks encountered at the surface and can vary significantly for many superficial deposits (Busby et al., 2009). The thermal conductivity of superficial deposits and soils depends on the nature of the deposit, the bulk porosity of the soil and the degree of saturation. An approximate guide to the thermal conductivity of a superficial deposit can be made using a simple classification based on soil particle size and composition. Deposits containing silt or clay portions have higher thermal conductivities than those of unsaturated clean granular sand. Clean sands have a low thermal conductivity when dry but a higher value when saturated. Typical values for the thermal diffusivity of bedrock range from about $0.065\text{ m}^2\text{ day}^{-1}$ for clay-rich rock to about $0.17\text{ m}^2\text{ day}^{-1}$ for high conductivity rocks such as quartzites. Many rocks have thermal diffusivities in the range $0.077\text{--}0.103\text{ m}^2\text{ day}^{-1}$.

3.4. Infiltration SuDS

The Earls Court masterplan prioritises infiltration SuDS, including permeable paving, bioretention planters and infiltration ponds, to facilitate the collection of surface water and its infiltration into the ground. This philosophy is consistent with the priorities set out in the Floods and Water Management Act 2010 (HMSO, 2010).

To test the suitability of the ground for infiltration SuDS, the BGS's infiltration SuDS detailed dataset was used (Dearden, 2011). The infiltration SuDS dataset integrates twenty-four layers of digital 2D spatial geological and hydrogeological data in a geographical information system (GIS) to evaluate the potential of the ground to accommodate infiltration. The full infiltration SuDS methodology is described in Dearden (2011) and Dearden et al. (2013). The assessment is based on the spatial relationships between different geospatial datasets at a scale of 1:50 000 with a raster cell size of 50 m. The methodology is based on a scoring system to determine four categories of infiltration SuDS potential; constraints to infiltration (e.g. presence of geohazards), drainage potential, ground instability and groundwater protection. Amongst the source data used, constraints to infiltration and stability are concerned with geohazards that could be activated or worsened by infiltration SuDS. Drainage potential and impacts on water quality are concerned with soil and bedrock permeability and proximity to groundwater source protection zones. An example of the infiltration SuDS workflow for constraints to infiltration and infiltration potential is given in Fig. 5.

The dataset provides a tool to provide background information to identify initial opportunities and constraints for infiltration SuDS design. It is not intended as a replacement for site-specific investigation including infiltration testing and groundwater level measurement. Such site-specific measurements would be required to validate the analysis presented here.

4. Results

4.1. 3D geological modelling

The results of the 3D geological modelling show a layered bedrock sequence of Thanet Sand Formation, Lambeth Group and London Clay Formation above the top surface of the Chalk Group. Bedrock is in turn overlain by Quaternary sediments of the Kempton Park Gravel Member, small pockets of Alluvium and Made Ground. An anomalous thickness of material appears to overlie the Chalk Group in the northwest of the site which has been interpreted to be caused by a normal fault that downthrows $\sim 23\text{ m}$ to the northwest. The interpreted depth to the top

of the Chalk Group in this area is recorded in borehole TQ27NW31 and assumed to be correct although its age and poor quality of description above the top of the Chalk Group results in subjective uncertainty with this interpretation. A further fault zone is interpreted in the southeast part of the site. Here, a normal fault is interpreted downthrowing by $\sim 6\text{ m}$ to the northwest. The lower elevation of the top of the Chalk Group in the northwest could also be analogous to the geological rockhead anomalies described by authors including Ellison et al. (2004), Banks et al. (2015) and Berry (1979). The 3D geological model is shown in Fig. 6.

The results of the 3D geological modelling described in terms of elevation and thickness of each geological layer in 2D are summarised in Table 4 and shown in Figs. 7–9 for superficial (Quaternary), bedrock and geological structure respectively.

Each geological layer was then exported from the 3D geological model and converted to a 2D surface layer using the raster to grid function in ESRI ArcGIS.

4.1.1. Limitations of the 3D geological model

- The geological model was constructed by considering 96 borehole and trial pit records. Other geological data may be available including additional borehole data and geophysical profiles;
- The geological model was classified for engineering geology using the lithostratigraphical units. The geological model does not show 3D variability of geotechnical properties or behaviour within the lithostratigraphical units;
- Some artefacts of manual correlation may remain in the geological model which may account for small differences in thickness and elevation of the geological units. The maximum vertical uncertainty associated with this is estimated to be 1.5 m but it is interpreted that this uncertainty is acceptable for the assessment of underground resource potential at development-site scale;
- Geological faults are not included as separate model entities. Their presence, geometry and extent should be investigated during future ground investigations including validation of the depth of the top of the Chalk Group recorded in borehole TQ27NW31.

4.2. Ground source heat potential

An estimate of the temperature profile beneath Earls Court is shown in Table 5. It has been made from the mean thicknesses of the strata shown in Table 4, the thermal conductivities in Table 6, a surface heat flow of 0.055 W m^{-2} and a mean annual air temperature of $10.5\text{ }^\circ\text{C}$ estimated from the UK Meteorological Office 30-year station average. The estimated values of thermal conductivity and diffusivity shown in Table 6 were used to create a geothermal classification which was then applied to the 3D geological model shown in Fig. 6.

Groundwater flow controlled by the transmissivity of geological material, may also influence temperature gradient and determine the suitability of a site for the use of open-loop geothermal systems. Potential groundwater yields for each geological unit are reported in Hoare Lea (2011). Reported yields are estimated to be low except in sands and gravelly sands of the Thanet Sand Formation and the fine-grained Chalk Group rocks; the latter dependant on groundwater flow through fissures. Yields within the low-permeability London Clay Formation are likely to be low although small yields may be obtained in sand or silty-sand units within it.

4.3. Infiltration SuDS

The results of the GIS infiltration SuDS analysis are presented as summary layers in Fig. 10 and described below.

4.3.1. Infiltration constraints

Infiltration constraints include an assessment of any geological or

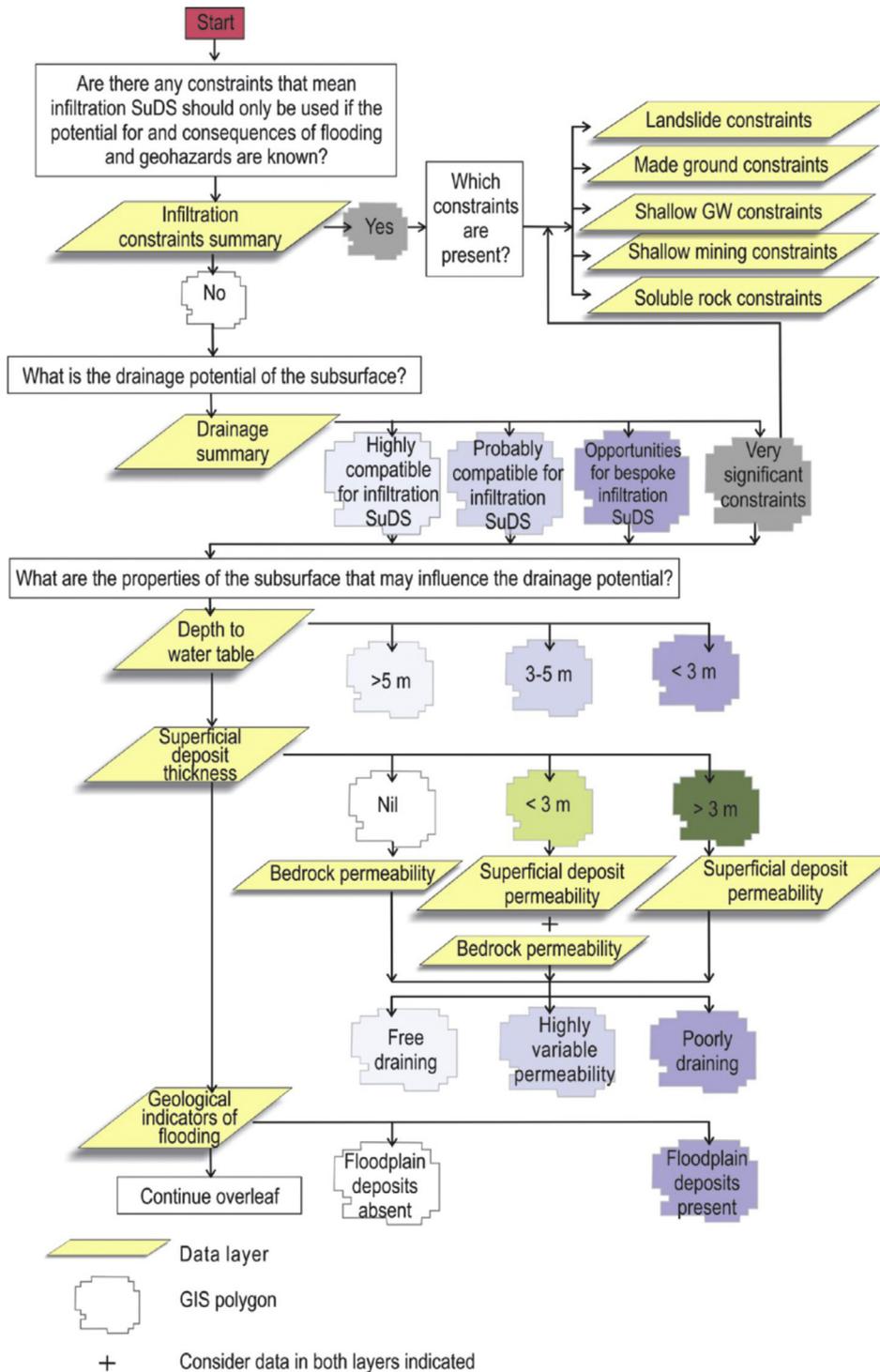


Fig. 5. Example GIS infiltration SuDS methodology and workflow for infiltration constraints and drainage potential after Dearden (2011).

hydrogeological factors that could be initiated or worsened by the installation of infiltration SuDS. These include ground instability in the form of landslides or soluble rocks, the presence of potentially contaminated material and depth to groundwater.

The results of the 2D analysis show that very significant constraints are present related to the interpreted potential for persistent or seasonally high shallow groundwater within the Kempton Park Gravel Member. Depth to groundwater is interpreted to be < 3 mbgl across the entire development site. At least 1 m of unsaturated zone thickness is required between the base of an infiltration SuDS and groundwater. In addition, increased infiltration may cause a temporary rise in water

table which has the potential to inundate current or planned subsurface developments. In these cases, infiltration SuDS should only be considered where an assessment of the potential for or consequences of the installation are designed and accounted for.

4.3.2. Drainage potential

The assessment of drainage potential considers the extent to which surface water could infiltrate into the ground. The factors considered include depth to groundwater, thickness and permeability of geological superficial deposits, bedrock permeability and geological indicators of flooding.

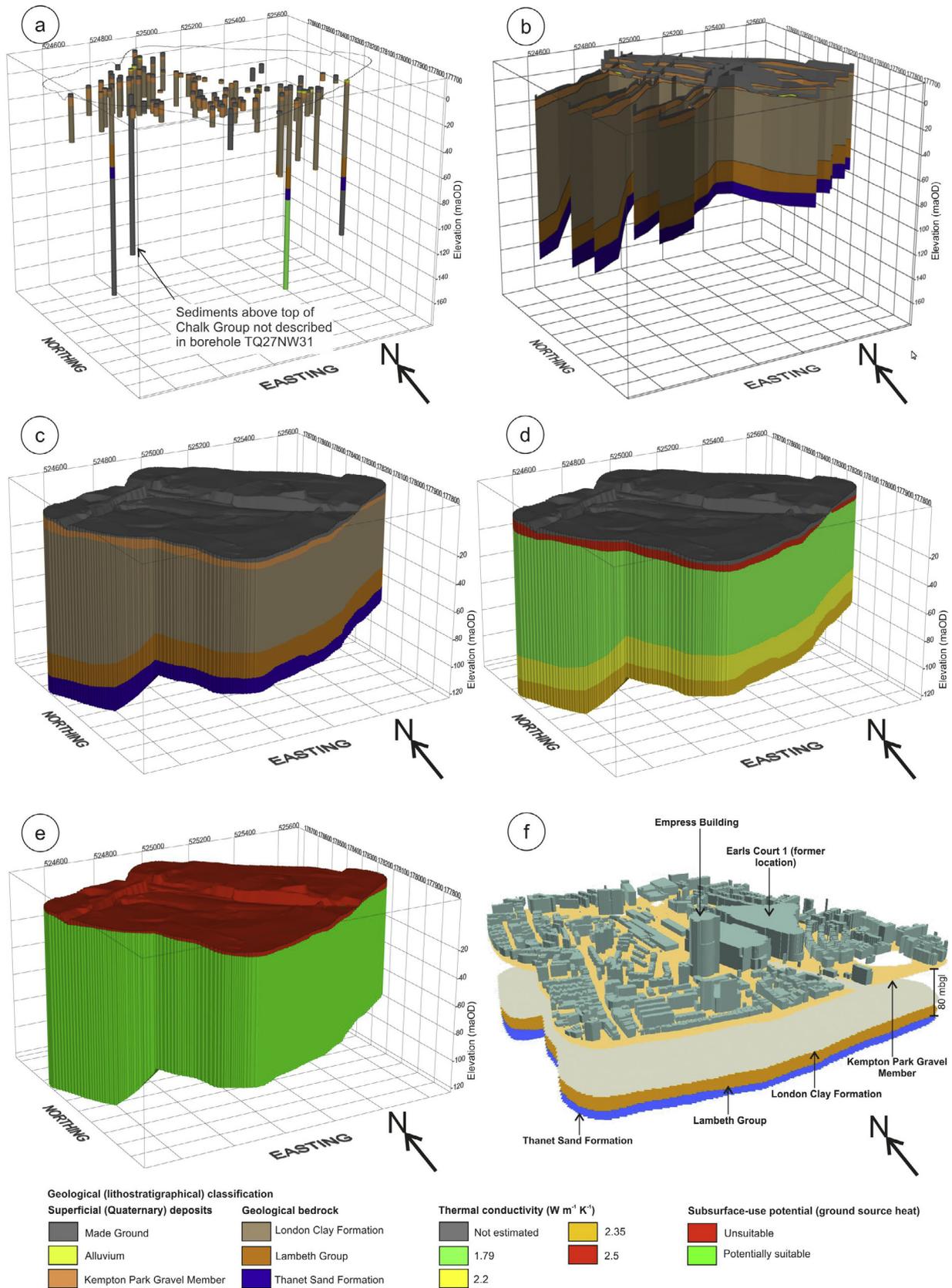


Fig. 6. 3D geological model visualisation of Earls Court. (a) Boreholes viewed in SubsurfaceViewerMX, (b) Selected cross-section profiles viewed in SubsurfaceViewerMX, (c) 3D volumetric model classified according to lithostratigraphy, (d) 3D volumetric model classified according to thermal conductivity, (e) Example of ground-use potential; 3D volumetric model classified according to ground source heat potential and (f) base elevation of selected geological units beneath pre-development 3D building visualisation viewed in ESRI's ArcScene. maOD (metres above Ordnance Datum), mbgl (metres below ground level). Vertical Exaggeration in (a) to (e) $\times 5$. Geological Map Data © NERC 2017. © Crown Copyright and Database Right [2017]. Ordnance Survey Digimap licence.

Table 4

Interpreted thickness and base elevation derived from the 3D geological ground model. Geological rockhead comprises the combined units of Made Ground, Kempton Park Gravel Member and Rockhead Anomaly. Standard deviation for the base elevations of London Clay Formation, Lambeth Group and Thanet Sand Formation influenced by their representation with steep geological dip in the position of an inferred normal beneath the northwest corner of the project area.

Geological unit	Unit base elevation (m aOD)				Unit thickness (m)			
	Max	Min	Mean	Std Dev	Max	Min	Mean	Std Dev
Made Ground	6.93	−3.76	2.81	1.46	12.24	< 0.1	3.40	2.04
Alluvium	4.78	0.13	2.03	1.16	2.01	< 0.1	0.76	0.52
Kempton Park Gravel Member	4.03	−5.86	−0.89	2.02	9.56	< 0.1	3.77	1.67
London Clay Formation	−51.06	−92.23	−60.40	9.3	89.92	48.60	59.45	8.46
Lambeth Group	−66.43	−110.79	−77.20	9.21	20.56	11.98	16.78	0.90
Thanet Sand Formation	−76.71	−123.25	−87.61	10.73	17.54	8.32	10.39	1.86
Geological rockhead	4.19	−5.86	−0.81	2.03	–	–	–	–

The 2D analysis show that there are very significant constraints to infiltration across much of the site associated with depth to groundwater interpreted to be < 3 m in the Kempton Park Gravel Member. Opportunities for bespoke infiltration might exist where depth to groundwater in the Kempton Park Gravel Member might be > 3 m when measured, dependant on site-specific ground condition. In addition, the permeability of the London Clay Formation is low and there are geological indicators of flooding. The latter may result in reduced function of infiltration systems through groundwater inundation.

4.3.3. Ground stability

Ground stability considers the presence of geological hazards that could be worsened or initiated by the installation of infiltration SuDS. It includes the assessment of compressibility, collapsibility, landslides, soluble rocks, running sand, shrink-swell, shallow non-coal mining.

The results show that there is potential for geohazards to be affected by the installation of infiltration SuDS and significant potential where two or more geohazards coincide spatially. There is significant potential for compressible ground associated with Made Ground and potential for running sands is associated with the Kempton Park Gravel Member. There is significant potential for swelling clays within the London Clay Formation.

The analysis shows that the geohazard associated with swelling clays is more significant where the Kempton Park Gravel Member is interpreted to be < 3 m thick. Swelling clays may heave where moisture content is increased through an infiltration system. Swelling clay-rich deposits may be considered unsuitable for infiltration systems requiring rapid drainage such as soakaways. Infiltration systems that require a larger infiltration area, water storage or slow infiltration may be appropriate however (Dearden, 2011). These systems could be combined with a secondary land-use such as recreational areas where they could be designed for high-return period events.

4.3.4. Groundwater protection

This criterion considers proximity to the UK's Environment Agency Source Protection Zones (SPZ), presence of potentially contaminated made ground and predominant groundwater flow mechanism through the unsaturated zone.

The results of the analysis show that there are very significant constraints beneath the former Earls Court site associated with the presence of potentially contaminated Made Ground. The results of the 3D geological modelling show that Made Ground is present over much of the site although its site-specific potential for contamination is not known.

5. Synthesis and discussion

The requirement for increased use of the urban subsurface is likely to drive a future need for integrated subsurface spatial planning. Planning for the use of UUS based on the (hydro)geological properties of the ground provides a framework to optimise subsurface uses by

matching proposed uses to compatible geological layers. The methodology presented here provides a means of establishing potentially suitable ground properties to support development planning based on available 2D and 3D geological datasets. The results of the spatial analysis are synthesised below in terms of their potential to assess the suitability of the ground for foundations, ground source heat and surface water infiltration.

5.1. Foundation conditions

The suitability of the ground for foundations is dependent on geotechnical, design-specific criteria including development type, structural design and foundation type. The methodology presented here identifies the potential use of the ground for shallow and deep foundations using an approach that considers lithology, consistency and/or density. Types of foundation and specifications for earthworks are not included in the Earls Court masterplan. The preliminary assessment is included here to test the potential application of a 3D geological model to identify the thickness and geometry of potentially suitable engineering soil or rock that could inform initial design proposals and does not replace site-specific ground investigation.

The geotechnical classification of the 3D geological model shows that dense sandy gravel and gravelly sand of the Kempton Park Gravel Member may be suitable for shallow (spread) foundations. The Thanet Sand Formation may be suitable for deep, piled foundations but its depth of occurrence may preclude its use. The maps in Fig. 11 illustrate the interpreted depths to the top of each unit of potentially suitable layers for foundations in Earls Court.

The interpreted depth to potentially suitable foundation layers beneath the site is intended to guide early decision-making influencing the foundation type design, geometry and suitability. Depth and engineering geological classification provide early-stage design constraints which data can be integrated with an assessment of soil-based parameters that influence engineering soil strength and stiffness to determine soil bearing capacity.

There is potential for shallow and/or deep foundations within the London Clay Formation depending on the pile type and consideration of volume change potential. The potential for the Lambeth Group at depth is limited unless strong layers associated with hard calcretes are identified (Entwisle et al., 2013). Made Ground may be suitable where it is dense and granular and compressible materials are absent or removed. The results of the modelling also highlight the potential to investigate the use of thermopiles for combined structural support and ground source heat generation or cooling. In all cases the presence of sulphate-rich groundwater may be encountered and should be considered in site-specific foundation design.

5.2. Ground source heat potential

The Earls Court energy strategy theme within the masterplan identifies ground source heat potential from vertical or horizontal loop

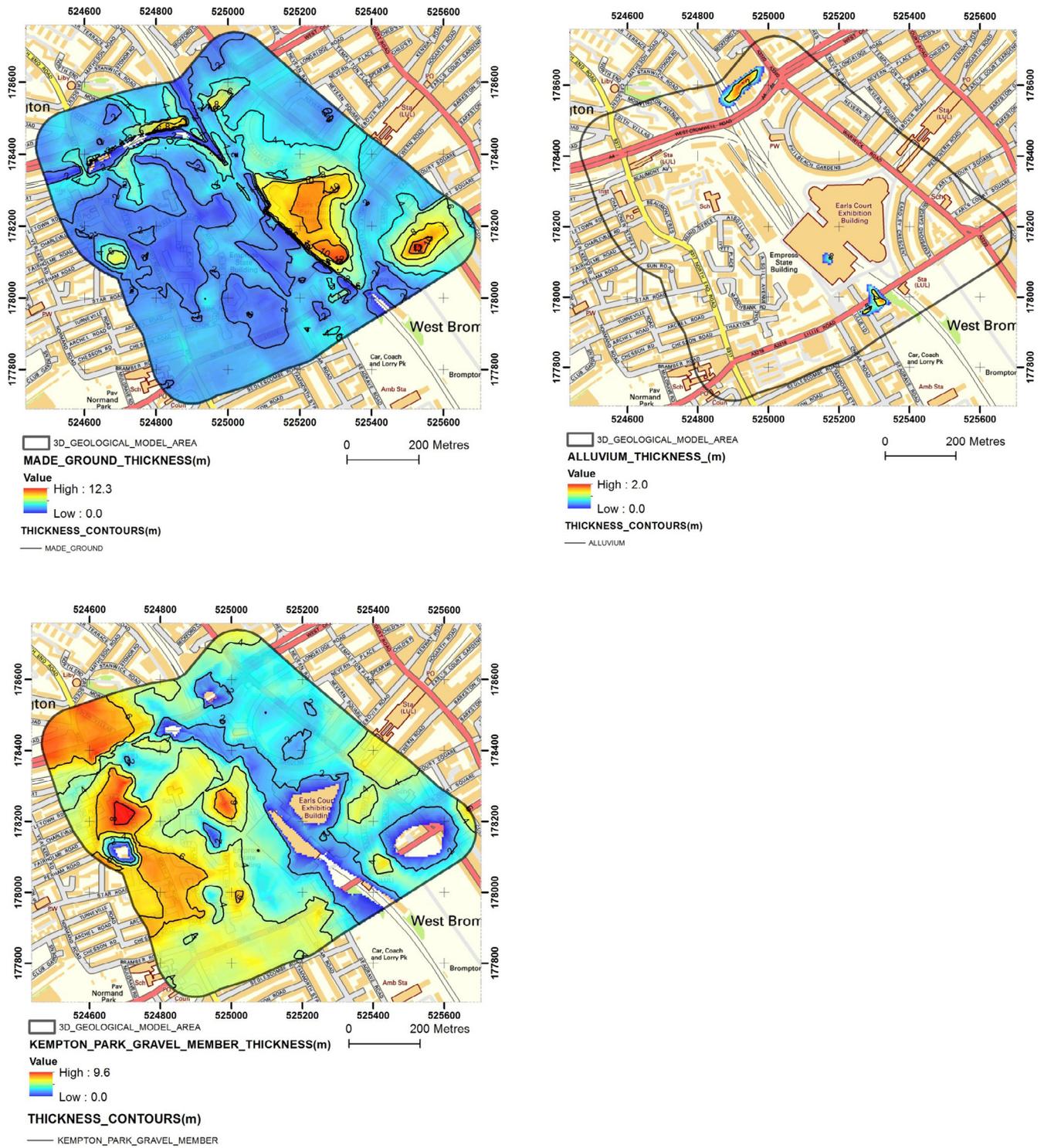


Fig. 7. Distribution and thickness maps of superficial (Quaternary) geological layers derived from the Earls Court 3D geological model; Made Ground, Alluvium and Kempton Park Gravel Member. © Crown Copyright and Database Right [2017]. Ordnance Survey Digimap licence. Unit absent where blank.

systems as one option for providing residential and commercial building heating and cooling (Lea, 2011). The highest groundwater yields required for the installation of open loop ground source heat pumps are likely to be associated with fissured chalk rocks of the Chalk Group although their yields at Earls Court are interpreted to be low (Lea, 2011). The conclusion in the Earls Court energy strategy was that the geological and hydrogeological conditions at the site were unsuitable for ground source heat pumps. The use of the Chalk Group aquifer for thermal control in London is established (Clarkson et al.,

2009) but requires site-specific ground investigation and hydraulic and thermal testing to establish its suitability for thermal control.

Concern for potential over-exploitation of the Chalk Group aquifer for thermal control prompted Birks et al. (2013) to investigate the use of alternative geological assets for thermal control. They investigated the shallow aquifer associated with Kempton Park Gravel Member as part of the development of the Tate Modern Gallery, London adjacent to the River Thames. Following the results of a detailed programme to investigate extraction-recharge potential, flow rate and groundwater

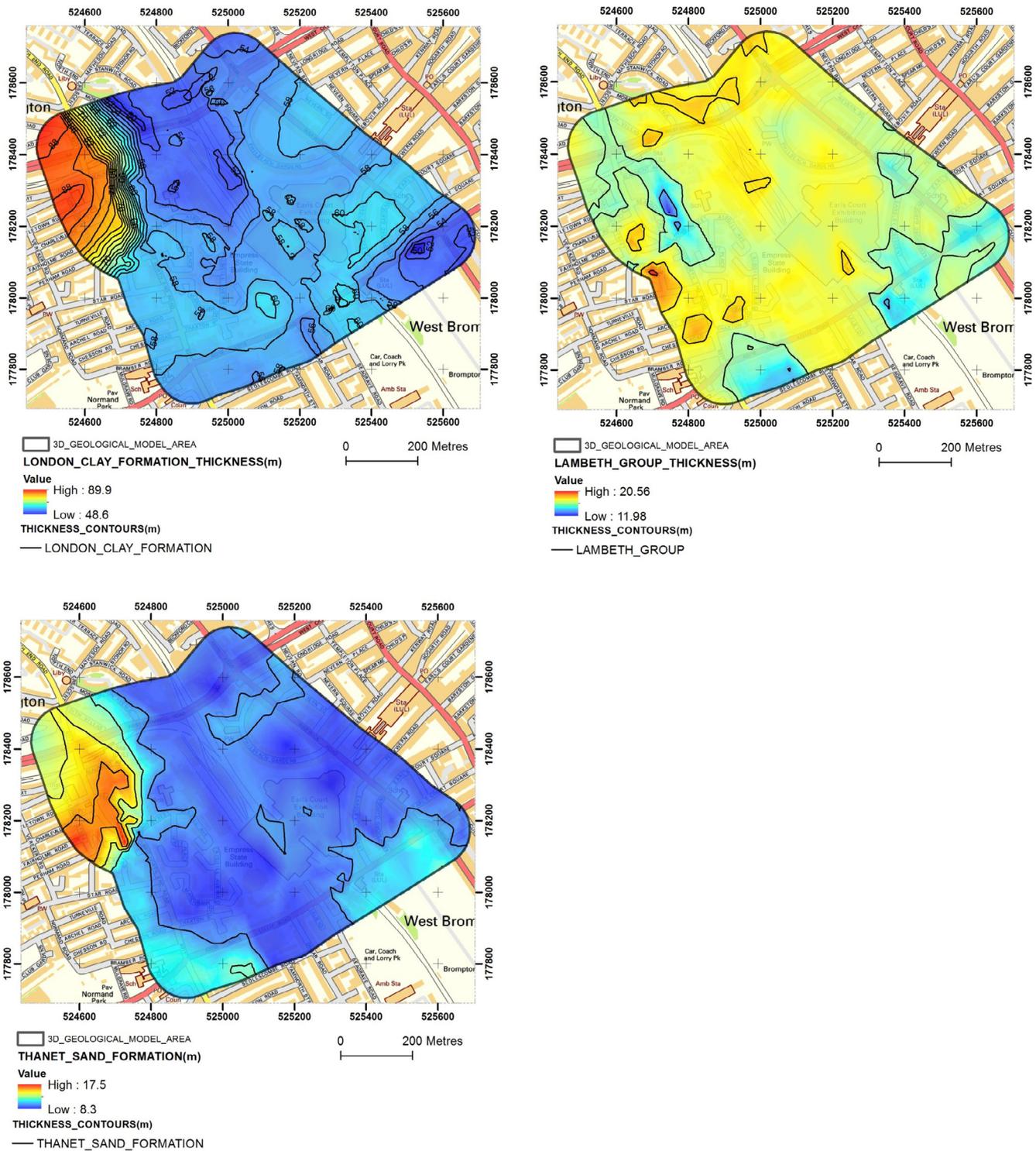


Fig. 8. Distribution and thickness maps of geological bedrock layers derived from the Earls Court 3D geological model. Extent of disturbance by the geological rockhead anomaly shown. LC – London Clay Formation, LMBE – Lambeth Group and TAB – Thanet Sand Formation. © Crown Copyright and Database Right [2017]. Ordnance Survey Digimap licence.

chemistry, the Kempton Park Gravel Member provided abstraction capacity of 40 l/s^{-1} and injection capacity of 20 l/s^{-1} . They also identified specific controls on the sustainable use of shallow aquifers for thermal control including depth and thickness of the aquifer and its permeability. As the porosity and permeability of the shallow aquifer is generally higher than that of the underlying bedrock, it has higher capacity to dissipate heat. Birks et al. (2013) concluded that there was potential for the Kempton Park Gravel Member to be used an

alternative to the Chalk Group for thermal control using open loop ground source heat systems subject to site-specific ground investigation and hydraulic testing.

The results of the 3D geological modelling and analysis of parameters for thermal diffusivity and conductivity, indicate that there may be potential for local sources of ground source heating or cooling depending on site-specific ground conditions. Yields in the shallow aquifer of the Kempton Park Gravel Member sand layers within the Lambeth

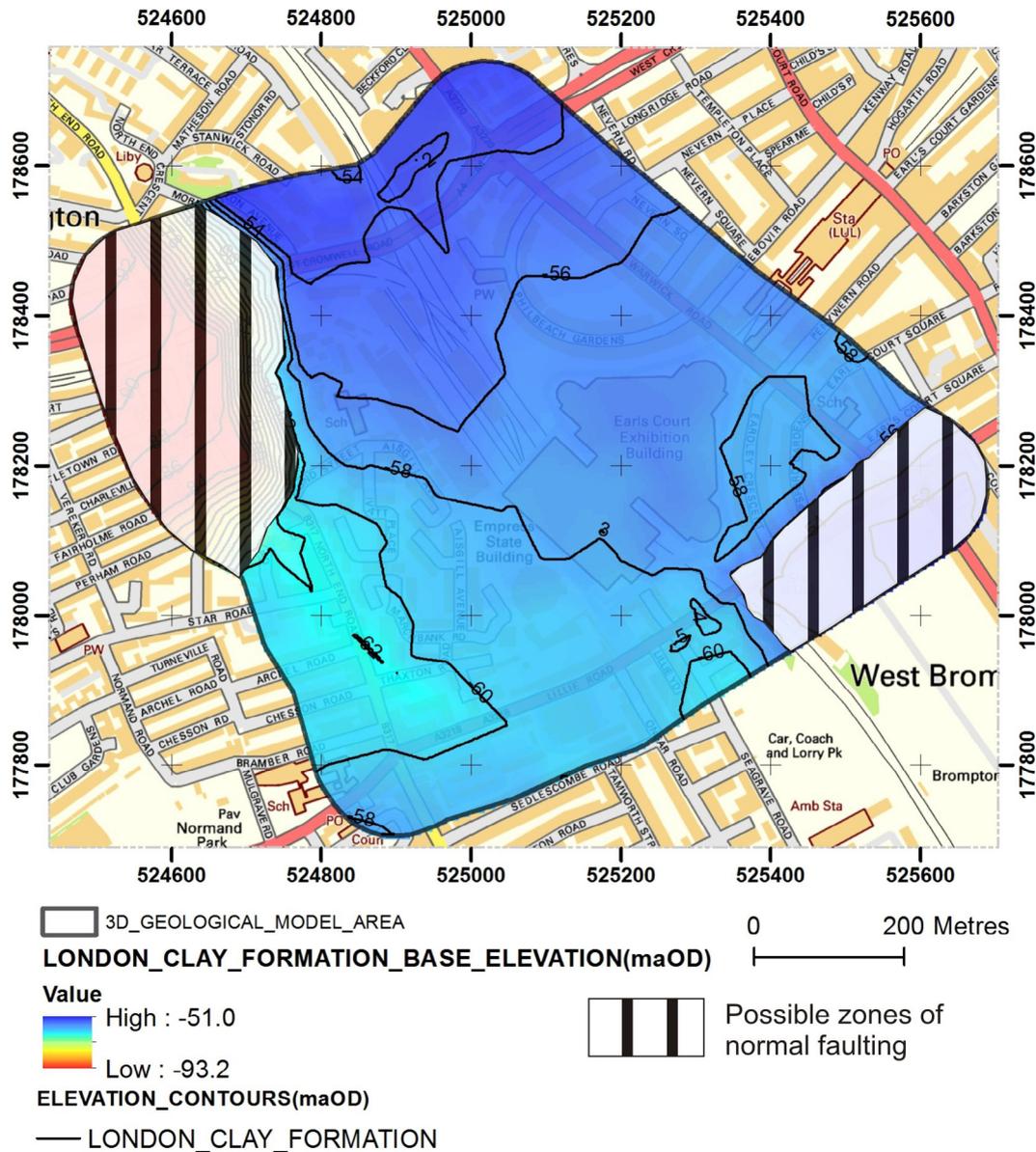


Fig. 9. Potential zones of normal faulting displacing bedrock. © Crown Copyright and Database Right [2017]. Ordnance Survey Digimap licence.

Table 5

Estimated shallow subsurface temperatures beneath Earls Court. Annual mean temperature variation based on mean January and July temperatures.

Criteria	Value (°C)
Mean annual air temperature	10.5
Mean annual temperature swing	8.3
Estimated mean soil temperature	11.5
Minimum annual soil temperature at 1 m	6
Maximum annual soil temperature at 1 m	17
Estimated temperature at 50 m depth	12
Estimated temperature at 100 m depth	13.3
Estimated temperature at 150 m depth	15.0

Table 6

Estimated thermal conductivity and thermal diffusivity for geological units in the Earls Court site. Data unavailable for Made Ground.

Geological unit	Thermal conductivity (W m ⁻¹ K ⁻¹)	Thermal diffusivity (m ² day ⁻¹)
Made Ground	–	–
Alluvium	0.91	0.042
Kempton Park Gravel Member (saturated)	2.5	0.079
Kempton Park Gravel Member (unsaturated)	0.77	0.039
London Clay Formation	1.79	0.0849
Lambeth Group	2.2	0.1078
Thanet Sand Formation	2.35	0.1074

Group and Thanet Sand Formation are interpreted to be low at the site (Lea, 2011). Yields within Alluvium and Made Ground are unknown. The London Clay Formation is interpreted as a low permeability aquiclude. As a result, the potential use of the geological units beneath the site for open-loop ground source heat pumps is low. The saturated Kempton Park Gravel Member, London Clay Formation, Lambeth Group and Thanet Sand Formation may all be suitable for closed-loop ground

source heat systems.

Installation of heat exchanger system within bored pile foundations may provide heat potential for the ground source heat systems to be installed via thermopiles if the potential of the Kempton Park Gravel Member and or/London Clay Formation is verified. Although the

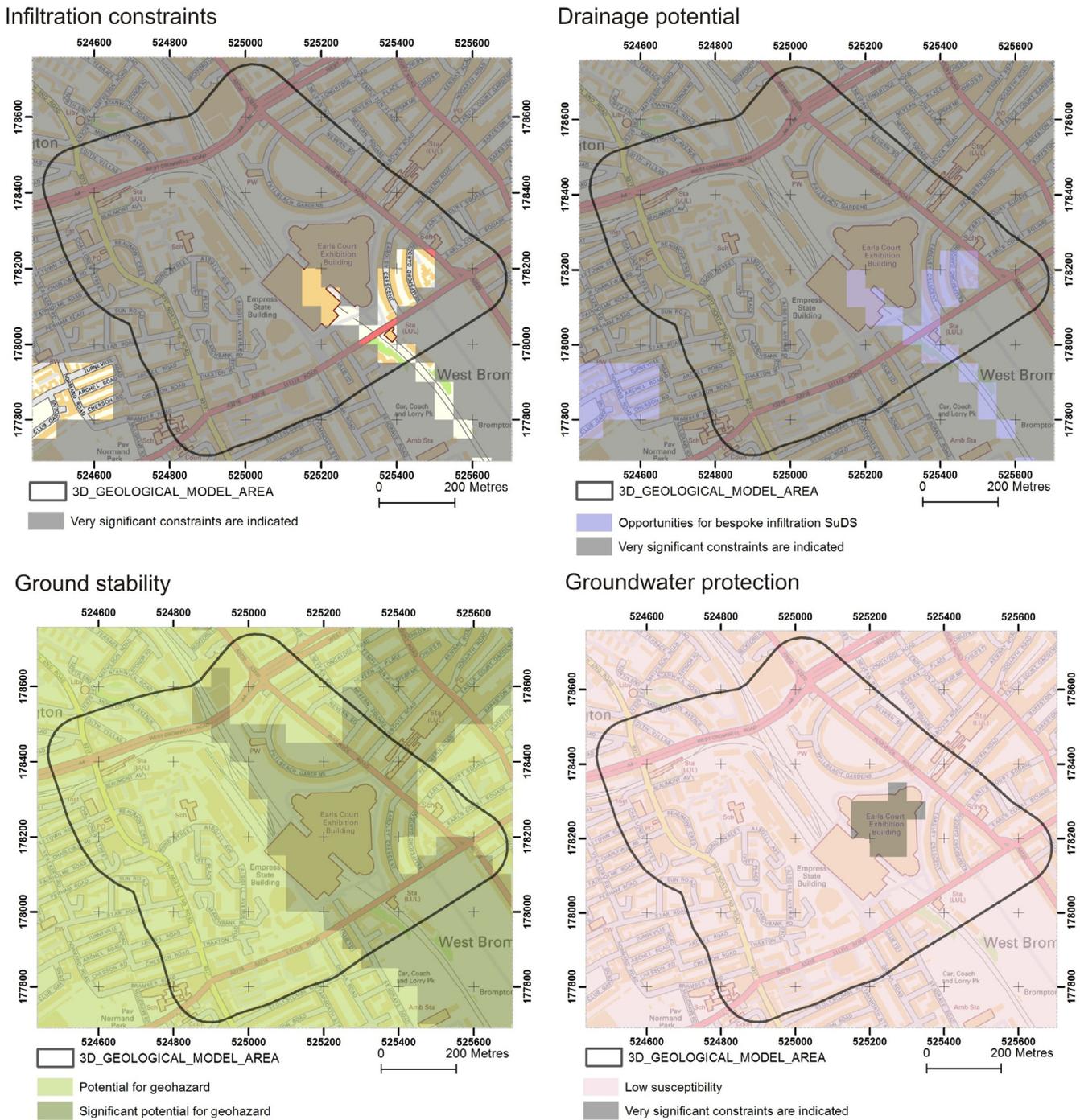


Fig. 10. Infiltration SuDS summary layers in Earls Court. Detailed datasets within each summary layer not shown. 50 m raster pixel size. © Crown Copyright and Database Right [2017]. Ordnance Survey Digimap licence. Based upon BGS Infiltration SuDS dataset, with the permission of the British Geological Survey.

thermal values given in Table 6 cannot be used to derive site-specific thermal suitability, they could have been used to investigate ground source heat potential and system design within the development area at an early design stage.

5.3. Infiltration SuDS potential

The use of infiltration SuDS as a surface water management strategy is identified within the masterplan for Earls Court as one means of delivering sustainability. The results of the 2D analysis provide a preliminary assessment for their suitability.

The analysis shows that there are constraints to the installation of

infiltration SuDS without the investigation of site-specific factors. The Kempton Park Gravel Member is potentially suitable for infiltration SuDS requiring rapid discharge to the ground providing that the depth to groundwater is assessed. Its regional hydraulic conductivity when grouped with other River Terrace deposits has a measured median of 1.7 m/day⁻¹ and mean of 19.92 m/day⁻¹ (Bricker and Bloomfield, 2014). The low permeability of the London Clay Formation means that it is poorly-draining and unsuitable for infiltration SuDS requiring rapid discharge. It may be suitable for bespoke design where slower infiltration, storage or a larger infiltration drainage area is required. Bespoke design must also consider the volume change potential of the London Clay Formation whose susceptibility to shrink-swell is an

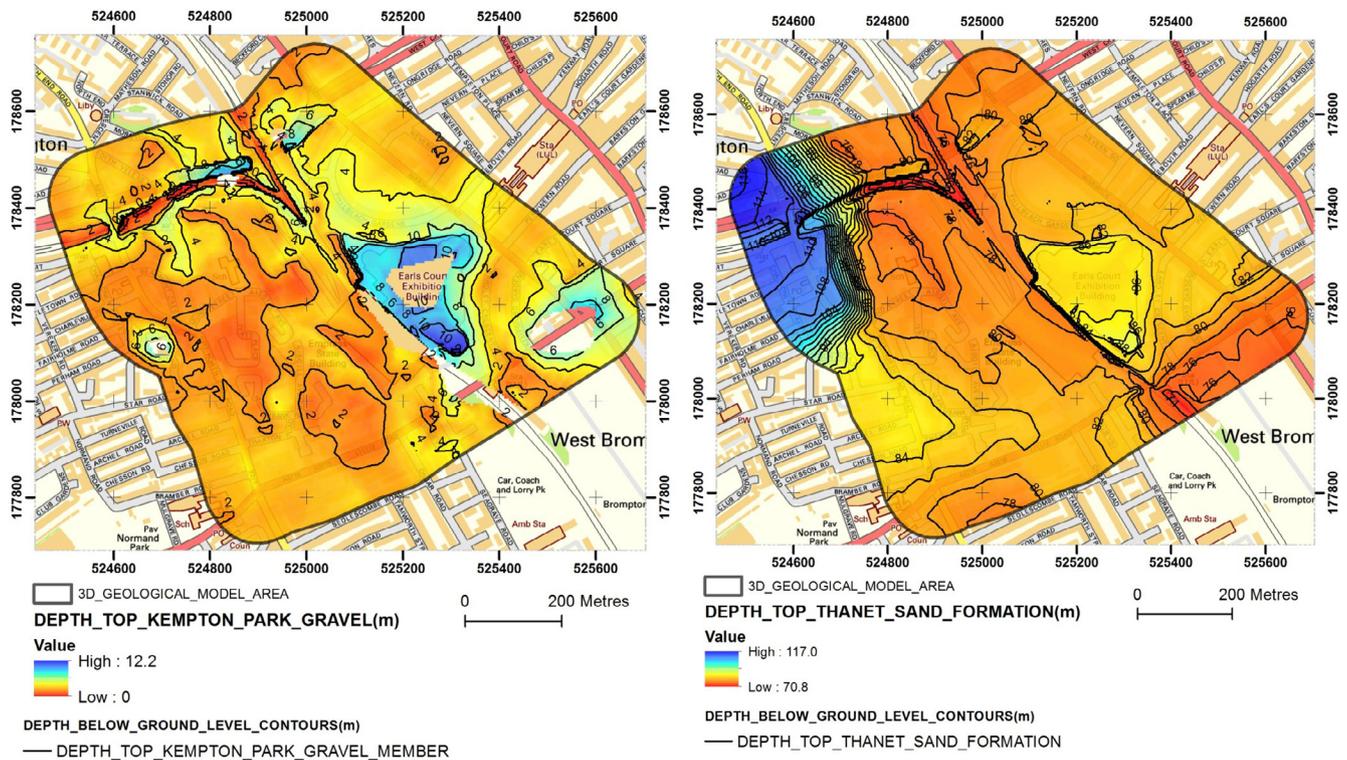


Fig. 11. Depth to the top of potential shallow foundation material (Kempton Park Gravel Member) and deep foundation material (Thanet Sand Formation). Values below 6 m for the Thanet Sand Formation are the result of small errors in the calculation of the 3D geological model near the geological Rockhead Anomaly. © Crown Copyright and Database Right [2016]. Ordnance Survey Digimap licence. Unit absent where blank.

important factor in foundation design. Design mitigation may include rafted foundations or consideration of building construction beyond a zone susceptible to ground movement.

Bespoke design could be considered where the thickness of the Kempton Park Gravel Member is greatest and if the depth to groundwater is > 3 mbgl. The Kempton Park Gravel Member is also a potential source of ground source heat where its thermal conductivity is increased by a factor of three when saturated. This may suggest that infiltration could increase the thermal conductivity of the Kempton Park Gravel Member if it is unsaturated but that the thermal performance of the system should not be compromised.

5.4. Ground-use optimisation

Considering the three UUS indicators described above, a relative assessment of ground suitability based on a qualitative assessment of their potential interactions is provided in Table 7. The ground suitability classes in Table 7 have been added to the 3D geological model to provide a 3D visualisation of relative ground-use suitability. Such an approach is consistent with protocols considered at national level in the Netherlands (de Mulder et al., 2012) and depth-related spatial zonation for UUS described by Li et al. (2012).

In relation to the Earls Court masterplan, the results demonstrate the potential for 2D, and especially 3D, (hydro)geological data to be used as a component part of a 3D UUS as advocated by Parriaux et al. (2004), Sterling et al. (2012), Bobylev (2016) and Li et al. (2016). The Earls Court masterplan makes provision for infiltration SuDS but the proposed (above ground) designs do not consider the spatial suitability of the ground to meet them. The results of the methodology described here provide information on the spatial variability in suitability of the ground for infiltration SuDS which could be included in the masterplan and used to inform preliminary design considerations.

Although the energy strategy of the Earls Court masterplan concludes that the ground is not suitable for ground source heat pumps, the results of this study demonstrate that opportunities for bespoke design may exist by using the shallow aquifer of the Kempton Park Gravel Member. The qualitative comparison of uses in Table 7 shows that the Kempton Park Gravel Member may also be suitable for infiltration SuDS and so highlights a potential negative interaction between the proposed uses.

The geology beneath the site is likely to be suitable or potentially suitable for bored pile and spread foundations depending on the site-specific load bearing and frictional strength of each geological layer. If bored piles are used, the assessment shown in Table 7 shows that are opportunities to support the use of thermopiles if they are installed in the London Clay Formation, Thanet Sand Formation or the Lambeth Group.

The results of the 3D geological modelling also show that the density of baseline borehole data used to constrain the model, is critical in determining the scale and resolution of the model for the assessment of UUS at the development-site scale. City-scale models developed in the UK (Royse et al., 2009; Campbell et al., 2010; Price et al., 2010; Mathers et al., 2014) provide 3D geological visualisations and baseline 3D data broadly equivalent to 1:50 000 scale geological maps. Despite claims that city-scale 3D models are suitable for background site appraisal (Royse et al., 2009), the results of this study show that increased source data density is needed for site-scale deterministic 3D geological modelling.

It is concluded that city-scale geological models provide a baseline 3D framework from which higher resolution 3D geological models can be developed but they cannot be used for development-site scale assessment. This is in agreement with the conclusions of Mathers et al. (2014) in consideration of the BGS London LithoFrame50 3D geological model.

Table 7

Qualitative ground-use suitability for four selected uses at Earls Court. Red – unsuitable (U), Orange – potentially suitable (P) and green – suitable (S). ND - no data available. Vertical hatching denotes not applicable due to depth at which the geological resource occurs relative to the proposed use. ¹Suitability interpreted for closed-loop ground source heat systems.

Geological unit	Potential ground-use suitability			
	Shallow Foundations	Deep Foundations	Ground source heat ¹	Infiltration SuDS
Made Ground	P		ND	U
Alluvium	U		U	U
Kempton Park Gravel Member	S		S	P
London Clay Formation	P	P	S	P
Lambeth Group		P	S	
Thanet Sand Formation		S	S	

5.5. Implications for mainstreaming underground geological resources into UUS planning

Consideration of the vertical dimension in assessing the geological suitability of the ground to satisfy sustainability criteria addresses one of the main limitations of UUS planning identified by Parriaux (2004), Bobylev (2009), and Sterling et al. (2012). 3D geological models classified according to their space, material, energy and groundwater potential, provide a means of mapping and visualising the subsurface and its underground resource potential during spatial planning for urban development. Using ground source heat potential, infiltration SuDs potential and foundation potential, it is argued here that 3D geological modelling and visualisation enables 3D mapping of underground resources as component parts of a 3D UUS. By using a qualitative spatial assessment of the (hydro)geological and thermal properties of geological layers beneath Earls Court, the methodology is shown to enhance the assessment of ground compatibility for proposed uses. Parriaux et al. (2004) show that one of the main barriers to efficient underground planning is a lack of knowledge about the potential interactions between different uses of underground geological resources. Although not tested quantitatively, the methodology presented here demonstrates the potential for quantifying the magnitude and extent of positive or negative interactions between underground resources. The development of a 3D methodology offers the potential to compliment the expert judgement-based methodology for 2D underground resource mapping for space, groundwater and geothermal energy potential applied in San Antonio, Texas (Doyle, 2016).

5.6. Limitations

The integrated 2D and 3D methodology presented here illustrates the potential for 3D geological models, classified according to their underground resource potential to be used to qualify the compatibility of different geological layers for proposed uses in support of development planning. At this stage, it is an assessment based on available 1D and 2D (hydro)geological and thermal datasets and does not use site-specific data from ground investigation and laboratory investigation that would be necessary to quantify compatibility. The relative assessment of potential interactions is also qualitative and subjective. The semi-quantitative, expert judgement system used for 2D underground resource mapping in San Antonio provides a potential method that could be integrated with the proposed methodology presented here in future work.

3D and indeed 2D geological data derived from geological maps and models remains the subjective interpretation of the geological modeller based on available data. The data used for 3D geological modelling is mainly derived from historical boreholes and is therefore limited by the age, depth of investigation and quality of description included in the borehole records. These factors contribute to uncertainty in 3D geological models. Quantification of uncertainty in the 3D geological model for Earls Court has not been assessed and so it remains a subjective interpretation based on the available borehole data.

6. Conclusions and future work

The methodology for building 3D geological models in urban areas is now well established. Case studies from the literature demonstrate that their direct application in cities tends to be where 2D outputs corresponding to the elevation and geometry of each geological layer have been derived. The results of the approach presented here also suggest that the 2D GIS outputs of 3D geological models are more easily integrated with existing 2D datasets for decision-making. Although a full 3D UUS is desirable, it is the derived 2D datasets that could provide the simplest integration with existing UUS spatial datasets.

Despite this, this research highlights the potential for 3D engineering geological models to be used in site appraisal before ground investigation, to identify underground resource potential based on a qualitative assessment the suitability of the ground for infiltration SuDS, ground source heat and foundations. Consideration of the distribution, thickness and geometry of geological layers converted from 3D to 2D provides a basis for consideration of potential UUS by allowing spatial comparison to nationally-available 2D datasets related to infiltration and geothermal potential.

This research has shown that the Kempton Park Gravel Member is suitable or potentially suitable for at least three potential ground-uses. Depending on site-specific conditions, this geological unit is likely to have high geo-asset value through potentially competing demands for foundations, ground source heat and infiltration SuDS. It highlights the potential to investigate opportunities for combined ground uses including thermopile construction.

The London Clay Formation has generally low permeability, high to very high plasticity and volume change potential (VCP) but may be potentially suitable for four uses. It is unsuitable for rapid infiltration SuDS except where bespoke engineering design that accounts for these factors could enable its use for large catchment infiltration basins for example. Engineering-based mitigation solutions could include the

establishment of building exclusion zones within which ground movements are expected or the design of bespoke foundations that account for decreasing shrink-swell behaviour with depth.

Opportunities for open-loop ground source heat systems may be limited because of low groundwater yield. The potential for installation of closed-loop systems within the saturated Kempton Park Gravel Member, London Clay Formation, Lambeth Group and Thanet Sand Formation could be investigated depending on site-specific design parameters.

The 3D spatial approach tested in the Earls Court development area provides the basis for a future methodology on which to assess and visualise the suitability of the ground for proposed uses during spatial development planning. This case study has shown that the energy and sustainability objectives described in the Earls Court masterplan could be modified by considering closed-loop geothermal energy systems and site-specific validation of slow infiltration SuDS. It is proposed that the 3D geological framework, or its derived 2D version, could be combined with quantitative UUS indicators as described by Bobylev (2016), to characterise the ground and optimise its use based on its physical properties. Such an approach could reduce the possibility of conflicting interventions in ground use including tunnelling and groundwater supply, cool surface water infiltration and soil thermal properties (Li et al., 2012; Li et al., 2013b).

Future work requires site-specific 3D geotechnical variability to be integrated with the results of the 3D geological modelling. The 3D approach can be further enhanced with visualisation and integration of anthropogenic, engineered and non-engineered structures buried in the ground. Critically, optimisation of potential subsurface uses requires consideration of the potential benefits and conflicts in uses where a geological unit is suitable for multiple uses. The semi-quantitative analysis using an Analytic Hierarchy Process approach demonstrated by Doyle (2016) could provide an opportunity to assess in 3D, multiple, potential subsurface resources, their relative value and potential interaction.

The 3D ground model should be treated as dynamic and continuously updated throughout all stages of the site development. It provides a future basis for integration with city masterplanning to ensure that the most efficient use of underground geo-assets is made to achieve above and below ground urban sustainability. Further quantitative assessment and future scenario analysis is required to quantify the likelihood and magnitude of subsurface space interactions.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.tust.2018.06.025>.

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