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The 3D characterisation of the zone of human interaction and the sustainable use of underground space in urban and peri-urban environments: case studies from the UK

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Abstract

Meeting the challenges of sustainable development and regeneration to support city growth requires the provision of attributed, 3D geological and geotechnical data, information and process understanding in the urban subsurface. This provides a framework for the characterisation of the spatial variability of the properties and processes within the shallow subsurface to aid sustainable land use planning and regeneration. The subsurface has to provide the resources and ecosystem services to sustain and create economic growth and meet societal needs, now and in the future while minimising the environmental impact of development.

The 3D variability of the ground results from anthropogenic (man-made) processes as well as geological. Human exploitation of the subsurface and rapid land use change in response to population growth and urbanisation results in temporal and spatial modification of the ground. The integration of 3D geological and anthropogenic deposits models is therefore essential for the characterisation of urban ‘zone of human interaction’ and its response to anthropogenic environmental change. Model integration to aid land use planning has been applied in the formerly heavily industrialised cities of NW England and Northern Ireland to provide a basis for linear transport assessment, urban planning and the assessment of aquifer vulnerability.

Keywords: urban regeneration, GSI3D, 3D modelling, GIS, Anthropocene, artificial ground

Introduction

This paper was written following a presentation given at the 6th European Congress on Regional Geoscientific Cartography and Information Systems (EUREGEO) in Munich, Germany in June 2009. The original paper presented the results of applied 3D geological modelling between the major urban areas of Manchester and Liverpool in NW England (Price et al., 2008a; Terrington et al., 2008; Burke et al., 2009a; Burke et al., 2009b), Figures 1 and 2. The paper presented the application of 3D geological modelling to underpin sustainable urban regeneration and environmental decision making in one of the major population centres of the UK. The paper and presentation focused on the application of 3D geological models of superficial deposits to the assessment of urban aquifer vulnerability overlying the Sherwood Sandstone aquifer (Lelliott et al., 2006; Price et al., 2008b) This paper expands the scope of the original to illustrate applications of 3D geological models to management of the geological and anthropogenic subsurface in UK urban environments. It aims to illustrate how applied, 3D geoscientific data is being used to manage and visualise the shallow (generally less than 100 m below ground level) urban subsurface and its properties in support of spatial planning, sustainable development and regeneration.

The Zone of Human Interaction and the Anthropocene

Over half of the world's population lives in urban areas. The interaction of people with the subsurface creates a complex anthropogenic and natural shallow earth system. The shallow geological subsurface provides a physical environment that provides people with the natural resources to extract (minerals, groundwater and ground source heat for example) and with which to deposit wastes. It also provides a medium to support the construction of engineered structures and the installation of below ground utilities and underground developments. This subsurface zone of human interaction is the focus for both temporal and spatial environmental changes as a result of anthropogenic activity, especially in urban environments.

The legacy of anthropogenic processes and their impacts on the environment are a direct result of rapid population expansion and the exploitation of the earth's resources to support that growth. Anthropogenic processes result in significant modification to the urban subsurface and the resulting landforms are a critical factor in urban landscape evolution and global environmental change. Phases of anthropogenic activity take places at different rates and have different scales of impact. For example, large scale industrial activity during the 18th and 19th Centuries resulted in widespread exploitation and contamination of the ground during industrial growth, commercial and residential land use change and urban expansion associated with the Industrial Revolution. However, landscape modification as a result of human activity pre-dates this with the earliest archaeological evidence of anthropogenic constructional landforms and excavations as early human populations began to exploit their environment.

These landforms, deposits, excavations and their associated sediment fluxes, therefore provide a record of the environmental impacts of past and present human processes and their impacts within the subsurface. Defining their spatial extent and properties is important for two reasons. Firstly, anthropogenic processes and their deposits represent latest Holocene geological processes and form the constituent 'geological' units of the proposed Anthropocene Epoch (Steffen et al., 2007; Zalasiewicz et al., 2008). These deposits are a physical record of how humans have influenced the landscape including its subsurface through time and represent a form of modern geological processes acting on the Earth today. Secondly, the spatial variability in thickness, composition and consolidation of the deposits (and depth of voids) creates a potential hazard to future sustainable urban development and regeneration initiatives.

The physical evidence of human activity left in the subsurface is represented by material classified by the British Geological Survey (BGS) as 'Artificial Deposits' (Powell et al., 1999; Price et al., 2004; Ford et al., 2006). These deposits have been included on 1:10 000 scale geological maps and are identified through field survey, historical map and aerial photography interpretation and borehole analysis. Culshaw (2005) identified the need for improved methods of characterisation of artificial ground (voids as well as deposits) for better risk and urban planning assessments. The widespread development and uptake of 3D geological modelling within the BGS using GSI3D software and methods (Hinze et al., 1999; Sobisch and Bombien, 2003; Kessler et al., 2008; Kessler et al., 2009) has enabled 3D geological models to be visualised and interrogated. These models include bedrock, and superficial deposits.

The development of methodologies to model the shallow subsurface in urban environments in 3D has provided a means to enhance geological models by including high resolution soils and artificial deposits. However, the characterisation of the shallow subsurface underground environment also includes infrastructure and utilities, foundations and archaeological features (the anthropogenic subsurface). This presents a significant challenge for the production of meaningful 3D models of urban underground environment (Rosenbaum, 2003).

Projects within the British Geological Survey in key urban areas including Manchester, Liverpool, Warrington, Glasgow (Merritt et al., 2007) and the Thames Gateway Redevelopment Zone (Royse et al., 2009) amongst others, have developed new methods for the 3D characterisation of artificial deposits within GSI3D. 3D models of anthropogenic deposits have been integrated with models of natural superficial deposits and bedrock, to characterise the complex variability within the anthropogenic and natural geological earth system (the zone of human interaction) to support planning and sustainable development.

Geoenvironmental ground conditions in urban environments and the application of 3D models to the development of an integrated subsurface management system

The management of the subsurface and provision of high quality geo-environmental information in support of urban development has two main aims. Firstly, to ensure that potentially difficult ground conditions are identified and mitigated against in engineering design and construction. Difficult ground conditions may include the presence of contaminated soils, voids and variable geotechnical properties that may result in ground instability hazards. Applied, 3D geological modelling aims to provide ground information to reduce uncertainty during ground investigation and subsequent above or below ground development. Secondly, ground information is required to quantify the potential environmental impacts of large scale development. The latter includes the assessment of potentially contaminating processes, sterilisation of ground based resources and the impacts of the introduction of utilities and engineered structures into the ground and its surrounding ecosystem.

The use and application of geo-environmental data and information to support urban development and regeneration in response to legislation is described by (Ellison et al., 1998; Smith and Ellison, 1999; Hough et al., 2003; Culshaw, 2005) amongst others. Rapid advances in the development and application of 3D geological models have provided novel ways of visualising and applying geo-environmental data for use in land use planning. Importantly, 3D communication tools such as the Subsurface Viewer (Terrington et al., 2009) allows non-specialist users to query and visualise 3D ground models on-the-fly.

The spatial variability within the underground environment can be analysed by visualising the 3D ground model or by deriving further 3D or 2D spatial outputs through the use of geospatial queries. This can be achieved as geological units within the 3D models take the form of volumes represented by their top and base boundaries. These volumes model and predict the distribution, thickness and geometry of geological deposits. The variability of the physical and chemical properties of each of the modelled geological units can be achieved through their classification based on the range of geotechnical, hydrogeological and geochemical property values. Examples of the application of hydrogeological attribution of 3D models and their application to the assessment of aquifer vulnerability are given in Lelliott et al. (2006) and Royse et al. (2009). The integration of geotechnical property data to attribute 3D geological models can be applied as a predictive decision-support tool to provide solutions to specific ground engineering problems prior to development. Geotechnical property attribution of 3D models to predict variability in ground conditions to assess their suitability for foundations has been applied in the Thames Gateway Redevelopment Zone Royse et al. (2009) for example.

Attributed, 3D models of the shallow geological subsurface can therefore provide the framework for the characterisation and sustainable use and exploitation of subsurface environment. However, the shallow geological underground environment should be recognised as not only comprising geological (including artificial deposits) material but also other anthropogenic structures including infrastructure, utilities, basements and foundations (the zone of human interaction). It should also be recognised that in the deeper subsurface, mining activity, groundwater abstraction and even petroleum exploration should be included within the zone of human interaction, where man has interacted with the natural earth system. The use of the underground environment, its resources and the processes that operate within it, need to be used in a sustainable way. Integration of subsurface infrastructure, utilities and archaeological deposits with 3D geological, hydrogeological and geotechnical models provides a basis from which to manage the subsurface through land use planning. Selected examples of the application of some these techniques are given in this paper.

3D Geological modelling of artificial deposits and the anthropogenic shallow subsurface in NW England

In north-west England, artificial ground research has focused on the urban areas of Manchester, Warrington and Liverpool, forming a major urban regeneration area referred to as the 'Mersey Corridor' (Figure 2). These areas are all linked by the Manchester Ship Canal constructed in the late 19th century. The region is now the focus of major urban redevelopment. Major redevelopment initiatives include the creation of MediaCityUK in Salford, the new Mersey Crossing between Runcorn and Widnes and major regeneration of the Kings Dock as part of the 'Wirral Waterfront' development in Liverpool. Manchester city centre was the focus of major regeneration in response to the Commonwealth Games in 2002 and the destruction of parts of the city centre through terrorist bombing in 1996. The Mersey Corridor area was the focus for rapid industrialisation and urban growth during the 17th and 18th Centuries. The industrial activity of the area centered around coal mining, petrochemicals, docklands and textiles (including bleaching and dyeing). The focus of 3D modelling and ground characterisation in the area was to develop new methods of 3D modelling using GSI3D and Geographic Information Systems (GIS) to characterise the legacy of artificial deposits left behind as a result of industrialisation and land use change and integrate them with models of natural superficial deposits and bedrock.

Classification of artificial ground

An enhanced artificial ground classification scheme based on the genetic origin of the feature and its morphology was devised by Ford et al. (2006) following the classification scheme of Rosenbaum (2003) and McMillan and Powell (1999). The artificial ground classification scheme consists of five primary subdivisions, each represented on 1:10 000 and 1:50 000 scale geological maps its own unique legend (Figure 3). These are: Made Ground (e.g. road and railway embankments); Worked Ground (e.g. canals, quarries and pits); Infilled Ground (Worked and Made Ground, e.g. backfilled gravel pits); Landscaped Ground (e.g. golf courses) and Disturbed Ground (such as old bell pits for coal extraction), Table 1.

Ford et al (2006) devised a new artificial ground classification scheme, where the five primary classes of artificial ground were subdivided and coded to provide a higher level of detail (for example, Table 2). This addressed a client-driven need for more accurate artificial ground representation on BGS maps. Using engineered embankments as an example, a road embankment (MBRO) can be distinguished from a flood (MBFL) or railway embankment (MBRA), which allows each subclass to be viewed independently.

Artificial Ground characterisation in 3D: Warrington and Liverpool

The artificial ground represented in the Warrington and Liverpool 3D models was captured at 1:10 000 scale in a 2D GIS, linked to a variety of archival material. The primary source for artificial ground information is 1:10 560 scale historic Ordnance Survey maps, which date back to around 1850. This is the primary data source for artificial ground information, with approximately 90% of the artificial ground data derived from them. This procedure follows a similar approach to that applied for artificial deposits characterisation in the Swansea-Neath-Port-Talbot urban area of South Wales, UK by Waters et al. (2005). These maps give valuable insight into anthropogenic impacts on the urban landscape through time and provide an approximate date for changes in land use.

The historic maps were examined in chronological order in a GIS, beginning with the oldest. Where several versions of the same map existed, the map that was most accurately geo-rectified was used. The historical Ordnance Survey maps for the area range from around 1849 through to 1951, usually with one map per decade. Each historic map was superimposed upon the modern topographic map for direct comparison and areas of artificial ground were digitised in a polygon feature class within a *geodatabase*. An example of the GIS polygon data capture of an area of Worked Ground is shown in Figure 4.

Each polygon was attributed with its primary artificial ground class (Made, Worked Ground etc), and subclass (WECA, for example, for canals), and a comments field. Data source information was recorded for traceability. This was taken from the publication date of the map the artificial ground first appeared on and the map on which it last appeared to give an approximate age range. A code to highlight the potential pollution hazard associated past land use was also applied (Anon, 2000).

Difficulties in capturing artificial ground in a 2D system arose where two types of made ground from different eras overlapped one another, such as a railway cutting exploiting an older sandstone quarry. In these instances, the quarry outline and railway cutting were captured as a single polygon and attributed as a railway cutting, with the disused quarry being noted in the comments field of the attribute table. Pits that were extended through extracting material over several decades were captured as their maximum overall extent. Instances of Made Ground that appeared on the historic map but not the modern topographic map were ignored as it was unknown if the material had been reused on site or removed. Areas of Infilled Ground were identified where a pit or quarry was present on one map, but not on a later map, or where a more recent map showed a landfill site, or appeared as a level or raised area on the Digital Terrain Model (DTM) of the project area.

Finally, the modern topographic maps themselves were examined for more recent road embankments and motorways etc. that post-date the historic maps. Other datasets were also examined in the GIS, including landfill site records held by the BGS, dating up to 1975; a DTM of the region and geologists' field slips.

For the Warrington artificial ground study within the Mersey Corridor area, 80 1:10 560 scale historic maps were examined and 767 instances of artificial ground were recorded within the project area of approximately 70 km^2. The Mersey Corridor project in Liverpool is still in progress and at the time of writing, 2000 artificial ground polygons have been digitised. The thickness of Artificial Deposits is generally less than 5 m but is occasionally up to 13 m thick.

Incorporating artificial ground into the 3D model

Geological modelling of artificial deposits in the project area was carried out using GSI3D modelling software (Kessler et al., 2008) The software and its workflow allow the user to create 3D geological models by combining interpreted digital borehole data, Digital Terrain Models (DTMs) and digital geological maps to construct an intersecting grid of cross-sections. From the series of intersecting cross-sections, the surface and subsurface distribution of each geological deposit is then defined and the geological model is calculated to derive the 3D distribution, geometry and elevation of each geological deposit.

Modelling artificial deposits in 3D required modifications to the GSI3D methodology. There were two reasons for this. Firstly, artificial deposits (especially areas of Worked Ground and Infilled Ground) have generally regular geometries. Definition of these geometries in GSI3D requires the user to digitise ‘helper’ sections to constrain them. This is often time consuming and not practical for city-scale 3D modelling. Secondly, artificial deposits proved in boreholes that did not lie along the length of a cross-section used to constrain the 3D model, would not be included in the 3D model algorithm.

The derived outputs of the artificial ground data capture in 2D were used to define the distribution of artificial deposits within the 3D model. This data was then combined with the thickness of artificial deposits proved in all boreholes. Where boreholes proving Made Ground, Infilled Ground or Landscaped Ground coincided with cross-sections used to define the model, they were correlated using the GSI3D methodology. Borehole points located off lines of section were included and the thickness of artificial deposits was calculated and integrated with the 3D model (Figure 5). In the Warrington area for example, 559 boreholes and excavations in the recorded 1 m or more of Made Ground.

Worked Ground was modelled in a similar way, except that in areas devoid of borehole information, an average depth of excavation was calculated and applied to the 3D model. This procedure could be further improved by the inclusion of observed or recorded depths of excavations from other historic records. This was beyond the scope of this study however. No areas of Disturbed Ground were modelled.

Case studies

Historic topographic maps show how the River Mersey in Warrington has been diverted through anthropogenic activity with the construction of the Manchester Ship Canal. To aid navigation, meander loops have been cut off and the river has been diverted to a more direct route. Figure 6 shows that the original course of the River Mersey has been diverted and completely back-filled in places, where it is often obscured by developments such as housing. Furthermore, the Mersey and Irwell Canal has been constructed and later back-filled when it fell into disuse. These examples of artificial ground are completely absent on the modern Ordnance Survey map, yet they have implications for modern redevelopment, such as potentially unstable fill material in the canal and meander loop and possible contaminants in the canal-bed sediments.

Historic maps of the Liverpool docks area show that the docks have been built out approximately 700 m from the original foreshore (Figure 7). The original shoreline is represented on 1:10 560 scale maps published in 1850. The 1894 map of the area shows the docks as they are depicted on the modern 1:10 000 scale topographical map. This represents a large -scale urban expansion of Liverpool during those 50 years and its establishment as a major port. The docks have been captured as Made

Ground as they have been built out from the original foreshore. Without detailed documentation and at this scale of modelling it is impossible to represent areas which were actually excavated.

The historic maps also show that the docks themselves have been extensively altered. Figure 8 shows the extent of the docks around the Liverpool Kingsway Tunnel entrance in 1851 in comparison to the present day. For the purposes of this study, only the modern outline was captured due to the complexity of representing multiple generations of excavation work and backfilling in detail at 1:10 000 scale. One way to address this would be to capture artificial ground information as a series of layers, with each layer representing a different time period. This could include much older archaeological information, but could also be updated with up-to-date information as and when it becomes available.

The Woolston Eyes Deposit Grounds, located between the River Mersey and the Manchester Ship Canal in Warrington, have been used as a disposal area for dredged material from the Manchester Ship Canal since the 1920s. Figure 9 shows that the spoil heaps are clearly visible on the NextMap DTM sub-sampled to 25 m resolution. A meander loop of the River Mersey has been cut off by the Manchester Ship Canal and its fill level is regulated. The area has become an important area for wildlife, particularly bird species, and has been assigned SSSI status.

Future work

Artificial deposits using an integrated GIS – GSI3D methodology provides a 3D framework for modelling the anthropogenic landscape evolution of NW England and its impact on the spatial variability on subsurface ground conditions (Figure 10). This artificial ground study has given valuable insight into the history of Liverpool and Warrington, particularly with respect to the diversion of the River Mersey when the Manchester Ship Canal was constructed. However, as the artificial ground information was captured in a 2D system, the 3D model shows a single layer of artificial ground. This could be more accurately represented in three dimensions if the artificial ground data was captured from the historic maps as a series of layers relating to specific time periods. These multiple generations of artificial ground would build up a picture of the industrial legacy of Warrington and Liverpool and reflect temporal changes in land use through subsequent redevelopment in these urban landscapes. Coupled with the borehole information, the artificial ground could then be attributed with composition and displayed in the 3D model accordingly. This can be added as new information becomes available and incorporated into the 3D model.

High resolution 3D geological modelling of soils in peri-urban environments

Modelling of artificial deposits in urban environments enhances the resolution of 3D ground models for the characterisation of variability in the subsurface to support sustainable land use planning. Modelling of the shallow subsurface in peri-urban and rural areas can support sustainable agricultural and heritage land use planning. Recent work undertaken within the BGS has developed the GSI3D modelling methodology to resolve high resolution (often centimetres) soil layers in the shallow subsurface. Combined with modelling of artificial deposits, the enhanced GSI3D methodology and the resulting models provide a powerful visualisation and land management tool across the urban-rural divide.

Modelling soils in Shelford, Nottinghamshire, UK

The village of Shelford is located approximately 8 km to the east of Nottingham (Figure 1). An integrated 3D pedogenic – geological (parent material) model was developed by adapting the GSI3D modelling methodology. The principles of soil classification are very similar to how geological units are described and classified. Mapped soil units are described as soil series or groups, depending on scale, and represent the top 1 - 1.5 m of the subsurface. Vertically, soils are divided into horizons, which differ in properties such as texture, organic matter and colour. Each soil series has its characteristic sequence of vertical horizons and a certain parent material from which it is derived. This sequence enables the soil model and the geological model to be integrated Scheib and Williams (2008).

To correlate soil information in GSI3D two sets of data were used; digital soil series maps and vertical augerhole information. The augerhole data contained the thickness of horizons along with horizon codes and information on texture, Munsell colour, organic and carbonate content and stoniness. This information was used to attribute the calculated soil units. Two different approaches of building a 3D soil-geology model for the Shelford study site were investigated:

1) Using soil series map only. In Shelford, 15 soil series were mapped ranging from groundwater gley soils across the floodplain to brown soils and pelosols along and up the slope. Each soil series represent an average depth of investigation of 1.2 m. In this approach the DTM was reduced by this amount and used to calculate a “soil series volume” model, or a 3D soil series map. Descriptions of clay content and permeability of soil series were used to attribute the 15 modelled units (Figure 11 a, b).

2) Combination of augerhole data and soil series map to construct a 3D soil-horizon model. A sequence of soil horizons is similar to geological stratigraphy. Hence, auger logs were used in the same way as borehole logs. Horizon codes and their attributes such as colour were digitally interpreted and coded. The soil horizon model was constructed in the same way as conventional geological models in GSI3D (Kessler et al., 2008) but using augerhole sticks and soil series maps instead to correlate sections and envelopes of horizons. The upper most and most dominant horizon across Shelford is the Ap (ploughed topsoil ~30 cm) horizon. The thickness (30-80 cm) and property of the B (subsoil) horizons varied depending on, for example, their texture

and if they were groundwater influenced. A total of nine different horizons were correlated.

Approach 1 is overall the simplest way to include a soil layer in a 3D geological model; although it results in the information of the soil within the top 1.2 m being generalised. The second approach is much more time consuming, but will result in a much more detailed representation of the soil layers shown in Figure 11c. However, there are limitations in the visualisation of soil layers, especially if the model area is larger than 1 km^2. The calculated soil units and especially horizons will only appear as very thin blankets even when the 3D model is viewed with a large vertical exaggeration (Figure 11). Nevertheless, soil layers should be integrated with geological models for environmental or hydrological studies where soils play a vital role in decision making and impact assessments.

Geotechnical characterisation of 3D ground models for linear transport route assessment

The sustainable use of the shallow subsurface should meet two key requirements. Firstly, that above ground development takes place so that below ground resources are not sterilised. Secondly, geological factors that have the potential to cause ground stability problems (geohazards) are identified through effective ground investigation prior to the development taking place. If not considered and effectively planned for, both factors have the potential to reduce the long-term performance of above ground developments. Above ground development includes commercial, residential and industrial buildings and transport infrastructure. The suitability of the ground to support rail and road infrastructure development is a critical factor in the effective planning of the location and construction of linear routes. Attributed 3D models of the shallow subsurface have the capacity to predict the variability in geotechnical ground conditions for example to anticipate and plan for difficult ground conditions. If accounted for at an early stage in ground investigation and planning, subsequent maintenance costs associated with ground stability problems can be avoided.

In the Manchester area of the Mersey Corridor (Figure 2) an engineering geological appraisal of the 3D geological model produced in GSI3D was undertaken (Reeves et al., 2005). This process included the assessment of geotechnical data including standard penetration tests, moisture content and particle size analysis to quantify the variability inherent in the ground. This assessment was undertaken according to British Standards Institution BS 5930 (1999) to determine the grain size of the material and its strength and density. Data was derived from the BGS's National Geotechnical Database. This enabled geological deposits within the 3D model to be classified according to their predicted engineering behaviour (Figure 12a and b). The variability in ground conditions along existing or proposed linear transport routes can then be predicted by producing synthetic cross-sections through the geological model (Figure 12a). In this example, the geological and interpreted engineering geological behaviour can be predicted along the route of the Manchester – Liverpool railway. A spatial inspection of the synthetic section can aid the identification of potentially difficult ground conditions that may impact on the performance of railway subgrade. For example, to the east of the cross-section (Figure 12c) an area of Engineering Unit 1 (Table 3 - Artificial Ground – Infilled Ground) can be identified at the surface with Engineering Unit 2 (Table 3 – Alluvium-River Channel Deposits or Glaciofluvial Ice-Contact Deposits) below. This area could have problems with variable ground conditions or contamination due to the Artificial Ground at the surface and possible differential settlement because there is a mixture of soft clayey and dense gravely Alluvial deposits

A similar approach was taken using a 3D geological model developed for the Belfast area of Northern Ireland (Figure 1). In 2006 the Geological Survey of Northern Ireland, in collaboration with British Geological Survey produced a basic 3D geological model of Belfast City centre. The modelling consulted a database of over 700 coded boreholes, 300 of which were used to draw 25 cross-sections spaced at 500 m. The modelling focused on complex geometries of the superficial deposits that infill the Lagan Valley.

The geological units were attributed with applied geological information using a themed approach similar to those described by Culshaw (2005), Reeves et al. (2005) and Royse et al. (2009). The applied themes incorporated into the model include stratigraphic name, formation name, lithology, generalised engineering description of soils and rocks, ground compressibility, permeability, excavation method, deep and shallow foundation conditions.

In Belfast the presence of a soft, post glacial estuarine clay deposit locally known as ‘sleech’ provides ground engineers a significant challenge. Sleech generally has high moisture contents, is highly compressible and has a low bearing capacity and undrained shear strength, causing potential instability in deep excavations, poor trafficability, poor placement properties and high settlements (Gregory and Bell, 1989). The modelled top and basal surface of the estuarine clay deposit were exported and contoured to produce isopleths maps to show the predicted depth to competent founding strata and thickness of compressible material (Figure 13).

A linear route assessment was conducted using a synthetic section along the route of the MI motorway east of Belfast City, to identify potentially problematic ground conditions. The expected ground conditions along the M1 motorway route east of Belfast City can be visualised and assessed to display applied information such as Stratigraphy, likely compressibility, permeability, and excavatability (Figure 14).

Integration of 3D geological and buried asset models: subsurface management and the use of underground space

The 3D integration of underground utilities and infrastructure models is increasingly important for two reasons. One is that the full variability of the shallow subsurface and the zone of human interaction would not be complete without consideration of the existing use of underground space to support urban development. Secondly, integration of geological models with planned subsurface developments such as tunnels will provide a decision support tool with which to predict the 3D variability in engineering ground conditions along proposed routes. Geological models are not a replacement for ground investigation however and they are one of a number of tools that can be used for subsurface planning purposes. By characterising the full geological and anthropogenic spatial variability in the subsurface, a 3D framework can be established that could allow the potential changes in ground conditions and their impacts on subsurface infrastructure to be quantified. This is the basis of sustainable subsurface management.

Integration of geological and buried utilities models can be used to visualise the urban subsurface, but importantly can be applied to aid environmental vulnerability assessments. In an area surrounding Knowsley Industrial Park, 6 km NW of Liverpool, a geological model of superficial deposits was developed by the BGS in collaboration with the UK’s environmental regulator; the Environment Agency (Price et al., 2008b). The 3D geological model was used to assess the vulnerability of the underlying Sherwood Sandstone aquifer to potential pollution from the buried utility network. Weakly permeable superficial deposits may provide a barrier to the downward migration of potential pollutants and reduce the vulnerability of the underlying aquifer.

To assess the vulnerability of the aquifer, the 3D relationship of weakly permeable geological deposits to the buried sewerage network was assessed. Spatial GIS utilities data provided by United Utilities contained attributes allowing the spatial distribution and elevation of over 4000 pipeline segments to be determined (Figure 15). A 3D geospatial analysis was carried out to identify those parts of the sewerage network that were above the inferred highest vulnerability parts of the aquifer. These areas coincided with parts of the sewerage network that were sited either directly within the aquifer or where there were thin (less than 2.5 m) weakly permeable deposits between it and the aquifer.

Integrating the geological and buried asset models provided a basis on which to develop a hazard and prioritisation scheme to protect potentially vulnerable groundwater resources. The location and characterisation of buried utilities and infrastructure will define the future land use characteristics and use of underground space (Rogers et al., 2009).

Conclusions

3D geological modelling using software and methods such as GSI3D, provides a means of characterising the geological and engineering variability in the shallow subsurface. Geoenvironmental characterisation of the shallow subsurface and its properties in urban areas is crucial to support above and below ground sustainable development and regeneration initiatives. 3D modelling methodologies have been adapted to enable characterisation of the anthropogenic subsurface and high resolution subdivision of soils in peri-urban areas. The integration and application of artificial deposits and subsurface utilities and infrastructure forms the basis for the characterisation of the zone of human interaction. The zone of human interaction recognises that the variability of the subsurface and its properties are the result of a complex interaction of natural and anthropogenic processes. Anthropogenic processes and their impacts in the subsurface occur in direct response to population growth, urbanisation and socioeconomic development. The exploitation of the ground and its resources to support that development has often been unsustainable leaving a legacy of sterilised resources, contaminated land and coastal and water side towns and cities susceptible to future environmental change.

The 3D applied geological framework has already been applied to support land use planning and environmental decision making in the UK. Applications range from linear route assessment and foundation condition assessment with associated geotechnical attribution to aquifer vulnerability. Space for above ground development to support populations and urban growth in the future is likely to be competitive as land is used and reused. The subsurface may increasingly be used for development. Knowledge of the resource and geohazard properties of the ground can provide the evidence base to support future sustainable development. Through integration of knowledge about existing use of underground space (utilities, infrastructure etc), the suitability of the ground to be used for future developments can be assessed. The further integration of temporal earth system process (including anthropogenic) models will establish a robust framework from which the susceptibility of future towns and cities to future changes in climate, can be assessed. This approach will form the basis of a fully integrated subsurface management system.

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Figures

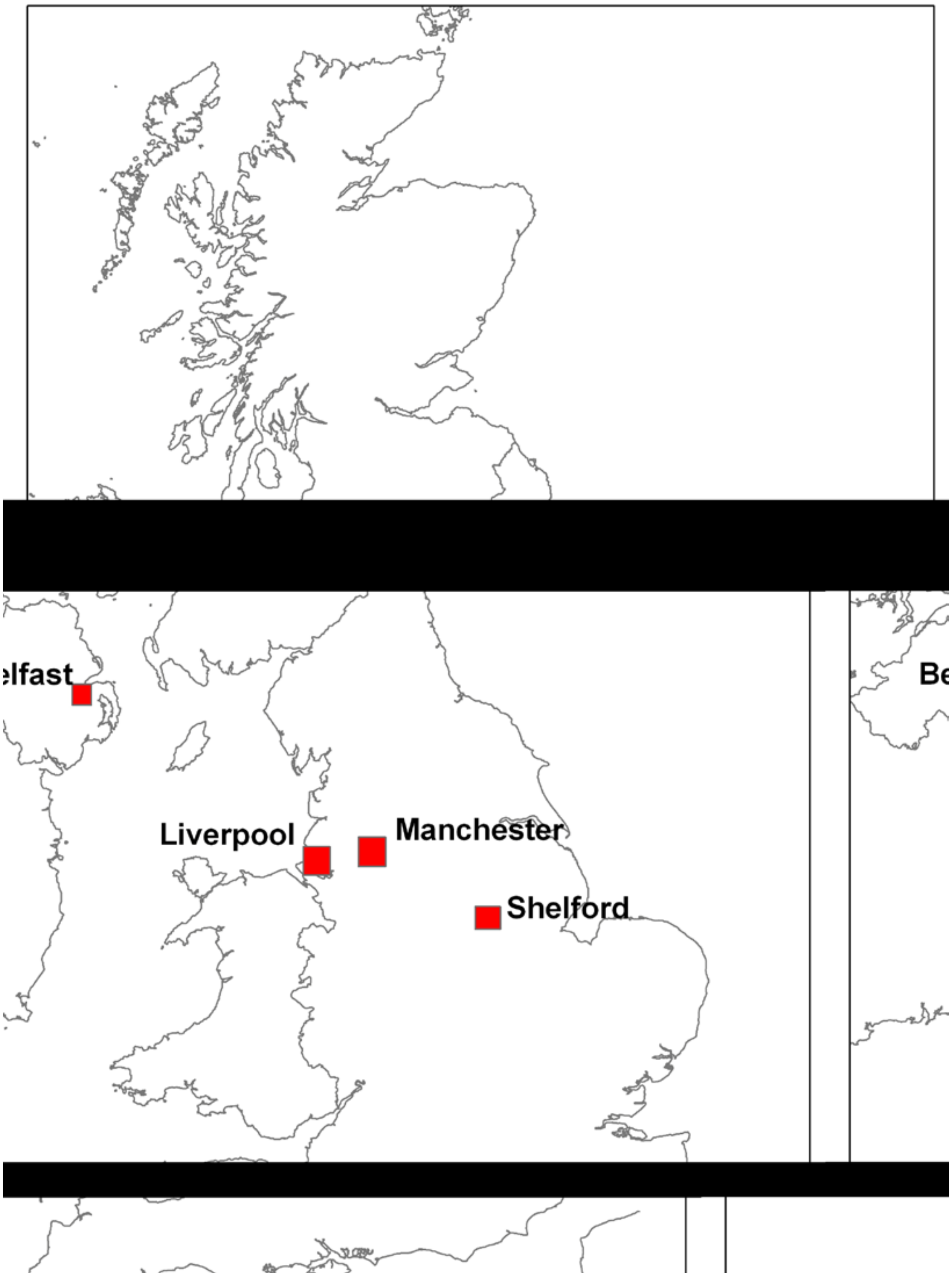

Figure 1. UK location map showing locations of places referred to in the text

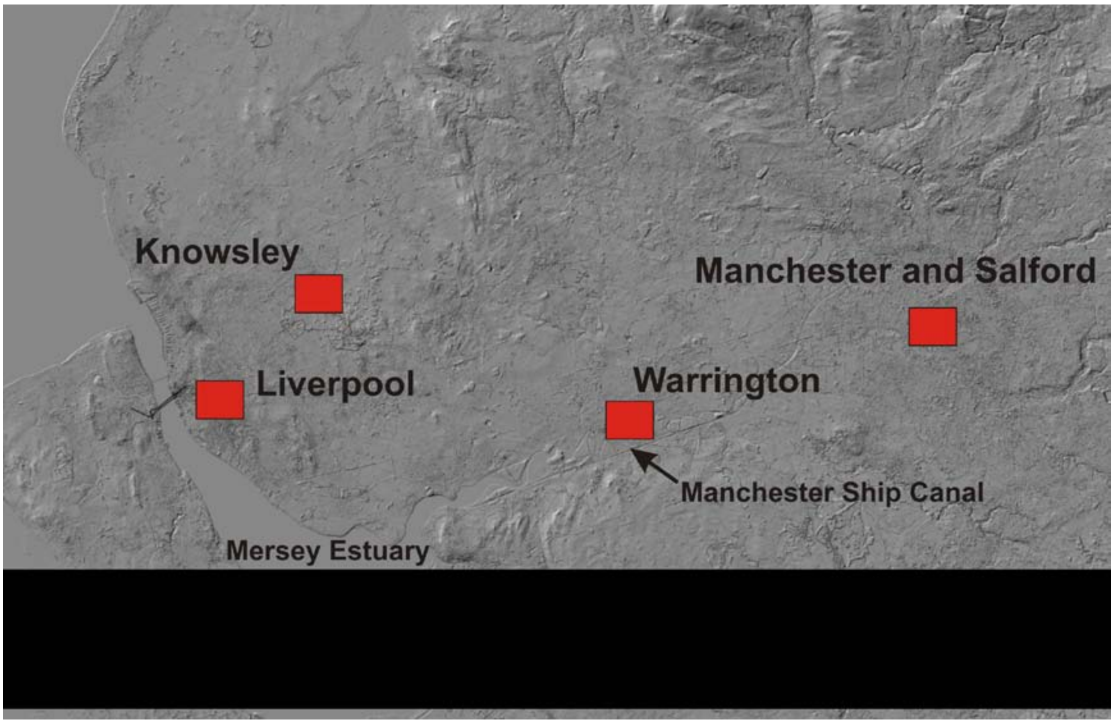

Figure 2. Location of places in NW England mentioned in the text comprising the ‘Mersey Corridor’ Development Zone. NextMap elevation data from Intermap Technologies Inc

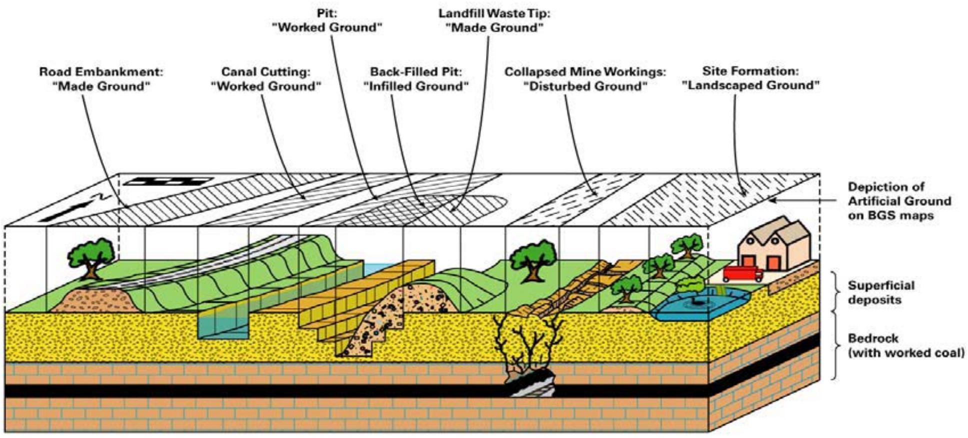

Figure 3. Examples of the main types of Artificial Ground and how they are shown on British Geological Survey maps (modified after McMillan, and Powell, 1999)

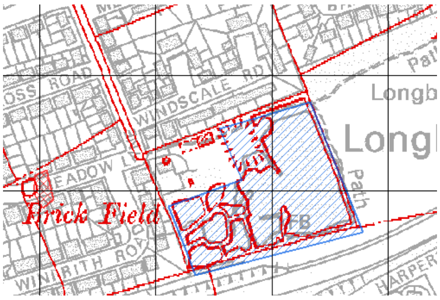

Figure 4. 1:10 000 scale modern Ordnance Survey topographic map overlain by 1:10 560 scale map Lancashire 109SW 1908 (shown in red) in Warrington. The brick pit is represented by a pond on the modern topographic map and was therefore captured as Worked Ground (blue hatched area). OS topography © Crown Copyright. All rights reserved. 100017897/2009

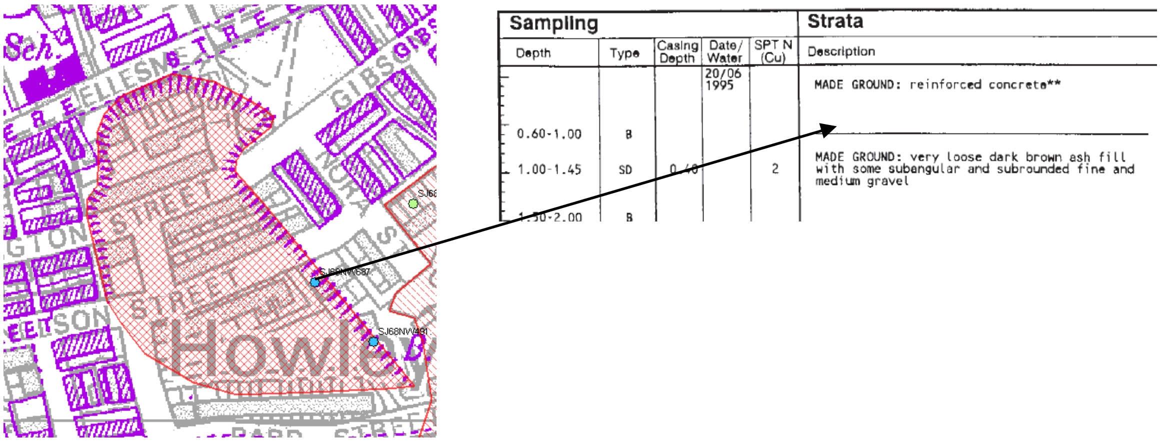

Figure 5. Example of a borehole record coincident with an area of Infilled Ground. OS topography © Crown Copyright. All rights reserved. 100017897/2009

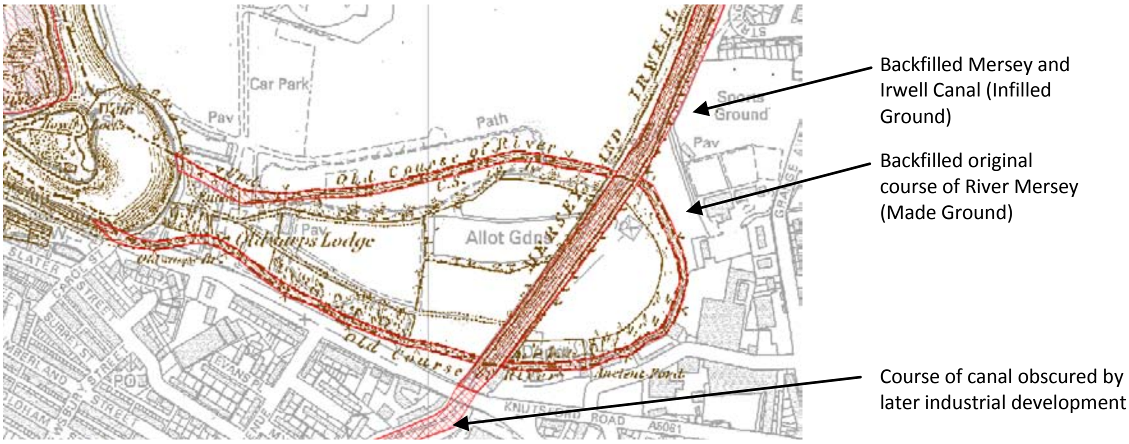

Figure 6. Anthropogenic alteration of the River Mersey and construction of the Irwell Canal. Modern 1:10 000 scale topographic map (grey) overlain by 1:10,560 scale map Lancashire 116, 1849 (brown). Artificial ground polygons are shown in red.

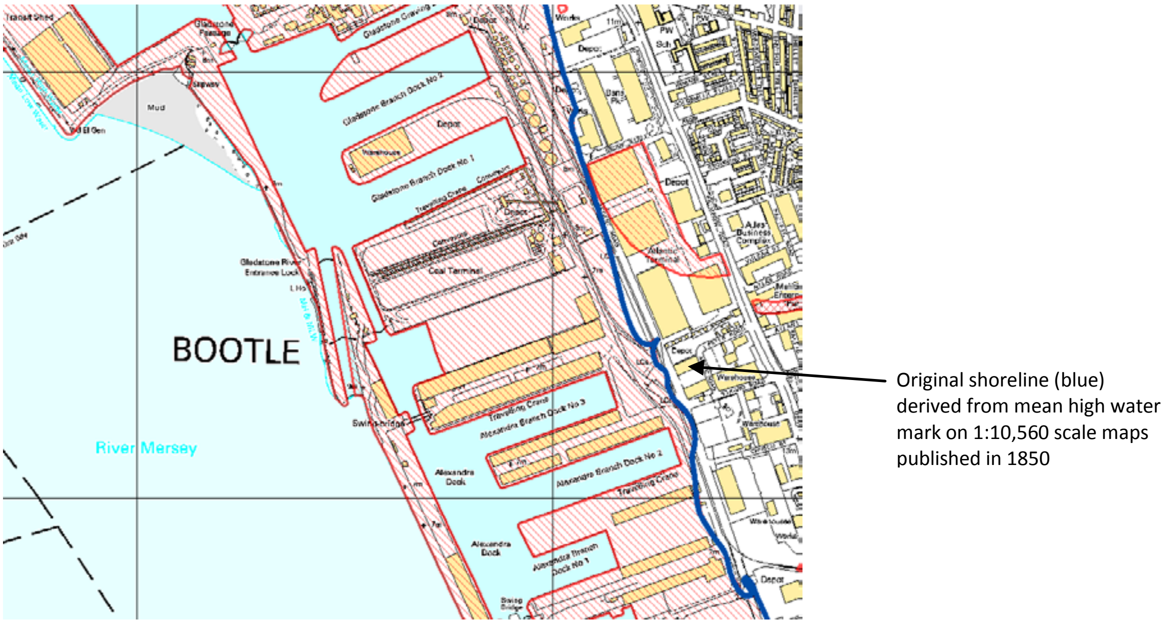

Figure 7. Artificial deposits (red hatching) and former position of the coast in the Liverpool docks area illustrating spatial extent of land reclamation. OS topography © Crown Copyright. All rights reserved. 100017897/2009

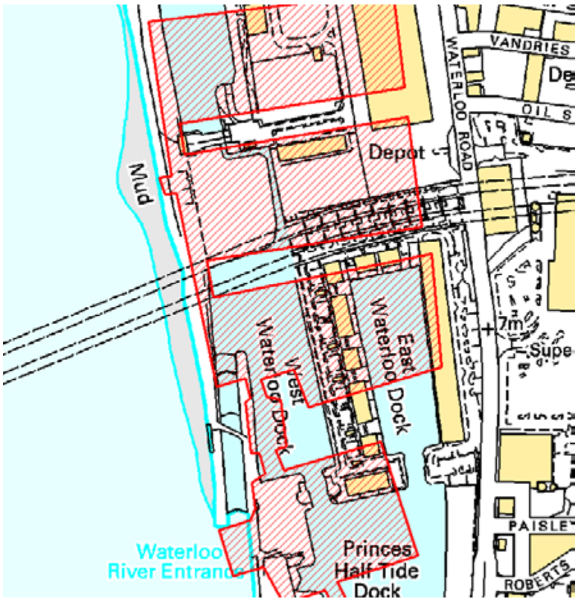

Figure 8. Extent of docks in 1851 represented in red, underlain by modern topographic map. OS topography © Crown Copyright. All rights reserved. 100017897/2009

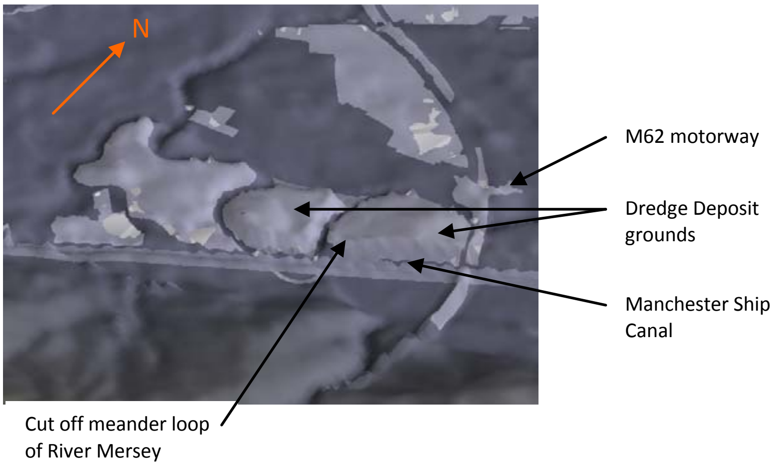

Figure 9. Extent Woolston Eyes dredge deposit grounds represented in the Warrington 3D model. NextMap Britain DTM data from Intermap Technologies Inc. OS topography © Crown Copyright. All rights reserved. 100017897/2009

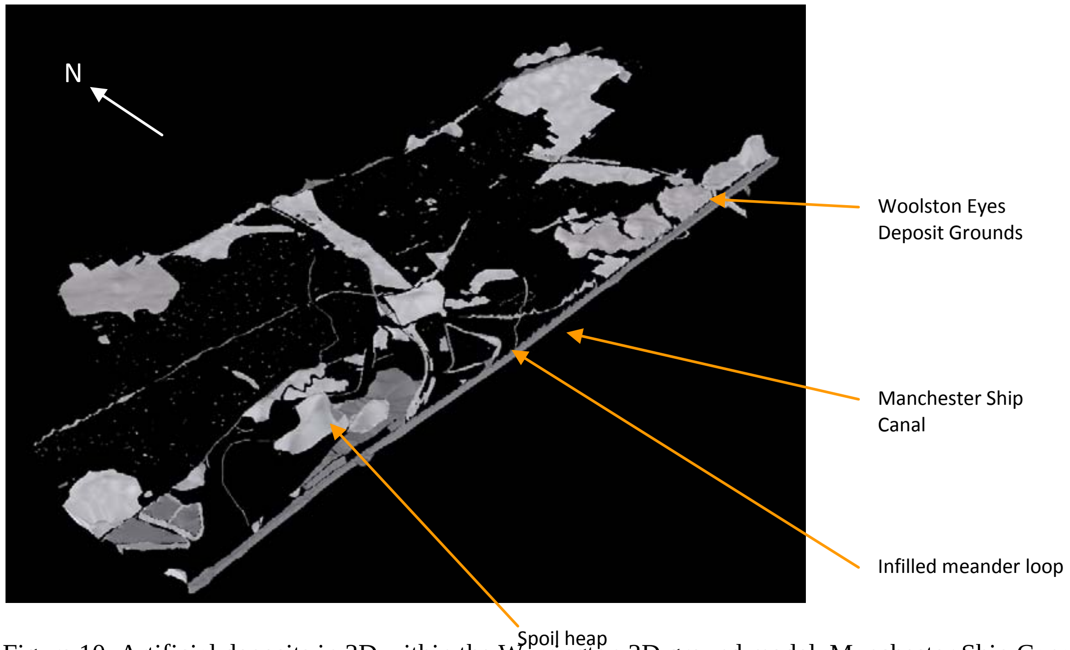

Figure 10. Artificial deposits in 3D within the Warrington 3D ground model. Manchester Ship Canal is approximately 12 km in length.

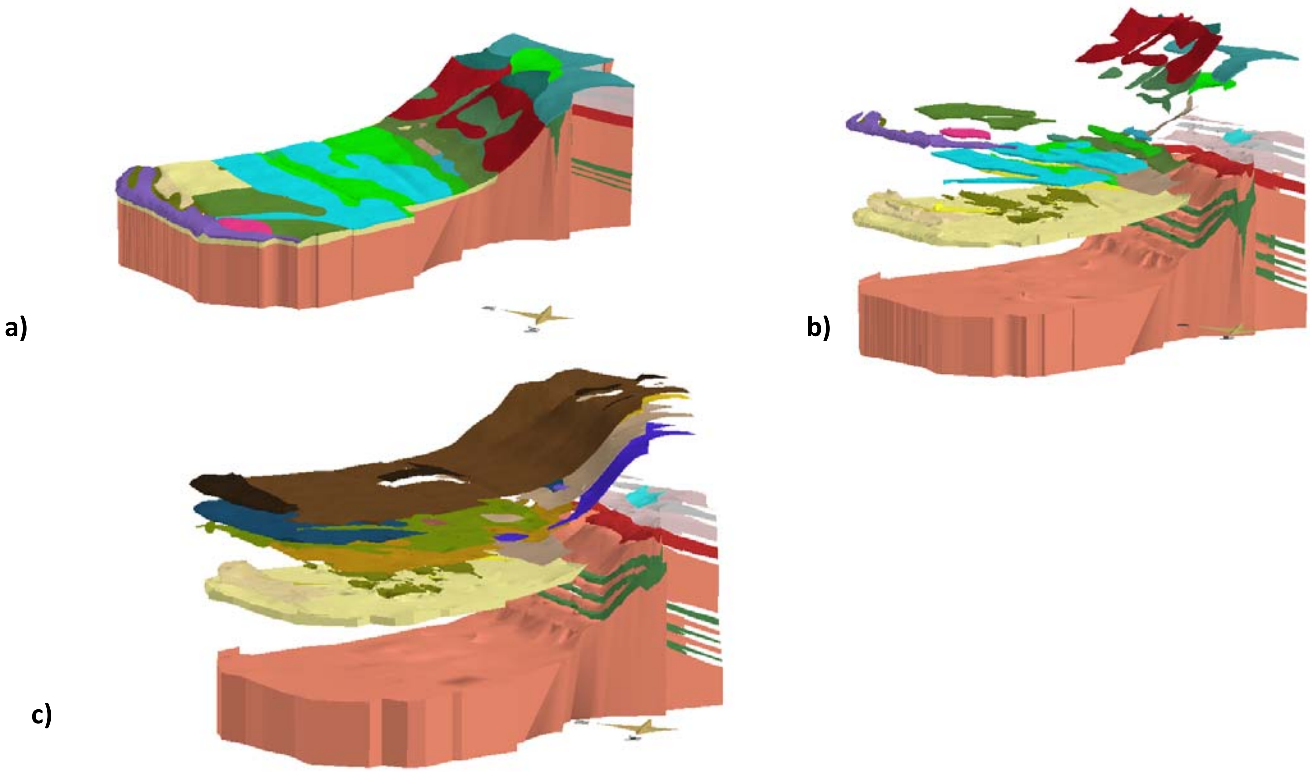

Figure 11. a) top left and 1b) top right display the soil-geology model based on approach 1 using the soil series map whilst and Figure 1c) beneath shows the soil-geology model based on approach 2 correlating 9 individual soil horizons. The models are of the Shelford area in the Trent Valley northeast of Nottingham and cover about 2 km^2; the views have a VE of x10. The bedrock geology comprises Triassic mudstone (pink) with hard siltstone bands in green (skerries) overlain by sandstone (red) and mudstones (pale grey). The superficial deposits are Quaternary river terrace deposits (pale yellow) of sand and gravel within the valley with thicknesses between 3 and 5 m.

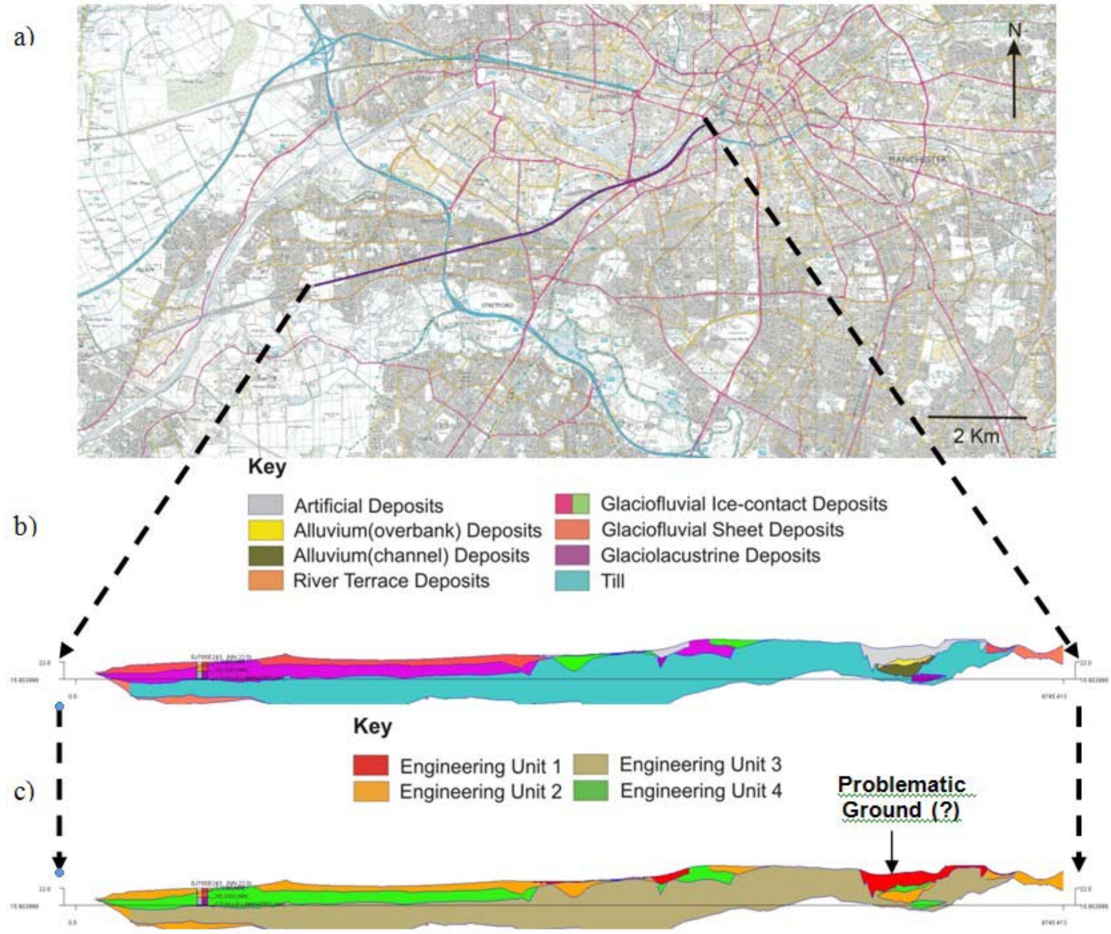

Figure 12. Prediction of engineering geological behaviour for railway subgrade assessment derived from the Manchester-Salford 3D geological model (after Reeves et al., 2005)

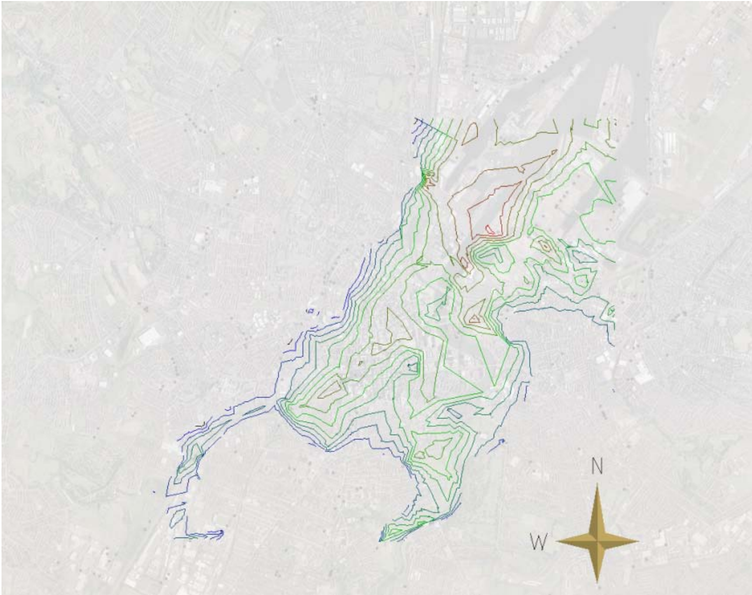

Figure 13. Contour map showing modelled depth to base of estuarine clay deposit beneath Belfast City. Red contours represent greater depths. OS topography © Crown Copyright. All rights reserved. 100017897/2009

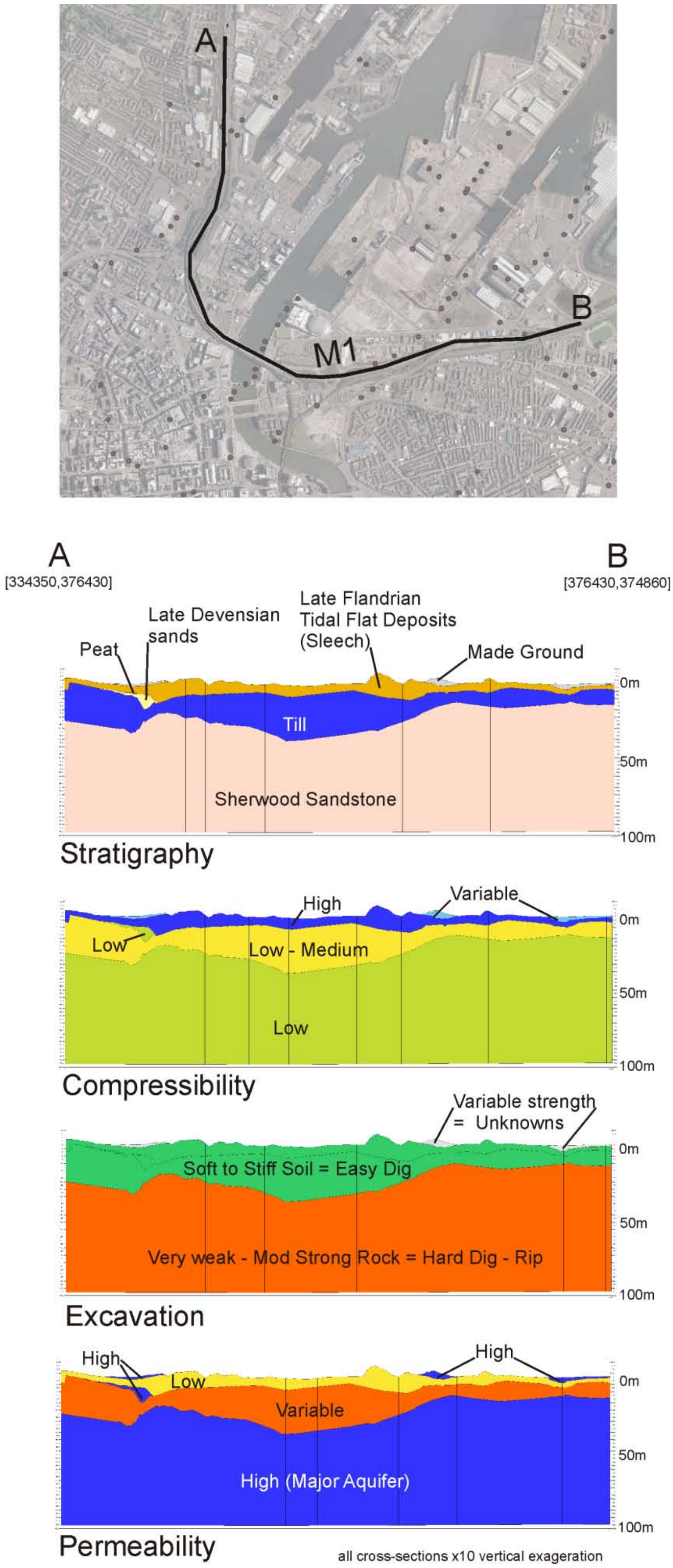

Figure 14. Linear route assessment along section of the M1 motorway in Belfast City. OS topography

Figure 15. Synthetic cross-sections derived from the Knowsely 3D geological model intersected by buried sewerage network (pink lines). Sherwood Sandstone (orange), Till (blue) Sand (brown) and sand and gravel (green). Model presented in the Subsurface Viewer. OS topography © Crown Copyright. All rights reserved. 100017897/2009

Tables

Made Ground	Areas where material is known to have been placed by man on the pre-existing land surface (including engineered fill)
Worked Ground	Areas where the pre-existing land surface is known to have been excavated by man
Infilled Ground	Areas where the pre-existing land surface has been excavated (Worked Ground) and subsequently partially or wholly backfilled (Made Ground)
Disturbed Ground	Areas of surface or near-surface mineral workings where ill-defined excavations (Worked Ground), areas of subsidence caused by the workings and spoil (Made Ground) are completely associated with each other
Landscaped Ground	Areas where the pre-existing land surface has been extensively remodelled, but where it is impracticable to delineate separate areas of Made Ground, Worked Ground or Disturbed Ground

Table 1. The pre-existing Artificial Ground Classification scheme (after McMillan & Powell, 1999)

Class	Type	Unit
Made Ground (undivided)	MBU Engineered Embankment (Undivided)	MBRO Road Embankment
		MBRA Rail Embankment
		MBFL Flood Embankment
		MBCA Canal Embankment
	MRU Raised Fill (Undivided)	MRIT Land Raising Inert Fill

Table 2. The pre-existing Artificial Ground Classification scheme (after Ford et al., 2006)

ENGINEERING GEOLOGICAL UNITS	GEOLOGICAL UNITS	DESCRIPTION/ CHARACTERISTICS	ENGINEERING CONSIDERATIONS			
			FOUNDATIONS	EXCAVATION	ENGINEERING FILL	SITE INVESTIGATION
ENGINEERING						
ENGINEERING UNIT 1 (HIGHLY VARIABLE ARTIFICAL DEPOSITS)	Disturbed Ground Landscaped Ground Made Ground Worked Ground Infilled Ground	Highly variable composition, thickness and geotechnical properties.	Highly variable. May be unevenly and highly compressible. Hazardous waste may be present causing leachate and methane production.	Usually diggable. Hazardous waste may be present at some sites.	Highly variable. Some material may be suitable.	Essential to determine depth, extent, condition and type of fill. Care needs to be taken as presence of pollution and contaminated ground likely. Essential to follow published guidelines for current best practice.
ENGINEERING UNIT 2 (COARSE SOILS)	Alluvium - River Channel deposits River Terrace deposits Glaciofluvial Sheet deposits	Medium dense to dense SAND & GRAVEL with some buried channels and lenses of clay, silt & peat.	Generally good. Variable thickness of deposit. Thick deposits in buried channels may be significant in foundation design due to differential settlement.	Diggable. Support may be required. May be water bearing.	Suitable as granular fill.	Important to identify the presence and dimension of buried channels and characteristic of infilling deposits. Geophysical methods may be appliciable.
	Glaciofluvial Ice-contact deposits	Loose to medium dense fine to medium SAND.	Poor foundation.	Easily diggable. Generally poor stability. Running sand conditions possible below the water table and in pockets at perched water tables.	Unsuitable as granular fill .	Determine the presence, depth and extent of deposit and depth to sound strata.
ENGINEERING UNIT 3 (FINE SOILS - FIRM)	Till	Firm to very stiff sandy, gravelly CLAY with some channels and lenses of medium dense to dense sand and gravel	Generally good foundation, although sand lenses may cause differential settlement. Possibility of pre-existing slips can also cause a strength reduction.	Diggable. Support may be required if sand lenses or pre-existing slips encountered. Ponding of water may cause problems when working.	Generally suitable if care taken in selection and extraction. Moisture content must be suitable.	Determine the depth and extent of deposit, especially the frequency and extent of lenses and channels. Investigate whether any pre-existing slips and shear planes are present.
ENGINEERING UNIT 4 (FINE SOILS - SOFT)	Alluvium - Overbank deposits	Soft to firm CLAY occasional sand, gravel and peat lenses.	Poor foundation. Soft highly compressible zones may be present; risk of differential settlement.	Easily diggable. Moderate stability, decreasing with increasing moisture content. Running sand conditions possible below the water table and in pockets with perched water tables. Risk of flooding.	Generally unsuitable.	Determine the presence, depth and extent of soft compressible zones and depth to sound strata.
	Glaciolacustrine deposits	Soft to stiff laminated CLAY with occasional lenses of sand.	Generally poor foundation as long term consolidation and differential settlement possible.	Easily diggable. Support may be required if sand lenses encountered in deep excavations. Ponding of water or exposure to rain may cause softening of formation.	Generally suitable if care taken in selection and extraction. Moisture content must be suitable.	Determine the depth and extent of deposit, especially the frequency and extent of lenses.

Table 3. Engineering geological classification in the Manchester area