

# 3D geological modeling and geotechnical GIS for planning and development: an example from Glasgow, UK

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## ABSTRACT

The Glasgow conurbation, Scotland's largest city, is built along the lower River Clyde and upper Clyde estuary. It has had a long history of heavy industry and mining, much of which has ceased, leaving brownfield sites with variable ground conditions and contamination. Many of these sites are now prioritized for redevelopment and regeneration. The British Geological Survey (BGS) has been working with local authorities in the area, especially Glasgow City Council, and regulatory partners, to acquire, integrate and supply a wide range of digital geodata to assist the redevelopment. Bulk-attributed three-dimensional (3D) geological models, produced by BGS, are useful for portraying general properties (e.g. engineering, hydrogeological) of the area. However, these models do not portray the inherent variability of each unit, necessary for more site-specific considerations, so limiting their usefulness. The data available were not considered suitable for cellular attribution and a range of Geographical Information System (GIS) methods have been used in conjunction with the 3D model, to present and interrogate the geodata. Part of the Clyde Gateway regeneration area is used as an example of how this has been done.

Keywords: 3D geological modeling, geotechnical engineering, GIS, planning, Glasgow

## 1 INTRODUCTION

The Glasgow conurbation, Scotland's largest urban development, is built along the lower floodplain and inner estuary of the River Clyde (Figure 1). It was once one of Europe's leading centers of heavy industry and of steel making and ship building in particular. These industries were supplied with locally mined coal and ironstone. Mining and much of the heavy industry have now ceased, leaving a legacy of brownfield sites with variable ground conditions and contamination.

A zone alongside the River Clyde, the Clyde Corridor, has become the Scottish Government's regeneration priority and many of the brownfield sites are now earmarked for redevelopment. Substantial progress has already been achieved, both by the local authorities and by private developers, but much more remains to be done. For example, the Clyde Gateway is a multi-agency project with a budget of €2 billion over 25 years, which aims to regenerate a large part of the East End of the city of Glasgow, an area of approximately 800 hectares.

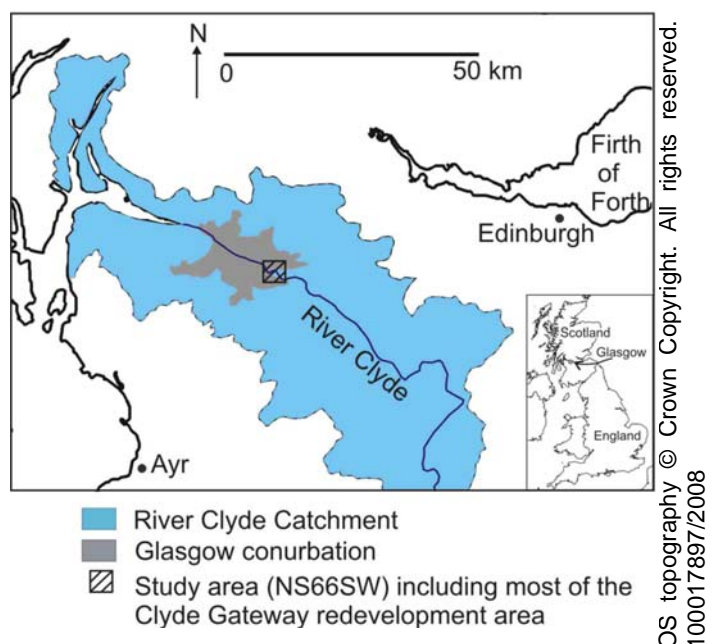


Figure 1. Location of study area.

The British Geological Survey (BGS) has been working closely with the local authorities in the area, especially Glasgow City Council, and regulatory

partners, to acquire, integrate and supply a wide range of reliable, up-to-date, and immediately accessible digital environmental and engineering geoscience data to assist in the redevelopment. Three-dimensional (3D) geological models of the complex superficial deposits (including artificial deposits) and faulted bedrock units are being developed. These models are based on the records of tens of thousands of boreholes for which the BGS holds records, and on extensive records of the mine workings. The models then provide a framework for modeling of the groundwater conditions and other purposes. However, while bulk attributions of these 3D geological models are useful for portraying general properties, such as engineering geological (Merritt *et al.*, 2006, Royse *et al.*, 2006) or hydrogeological (Lelliott *et al.*, 2006) characteristics of the area, they do not portray the inherent variability of each unit needed for more site-specific considerations. This limits their usefulness. As insufficient data are available in relation to the variability of the unit for more detailed, cellular (voxel) attribution, a range of GIS methods has been developed, in conjunction with the 3D model, to present and interrogate the geodata.

Part of the Clyde Gateway regeneration area is used as an example, but BGS is using similar approaches elsewhere in the UK, including the Thames Gateway area in the south-east of England, where the 2012 Olympic Games will be held.

## 2 GEOLOGY

The study location selected (Ordnance Survey map area: NS66SW) is a 5 x 5 km square which includes the Clyde Gateway area. The geology of the area is complex, comprising faulted Upper Carboniferous bedrock and Quaternary superficial deposits, including artificial (anthropogenic, “made ground”) deposits. The Quaternary deposits were described in detail by Browne and McMillan (1989). These, and the artificial deposits, have been classified in terms of their engineering characteristics by Merritt *et al.* (2006) for use in attributing the 3D model.

### 2.1 Bedrock

The bedrock comprises the faulted Upper Carboniferous Clackmannan Group and Coal Measures (Scotland). These consist largely of repetitive, cyclical sedimentary sequences of sandstone, siltstone and mudstone, with beds of coal. A number of coal seams have been mined within the area at different levels and using different mining methods. Evidence of pillar and stall workings is seen in borehole logs as voids, “packed waste” or presumed collapsed strata.

### 2.2 Superficial deposits

A summary of the superficial deposits in NS66SW is given in Table 1. Glacial till was deposited during the last ice age and covers much of the bedrock in the study area. Overlying the till, particularly along the River Clyde and Kelvin valley just to the north, are a sequence of glaciofluvial sands and gravels, deposited by meltwater streams and in deltas, and glaciolacustrine silt and clay, deposited in ice-margin lakes. After glaciation, extensive marine sand, gravel, silt and clay were laid down. These deposits, and those preceding them, were raised due to isostatic uplift following the last ice age. Alluvium was then deposited on the flood plain of the River Clyde and along its tributaries. Small peat deposits occur locally in suitable poorly drained areas but may also be present within the fluvial Gourock Formation.

Table 1. Summary of Quaternary and artificial deposits used in the 3D model of NS66SW (after Brown and McMillan, 1989).

| Modelled unit (map unit code)                    | Description  | Depositional origin                                     |
|--|--|---|
| Artificial deposits (Made Ground), (MGR)         | Highly variable natural and man-made materials               | Anthropogenic deposits                                  |
| Peat, P  | Peat   |   |
| Law Formation, (LAW)                             | Silty gravelly sand  | Modern alluvium   |
| Gourock Formation, (GUF)                         | Upper part fine grained; lower part coarse; may contain peat | Estuarine to fluvial                                    |
| Killearn Sand and Gravel Member, (KARN)          | Fine to medium sand and gravel with a few clay and silt beds | Beach, river terrace and delta deposits                 |
| Paisley Clay Member, (PAIS)                      | Laminated clay and silt; some sand beds                      | Glaciolacustrine  |
| Bridgeton Sand Member, (BRON)                    | Fine to medium sand; local gravel and boulders               | Sub-marine flood deposits                               |
| Ross Sand Member: Sand facies, (ROSS)            | Fine to medium sand  | Glaciodeltaic in palaeovalley                           |
| Ross Sand Member: Sand and silt facies, (ROSSSZ) | Interbedded sand and silt                                    | Glaciodeltaic in palaeovalley                           |
| Broomhouse Sand and Gravel Formation, (BHSE)     | Sand and gravel  | Glaciofluvial ice-contact deposits, eskers, mounds etc. |
| Broomhouse Clay, (BHSECLAY)                      | Clay   | Glaciolacustrine  |
| Wilderness Till Formation, (WITI)                | Sandy gravelly clay with sand and gravel beds and lenses     | Glacial Till  |

### 2.3 Artificial deposits (‘Made Ground’)

Artificial deposits cover much of the study area and are a testimony to the industrial heritage of Glasgow

and the Lower Clyde Valley. This area supported a wide range of heavy industries; including heavy engineering such as ship building, coal mining, chemical and metal manufacturing. The heavy industry and its decline have resulted in both industrial and domestic waste being widespread. The content of the artificial deposits is highly variable and depends, to a significant extent, on the previous land use. As these deposits are so widespread, it is important to understand their content, characteristics and thickness as they are likely to impact on redevelopment, sustainable urban drainage and shallow groundwater quality.

### 3 DATA

The geotechnical data and descriptions used in this study come from borehole logs contained in selected ground investigation reports. These have been provided to BGS by clients, consultants and contractors as both paper copies and in digital AGS (Association of Geotechnical and Geoenvironmental Specialists) data format (AGS, 2005). The data have been added to the National Geotechnical Properties Database, the BGS database containing data typically found in factual ground investigation reports. Data from paper records are added by hand while the digital data are added semi-automatically. The National Geotechnical Properties Database is based on the tables of the AGS data format (Merritt *et al.*, 2006) with additional fields for geology and information extracted from the description, including a lithological code used in the modeling, strength, density and potential contaminants such as tar or domestic waste.

In selecting the ground investigation data, preference was given to those that are likely to be of higher quality. These tended to be more recent investigations, carried out by well known contractors and for clients who are known to require high quality results. Generally, larger ground investigations were included, particularly those that contained a number of deeper boreholes as these often contain a wider range of test data. These were generally investigations for major roads and, in particular, those carried out for the extension of a new section of the M74 motorway. Data from this investigation were mostly provided in AGS digital format. Other ground investigation data were added to fill in gaps either by area or lithostratigraphy. These investigations, generally in relation to larger building projects such as housing estates, may not have had such a broad scope as the larger investigations but they did provide much useful data. The complex lithostratigraphy and local extent of some units meant that not all units are represented in the database by local sources of information. To complete the database, therefore, some data were gleaned from other areas or references. Currently, the database for the 5 km x

5 km square contains data from 77 ground investigations with over 1600 boreholes and trial pits.

Data from the National Geotechnical Properties Database were analyzed to illustrate the variability of a number of parameters for individual units, or a number of units for easy comparison and with depth. A range of standard cross-plots and more complex graphs, such as particle size distribution and consolidation, were produced.

## 4 ENGINEERING GIS

The objective of the GIS is to provide an interface to display the geology, images (as jpegs etc), Excel® files and tabular data in the GIS. The GIS searches specific folders (listed in a set-up document), returns a list of all those that meet the search criteria and then displays those selected.

The GIS was developed using ESRI's ArcMap™ 9.2 with additional functionality generated using Visual Basic for Applications (VBA)® and ArcObjects®. The functions are all called from within the GIS by a series of buttons on the toolbar, or by interrogating a particular geological layer in the GIS. In the latter case, the search performed by the GIS is automatically restricted so that any results are filtered by the selected geological layer.

The GIS has three main functions which are discussed below.

### 4.1 Display images

Called from within the GIS, this function lists all the images that match a particular search criterion. The function will either search on geological formation, cross-section, or type (e.g. box and whisker plot). The selected images are then opened alongside the GIS, allowing the user to reference both the GIS and the images.

The cross-sections display the lithostratigraphy with color-coded classified data in 'borehole sticks'. The classified data may describe lithology, strength, density, the presence of specific contents such as wood or coal, or downhole tests such as standard penetration test (SPT) N values, rock fracture state including rock quality designation, fracture index, or laboratory data.

An example of the user dialogue (Figure 2) shows a selection for cross-section 1 (lith\_spt\_3\_sectEng1.jpg) (Figure 3) and the key (Colours\_sectEng1). The selected cross-section contains the lithostratigraphy in the background, lithology in the left hand side of the borehole stick and the color-coded SPT (N) values in the right hand side. It illustrates the variability of SPT (N) values particularly in the man-made deposits (made ground), which varies between very low values (red, 0 – 4 blows) in the centre of the figure to higher values on either side (orange and pale blue, 5 to 30 blows).

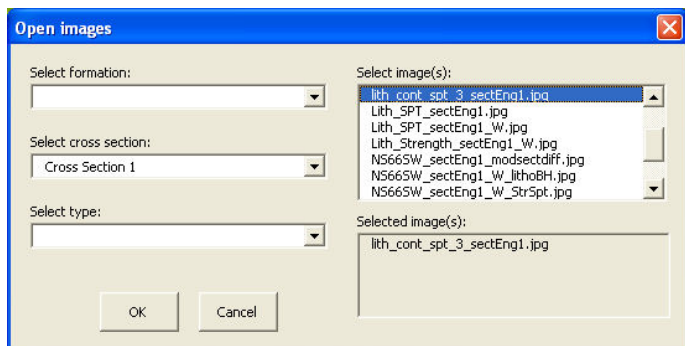


Figure 2. Dialogue box for displaying prepared images.

Data are also summarized in extended box and whisker plots to provide a means of rapidly assessing the variability of a property within one unit, or for comparing a number of units (Culshaw, 2005). Figure 4 is an example of an extended box and whisker plot of the undrained shear strength of the fine-grained superficial and artificial deposits.

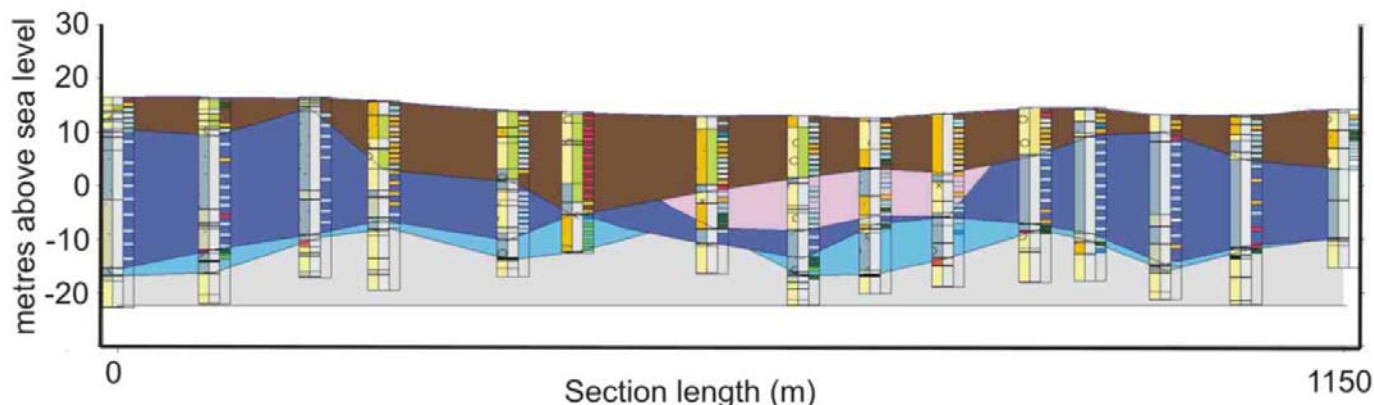


Figure 3. Cross-section displaying color-coded lithostratigraphy along the section, (pale brown – Made Ground, pink – Gourock Sand Member, dark blue – Paisley Clay Member, pale blue, Wilderness Till Formation, grey – Scottish Upper Coal Measures Formation), lithology in left hand borehole stick (orange – gravel, yellow – sand, greenish grey – silt, grey – clay, equivalent rocks types in the Scottish Upper Coal Measure Formation) and SPT(N) values, red – 0 to 4 blows, orange - 5 to 10 blows, pale blue - 11 to 30 blows, blue – 31 to 50 blows, pale green – 51 to 100 blows, dark green – more than 100 blows.

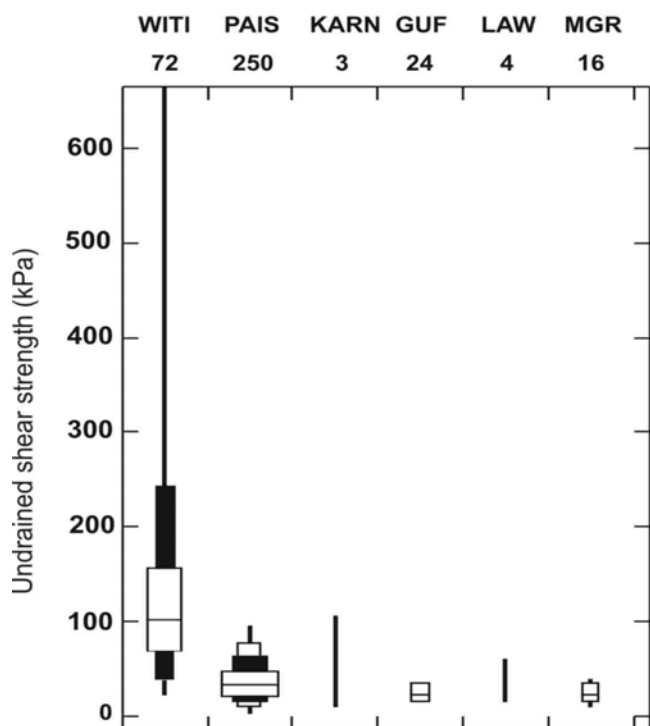


Figure 4. Extended box and whisker plot of undrained shear strength of the superficial and artificial deposits. The number of data points are above the graph. Lithostratigraphical codes are in Table 1.

#### 4.2 Display Excel® files.

Geotechnical data can be held and analyzed using the functionality in Microsoft Office Excel®. ArcMap™ cannot replicate this functionality so, to compensate for this, the GIS searches for Excel® files, and lists the various workbooks (Excel® file) and worksheets that it finds. The user can then specify what workbook to load and what worksheet to display on opening. The GIS opens the specified workbook, allowing the user to interrogate both the GIS layers and the Excel® data simultaneously. In this case, the dialogue box (Figure 5) shows the selected formation is 'pais' (Paisley Clay Member), and the selected Excel® file is NS66SW\_CLSS07.xls, which contains data on water content, plasticity and density. The selected worksheet 'paisplas' is the plasticity chart of the Paisley Clay Member (Figure 6).

Workbooks are based on AGS tables with additional positional and geological information. Current files include particle size, consolidation, plasticity index and density and compaction.



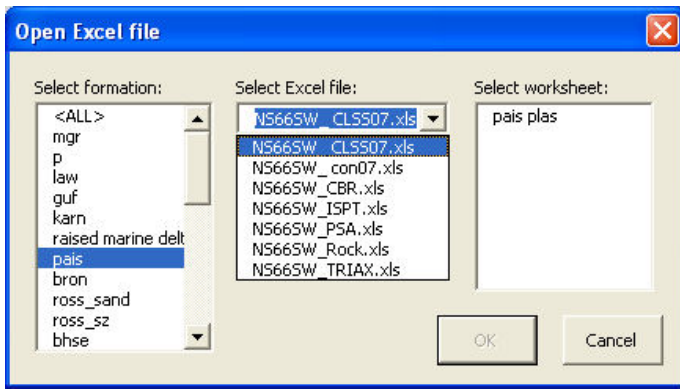


Figure 5. User dialogue box for displaying images of prepared graphs for one dimensional consolidation tests (oedometer test) for the Paisley Clay Member (pais).

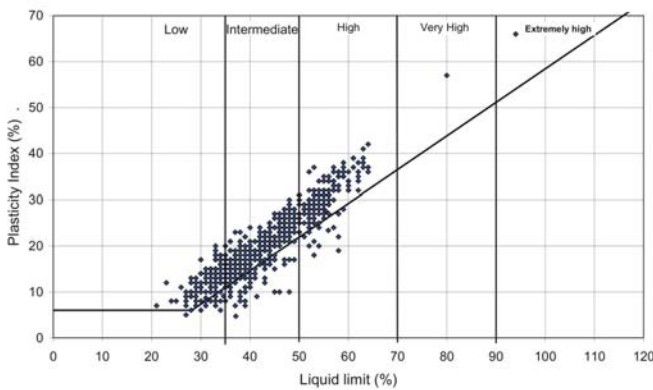


Figure 6. Paisley Clay Member plasticity chart.

#### 4.3 Display data as graph (plot)

This function allows the user to specify a data table from a database held outside the GIS. It then dynamically extracts two numerical fields from that data table and displays them as a scattergraph. The data displayed can be filtered by geological formation, for example, plotting only data relating to artificial ground ('made ground' - mgr, Figure 7). The scattergraph of SPT (N) data (x-axis) and test mean depth (y-axis) have been selected (Figure 8) and presented in Figure 9. The positions of the data points are shown alongside the scattergraph in the GIS map window. This allows the data to be further selected either by selecting points from the graph or from the GIS map window. When selecting from the graph, the geographical position of the point or points are dynamically displayed in the GIS map. Selecting points from an area on the map will result in the relevant data point being shown on the graph. A selection from a site is presented in Figure 10.

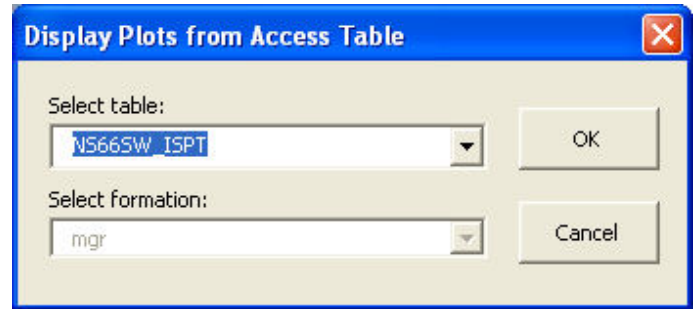


Figure 7. User dialogue box for displaying data from the project access data base table NS665W\_ISPT; made ground has been selected.

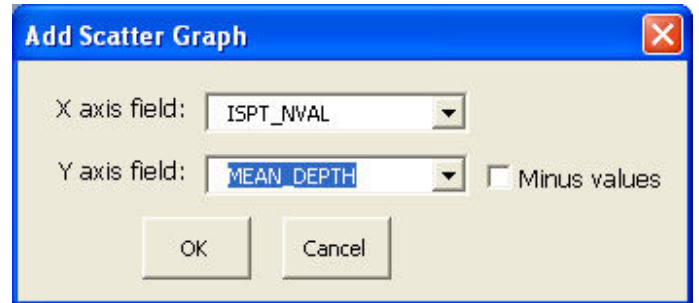


Figure 8. User dialogue box the selected scatter graph, x-axis SPT (N) values (ISPT\_NVAL) and mean test depth (MEAN\_DEPTH).

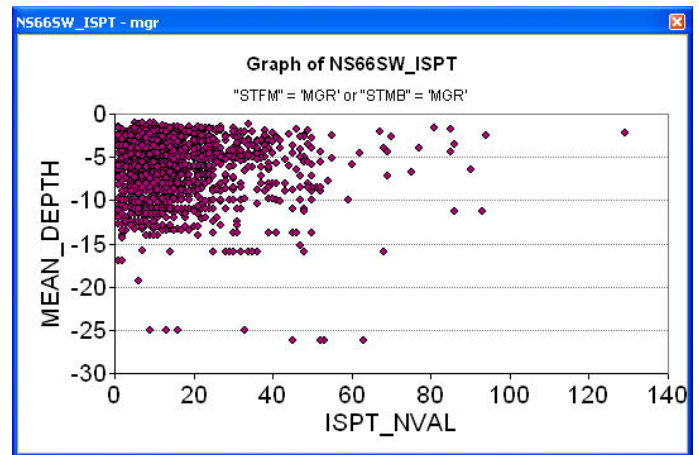


Figure 9. Scattergraph of the data selected in Figure 8.

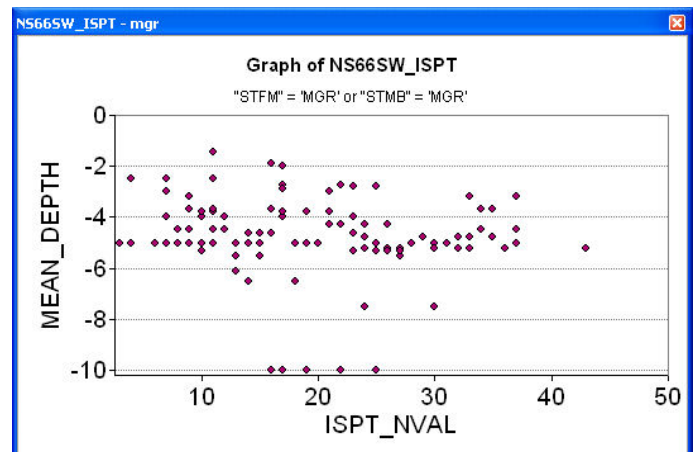


Figure 5. Scattergraph of a sub set of Figure 8 for a selected area of NS665W (Cambuslang Industrial Estate).

## 5 DISCUSSION AND SUMMARY

The 3D geological model provides the user with a powerful tool to visualize the relationships between the modeled geological units. Attributing individual model layers with alternative characteristics, such as engineering, hydrogeological or other characteristics, broadens the model's uses. The variability of each unit in the model can be expressed in the description of each attribute. However, bulk attribution of units has limitations. For example, although some modeled units may be lithologically fairly uniform; their geotechnical characteristics may be more variable. Also, some units, such as glacial till and artificial deposits, are inherently variable. Therefore, some data cannot be adequately represented within the current 3D modeling system and representation of their variability is instead limited to summary reports presented elsewhere.

Instead, the GIS provide the user with an easy-to-use interface to view pre-prepared diagrams, generally cross-sections and graphs, and interrogate data from databases. Changes in lithology and content are illustrated using the 'display images' as is the variability of some geotechnical parameters with extended box and whisker plots. Other cross-plots and graphs that require a specific output, or are more complex, are presented via Excel® spreadsheets. These two types of graphical presentation are summaries of the whole of the study area and cannot provide data for specific parts. This is done in the interactive 'display data as a graph'. The position of each point, or a number of points, in the graph can be seen on the GIS map. Alternatively, the data for a selected area can be shown on the graph.

Together, these techniques provide a method of displaying lithology and a wide range of geotechnical information for an area (in this case the modeled area) or for part of that area. This does not provide statistically modeled geotechnical data in 3D but is a factual data resource that can be used to aid planning and as a desk study tool to aid the planning of projects and ground investigation.

## 6 CONCLUSIONS

The attributed 3D geological model and GIS provide a method of visualizing the geology and a wide range of geodata as cross-sections and graphs which characterize variability of the modeled units. This can be used to communicate to both specialists and non-specialists alike, a broad range of geological information from ground investigations. The integration of information from the 3D model with the GIS provides a powerful desk study tool to aid planning in general, and the planning of ground investigations in particular, and so can be an important aid to achieving sustainable urban development.

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