

Integrated geoscience data, maps and 3D models for the City of Glasgow, UK

JOANNE MERRITT¹, DAVID ENTWISLE² & ALISON MONAGHAN³

¹ BGS. (e-mail: jeca@bgs.ac.uk)

² BGS. (e-mail: dce@bgs.ac.uk)

³ BGS. (e-mail: als@bgs.ac.uk)

Abstract: The British Geological Survey (BGS) is working with Glasgow City Council and other partners to obtain, integrate and supply a wide range of digital geodata relevant to development and planning. The issues include hazard mitigation and land use in a sustainable development context, flooding and sea-level change and land and water contamination. Glasgow is situated on and around the lower River Clyde floodplain and upper estuary and has a substantial legacy from former heavy industry and mining, mainly for coal and ironstone, and has areas prioritised for development and regeneration.

The initial stage of the work involved gathering, exchanging, scanning, digitising and storing borehole, map and mining data into corporate BGS databases. Subsequently, revised geological 2D maps and 3D models of the complex superficial deposits succession and faulted, mined bedrock formed a basic framework for derived products. Drift thickness and rockhead maps, and synthetic boreholes and cross-sections can be extracted from these models. Estuarine, tributaries and urban soils geochemical data, physical properties data (geotechnical) and hydrogeological data have been integrated with the geological framework models to help answer the geoenvironmental questions. Outputs can be provided in GIS format or in a 3D model viewer. They provide valuable input for development and planning in an area endeavouring to capture inward investment to stimulate regeneration and redevelopment.

Résumé: Le British Geological Survey (BGS) travaille en coopération avec le conseil municipal de Glasgow et d'autres partenaires afin d'obtenir, d'intégrer et de fournir une large gamme de géo-données numériques, utilisées pour la planification et le développement. Les problèmes abordés incluent la maîtrise des risques et l'utilisation des sols dans un contexte de développement durable, les inondations, les changements du niveau des mers, et les contaminations des milieux terrestres et de l'eau. La ville de Glasgow est située dans et autour de la plaine inondable de la rivière Clyde inférieure et de son estuaire supérieur, et porte un héritage important de son industrie lourde passée et de ses activités minières, principalement du charbon et du fer ; des zones prioritaires de développement et de régénération ont été définies.

La première étape du travail a impliqué le regroupement, l'échange, la digitalisation et l'enregistrement des sondages, cartes et données minières dans la base de données du BGS. A la suite de quoi des cartes géologiques révisées et des modèles 3D de la succession complexe des dépôts superficiels et du substratum rocheux, faillé et exploité, ont été réalisés et ont constitué le cadre de l'étude. Des cartes d'épaisseur dérivée et d'occurrence de roches, de sondages et des cross-sections peuvent être extraits de ces cartes et modèles. Les estuaires, affluents et les données géochimiques des sols urbanisés, les propriétés physiques (données géotechniques) ainsi que les données hydrogéologiques ont été intégrées aux modèles géologiques initiaux, pour mieux répondre aux problèmes géo-environnementaux posés. Les produits de cette étude peuvent être fournis aux formats SIG ou pour des visualisateurs 3D et constituer un apport précieux à la planification et au développement des zones à la recherche d'investissements pour stimuler leur re-développement et régénération.

Keywords: 3D models, geology of cities, geotechnical maps, groundwater contamination, land use, regional planning.

INTRODUCTION

The traditional representation of geological data by the British Geological Survey (BGS) has been in the form of 2D geological solid and superficial paper maps. Cross-sections and generalised vertical sections added to the map face are intended to give the user a better understanding and a feel for the geology in the third dimension. Without the third dimension, geological maps can be difficult to interpret. Additionally, users of BGS maps are informed, via a small caveat, that the map is an interpretation of the geology at the surface based on all the information the geologist had available at the time of compilation. It is not fact or a true representation of what really exists; it is a geological interpretation of the data available at that time. As new data become available, in particular borehole, pit and excavation descriptions, the map is soon out of date. The introduction, in the last decade, of digital map-making techniques by the BGS has allowed new data to be easily incorporated into the existing geological maps and regular updates made. With the explosion in software development, and the customer demand for better, more user friendly products showing a wider range of geological information, BGS has taken a step forward in the way its is conveying geological data to the user community. The 3D attributed geological model has been a focus of development for BGS geologists in the last five years. The 3D model gives the user a better picture of the geology at ground level and in the shallow subsurface. The attributed 3D model has the advantage, over a 2D map, that it can be produced at any scale over any specified area, it is easily updated and improved as soon as new data become available, it can incorporate

many different geological properties such as engineering, geotechnical, hydrogeological, geochemical and geophysical ones. The 3D model has the advantage of being user friendly, especially to the non-geological user community who may have struggled to interpret a 2D geological map (Culshaw 2005).

BGS has been working in partnership with Glasgow City Council to produce a pilot 3D geological model aimed at addressing some of the geological problems within an area of the Clyde valley designated for urban development and regeneration. A 1:10,000 scale 3D model of the superficial geology of the Rutherglen area of central Glasgow (NS66SW) was constructed using borehole data from the BGS Borehole Database, existing digital geological lines from the BGS 1:10,000 scale DigMap (Digital Mapping) series and a digital terrain model (Merritt et al. 2005). The modelling software, GSI3D (Geological Surveying and Investigation in 3D), was written by INSIGHT Geologische Softwaresysteme GmbH, a company based in Cologne, Germany, and has been developed according to BGS needs based on feedback from this and other BGS modelling projects.

Key features of the bedrock geology, such as important coal seams, were modelled in GOCAD (a 3D modelling package by Earth Decision Sciences™) and imported into the final model-viewing package called the GSI3D Subsurface Viewer.

This work has developed in response to a customer need for better representation of BGS held geological data and as a result of software development that has allowed us to use our borehole database and digital data to better effect. This paper describes how the work was initiated, how it evolved to produce the first ever externally available BGS 3D onshore model in Scotland and how the difficult problem of conveying model uncertainty was addressed.

CLYDE BASIN ENVIRONMENTAL PROGRAMME

Vision and Drivers

The British Geological Survey (BGS) is working with Glasgow City Council and other partners to obtain, integrate and supply a wide range of digital geodata relevant to development and planning. In 2004, BGS set up the Clyde Basin Environmental Programme with the vision of delivering sustainable environmental geodata for Scotland's cities. The project is due to continue until at least 2010. The main drivers are the commitment of the Scottish Executive and Scottish Parliament to delivering a sustainable economy that takes into account social and environmental factors. Transport, energy, water and waste are key issues. The Scottish Environmental Protection Agency (SEPA) requires data to address such issues nationally including surface- and ground- water flows, flooding, sea-level change, pollution and waste disposal. Glasgow City Council (the current project co-funding partner) needs to address all these issues at the local level. Here, natural and anthropogenic processes are causing environmental problems that relate to global scale climate change and to local factors such as contaminated land and the decline of dredging in the Clyde's river channel. In particular, ground stability is a major local factor especially former shallow mine workings. The built environment is also a growing concern as traditional stone-built properties show their age and require major maintenance and restoration. Integrated knowledge and digital information on the above themes are vital for the sustainable development of urban and semi-urban brownfield sites and greenfield developments, and for human health.

Objectives

- The Clyde Basin Environmental Programme aims to produce a comprehensive database of geoscience solutions to address the environmental problems within the catchment area of the River Clyde, its estuary, and the inner Firth of Clyde.
- The project will deliver geoscience data and solutions relevant to the issues of flooding, sea-level change, surface- and ground-water flow, contamination, and ground stability. These data and solutions will be capable of integration with socio-economic data in a GIS environment to deliver effective E-Planning.

One of the key deliverables of this project is a digital 3D integrated geological model for the city of Glasgow with hydrogeological and geotechnical attributes. Additional products resulting from this work include updated 1:10,000 scale digital geological maps and a comprehensive digital borehole database for the City of Glasgow area including index and scientific data (stratigraphy, geotechnics and hydrogeology).

Clyde Basin pilot study (NS66SW: Rutherglen)

1:10,000 sheet NS66SW (Rutherglen) was chosen for a pilot study to test whether recently acquired GSI3D modelling software could provide useable models that help to solve some of the geoscience problems in the Glasgow area (Merritt et al. 2005). The aim was to investigate, document and improve the methods of producing 3D models using the GSI3D software and explore the best ways of presenting final models to the customer, who, in this case were Glasgow City Council. The area was chosen because it lies within the boundaries of the Clyde Gateway, a major regeneration project of around 840 hectares (2000 acres) centred on a triangular area of potential development between Bridgeton Cross, Parkhead Cross and Farme Cross in east-central Glasgow. The project has a budget of £112 million over twenty-five years from 2004 to 2029. Partners include Glasgow City Council, South Lanarkshire Council, Scottish Enterprise National, Scottish Enterprise Glasgow and Scottish Enterprise Lanarkshire. The project aims to build upon the heightened demand that will be created by the construction of the M74 motorway and the East End Regeneration Route that will link at Polmadie in the form of a four-way junction. A similar junction will be created at Cambuslang Road and the economic impact of these junctions will be enormous. The overall aim of the

project is to stimulate the regeneration of the southeast quadrant of the Glasgow conurbation through an integrated programme of actions covering economic, social and environmental conditions within this area. Key targets include:

- Construction of 10,000 new homes
- Increase in population of 20,000
- Creation of 400,000 square metres of business and industrial floor space
- A new and upgraded road infrastructure
- Removal of development constraints such as overhead power cables, decontamination and consolidation of land
- New social and community facilities

BGS holds a large amount of data for the Glasgow area in the form of borehole records, site investigations records, mine plans and geological maps. This richness of data, along with a strategic location, makes it a good starting point for 3D modelling. Large amounts of data in the third dimension, in the form of borehole records, for example, allow a better quality model to be produced. Areas of high data concentration lead to models with high confidence and minimum amount of uncertainty. Knowing the confidence level of a model is important to the user so that the model is not misused or misinterpreted. The representation of model confidence remains a challenge and our early attempts for Glasgow City Council are discussed under the subheading Modelling Uncertainty. For this project it was decided that an initial GSI3D model of the superficial deposits would be supplemented by adding some of the important coal seams from the Middle Coal Measures and the base of the Middle and Upper Coal Measures. The complicated structure and the nature of the data available for the solid geology (especially the faults) meant that the coals had to be modelled in GOCAD and later imported into the GSI3D Subsurface Viewer as individual surfaces.

The Modelling Package: GSI3D

The GSI3D software is written and owned by INSIGHT Geologische Softwaresysteme GmbH. The software developer, Hans-Georg Sobisch, has worked closely with BGS to develop the software according to both BGS and its customer's needs (Kessler et al. 2005). The GSI3D method utilises a digital terrain model, geological surface crop lines and down-hole borehole data to enable the geologist to construct intersecting cross-sections by correlating boreholes and the outcrops or subcrops of geological units to produce a geological fence diagram of the area. Mathematical interpolation between the correlation points or nodes picked by the geologist along correlation lines, and the limits of the geological units, called envelopes, results in the calculation of a solid model that comprises a series of stacked triangulated objects corresponding to each of the geological units. The modelling workflow is shown in Figure 1. The software maximises the geologist's experience in creating and correlating surfaces between data points, boreholes and crop lines rather than allowing the computer to make decisions on where the geological surfaces should be. The results are, therefore, geologically more realistic and take into account the geologist's local knowledge. The final model is a series of empty volumes or 'skins' around the top, base and sides of each geological unit. Using the software the interpreter can rotate, explode, remove layers, view the triangulation points and zoom in and out of the 3D model within the 3D modelling window. The 2D modelling window allows the interpreter to view the envelopes of the geological units, remove units from display and overlay JPEG images such as air photos, topographic maps and confidence layers. The cross-section window allows the display of any of the correlation lines created within the model and also synthetic cross-sections created along any specified line within the calculated model. The borehole viewer allows display of any borehole loaded into the model and the creation and display of a synthetic borehole at any chosen location within the model.

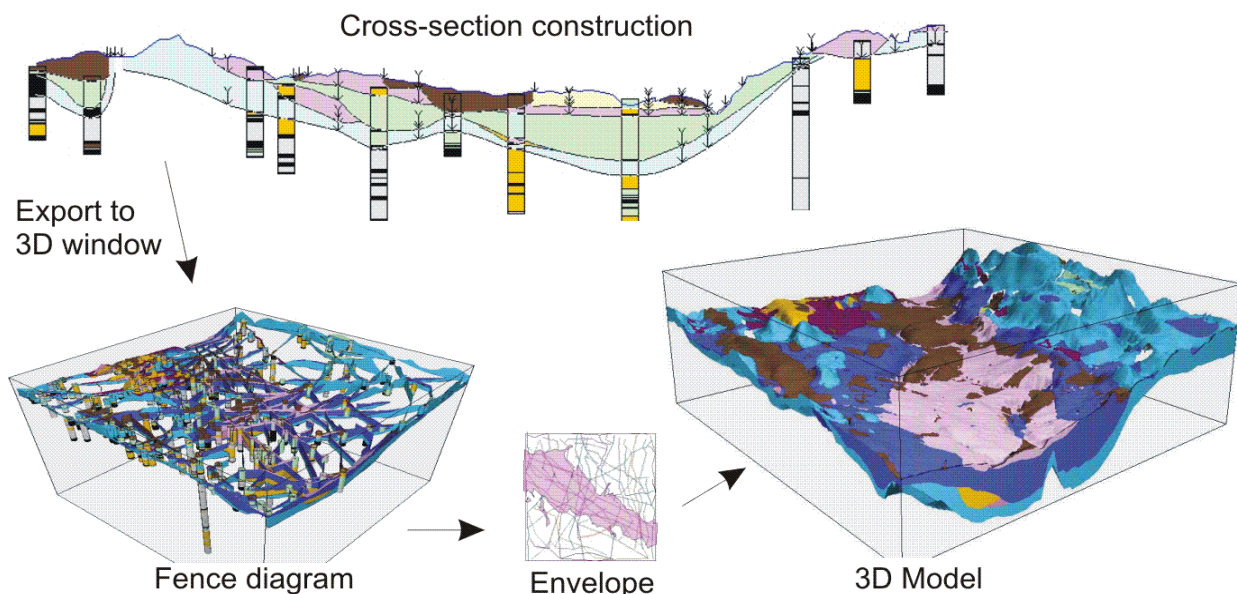


Figure 1. GSI3D modelling workflow.

GSI3D is designed to be a simple to use desktop application for use by geologists and not a complicated GIS-type or CAD package. It is best used for simple geological structures in the shallow subsurface. The software has limitations for modelling complicated bedrock structures. The current version of the software does not cope with structures such as repetition of layers, reverse faults or overturned folds. It is most useful for modelling the Quaternary sequence in the shallow subsurface and for solid geology with simple, layer-cake structures. For these purposes it is a highly developed modelling tool. In Glasgow the superficial deposits were modelled using GSI3D and the more structurally complicated coals and the bases of the Middle and Upper Coal Measures were modelled in GOCAD and exported as individual surfaces into the GSI3D Subsurface Viewer (© INSIGHT). The software is designed to be compatible with ARC GIS and GOCAD for both input and output of data and the language is the universal 'xml' format.

The Viewing Package: GSI3D Subsurface Viewer

BGS is now able to use the Subsurface Viewer to publish geological models, effectively replacing the two dimensional paper and GIS based map with the three dimensional equivalent. The viewer interface is similar to that of the modelling package with a map window, a cross-section window, a 3D window and a borehole viewer. The 3D model is encrypted into the viewer so that the client can view the embedded model but not alter it in any way. The viewer contains a topographic overlay and, in the Glasgow model, a confidence overlay which can be viewed in both map and 3D windows. The user is able to view the model from any angle, explode it, rotate it, remove layers, contour the geological surfaces and create synthetic cross-sections, horizontal sections and boreholes at any point within the model. The synthetic sections and boreholes are an especially valuable tool for planning site investigation work and, indeed, for all aspects of planning and development. However, the user must understand that the sections are not meant to be a replacement for site investigation work as the model is an interpreted representation of the data and not fact. The GSI3D Subsurface Viewer interface can be seen in Figure 2.

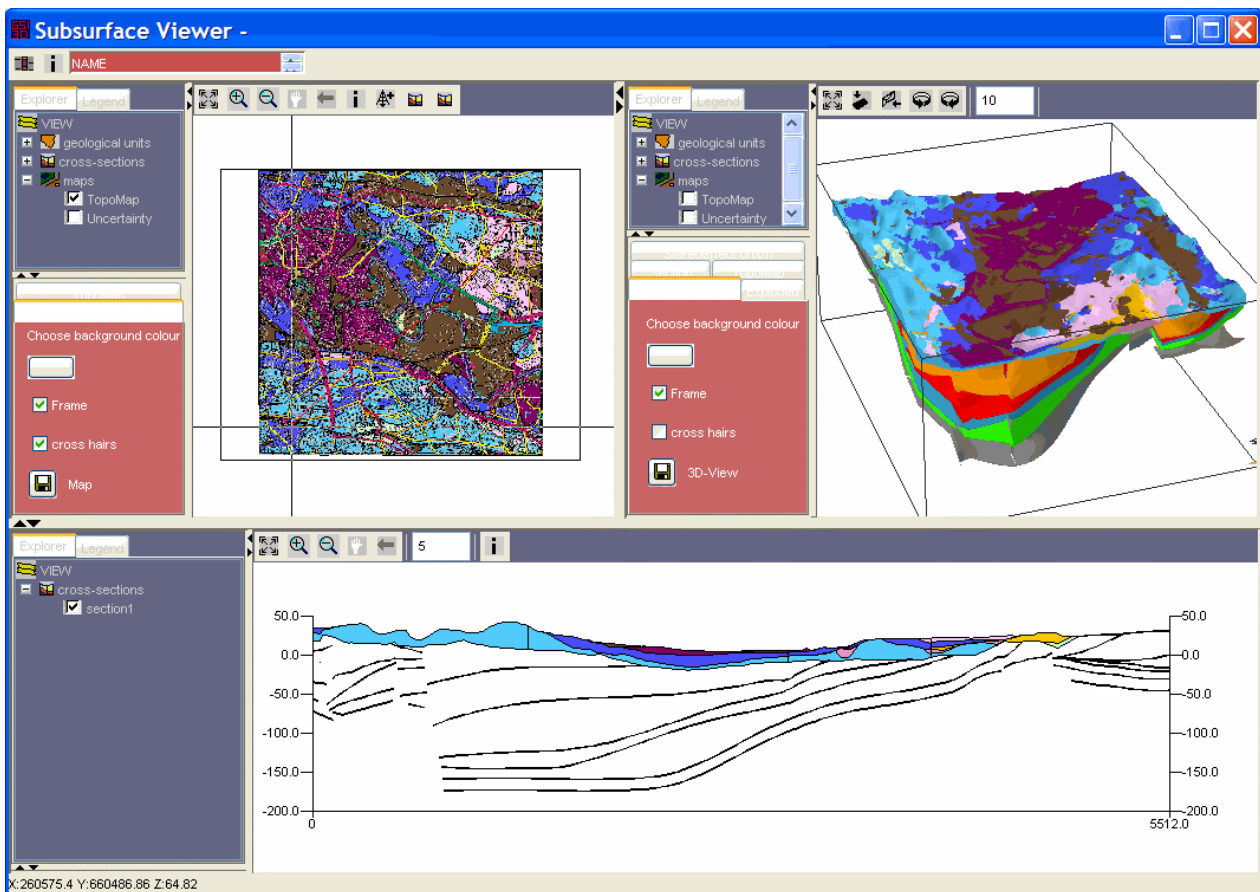


Figure 2. GSI3D Subsurface Viewer interface.

MODELLING UNCERTAINTY

The colourful 3D geological models produced in GSI3D look very realistic and there is a danger of them being accepted as the truth by uninformed users. It is our job as modellers to ensure that each model supplied to a user or customer comes with caveats explaining the model's limitations with regard to scale and suitable use, and also that a confidence level placed on the model. BGS has been producing 3D models for the last five years as part of the Digital Geoscience Spatial Model (DGSM) Project. The models produced in this project are only available for internal use by BGS geologists who better understand the accuracy and limitations of geological maps and models. Until now we

have not placed great emphasis on attaching detailed confidence information to our existing models. The Glasgow model described in this paper is the first 3D model to be licensed commercially by BGS. With this and future models it is necessary to supply confidence information for each model layer so that the user understands the limitations, understands where the model is most and least accurate and therefore, will hopefully not misuse it. Cave and Wood (2002) tried to address the problem of confidence or uncertainty modelling as part of the BGS DGSM Project. They described mathematical methods for calculating uncertainty such as bootstrap-resampling and fuzzy logic. In their report conclusions they state that:

- Equal importance should be given to the measurement of uncertainty as is given to the final model.
- It is critical to have a multidisciplinary team with expert representatives from each stage of the modelling project providing information on the uncertainty of each step of the process and to ensure that the emphasis is placed on obtaining good uncertainty estimates for those inputs that critically affect the model.
- There should be a formalised mechanism for all BGS geoscience modelling projects that allows all sources of uncertainty within the project to be recorded in a formalised manner. A suitable tool for this is the use of 'cause and effect' diagrams.
- Geoscience data models include both quantitative and subjective/ semi-quantitative inputs and outputs. It is suggested that bootstrap-resampling and fuzzy logic approaches, respectively, are suitable methods for producing robust estimates of uncertainty on these two types of data.
- The final estimate of uncertainty of any model must include contributions from all of the significant sources of uncertainty identified by the cause and effect diagram of the project.

This report was the first reference point in an attempt to represent confidence levels in the Glasgow model. We prefer to use the term confidence rather than uncertainty because it has a more positive connotation. We started with a 'cause and effect' diagram to which all team members contributed (an example is shown in Figure 3). The sources of uncertainty are numerous, for example, data quality, data distribution and density, experience of modellers, reliability of software, level of geological expertise. The 'cause and effect' diagram shows that we are aware of all the contributing factors to the confidence level of the model. The mathematical methods for coping with these many uncertainties and the limitations of the GSI3D software at this stage of development lead us to follow a simplistic approach to confidence modelling for the test case Glasgow model. With the limited time and resources available we decided to represent confidence as a series of 2D layers showing the density of borehole data used in the model interpretation. The level of data density was shown by colour contouring the data density in ARC GIS using the Buffer Wizard (green for points within 100m, orange for points within 200m and red for points greater than 200m from a borehole location) to give a red, orange, green coloured confidence layer in which green represents the highest level, orange intermediate level and red the lowest level of confidence within the model. A single layer was created of total data used to represent confidence at ground level and within the superficial volume. Further layers were created at the level of each coal seam surface and at the bases of the Middle and Upper Coal Measures to represent the confidence rating associated with each of these layers. The contour layers were blurred using the CorelPaint gaussian blur facility to prevent the user reproducing the exact X, Y co-ordinates of the boreholes used in the interpretation. This was done to protect the confidentiality of the boreholes. The contoured layers were then exported as JPG World files to the GSI3D Subsurface Viewer for display with the model (Figure 4). This method of confidence representation is simple to use and understand. Red areas tell the model user that the model may not be accurate because the data density is sparse or non-existent. Green areas tell the user that that this part of the model has the highest level of confidence because the greatest density of original data exists there. It is entirely one-dimensional and descriptive approach, that is, it does not attach a figure to the confidence level, only a description of high, medium or low. It does not account for any of the subjective sources of uncertainty documented in the cause and effect diagram. It is also a 2D representation on a 3D model. The aim is to develop our confidence modelling in the coming years to produce 3D confidence models within which a confidence rating can be identified at any point within the model rather than at a particular surface. We hope also to incorporate other sources of uncertainty and be able to attach a qualitative value to the confidence level, for example, a percentage confidence rating. BGS is investing a large amount time and effort in developing this very important part of 3D model building. A great importance is attached to the fact that our models may be misused or misunderstood and we are doing everything possible to educate the user on the limitations and intended purpose of the models.

ATTRIBUTION OF GEOTECHNICAL AND ENGINEERING GEOLOGICAL PROPERTIES

The high detail 3D model presents an excellent opportunity to improve the understanding of the relationships between deposits with different geotechnical behaviour and engineering geological characteristics thus providing an important tool for planning, and civil engineering project desk study. This information is not a substitute for ground investigations but should lead to better targeting of ground investigation design and provides some pre-ground investigation indicators of ground conditions allowing some design work to be carried out early in the project. The ground investigation may then be added to the 3D model to provide a 3D ground model of the site, which can then be attributed for a number of geotechnical or engineering geological properties such as consolidation parameters or foundation conditions. This model may be further refined during construction.

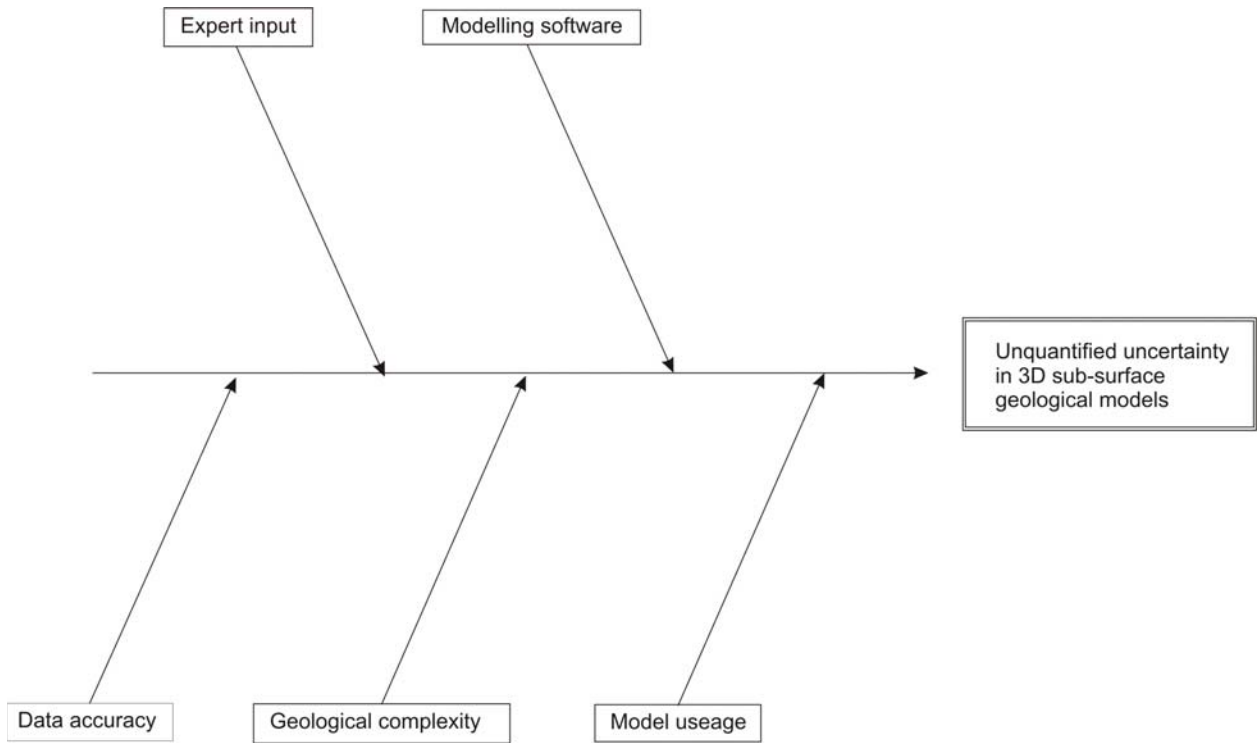


Figure 3. Cause and effect diagram template.

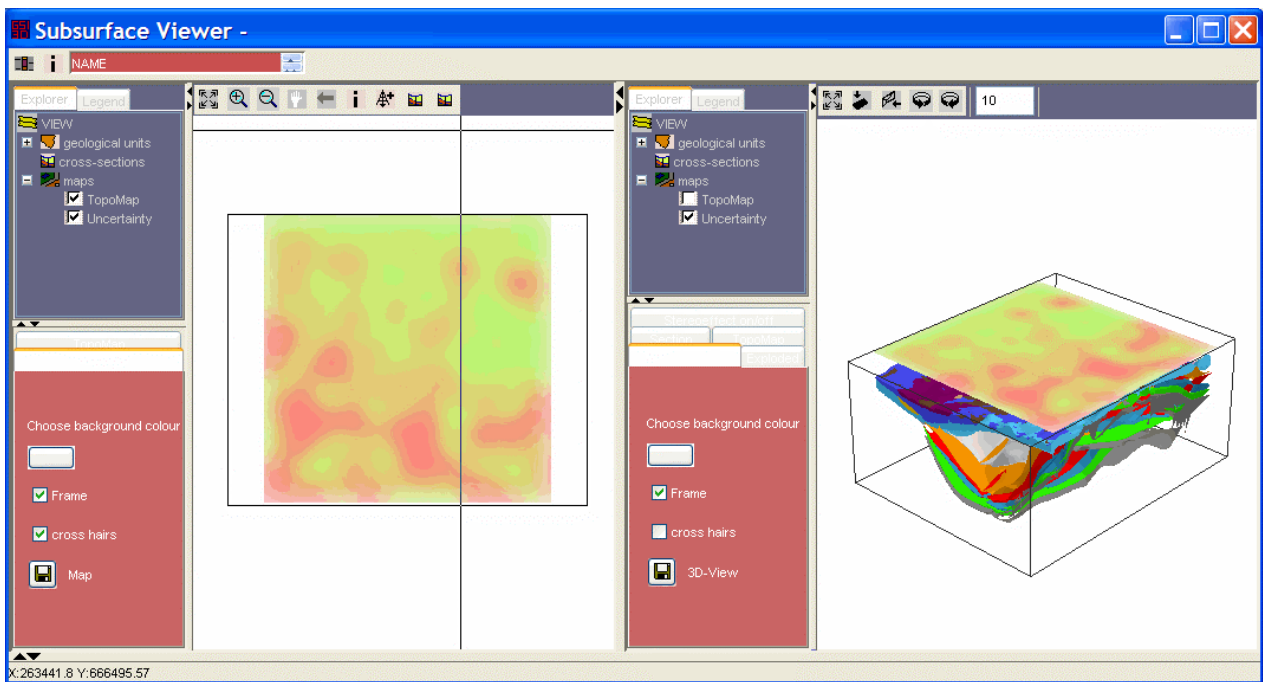


Figure 4. Confidence layer for superficial deposits based on borehole data density at ground surface (displayed in the map and 3D windows of the GSI3D Subsurface Viewer).

The geotechnical data and engineering characteristics of the deposits in the Glasgow area were obtained from civil engineering site investigation reports provided by clients, consultants and contractors to the various BGS offices. The data were added to the National Geotechnical Properties Database, which is a BGS corporate standard database containing geotechnical and chemical data. Data were supplied as paper copies or as digital files using the Association of Geotechnical and Geoenvironmental Specialists (AGS) data format. The National Geotechnical Properties Database follows the AGS digital format including the full description, but has additional fields for geology and various characteristics from the borehole description, such as discontinuities, colour and a lithological code. Data from paper records are input by hand but AGS digital data is added automatically saving time. For this reason digital data are preferred. The data are stored in Oracle© and added and accessed through Microsoft Access©. A highly simplified diagram of the database structure is shown in Figure 5. Information from this data were not only used to investigate geotechnical properties and engineering geological characteristics but were also used in 3D geological modelling.

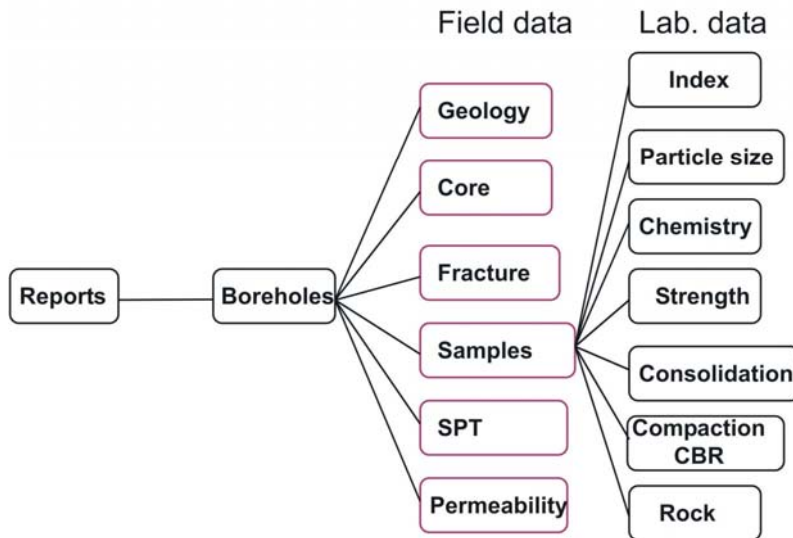


Figure 5. Simplified diagram of the National Geotechnical Properties Database.

Site investigation data to be used were selected initially by age, client and by the likely quality of the ground investigation company. In general, large investigations and those that had deeper boreholes were preferred as they were likely to encounter a range of geological ‘formations’ and generally have a greater range of geotechnical data. A second tranche of data from smaller investigations was added, particularly in areas where there were few data or where a ‘formation’ was poorly represented in the database or to provide more data on certain aspects such as foundations for buildings. However, the complex nature of the superficial deposits and their thickness in this area meant that some ‘formations’ were likely to be poorly represented. Data from over 800 boreholes and 65 site investigations were used in the analysis.

The descriptions and geotechnical data were analysed to provide summary information and to divide the lithostratigraphical units based on their engineering geological behaviour with regard to land use and construction. Engineering classification divided the deposits into their fundamental type, that is ‘engineering soil’ or ‘engineering rock’. The borehole descriptions indicated that, in general, the bedrock was not weathered to a ‘soil-like’ material to any great depth. Therefore, in this area the superficial deposits were classified as engineering soils and the ‘solid’ geology materials are classified as rocks. This allowed for the main classification between rock and soil to be on the basis of lithostratigraphy. However, a bed of gravel sometimes occurs above the bedrock. This may be either a glacial deposit or weathered rock. The rock classification, not shown in the models presented here, was based on lithology and rock strength. The engineering soils were divided into fine-grained (those deposits whose behaviour was dominated by clay or silt), coarse-grained (those deposits dominated by sand, gravel and larger particles) and mixed materials (those deposits whose behaviour is primarily controlled by either fine grained or coarse grained particles). Further subdivision took into account other factors, such as strength or density. The engineering geological classification of the geological units of the study area is presented in Table 1. This forms the basis of the derived classification in terms of, for example, foundation conditions, excavatability and suitability as fill.

This approach has been used for a number of years for thematic and environmental geological mapping projects (Forster et al., 1985, 1995, Haines et al., 1991, Lake et al., 1992, Powell et al., 1992, Waters et al., 1996), which provided a series of maps for various UK cities, including engineering geological classification, superficial deposits and solid geology. Typically, the information was constrained by the lack of subsurface data. This is of greatest importance for deeper foundations, tunnels and deep pipes as the material on which the foundation is to be placed or through which a tunnel is driven may not be represented on the map. Attempts have been made to indicate conditions below the surface deposit on the map using a variation of the ‘stripe’ method of Pasek & Rybar (1961) (Forster et al., 1995, 2004). Where bedrock formations crop out at surface or where superficial deposits are greater than 5 m thick the engineering geological unit is shown as a solid block of colour. Where the superficial material is less than 5 m thick the colour of the unit is shown in stripes, interspersed with stripes of the underlying bedrock colour indicating the surface and subsurface bedrock material. However, this method does not consider different types of superficial deposit. The 3D approach provides much more information.

The engineering geological classification is applied to the 3D model in Figure 6. The colours selected have themes: mixed lithologies are blue, fine-grained lithologies are brown and coarse-grained lithologies are yellow to orange, the darker the colour the denser or stiffer the formation apart from made ground which is extremely variable (see description in Table 1).

Geotechnical parameter data can also be represented as, for example, in Figure 7, which shows the lithostratigraphical model indicating the liquid limit variation for each unit. Any characteristic may be represented in the model as long as it has a lithostratigraphical basis, even if classified as ‘variable’ as long as this can be justified by the data.

The model retains the same functionality as for lithostratigraphy so it can be exploded, lithostratigraphical units can be removed and virtual boreholes and cross-sections can be drawn.

Table 1. Geological materials classification on the basis of their engineering geological behaviour with regard to land use and construction.

Engineering Unit	Geological Unit	Characteristics
ROCKS	Coal Measures	
'Strong' Sandstone	Coal Measures: Sandstone	Moderately strong to strong, thin to thickly bedded sometimes laminated, white or grey and red or purple fine to coarse SANDSTONE. Weathers to a light brownish grey, gravely fine to moderately weak, brown SANDSTONE and then to very dense red or yellow SAND.
Mudstone	Coal Measures: Mudstone	Very weak to moderately strong, sometimes laminated grey or purplish grey or black, MUDSTONE and SILTSTONE. Some thin sandstones are present. (Not described fully weathered).
Coal	Coal Measures: Coal	Very weak to moderately weak, black COAL
SOILS		
Mixed fine/coarse		
Very soft to very stiff/ Loose to dense	Made Ground	Very soft to very dense, very loose to very dense. Highly variable in colour and lithology. May contain made-made materials such as ash, slag, glass, metal, brick, wood, tarmac etc.
Soft to firm/Loose to medium dense	Gourock Sand Member	Upper part: soft to firm, sometimes laminated, dark grey or brown or light yellowish brown sometimes mottled, sometimes organic or peaty CLAY or sandy CLAY or SILT. Contains layers of peat generally a few centimetres thick. Main lithology: loose to medium dense, brown or greyish brown or orange brown, slightly silty fine to medium or fine to coarse SAND. Lower lithology: loose to medium dense, brown or greyish brown or orange brown, fine to coarse SAND and fine to coarse sub angular GRAVEL. Sometimes silty or clayey.
Stiff/dense	Wilderness Till Formation	Mainly firm to very stiff, grey, greyish brown or mottled grey brown near surface, gravely sandy CLAY with occasional cobbles and boulders. Gravel fine to coarse, sub angular to rounded. Contains lenses and layers of silt, dense to very dense sand and gravel.
Mostly fine-grained		
Very soft to firm/(loose) (mostly fine grained)	Paisley Clay Member	Very soft to firm, laminated brown, SILT and CLAY with some fine SAND laminae.
Firm to stiff	Bellshill Clay Member Broomhouse Sand and Gravel Formation (fine grained)	Firm to stiff, brown, sometimes laminated SILT, CLAY and sometimes SAND.
Coarse-grained		
Loose to medium dense	Bridgeton Sand Member Ross Sand Member Killearn Sand and Gravel Member	Loose to medium dense, pale brown or grey, fine or medium (coarse) SAND or sometimes laminated, medium dense grey or dark brown or pale brown, clayey or silty SAND sometimes with occasional fine to coarse gravel
Medium dense to very dense	Broomhouse Sand and Gravel Formation (coarse)	Medium dense to very dense, grey or brown, sometimes gravely, silty fine to medium SAND or fine to coarse GRAVEL sometimes with cobbles and occasional boulders.

SUMMARY

The provision of geological data by the BGS is changing from 2D paper maps to attributed 3D geological models. This change has been facilitated by the development of 3D modelling software and the digitization of increasing amounts of geological data held by BGS, local authorities, councils, water authorities and site investigation companies. Using GSI3D modelling software BGS has been able to produce a 3D attributed solid and superficial geological model for the Rutherglen area of Glasgow. The model has been embedded into a viewing package called GSI3D Subsurface Viewer and supplied under an evaluation license to Glasgow City Council for use in the planning, development and regeneration of the Clyde Gateway area, an area of major development and construction in east-central Glasgow. The model is invaluable for planning site investigations and is attributed with geotechnical information to give the user additional information about the ground conditions. It is easier to use and understand than a traditional geological paper map but the realistic or true to life appearance of the model means that it could be misinterpreted and used for reasons it is not intended. For example, it may be mistakenly used as a replacement for proper site investigation. BGS modellers have tried to deal with this problem by attaching confidence layers to the model. The confidence layers tell the user where the model is most and least reliable based on the density of data used in the interpretation. It is made clear to the user that the model is an interpretation and not fact. Once the user understands the limitations, the model becomes a very powerful and time saving investigation tool.

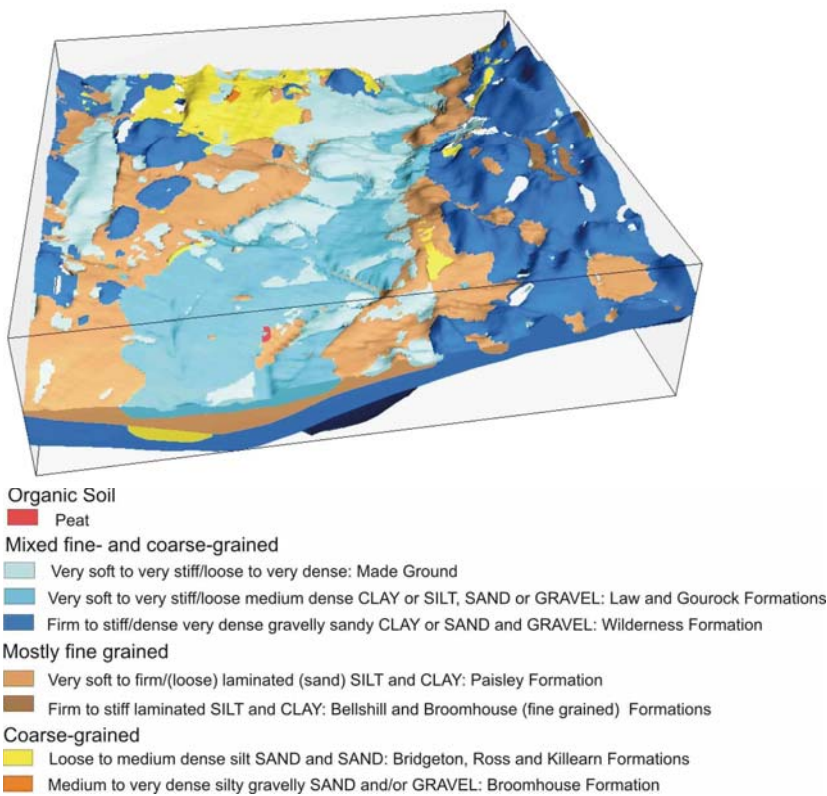


Figure 6. The 3D model coloured for engineering geological classification.

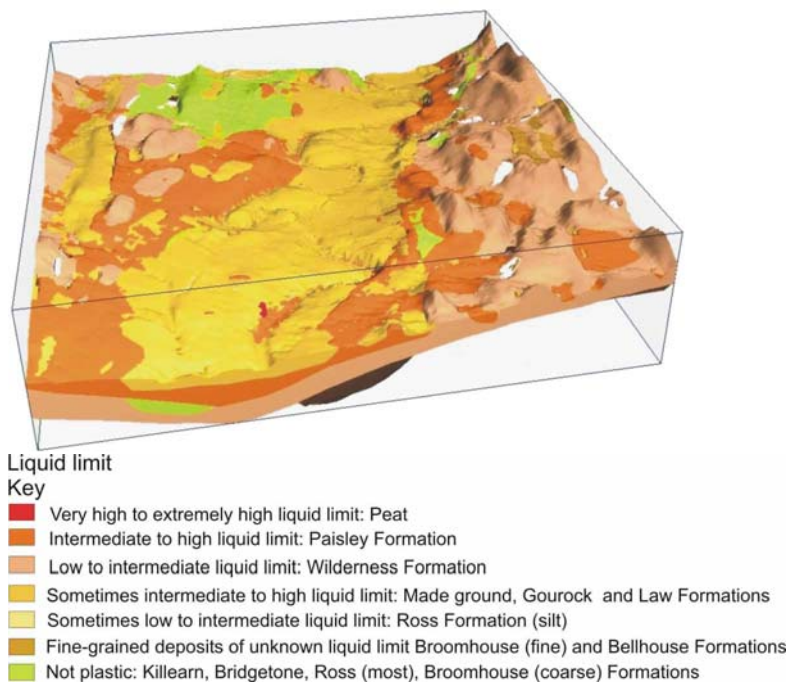


Figure 7. 3D model classified for liquid limit.

Future work will be customer and user driven and will depend on co-funding from national bodies and local authorities. The needs of the user community will be assessed in terms of the kind of information they would like to be able to retrieve from the model (geotechnical properties, engineering information, hydrogeological properties etc), scale, functionality and compatibility with other software packages such as ARC GIS. BGS is responsible for improving the representation of uncertainty if it is to continue successfully with 3D model production for the wider community and is committed to investing time and resources into the development of its confidence models. At the moment, uncertainty is represented as 2D confidence layers compiled from data density plots. The aim is to produce 3D confidence volumes that take into account data density and other factors that contribute to the uncertainty of the model. Working in partnership with both local councils and the software developer, future BGS attributed 3D models could be tailored exactly to customer needs and be able to display a wide variety of geodata in a highly useable and

understandable fashion. The models, in future, may be used to answer the major geoenvironmental and planning questions posed by local authorities and environmental agencies within the UK. If data sharing is encouraged with site investigation companies, local authorities and environmental agencies, the models can be continually improved by updating with new data as they become available. Each organisation would benefit from the increased confidence rating of the model as the newly acquired data are used to validate the model.

Acknowledgements: This work could not have been completed without the help of BGS colleagues Mat Hardenberg, Mike Browne, Gaud Poulighen, Holger Kessler, Simon Price, Susan Loughlin, Steve Mathers and Jonathan Ford. Thank are also due to Paul Mellon of Glasgow City Council for helpful feedback on the Subsurface Viewer, and to Hans-Georg Sobisch for delivering all software updates and viewing packages to BGS within the required deadlines. The paper is published with the permission of the Executive Director of the British Geological Survey (NERC).

Corresponding author: Mrs Joanne Merritt, British Geological Survey (BGS), Murchison House, West Mains Road, Edinburgh, EH9 3LA, United Kingdom. Tel: 00 44 131 650 0400. Email: jeca@bgs.ac.uk.

REFERENCES

- CAVE, M.R., & WOOD, B. 2002. Approaches to the Measurement of Uncertainty in Geoscience Data Modelling. *British Geological Survey Internal Report*, **IR/02/068**, 42pp.
- CULSHAW, M.G. 2005. From concept towards reality: developing the attributed 3D geological model of the shallow subsurface. *Quarterly Journal of Engineering Geology and Hydrogeology*, **38**, 231-284.
- FORSTER, A., LAWRENCE, D.J.D., HIGHLEY, D.E., CHENEY, C.S. & ARRICK, A. 2004. Applied geological mapping for planning and development: an example from Wigan, UK. *Quaternary Journal of Engineering Geology and Hydrogeology*, **37**, 301-315.
- FORSTER, A., HOBBS, P.R.N., MONKHOUSE, R.A. & WYATT R.J. 1985. Environmental geology study: parts of West Wiltshire and South-east Avon. *British Geological Survey Technical Report*, **WN/85/8**.
- FORSTER, A., & ARRICK, A., CULSHAW, M.G. & JOHNSTON, M. (eds) 1995. A geological background for planning and development in Wigan. *British Geological Survey Technical Report*, **WN/95/3**.
- HAINES, B.H., CULSHAW, M.G. & MONKHOUSE, R.A. 1991. Applied geological mapping in the Wrexham area: geology and land-use planning. *British Geological Survey Technical Report*, **WA/91/4**.
- KESSLER, H.K., SOBISCH, H.G., MATHERS, S., LELLIOTT, M., PRICE, S., MERRITT, J.E., FORD, J., ROYSE, K. & BRIDGE, D.Mc. 2005. Three-dimensional geoscience models and their delivery to customers. In: Russell, H.A., BERG, R.C. & THORLEIFSON, L.H. 2005: Three-dimensional geologic mapping for groundwater applications. *Geological Survey of Canada, Open File*, **5048**, pp 39-42.
- LAKE, R.D., NORTHMORE, K.J., DEAN, M.T. & TRAGHEIM, D.G. 1992. Leeds: a geological background for planning and development. *British Geological Survey Technical Report* **WA/92/1**.
- MERRITT, J.E., HARDENBERG, M.F., MONAGHAN A.L., BROWNE, M.A.E., & LOUGHLIN, S. 2005. 3D model of the solid and superficial geology of 1:10,000 Sheet NS66SW (Rutherglen). *British Geological Survey Internal Report*, **IR/05/127R**.
- PASEK, J. & RYBAR, J. 1961. Die Darstellung ingenieurgeologischer Verhältnisse in der Karte 1:25,000. *Zeitschrift für Angewandte Geologie*, **7**, 3, 136-139.
- POWELL, J.H., GLOVER, B.W., & WATERS, C.N. 1992. A geological background for planning and developing and development in the 'Black Country'. *British Geological Survey Technical Report* **WA/92/33**.
- WATERS, C.N., NORTHMORE, K.J., HIGHLY, D.E., LAWRENCE, D.J.D., PRINCE, G., MARKER, B.R., BUNTON, S., BUTCHER, A., & SNEE, C.P.M. 1996. A geological background for planning and developing and development in the City of Bradford Metropolitan district. *British Geological Survey Technical Report* **WA/96/1**.