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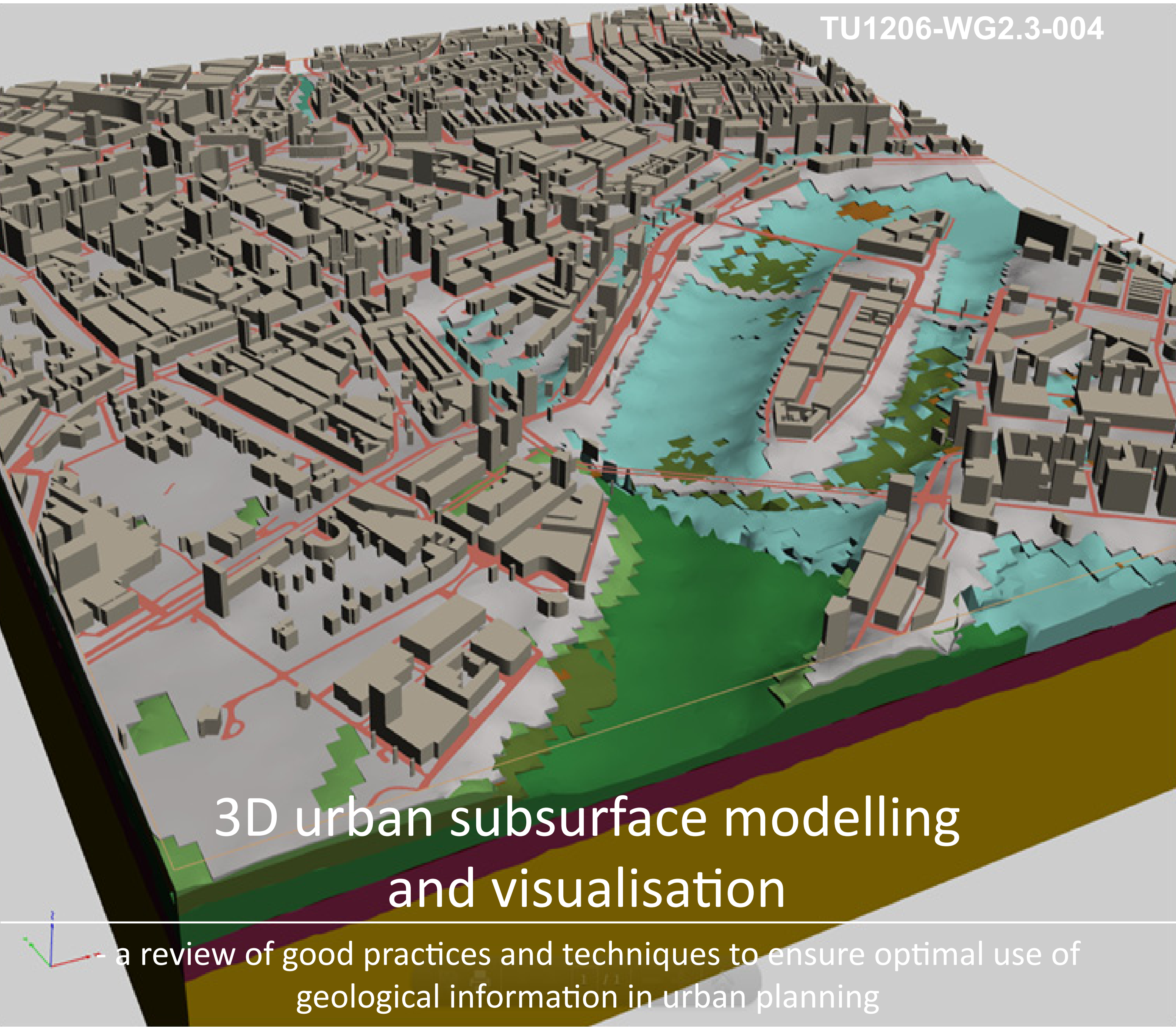

3D urban subsurface modelling and visualisation

– a review of good practices and techniques to ensure optimal use of geological information in urban planning

TU1206 COST Sub-Urban WG2 Report

J. Schokker, P. Sandersen, H. de Beer, I. Eriksson, H. Kallio, T. Kearsey, S. Pfleiderer & A. Seither

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The Sub-Urban community is thanked for stimulating discussions throughout the length of the COST action. We would particularly like to thank Diarmad Campbell for his relentless efforts to make this cooperation between major European cities, geological surveys and other research institutes a remarkable success.

Contents

Summary

This report is the result of COST Action TU1206 Working Group 2, Work package 2.3, and focusses on 3D urban subsurface modelling and visualisation. The major aims of this report are: 1) evaluating current techniques and identify good practices / best efforts in 3D geological modelling and visualisation of the urban subsurface, based on case studies, and 2) co-developing (subsurface specialists & model users) requirements for optimal use of 3D geological modelling information in specific planning and policy contexts.

Three major topics have been considered:

- Constructing and maintaining 3D urban geological models
- Modelling man-made ground
- Visualising 3D urban subsurface model results

To improve the use of subsurface modelling in urban planning in the future, the following challenges have been identified:

- The complexity of the urban subsurface, including man-made ground, combined with the level of detail of information asked for in many urban planning issues demand that geologists look beyond their traditional data sources.
- Combined 3D property modelling of the small-scale heterogeneity of man-made deposits and natural deposits requires new modelling approaches.
- Management of the shallow urban subsurface requires model tools that can be frequently updated to reflect the frequently changing properties and functions of the urban subsurface.
- There is a need for dynamic (4D) urban subsurface models that can be used for real-time monitoring and incorporation of time-series data on subsurface properties.
- It would be cost-effective to have an actively maintained, scalable geological framework model of a city available that forms a common basis for the various kinds of dedicated models of parts of the city.
- To give subsurface information a firm position in urban planning and management, geological information will have to be presented in the right format, and at the right time. It is absolutely necessary to include the subsurface infrastructure and to combine the model with above-ground information.

1. Introduction

Jeroen Schokker & Peter Sandersen

1.1 Rationale

The urban subsurface is nowadays being used more and more intensively, to an increasing depth and for ever more purposes. In many countries across the world the subsurface space is gradually becoming an integral part of 3D urban planning. Depending on the planning theme and stage, this requires adequate information on the 3D geometry and properties of both natural sediments / rocks and man-made deposits at the right level of detail. This data could then be visualised and analysed in combination with information on man-made subsurface and above-ground structures, and the extent of subsurface spatial claims related to e.g. groundwater protection, the presence of polluted zones or the in-situ preservation of archaeological heritage.

Most often, the information needed to create a reliable and useful urban subsurface model is not available within a single organisation, let alone a single database. Different data types have to be combined to construct the model, data density is typically very variable and the data come in an array of different formats and are therefore not easily interoperable. Furthermore, data requirements vary at different stages within the planning process and with the planning issue and scale at stake. Due to the dynamic nature of the urban subsurface, after model delivery regular maintenance is required to prevent the model from quickly being outdated.

Typically, 3D subsurface modelling output is not used directly in the urban planning process, but forms the basis for applied models, for example a geohydrological schematisation to model the effects of groundwater extraction or a geotechnical calculation connected to a building project (the Vienna model is a good example of this). Consequently, the direct user of geological data is typically another subsurface specialist, rather than an urban planner. Ultimately however, geological property models form a common ground to make sure that all applied models can interact.

Both the user’s questions and associated model specifications are the result of a dynamic interaction between the demand side (planners / model users) and supply side (subsurface specialists). End users might not know exactly what they need and what is possible in modelling and therefore would profit from a dialogue with the subsurface specialist / modeller, whereas the modeller needs to have a very clear picture of the user’s needs to formulate detailed model specifications.

To ensure optimal use of subsurface information in urban planning, no matter in what planning context the work is carried out, the challenges above ask for a review of good practices and techniques in 3D geological subsurface modelling and visualisation. This report addresses different aspects of 3D urban subsurface modelling, collects current approaches and identifies knowledge gaps. As such, it could act as a guidance for future work.

1.2 Aim

The major aims of this report are:

- To evaluate current techniques and identify good practices / best efforts in 3D geological modelling and visualisation of the urban subsurface, based on use cases
- To co-develop (subsurface specialists & model users) requirements for optimal use of 3D geological modelling information in specific planning and policy contexts

1.3 Context

1.3.1 Within COST Sub-Urban

In the context of WG2 (Evaluation of practices and techniques), data and model requirements necessary for the respective urban planning tasks and policy themes are formulated in WP2.1 (Subsurface urban planning and management). WP2.2 considers data acquisition and management, whereas this work package (WP2.3) considers 3D modelling and visualisation of the data. WP2.4 (Groundwater, geothermal modelling & monitoring), WP2.5 (Geotechnical modelling and hazards), WP2.6 (Geochemical modelling) and WP2.7 (Geo-archaeological heritage conservation) can be regarded as major fields of application in which the results of 3D geological modelling are being used.

1.3.2 Beyond COST Sub-Urban

We operate in the context of rapid developments in the field of 3D geomodelling, both on a European level (Bi-annual European meeting on 3D geological modelling) and globally (GSA bi-annual workshop on 3D Geological Mapping and Modelling). Within this context, we focus on the urban subsurface. In urban planning, the development of Building Information Models (BIM) is a hot topic. COST Sub-Urban’s main asset is the full integration of the geoscientific community and the urban planning community (Figure 1).

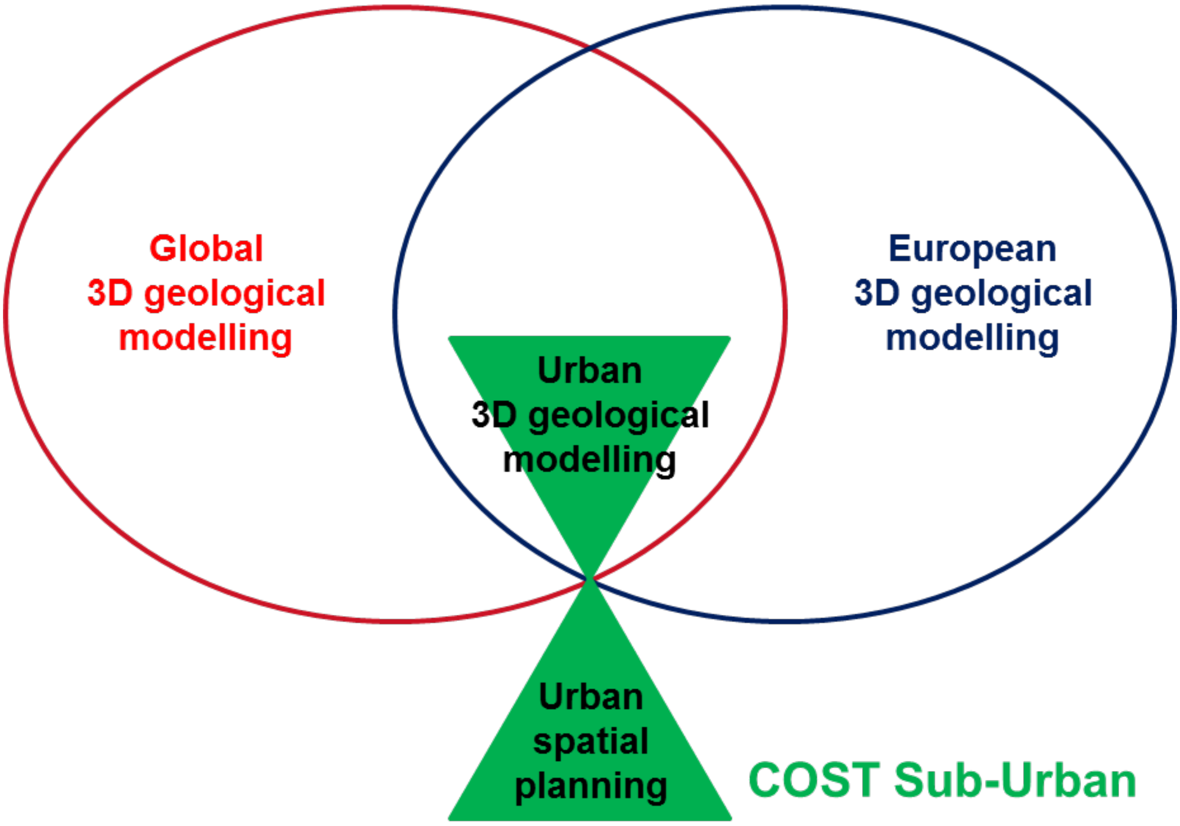

Figure 1 3D modelling and visualisation within the framework of COST Sub-Urban and the 3D geological modelling community.

1.4 Specifications of 3D urban subsurface modelling and visualisation

As stated before, the urban planning tasks and/or policy themes at hand determine the 3D urban model specifications. This includes for example which types of geological and non-geological subsurface data are used to build the model. Data requirements also vary at different stages of the planning process. Concerning geological data, one can think of:

- Which data types are included?
- Which parameters are modelled?
- What is the scale of the model?
- What is the accuracy of the model?
- What is the data density?
- How are man-made ground / anthropogenic layers included in the model?
- Are man-made structures included in the model?
- Are spatial reservations / claims included in the model?

Technical functionalities of the resulting 3D model are also dependent on the planning task and/or policy theme, as well as the stage of the planning process. Here, one can think of:

- Which modelling method has been used (layer-based or voxel modelling, static or dynamic modelling, etc.)?
- Which modelling software has been used?
- How has the model been visualised?
- How has interoperability between geological data, other subsurface and above-ground data been assured (e.g. relation to Building Information Models)?
- Is the model being maintained?

Luckily, based on examples from European cities, several 3D urban geological modelling and visualisation issues have already been explored and good practices can be identified. A short inventory of available 3D urban subsurface models has yielded the following list (see also Figure 2):

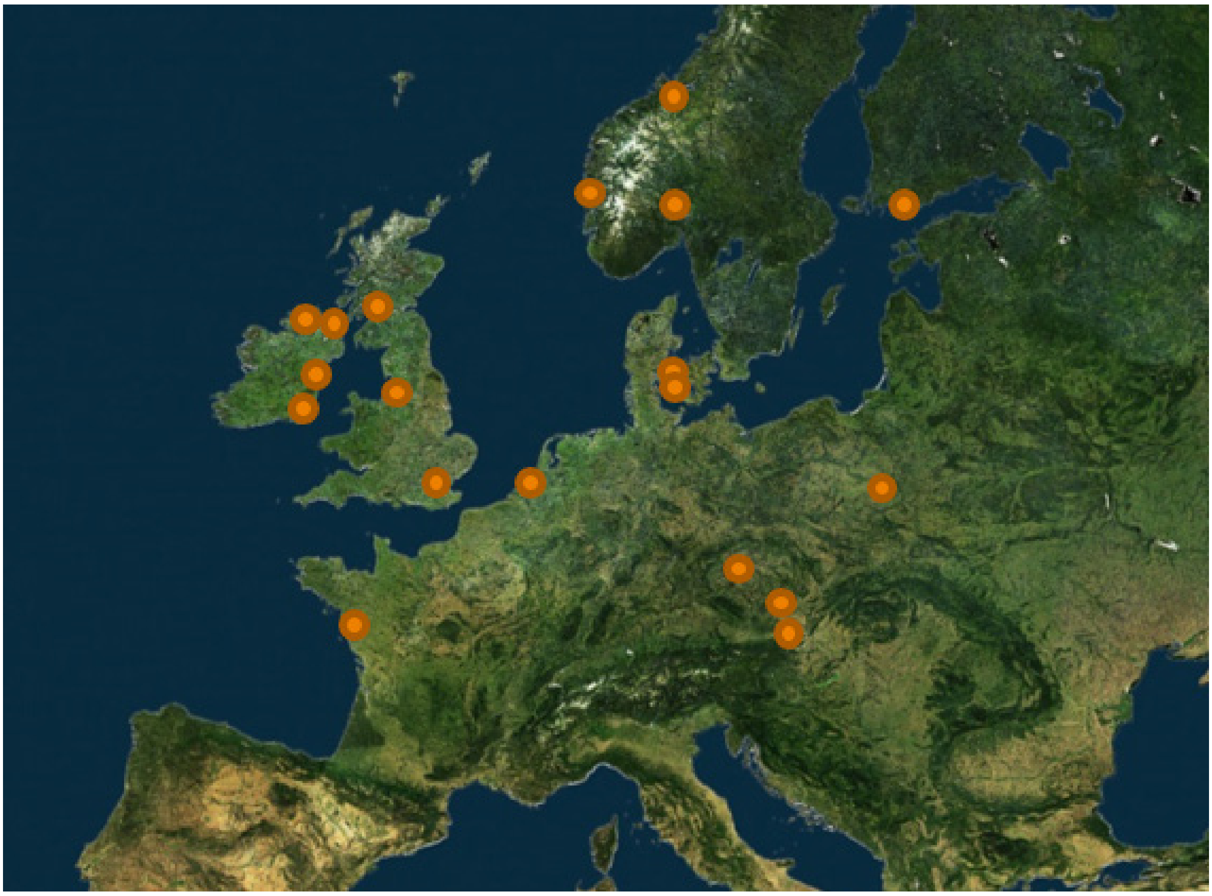

Figure 2 Geographical overview of 3D urban subsurface models that have been part of the 3D urban model inventory.

- Belfast, Londonderry (Alex Donald)
- Bergen, Melhus (Anna Seither, Hans de Beer)
- Dublin, Cork (Beatriz Mozo Lopez)
- Glasgow, Manchester, London (Diarmad Campbell, Tim Kearsey)

- Helsinki (Ossi Ikävalko, Hilkka Kallio)
- Nantes (Cecile Le Guern)
- Olomouc, Brno (Lucie Kondrová, Jan Jelének)
- Oslo (Ingelöv Eriksson, Cecília Cerdeira, Mats Hallen)
- Rotterdam (Ignace van Campenhout, Jeroen Schokker)
- Svendborg, Odense (Peter Sandersen)
- Warszawa (Tomasz Żuk)
- Wien (Sebastian Pfleiderer)

3D subsurface models that are available for each of these cities can for example be linked to policy themes, both with respect to the geological data included and the technical model functionality. This is summarised in Table 1.

Table 1 Relation of existing European 3D urban subsurface models to policy themes, as based on the inventory of 3D urban subsurface models. Black crosses indicate a possible link, red crosses indicate a strong relationship.

Policy theme	Belfast / Londonderry	Bergen	Brno / Olomouc	Dublin / Cork	Glasgow	Helsinki	London	Manchester	Melhus	Nantes	Odense	Oslo	Prague	Rotterdam	Svendborg	Vienna
Hazard management & safety	X	-	X	-	X	X	X	X	X	-	-	-	X	-	-	-
Sustainable development	X	X	-	-	X	X	X	X	X	X	-	X	-	X	-	-
Sustainable energy	-	-	-	-	-	-	-	-	X	-	-	-	-	X	-	X
Climate change (adaptation & mitigation)	-	-	-	X	-	-	X	-	-	-	X	-	-	-	-	-
Ecology & natural protection	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-
Archaeology / cultural heritage	-	X	X	-	-	-	-	-	-	-	-	-	X	X	-	-
Water management (quality & quantity)	X	X	-	-	X	-	X	X	X	-	X	-	-	-	X	X
Soil management & pollution	-	-	-	X	-	-	-	-	-	X	-	-	X	-	X	X
Underground storage	-	-	X	-	-	-	-	-	-	-	-	-	-	X	-	-
Integral planning (e.g. urban development plans)	-	-	X	X	X	X	X	X	-	X	-	X	X	X	-	-

1.5 Report structure

The remainder of this report focuses on three major topics that are considered of special relevance when modelling the urban subsurface for planning purposes: technical modelling issues that are centered around the use of multiple datasets and model updating, modelling man-made ground, and visualising model results to ensure optimal use.

1.5.1 Constructing and maintaining 3D urban geological models

Based on the user's needs and model possibilities, the subsurface specialist has to tailor the modelling process. This involves many different, interacting issues, which should be taken into account in more or less detail:

- Which subsurface properties should actually be modelled? (stratigraphy, lithology, grain-size characteristics, etc.)?
- What type of modelling should be performed?
- Which input data types are useful (including minimum requirements for metadata and data)?
- What data density is required (and how to deal with uneven geographical data distribution, typical in an urban setting)?
- What model resolution (x,y,z) is required?
- Do we need to take model uncertainty into account (and how to calculate and communicate this)?
- How to deal with the dynamic nature of the urban subsurface?
- Does the model have to be maintained / updated?

Good practice examples: Vienna & Glasgow

1.5.2 Modelling man-made ground

The upper meters of the urban subsurface have almost always been modified by man. This concerns both reworked natural and non-natural materials. It could even be argued that subsurface infrastructure itself is part of man-made ground. On traditional geological maps, man-made deposits have mostly been grouped into one unit or ignored altogether. In the last decade, several attempts have been made to set up a classification scheme for man-made ground. Depending on the purpose of your 3D model, the heterogeneity and dynamic nature of man-made ground request the use of a range of sources to map these deposits in the appropriate detail. The same amounts to the properties of man-made ground. And can we make use of the same modelling procedures as used for natural deposits?

Good practice examples: Odense & Bergen

1.5.3 Visualising 3D urban subsurface model results

Good visualisation possibilities of 3D data are fundamental to communicate results to the user. Depending on the user's questions, 3D geological subsurface information usually only provides part of the answer. Geological information is generally assessed in combination with subsurface infrastructure and above-ground data (buildings, infrastructure, etc.). This data is often available in a different standard (e.g. BIM) in a different environment (e.g. CAD). Visualisation involves both technical issues (short overview of available software, etc.) and interoperability issues (combination with other data sources) and the optimal solution depends on the user's possibilities and capabilities. Which possibilities are there to show your model to your customer? How to make sure visualisation adds to the value and use of subsurface data in the planning process?

Best effort examples: Helsinki, Espoo & Oslo

2. Constructing and maintaining 3D urban geological models

Tim Kearsey, Jeroen Schokker & Sebastian Pfleiderer

2.1 Introduction

The majority of 3D geological models created by geological surveys in Europe are built upon a geological mapping heritage (e.g. Van der Meulen et al., 2013). As a result they tend to be largely constructed based on the information from boreholes and/or outcrops and show the geometries of stratigraphic units as their main parameter. This heritage also determines the modelling scale (x,y,z), which is typically bound to a 1:50,000-1:200,000 scale on a 2D map. Furthermore geological coverage in urban areas is traditionally poor and in some countries even non-existent, in which case cities are depicted as grey areas on the map.

3D urban geological models often have different users than national-scale models, for example urban planners and engineering geologists (see WG2.1 report). It has been noted that in general "Urban users are less able to interpret geological information", and they need it to be "related specifically to the problems for which they require solutions" (Culshaw & Price 2011). This issue is summarised in Figure 3. Therefore, 3D geological modelling in urban areas is different from traditional national geological mapping and modelling and it may involve additional effort for both the subsurface specialist and end user to adequately bring subsurface information across.

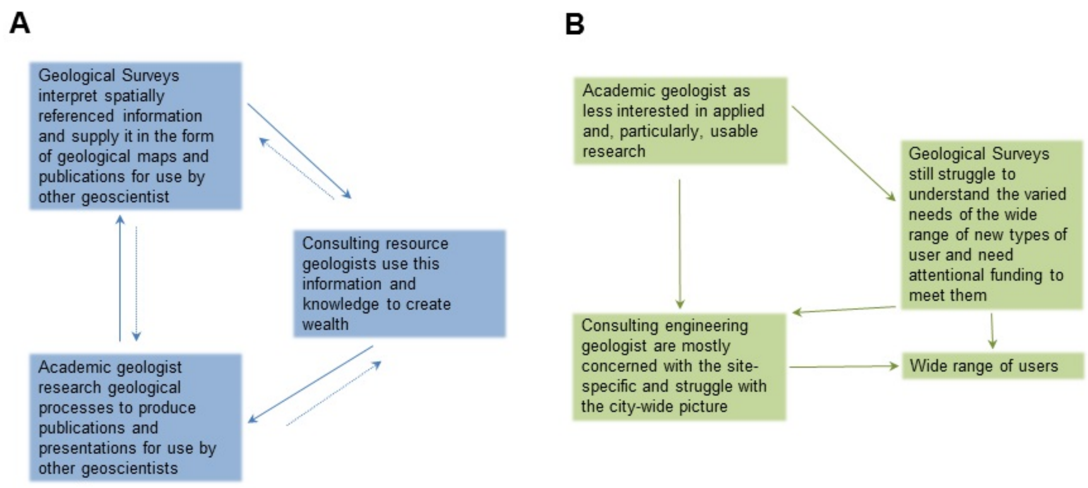

Figure 3 (a) Traditional geological producer-user relationship. (b) Geological producer-user relationship applied to urban areas (adapted from: Culshaw & Price, 2011).

When constructing a 3D urban subsurface model that will be used in a planning context, it is important to focus on the geological problems identified by planners in their cities. Many of these geological problems may be specific to the individual city, based on the nature of the geology under the city and history of the development of that city. Table 2 shows various city issues that can be at least partly caused by the nature of the subsurface and examples of cities where this is relevant.

Table 2 Examples of Urban subsurface Issues and some European Cities where they are relevant.

Urban subsurface issue	Subsurface feature related to this issue	Example of a European city where this is an issue
Groundwater management	Heterogeneous Quaternary alluvial deposits	Vienna
Archaeology / cultural heritage preservation	Quaternary (raised marine and glacio-fluvial and glacial) and man-made ground	Bergen
Subsidence	Quaternary (raised marine and glacio-fluvial and glacial)	Oslo
Deteriorating foundation conditions	Heterogeneous Quaternary deltaic deposits and man-made ground	Rotterdam
Mining subsidence	Faulted Carboniferous coal field sediments	Glasgow
Tunnelling and infrastructure	Quaternary (glacio-fluvial and glacial) and Bedrock (Paleozoic metamorphic and igneous intrusions)	Helsinki

There are some geological conditions that are common to many cities. For instance information on depth to bedrock is important when assessing subsurface-related questions in European cities such as Glasgow, Helsinki and Oslo. However, in cities on thick unconsolidated successions such as Rotterdam and Vienna this is not an issue.

Equally relevant to the question as to what geological problems are addressed in urban 3D models is the availability and density of observational data. The acquisition of observational data is being addressed by Watson et al. (2017), but it must be considered here that the accuracy of each model is largely determined by the observations available.

The aim of this Topic is to describe current workflows for 3D geological modelling of the urban subsurface, concentrating on technical modelling issues and illustrated by good practice examples from Vienna and Glasgow.

2.2 Model input data

The requirements of the model user combined with the observational data available determine both the model content and level of detail. The nature and quality of the input data is critical in controlling what urban issues can be addressed. In urban areas it is often difficult to collect input observations through traditional geological methods. As a result most 3D urban subsurface models are reliant on a combination of borehole data from geological survey organisations and third party data collected by contractors, engineers, universities, other government agencies and planners (Royse et al., 2015). Use of this inhomogeneous data set has its own limitations as data have been collected for a range of purposes, with a range of methods, in a range of scales and with inconstant levels of interpretation.

2.2.1 Using multiple sources of input data

Nearly all urban 3D geological models use a wide range of input data sources. In the models described in the 3D model inventory (see paragraph 1.4) at least ten different data sources have been used:

1. Borehole descriptions (geological, geotechnical, etc.)
2. Geotechnical tests (e.g. cone penetration test data)
3. Hydrological data
4. Historical and archaeological data
5. Surface elevation data
6. Surface geological maps
7. Soil maps
8. Mine plans
9. Construction drawings
10. Data on (subsurface) man-made structures

These data sources all need to be collated, digitised and standardised before they can be used in a 3D model. For instance borehole descriptions may use different description standards or other local datums instead of the national grid system and thus would need to be converted to common standards before being used as input for a 3D model. Another big time investment is digitally capturing analogue or scanned pdf's of data such as mine workings, borehole logs, ground investigations and other datasets.

Many geological surveys now maintain national databases for both their own borehole descriptions and information from boreholes drilled by others. For instance in the Netherlands TNO maintains the DINO (in future BRO) database, which contains not only borehole descriptions, but for example also cone penetration test data, information on groundwater levels, and chemical and physical analyses (Van der Meulen et al., 2013; Watson et al., 2017).

Many geological surveys are now building web portals to allow companies to deposit their digital data directly into the survey databases (Bonsor et al., 2013; Van der Meulen et al., 2013). These portals can also have an element of automatic quality assurance to check if the relevant metadata, such as borehole location, elevation and start date have been entered (Bonsor et al., 2013).

2.2.2 Data quality

One of the biggest issues with using input data from various data sources is that they can have poor quality lithological descriptions which muddle different grain-size standards or mix up descriptive, genetic and age terms (Figure 4). Equally they can use antiquated terms. for instance in Scotland in mining boreholes the term 'Blaes' is often used to describe a laminated friable mudstone and 'Fakes' to describe sandy shale. Such terms need to be translated to be used in 3D urban modelling, a task that can take a lot of time when compiling a large urban data set.

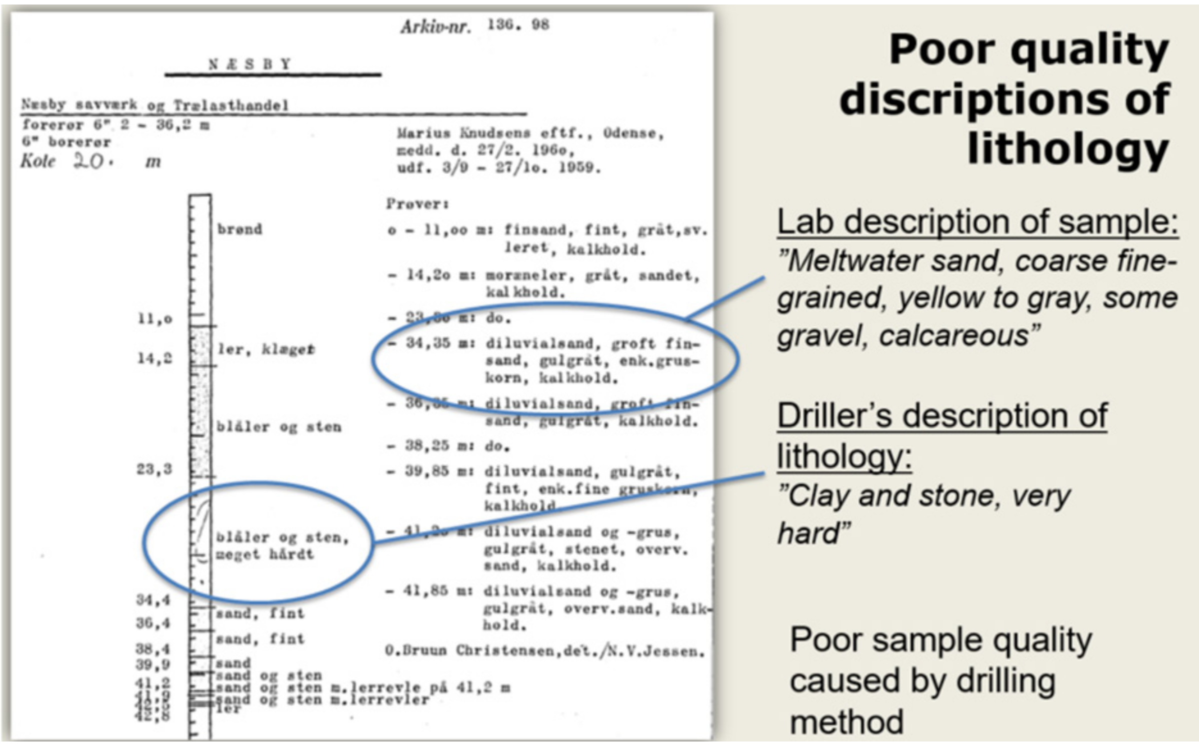

Figure 4 Example of quality issues with borehole input data from Denmark (source: Peter Sandersen, GEUS).

2.2.3 Data distribution

Another issue with using diverse input data is uneven data distribution. Geologist are used to working with uneven datasets when doing fieldwork and use geological interpretation to fill in the gaps. However, uneven data coverage can cause problems when using interpolation and stochastic methods.

The effects of data distribution can be best illustrated by borehole maps. Even in areas with a large number of boreholes the distribution of these boreholes can affect the results of any modelling (Figure 5).

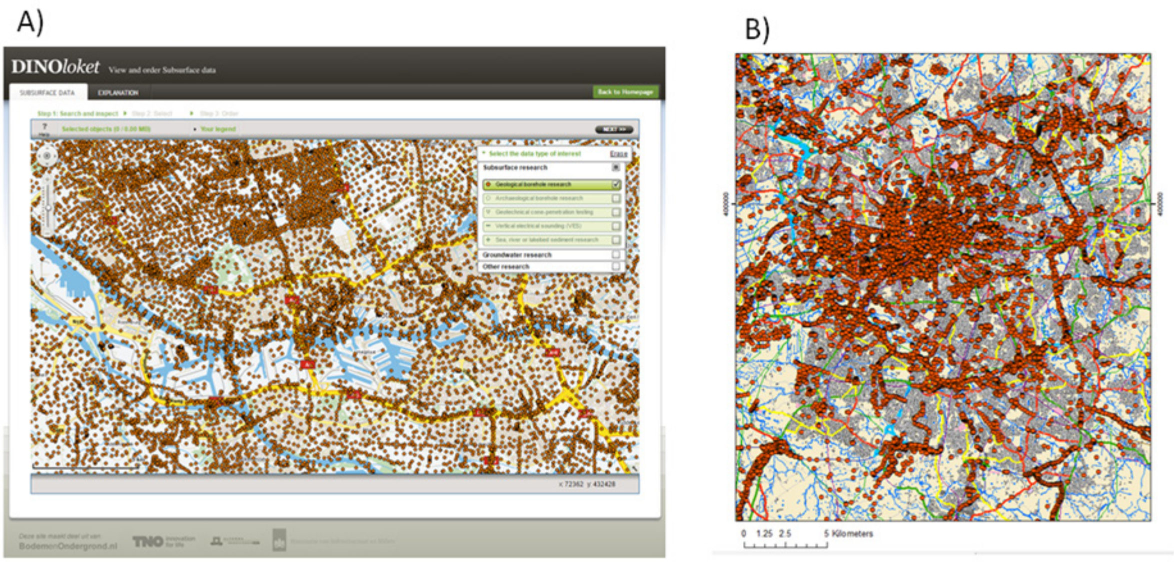

Figure 5 Comparison of Borehole clustering. (a) A relatively even and regular dataset from Rotterdam (using www.Dinoloket.nl). (b) A similar number of boreholes, but highly clustered from Manchester (BGS © NERC; also contains Ordnance Survey data © Crown copyright and database right 2015).

It has been shown that cluster bias has a strong control over the ability of the model to predict the correct answer. MacCormack & Eyles (2012) investigated how the accuracy of a model is affected by the distribution of borehole data. They tested three sample patters of borehole datasets Figure 6 and found that there was a decrease in model accuracy from a regular borehole distribution to a random distribution. The model accuracy decreases even more sharply between random distribution and a clustered distribution of boreholes and this can outweigh the effects of having a large numbers of boreholes. This is compounded by the geological complexity modelled. In complex glacio-fluvial sediments with a clustered input dataset in Glasgow it has been shown that the models can only predict the correct answer on an excluded borehole 60% of the time, regardless of which modelling methodology was used (Kearsey et al., 2015).

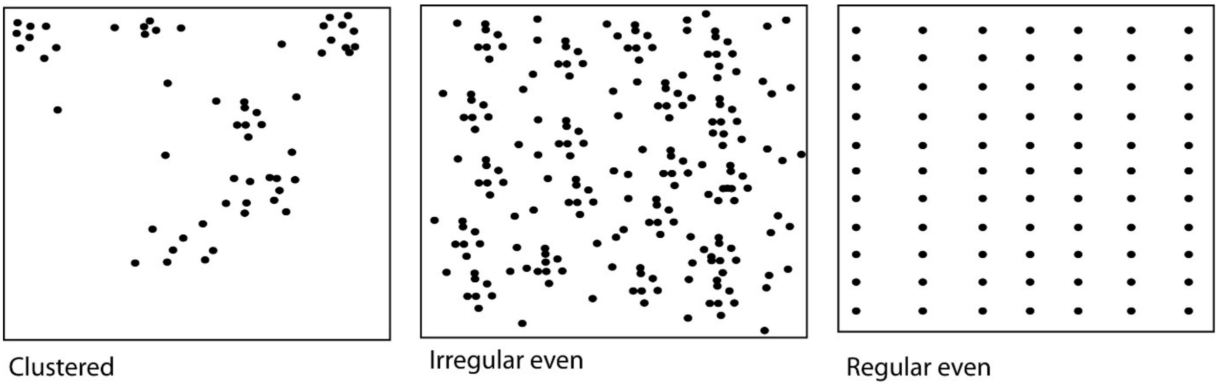

Figure 6 Borehole distribution tests using a 256-point dataset (adapted from: MacCormack & Eyles (2012)).

2.3 Modelling methodology

There is a wealth of literature describing 3D geological modelling, for example in relation to the 3D mapping workshops at the meeting of the Geological Society of America (http://isgs.illinois.edu/content/workshop-extended-abstracts). In general, there are two main methods that are currently used to represent geology in a computer: layer modelling and stochastic modelling. Layer (or: layer-based) modelling is the most common method and is based around creating a set of surfaces that represent changes in the geology (usually stratigraphic) and other elements such as faults (e.g. Gunnink et al., 2013). This is the most common method used, although it has its limitations. Firstly, it is often manually intensive and creating a model may take many man-months to create and update. Also, if geological units contain multiple lithologies this can often be hard to illustrate in a layer model (Stafleu et al., 2011).

Stochastic modelling uses geostatistical techniques to work out the probabilities of a certain set of properties, such as lithology or hydraulic connectivity, in 3D space. To do this first a 3D grid must be created (also termed a voxet) in which the simulation can run. In cases where there is enough input data and the geological situation is not too complex it might be possible to perform unconditional lithological modelling. However, in urban geological models, due to the issues with data clustering and distribution described before this is usually not possible. Instead as a first step stratigraphic layers are created. Subsequently, the 3D grid is created within them and the properties are stochastically modelled (Stafleu et al., 2011; Schokker et al., 2015). Some geological features, such as faults, cannot be stochastically modelled and are usually created as part of layer models.

Non-geological elements can be part of the subsurface model, for example man-made structures such as cables and tunnels (Oslo), mineworkings (Glasgow), but also man-made deposits (cf. Chapter 3). Eventually it might be useful to combine the subsurface and above-ground worlds in one model (cf. Chapter 4).

2.4 Model update

The urban subsurface changes quickly. Ground investigations, which are the major source of input data for 3D geological models, often precede a period of extensive alteration of the subsurface. This means that the input data for 3D geological models might already be out of date even before the model is created. Due to the frequent man-induced alterations of the subsurface, 3D urban subsurface models need to be updated regularly (or even interactively) in order to remain useful. The amount of time and money to do this depends on several features:

- 3D modelling method used. Unconditioned stochastic models are easier to update than layer-based models
- Model complexity. 3D models containing many surfaces and faults are harder to update than simple models
- The software used to create the model
- The resources (in both time and money) available to the 3D modeller

For instance the Glasgow model (see Good practice example 2) took 1 man-year to create. Updating it would again require a considerable portion of this time. Current efforts to incorporate time as a fourth dimension to urban subsurface modelling would make this problem even more acute (Van der Meulen et al., 2013).

2.5 Case studies

Two case studies have been identified that can be considered good practice examples: Vienna (Appendix A) and Glasgow (Appendix B).

The 3D geological subsurface model of **Vienna** (Austria) was originally constructed as part of a study to improve existing maps of surface geology as well as to create structural maps of underground geological formations (Pfleiderer & Hofmann, 2004). The Geological Survey of Austria (GBA) carried out the study for the Vienna City Administration, with the objective of extracting the geological information inherent in tens of thousands of borehole logs. Almost as a byproduct, GBA combined all raw data and derived subsurface information to construct a 3D geological model. The city later commissioned GBA to complement the geological model with hydrogeological and geotechnical data and after that to characterize geological modelling units and groundwater with respect to geochemical baseline values. Thus, the geological model became a multi-purpose application in the fields of urban geology, geotechnical engineering, hydrogeology and geochemistry. Recently another aspect has been added to the applications of the Vienna City model by investigating the potential of shallow surface geothermal energy usage within Vienna both for closed-loop systems and for groundwater heat pumps. This study benefitted significantly from the existing 3D model and especially from the knowledge of geological structures, depth to water table and hydrological properties. As such, all applications of the Vienna City model are based on the same geological information and the results can be readily combined. The multi-purpose model is being maintained for the city by GBA.

Glasgow (UK) has been identified by the Scottish Government as a major area of regeneration. Critical in this regeneration is understanding how geology controls issues that affect new developments. The main reason for the construction of the Glasgow model is to understand issues associated with: the siting of buildings in relation to shallow mining and the potential for instability; the thickness and composition of glacial units; and other hazards, such as the movement of industrial contaminants through the subsurface, associated with urban regeneration in a post-industrial city (Campbell et al., 2010). The Glasgow 3D model comprises both bedrock units, and unconsolidated sediments and anthropogenic deposits. Anthropogenic deposits (made ground) represent a combination of made and worked ground, including filled and partially back-filled pits and quarries. As such, anthropogenic and natural subsurface layers are both present, and have been modelled in considerable detail. The Glasgow Conurbation geological model was designed for use by a range of end-users, including practitioners, and has been released through the ASK (Accessing Subsurface Knowledge) Network, which was developed by the British Geological Survey (BGS) and Glasgow City Council (GCC), with support from other partners in the public and private sectors. Its main aim is to make geological data more readily available to consultants, contractors, local and regulatory authorities, and researchers, to help reduce the cost of ground investigation when delivering successful construction and regeneration projects, and to encourage further innovation and research. Higher resolution versions of some parts of the model have been prepared, where a specific need has been highlighted (e.g. regeneration and development areas, and linear transport and other infrastructure corridors). A lower resolution catchment-scale model of the River Clyde, which passes through the centre of Glasgow, has also been developed for groundwater modelling, etc. The 3D model is also designed to fit within the British Geological Survey's National Geological Model, which is a multi-scalar, geospatial model of the subsurface arrangement of the rocks and sediments of the UK.

2.6 Key knowledge gaps

- The complexity of the urban subsurface, including man-made ground, combined with the level of detail of information asked for in many urban planning issues, and the difficulties involved in collecting new data in a city environment, demand that geologists look beyond their traditional data sources (e.g. borehole descriptions, shallow geophysics) and use data from third parties. However, the integration and "translation" of all of the different data sources into one model workflow is currently very time-consuming and case-specific.

- The properties and functions of the urban subsurface are subject to frequent alterations, making models quickly out-of-date. Management of the shallow urban subsurface requires model tools that can be frequently updated to reflect the current situation (e.g. in conjunction with hazard management) or can quickly incorporate additional information. Currently, there are no general workflows available that enable quick model update (see also Chapter 3).

- At the present time, shallow subsurface models are largely constructed on an ad hoc basis when a subsurface-related problem occurs. It would be much more cost-effective if one geological framework model were available, that formed a common basis for the various kinds of dedicated models of parts of the city. Apart from being actively maintained, a framework model would have to be scalable (5D), in order to be of real use (see also Chapter 4).

3. Modelling man-made ground

Peter Sandersen, Anna Seither, Hans de Beer, Jeroen Schokker & Tim Kearsey

3.1 Introduction

Many interests are related to the urban subsurface because of the varied activities in the cities. The interests are for instance related to geotechnical and constructional activities, geothermal installations, management of suburban infrastructure and management of surface water and groundwater. But the many interests also reveal many problems related to the urban subsurface. These problems arise because all the activities listed before involve working of the existing ground. The reworked ground itself and the covering of the ground in the cities in many ways change the physical properties of the uppermost parts of the subsurface. Problems for instance are seen when pavements and buildings seal off the urban surface leading to alterations in surface water run-off (e.g. Scalenghe & Marsan, 2009), when old waste-dumps cause health issues and when the man-made ground causes general geotechnical problems or creates areas with subsiding ground (De Beer, 2005; 2008; De Beer et al., 2012). But the man-made ground may also create positive effects, for instance when gravel-filled excavations create new possibilities for run-off, retainment and infiltration of excess water in an urban area with an impermeable clayey subsurface (Mielby et al., 2015a).

Therefore, there is a growing need for detailed 3D models of the urban subsurface, because urban planners and managers need tools to map the present structure and properties of the subsurface - both the anthropogenic layers and the pre-anthropogenic layers beneath. In addition to this it may be needed to model future man-made changes to the subsurface and thus construct 4D models (e.g. Rosenbaum et al., 2003; Van der Meulen et al., 2013). The city limits are ever-expanding and with it comes a continuous change of the spatial extent and properties of the man-made layers; this brings forward a need for dynamic models of the urban subsurface.

Modelling the urban subsurface generally requires operating at small scales because the man-made structures and the suburban infrastructure typically are in decimetre- to meter-scale. This means a high degree of model detail and as a consequence this also means a need for very dense input data. There will be a need for boreholes, CPTs (Cone Penetration Tests), data from excavations, water level gauges and geophysics, and in addition to this, suburban infrastructure (conduits, cables, subsurface building parts, etc.) and maps of historical city and landscape development can be used as proxies to model the man-made ground. But the foreseeable questions in this relation are: do we have enough data to be able to make the model we need at the needed scale? Can we meet the demands and expectations of the end users (planners/geoscientific specialists) or do we need to collect additional data? And last but not least: how do we model a heterogeneous and apparently unpredictable subsurface body such as the anthropogenic layer, and can we make our model sufficiently dynamic to encompass the future changes of the urban subsurface?

As part of this Topic, we describe examples of the current practice of mapping and modelling of man-made ground beneath two European cities. We have chosen modelling projects in Bergen, Norway, and Odense, Denmark, as examples of good practice. Considering the purpose of the modelling the two chosen examples are very different: in Bergen the city is subsiding because of disintegration of organic material in the man-made ground, whereas in Odense the purpose of the mapping of the man-made layers is to include these as an active part of the hydraulic system beneath the city and thereby be able to model groundwater flow more accurately beneath the city.

3.2 Definitions

In this Topic we will only address mapping and modelling of man-made ground (the anthropogenic layer) and not mapping and modelling of the unaltered part of the subsurface (the “pristine” geology). The terms “man-made ground” and “anthropogenic layer” are preferred in this report, but terms such as “anthropogenic deposits”, “anthropogenic ground”, “archaeological stratigraphy” or “artificial ground” are widely used (e.g. Edgeworth et al., 2015; Ford et al. 2004; 2014; Rosenbaum et al., 2003). The term “Archaeosphere” is used for the anthropogenic infill in the example shown in Figure 7.

The Anthropocene has been proposed as a new geological epoch as being the period with human impact on the Earth (Edgeworth et al., 2015). However, not all deposits from the Anthropocene may be necessarily anthropogenic in nature.

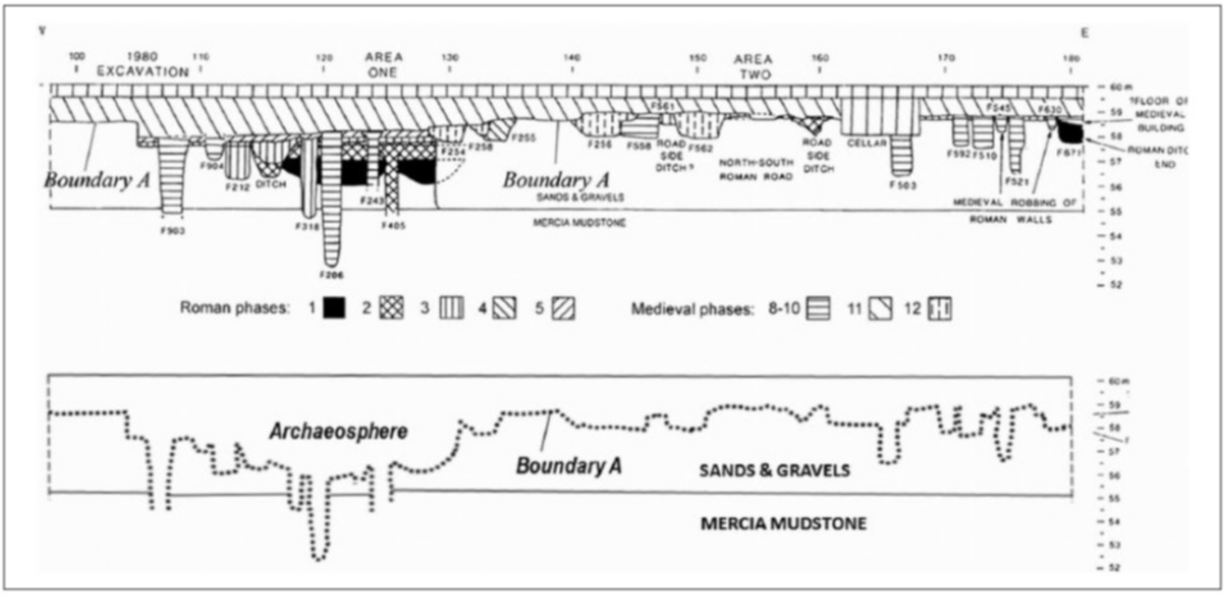

Figure 7 Coalescence of lower boundaries of multiple intercutting surfaces from different periods into a single continuous stratigraphic surface. An example from Leicester, UK, by Connor & Buckley (1999), reproduced in: Edgeworth et al. (2015).

As can be seen in Figure 7, a series of events separated in time, creates a lower boundary ("Boundary A"), representing the bottom of the anthropogenic layer. The figure illustrates the heterogeneous nature of the man-made ground and the highly irregular lower boundary surface.

Perhaps the most comprehensive classification of man-made ground has been made by BGS in the UK (see Ford et al., 2004; Price et al., 2011; Rosenbaum et al., 2003) (Figure 8). This classification was first intended for the production of 2D geology maps but later adapted for 3D modelling (Ford et al., 2004). As mentioned by Rosenbaum et al. (2003) it is theoretically possible to subdivide any man-made ground into a textural, a morphological and a genetic component, but in practice it is seldomly possible.

Ford et al. (2014) take the classification further and suggest a lithostratigraphical classification for the man-made deposits. However, the authors mention that defined litho-units may be significantly thinner and far less continuous than natural deposits, typically resulting in a far more complex architecture of the anthropogenic deposits compared to the unaltered geology below.

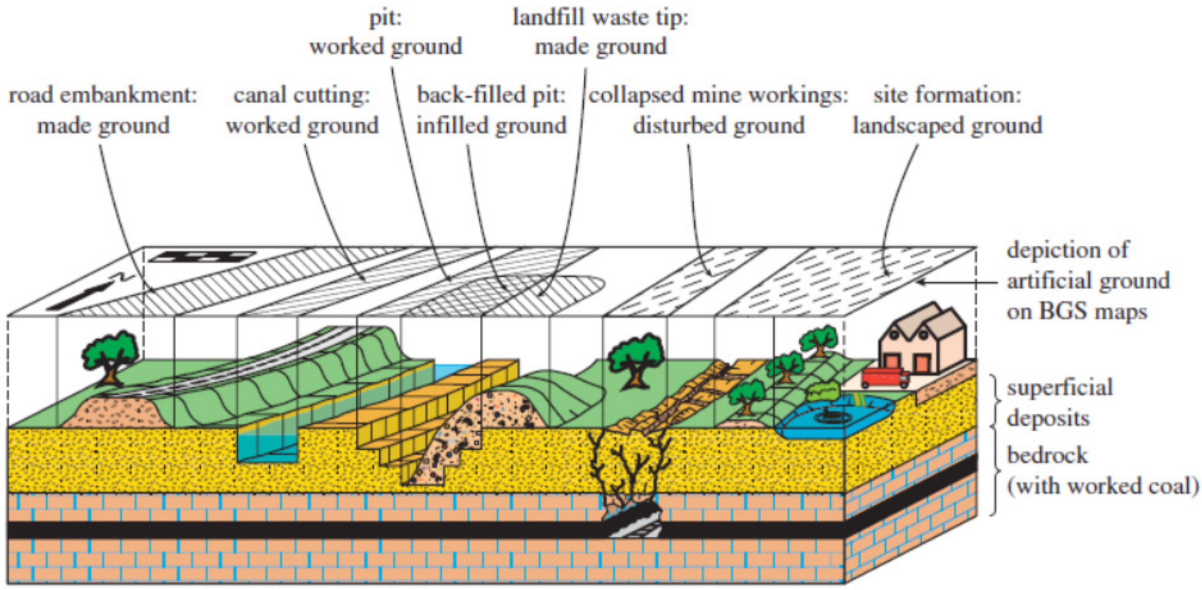

Figure 8 Examples of the main types of man-made ground (artificial ground) and the corresponding signature on geological maps by BGS (reproduced from: Price et al., 2011).

3.3 Mapping and modelling workflow

When attempting to map and model the man-made layers in the urban subsurface it is important to focus on the purpose of the mapping and the end-user needs. Important is also to evaluate if the existing data can produce the model detail that is required. The complexity of the man-made ground poses challenges seen from a modelling perspective, and we need to consider if it is important to classify and describe the long series of anthropogene events that lead to the composite subsurface volume of man-made ground (Figure 7), or if we can just focus on lithology from boreholes and excavations. If we need a dynamic model that is continuously updated an important part of the modelling work are the considerations and decisions of how future updating is done.

Most likely, the available hard data will not be enough for a comprehensive mapping of the man-made ground. The alterations to the subsurface for instance caused by multiple instalments of subsurface infrastructure and the infill around them add a complexity that will require a very large amount of hard data to map. Therefore the knowledge of the type of subsurface infrastructures, their age and their size can be valuable proxies for modelling the (assumed) infill of the excavations. Generally, mapping and modelling of heterogeneous anthropogenic deposits is associated with larger uncertainties than modelling natural deposits.

Because mapping of man-made ground is typically complicated and very time-consuming, a phased approach may be applied (Table 3):

Table 3 Phased approach as applied in the construction of the 3D geological model for the city of Odense.

1	**Initial model consideration phase**	• Which types of problems/challenges are related to the man-made ground? • What is the 3D/4D model intended to be used for (overview, urban planning, construction, remediation etc.)? • Who is the end user of the model? • What types of questions should the model be able to answer? • Are data from boreholes, CPTs, excavations, etc. going to be merged with modelling of infrastructure data (modelling of possible infill of excavations around conduits, cables, etc.)? • Do we include man-made subsurface structures (basements, etc.?) as man-made ground? • Which model scale is needed? • Can we accept a model with varying detail? • What is the expected model output for the end-users?
2	**Data evaluation phase**	• Evaluation of data density (existing hard data). Do we have an adequate number of data points and a fair distribution within the model area? • Evaluation of data detail (existing hard data). Does the data detail meet our requirements? • Do we have enough infrastructure data to model the excavation infill? • Do we have enough descriptions of the city development in the past (e.g. historic sources and maps) and enough descriptions on the planned future city development? • Can detailed Digital Elevation Models (DEMs) contribute to the modelling of the man-made ground? • Can geophysical methods be applied in the urban areas (electromagnetic and electric methods, georadar, seismics, etc.)? • Evaluation of data quality. Does the data quality meet our requirements? Are the data from old surveys still usable today? • Are the data sets present in a format that can be used directly or do we need one or more data conversion phases? • Decision on data focus. Use of existing hard data (boreholes, excavations, CPTs, etc.) alone, or in combination with modelling of subsurface/above ground infrastructure data (character of infill)?

3	**Data collection phase**	• Field data acquisition. • Conversion of old data to suitable formats. • Collection of third party data (e.g. by buying borehole data from private sources, etc.).
4	**Modelling phase**	• Decision on model type (3D/4D, layer model, voxel/volumetric cells model, use of statistics, etc.). • Decision on model scale. • Combination/merging with existing geological models? • Parameterization of the man-made ground.
5	**Model delivery phase**	• Decisions on how and which parts of the model/data should be accessible to the end-users. • Is tailoring of specific types of output needed? • Teaching the end-user how to use (and not use) the model. • Appropriate communication of model uncertainty.
6	**Update phase**	• Decisions on update cycles and procedures. • Decisions on organizing the ongoing data collection and modelling to keep the model up-to-date (data availability, scientific staff, planners, stakeholders, funding, etc.). • Continuous focus on adding relevant data from new (and maybe unconventional) sources.

The considerations concerning the construction of an urban 3D model including man-made ground are basically not different from making a “normal” geological or hydrostratigraphical model. But there are special challenges in the city areas, such as a lack of detailed data, subsurface complexity and the geometry and parameterisation of the anthropogenic deposits. Generally, we need more data and more detail compared to geological modelling in e.g. sparsely populated rural environments. We will therefore have to rethink our modelling approach and realise that model update will be more important when dealing with modelling in urban areas.

3.4 Case studies

Two case studies have been identified that can be considered good practice examples: Odense (Appendix C) and Bergen (Appendix D).

Climate change and man-induced changes in the water cycle will create increasing stress on existing urban run-off systems. The municipality of **Odense** (Denmark) therefore needed a tool to be able to handle the water cycle of the city in the future and to calculate probable scenarios and be able to address the changes in due time. A vital part of this tool is the physical framework - a 3D geological model of the subsurface that visualises the aquifers and aquitards. This model of the physical framework had to be constructed before the hydrological modelling was initiated. As large volumes of the city's subsurface have been and are being reworked and altered as part of urban activities, the man-made parts of the subsurface play a vital role in the hydrological cycle. In realising this, mapping and modelling of the subsurface of Odense needed to include mapping and modelling of the man-made component of the subsurface. The approach adopted was to: identify the series of main events that have affected the upper part of the subsurface (e.g. digging and infilling of trenches for sewers, water pipes and power cables); order these chronologically; decide which ones to include in the mapping and use the events as proxies for the extent and physical properties of the man-made layers. The Municipality of Odense, VCS Denmark waterworks, private companies and the Geological Survey of Denmark and Greenland (GEUS) collaborated to construct the 3D geological/hydrogeological model. The results of the Odense project are a hydro stratigraphic model that can be used at different scales, and a tool targeted at mapping and modelling of the man-made layers. The final off-the-shelf product is a standard hydro stratigraphic model with surfaces in a 100 m grid (Mielby et al., 2015).

Anthropogenic processes and deposits include a wide ranging from archaeological activities to modern urban development. The city of **Bergen** (Norway) is an example where both buried heritage and standing monuments are of prime significance. The subsurface in the whole city centre is characterised by significant thicknesses of anthropogenic deposits up to 1000 years old with high archaeological value. These so-called archaeological deposits are "sandwiched" between the natural geological deposits below, and the modern man-made deposits of various compositions above. Deterioration of organic material often occurs as a consequence of lowering of the groundwater level, which make archaeological deposits such as those in Bergen particularly vulnerable. A main goal for the medieval centre of Bergen is therefore to establish a stable hydrological environment. A 3D geological model provides a framework for the integration of other spatial and process models to help assess the preservation potential for Bergen's buried heritage. At the World Heritage Site of Bryggen, the Geological Survey of Norway (NGU) constructed such a 3D geological model in conjunction with a numerical groundwater flow model (De Beer et al., 2012).

3.5 Key knowledge gaps

- Combined 3D property modelling of the small-scale heterogeneity of man-made deposits and natural deposits requires new modelling approaches. The combined approach used in Odense looks promising, but has yet to be tested in other cities.

- The properties and functions of the urban subsurface are subject to frequent alterations, making models quickly out-of-date. Management of the shallow urban subsurface requires model tools that can be frequently updated to reflect the current situation (e.g. in conjunction with hazard management) or can quickly incorporate additional information. Currently, there are no general workflows available that enable quick model update (see also Chapter 2).

- There is a need for dynamic (4D) urban subsurface models that can be used for real-time monitoring and incorporation of time-series data on subsurface properties, e.g. in conjunction with cultural heritage management or monitoring building activities.

4. Visualising 3D urban subsurface model results

Hilkka Kallio & Ingelöv Eriksson

4.1 Introduction

Generally speaking visualisation is any technique for creating images, diagrams, models or animations to communicate a message. A good visualisation can help users explore and understand data, and also communicate that understanding to others, especially if complex structures or ideas are to be explained to people that don't have the same background or professional expertise. Good data visualisations can also help users to make robust decisions based on the data being presented. Geological visualisations of 3D models are often created with computer aided design, but also an artist's impression can animate and clarify the message (Figure 9). The basic question is: what is the message to be communicated?

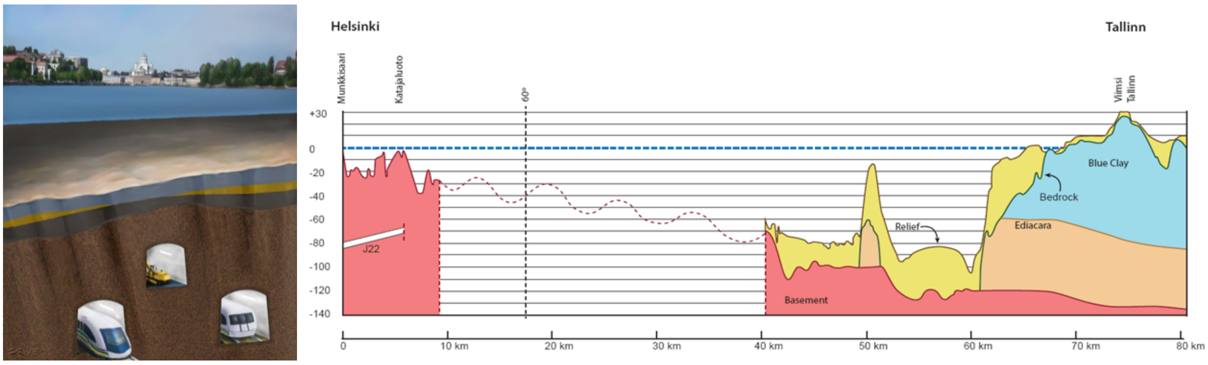

Figure 9 Visualisations for the big audience and decision makers in the Tallinn-Helsinki tunnel project. The drawing is made by an artist (H. Kutvonen, GTK), the cross section is based on real 3D models across the sea (H. Kutvonen, GTK).

Traditional examples of visualisation of geological data are 2D maps and cross sections reflecting rock units, lithology, or particular themes like groundwater quality or geochemical signature. The development of computerised geological 3D modelling enabled the representation of geological features in 3D software. However, the visualisation of a 3D model can be generated either in 2D or 3D format depending on the use of the illustration, the availability and format of other data sources the user wants to combine the model with and the resources of the external user. It is possible that the end user does not have the technical possibilities to view 3D or the message is just easier to understand in planar 2D view than in 3D scene. Discerning distances, scales or orientations can be demanding in a 3D view. On the other hand, the advantage of a 3D visualisation is to deliver better insight into the model by being able to demonstrate the relationships between different features.

One of the most important new datasets that recently improved geological visualisations are LiDAR (LIght Detection And Ranging) high-resolution terrain models. Since the mid-2000s the land areas of Europe have been scanned with LiDAR. The resulting high-resolution terrain models can expose ground surface details that could not be recognised with traditional methods. The high-resolution elevation data also increase the value of the superficial deposit maps and makes them easier to interpret (Figure 10). For example the most popular map service of the Geological Survey of Finland (Maankamara; http://gtkdata.gtk.fi/Maankamara/index.html) is based on this method. The Maankamara map service is available as an application for mobile devices as well.

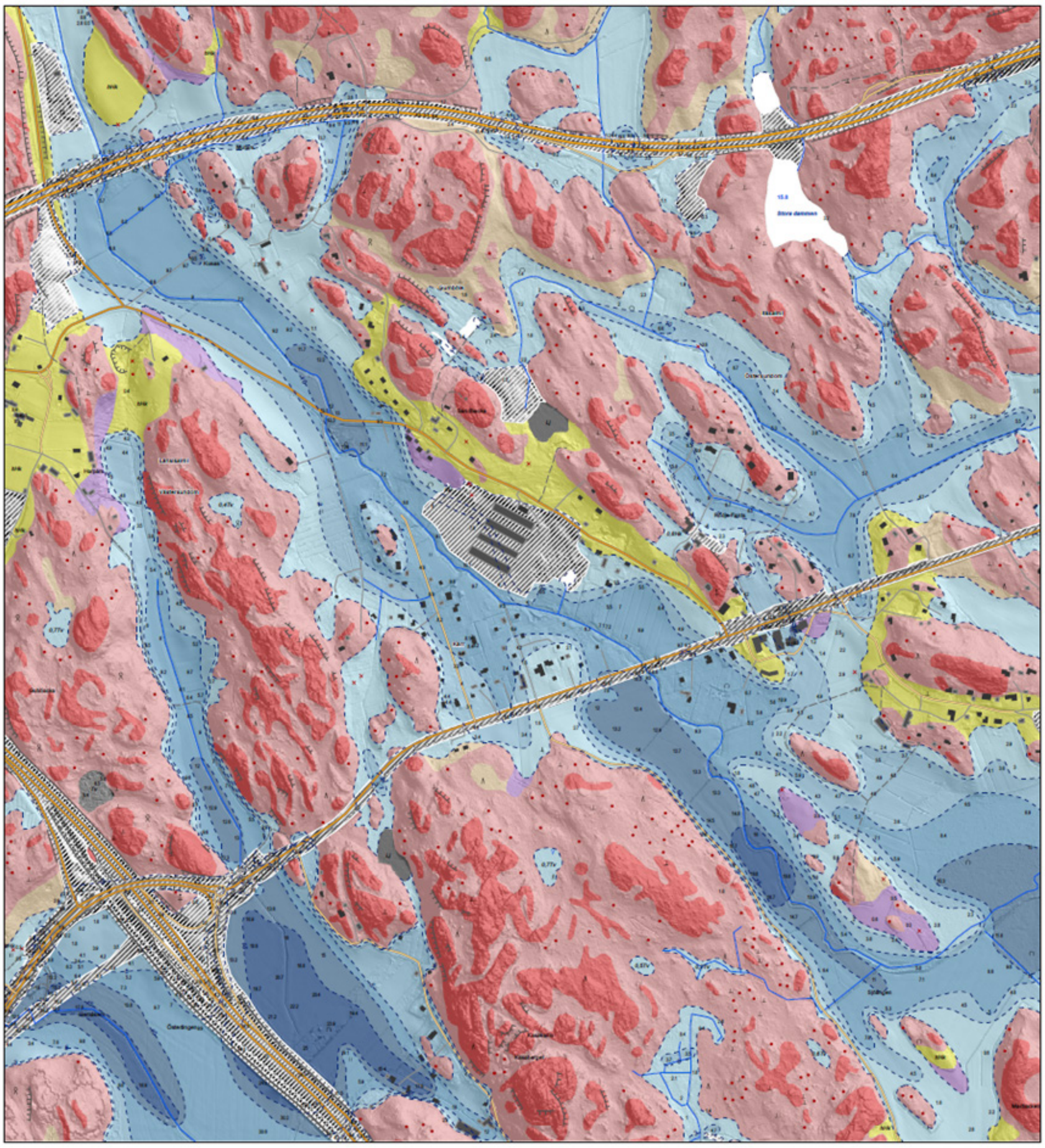

Figure 10 The hillshade of the LiDAR elevation model overlain with Quaternary deposits in Östersundom, Helsinki. Blue areas on the map represent clay thicknesses, dark red are bedrock outcrops and lighter red moraine, yellow is sand and violet is silt. This kind of terrain model is used for the interpretation of geological structures, but they also provide an approach for impressive visualisations. Quaternary deposits © GTK, elevation model and base map © National Land Survey of Finland.

To give subsurface information a firm position in urban planning and management, geological information will have to be presented not only in the right format at the right time, but also combined with subsurface infrastructure and above-ground information. Building information modelling (BIM) provides a platform that allows interactive design between different actors, having geological data as one component among the others. This provides a great opportunity to better integrate geological knowledge into urban planning. It also provides new challenges in visualisation of geological data when many other objects are included in the same view (Figure 11).

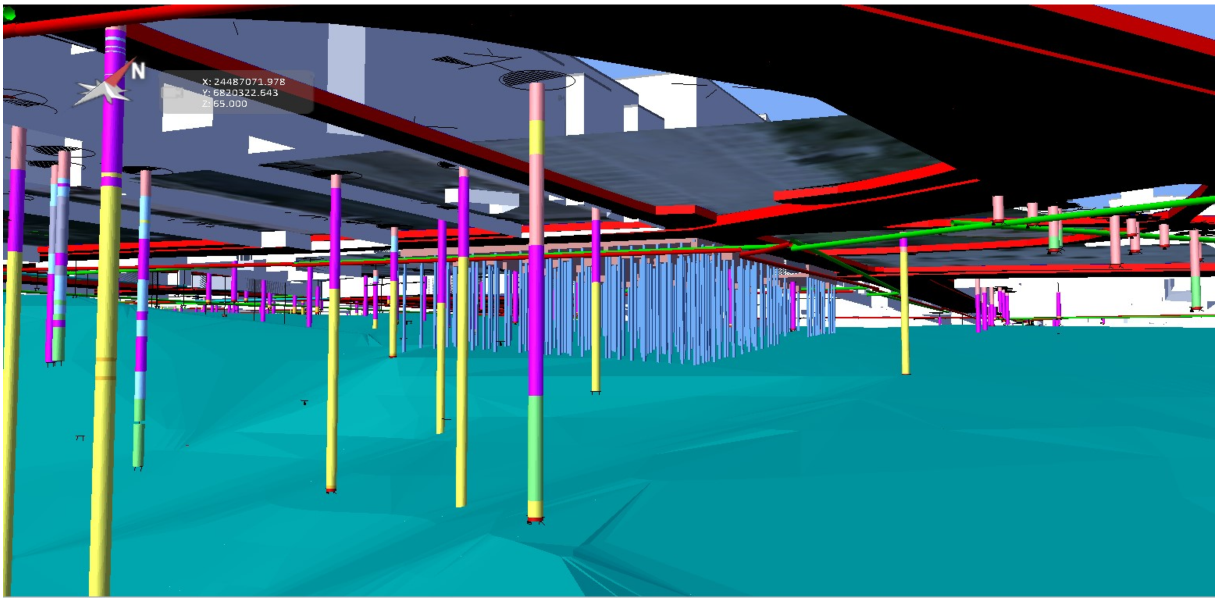

Figure 11 The combination of buildings, piles, traffic lanes, boreholes and modelled bedrock surface. This city model example is from Tampere Finland.

As part of this Topic, we present three examples of subsurface visualisations with a geological component made for urban planning needs. The two first examples are from Finland and are focused on visualising construction suitability of new housing zones in a metropolitan area. The third example is from Oslo (Norway) and discusses an ongoing pilot project used to identify which level of integrated 3D modelling is needed in urban planning.

4.2 Current status of land use planners' demands: an example from Finland

In Finland, geological modelling is commonly used for quantifying ore and aggregate deposits and also for some large groundwater aquifers. In urban environments however, the main interest is in construction properties. The Geological Survey of Finland has focused on construction suitability assessments on the city master plan level, whereas on the plot scale usually geotechnical tests are performed to assess suitability for building. Constructing suitability assessments on a plot scale estimate the feasibility of the plan. Local drainage, ground settlement, stability and other special characteristics are considered in the detailed plan. Furthermore, ground construction methods and foundation types are tentatively decided upon. More generalised assessments, made at master plan or partial master plan level, are not that common. In Finland, these are based on the interpretation of different geological deposits and their relation to varying ground conditions. The aim of the master plan scale reviews is to help planners to distinguish areas with normal, demanding and very demanding ground conditions when optimising land use activities. In Finland the risk for landslide hazard due to the occurrence of extremely sensitive clays (quick clays) is smaller than for example in Norway or western Sweden. Higher landslide risks are associated with decreased slope stability near river channels.

Usually, planners and construction experts mainly desire knowledge on the location of geological discontinuities like surface of the crystalline bedrock and the bottom and top surfaces of soft sediments, as well as the geotechnical properties of sediments. The visualisation of geological and geotechnical information is largely based on two-dimensional drawings (Quaternary maps, cross-sections, etc.). The input data of these visualisations are often stored in separate AutoCAD projects. The situation is slightly changing however and the largest operators of the infra sector in Finland now requires use of the national XML-based exchange format (Infra Model) in their projects. Infra Model is not just an exchange format, but also a set of requirements, instructions and classifications supporting the BIM philosophy of interoperability of digital information. The adoption of Infra Model has intensified the use of BIM in the infrastructure sector in Finland. The format of geological observations and interpretations will also be defined during the ongoing development of Infra Model requirements. Geological Survey of Finland has a main role in the definition of geological features in Infra Model.

In Finnish cities the use of 3D design is common in the field of geotechnical and civil engineering, but 3D visualisations are not actually used. However, the advancement of urban information models demands 3D visualisations within these fields in the future. The City of Helsinki is clearly turning to using BIM and Infra Model. The goal of the Public Works Department (Rakennusvirasto) of the City of Helsinki is to gradually replace 2D drawings by 3D visualisations also on sites. According to the Public Works Department, the greatest benefit of BIM, at the moment, is not provided by 3D visualisation or machine control, but management of decentralised maintenance data. Like in most cities, in Helsinki many kinds of pipes and cables are buried underground, but no exact information is available on them. The harmonisation of 3D datasets from different sources may also reveal problems, for instance conflicts between colliding objects. When a subsurface pipeline collides with an underground bedrock hillock, could this be a case of an unrecorded bedrock excavation or rather an error in bedrock surface modelling? Overall, shared databases would provide many types of up-to-date data on assets and their condition, also useful to contractors.

4.3 Case studies

Three case studies have been identified that can be considered best effort examples: Helsinki (Appendix E) and Espoo (Appendix F) and Oslo (Appendix G). At current, no good practice examples are available. Integrated urban and sub-urban modelling might benefit from the GeoCIM concept (Mielby et al., 2017).

The example presented here are subsurface visualisations with a geological component made for urban planning needs. The two first examples (Appendices E and F) are from Finland and are focused on visualising construction suitability of new housing zones in a metropolitan area. The third example (Appendix G) is from Oslo (Norway) and discusses an ongoing pilot project used to identify which level of integrated 3D modelling is needed in urban planning.

4.4 Key knowledge gaps

- To give subsurface information a firm position in urban planning and management, geological information will have to be presented in the right format, and at the right time. It should also possible to incorporate the subsurface infrastructure and to combine the model with aboveground information. At present, there are no good examples of a truly integrated modelling approach that extends both above and below the surface.

- At the present time, shallow subsurface models are largely constructed on an ad hoc basis when a subsurface-related problem occurs. It would be much more cost-effective if one geological framework model were available, that formed a common basis for the various kinds of dedicated models of parts of the city. Apart from being actively maintained, a framework model would have to be scalable (5D), in order to be of real use (see also Chapter 2).

- There is no obvious way to effectively visualise uncertainty of data. The datasets included in geological models are normally very heterogeneous. Also the interpretations performed during the geological modelling have a high degree of subjectivity. These facts favour a qualitative approach to visualise uncertainty (Sandersen, 2008). The uncertainty of geological models can be classified into three different types: 1. data imprecision and quality (e.g. accuracy and precision of the input measurements), 2. inherent randomness (uncertainty of interpolation and extrapolation away from known points) and 3. incomplete geological knowledge (Wellmann et al., 2010). Basically, the type 1 uncertainty is connected to the measurement method, e.g. drilling and sampling generally offer better accuracy than geophysical sounding. By classifying the input data based on the method, the user can estimate the reliability of the data. The type 2 and 3 uncertainties are mainly connected to data density and geographical data distribution. In general, illustration of the location of input data points based on method is the basis of a qualitative uncertainty visualisation (e.g. applied by Schokker et al., 2015). To visualise the uncertainties in 3D voxel models, information entropy may also be used (e.g. www.dinoloket.nl/sites/www.dinoloket.nl/files/file/dinoloket_toelichtingmodellen_20140711_modelonzekerheid_in_geotop.pdf). This method is useful when the end user is a subsurface specialist. In many cases planners state that a written (qualitative) comment is enough to communicate the uncertainty. In conclusion, the end user defines the type and degree of uncertainty visualisation.

4.5 Requirements for optimal use of 3D subsurface information in urban planning

Local geological knowledge and good input data are important factors in building geologically valid and consistent models. In addition to this however, the understanding of customer's needs and standards is fundamental to effectively communicate model results. It is therefore important to strengthen the dialogue between the geoscience, engineering and urban planning branches. Effective co-operation is needed when cities and other actors adopt BIM standards for managing infrastructure, construction and maintenance. The integration of subsurface information into BIM requires that geologists also develop knowledge of technical design systems like AutoCAD.

Another suggestion for future research is the visualisation of uncertainty. It is important to improve the understanding of the different sources of uncertainty and test different visualisation methods. This will provide an opportunity to examine the reliability of models. Uphold of integrity is also a good reason to incorporate the uncertainty into a visualisation. The methods to visualise uncertainty should however always be discussed with the customer.

Urban subsurface modelling is starting to extend beyond 3D. With regards to optimal model usage, but also considering effective maintenance of subsurface information, time-dependent (4D) and space-dependent (5D) modelling are worthwhile investigating to capture the dynamics of the urban subsurface. At the same time, it should be realised that the results of these complicated models might have to be reprocessed to more simple forms of visualisation (e.g. 2D maps or cross sections) to help the urban planners and decision makers.

One of the objectives of many urban subsurface modelling projects is to relate the outcomes of geological modelling to ground improvement costs and to visualise the model results in terms of costs. The visualisation of cost estimates could be simple maps or 3D visualisations based on prebuilding and building prices in normal vs. demanding ground conditions. The ground construction costs are partly dependent on geological conditions and the possibility to influence these costs decreases as planning evolves from a general master plan level to detailed site plans. To be realistic in this context however, it is good to recall the other criterions for urban planning. What is the importance of demanding ground conditions in the decision making process as compared to other factors like location logistics? However, geoscientists could have a real impact on sustainable development of urban areas by making development costs and their connection to different geological settings clearly visible to both urban planners, decision makers and the general public.

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Appendix A: Vienna geological subsurface model

Sebastian Pfleiderer

Rationale

The 3D geological subsurface model of Vienna, Austria, was originally constructed as part of a study to improve existing maps of surface geology as well as create structural maps of underground geological formations within the city limits of Vienna (Hofmann & Pfleiderer, 2003). The study was carried out by the Geological Survey of Austria (GBA) for the Vienna City Administration – Department of Bridge Construction and Foundation Engineering (MA29) – with the objective to extract the geological information inherent in borehole logs (40,000 boreholes in 2001). Surface layers described in these logs were used to update the existing surface geological map whereas the depth information of underlying formation tops was used to construct structural maps of the subsurface. Almost as a by-product, GBA combined all raw data and derived subsurface information to construct a 3D geological model of Vienna's subsurface (Pfleiderer & Hofmann, 2004a).

Within the Vienna City Administration, MA29 is responsible for ground investigations and the geotechnical analysis of sediments and rocks in the shallow subsurface, be it for the construction of subway tunnels or the foundation of bridges and large buildings. The department is also in charge of the investigation of landfill sites, the motion detection of building structures and natural slopes (landslides), and environmental impact assessments. The department has built a database of digital borehole logs, which were collected during the last 100 years and which describe the geological formations in the subsurface. Until 2001, MA29 for their day-to-day work made individual queries of this database and used a surface geology map dating from 1972 (Brix, 1972). The updated geological map, which in addition to stratigraphic units also contains lithological description, and the structural maps, which depict e.g. the depth to fine-grained Tertiary sediments underneath Quaternary gravel, constituted a significant improvement for visualising the geological structures in the shallow subsurface. The surface and depth maps were used intensively, however the 3D model was not applied immediately within the department.

The Department of Water Management (MA45) is responsible for surface and groundwater management and protection within Vienna. It is also in charge of flood protection and surface water ecology, and runs monitoring stations for groundwater table (114 stations) and quality (66 stations). These stations mainly regard a gravel aquifer in the eastern half of the city, which is utilised for part of Vienna's drinking water supply. But also deeper layers, carrying groundwater within Tertiary sediments, are considered as possible alternative water supply options for the city. Concerning groundwater, MA45 closely collaborates with MA29 to put its monitoring stations into a geological context and to link geological formations to aquifers. Both departments commissioned GBA in 2003 to complement the geological model with hydrogeological and geotechnical data (Pfleiderer & Hofmann, 2004b), and in 2009 to characterize geological modelling units and groundwater with respect to geochemical baseline values (Pfleiderer et al., 2010). Thus, the geological model became a multi-purpose application in the fields of urban geology, geotechnical engineering, hydrogeology and geochemistry.

The Department of Energy Planning (MA20) recently has added another aspect to the applications of the Vienna City model by commissioning GBA to investigate the potential of shallow surface geothermal energy usage within Vienna both for closed-loop systems and for groundwater heat pumps (Götzl et al., 2014). This study benefited significantly from the existing 3D model, especially from the knowledge of geological structures, depth to water table and hydrological properties contained in the model. In addition to geotechnical, hydrological and geochemical parameters, the modelling units are now also described by values of thermal conductivity as a result of this study.

Finally, there are two other departments within the Vienna City Administration, the Department of Urban Development and Planning (MA18) and the Department of District Planning and Land Use (MA21), which could benefit from or make use of the geological subsurface model. However, these two departments up until now have not included the model into their day-to-day work.

Geological setting

The geological situation of the city area of Vienna is described by Brix (1972). The western part of Vienna – the hills of the Vienna Woods – is dominated by flysch nappes (sandstones, shales and marls; brittle material with poor conductivity for groundwater), while the central and eastern parts constitute the Vienna basin which is filled with Neogene marine to lacustrine sediments, Pleistocene fluvial gravel and Holocene eolian and floodplain deposits. At the western edge of the basin, along a narrow N-S-trending band, Neogene clay and silt units occur at the surface (impermeable, fine-grained layers with occasional coarse-grained units). In the central and eastern part of the basin, these clay and silt layers are overlain by Quaternary gravel terraces (coarse-grained layers with high conductivity for groundwater), which were deposited by the river Danube coming from the North (rounded pebbles, mainly quartz) and by tributaries from the East (platy particles, mainly sandstone). Between the Danube gravel layers on top and the platy gravel layers underneath, a thin layer of finer-grained sediment (colluvium) can sometimes be observed. At ground surface, gravels are occasionally covered by a thin layer of fine-grained material (loess and loam). Figure 12 shows a cross-section of the Flysch zone and the Vienna basin with Holocene deposits removed (modified from Pfleiderer et al., 2012).

Structure and tectonic evolution of the Vienna basin are described by Decker (1996) and Decker et al. (2004). The rhomboidal pull-apart basin developed at the beginning of the Neogene. Syn-sedimentary normal faults trending North-South progressively lowered the base of the Vienna basin step-wise from West to East down to 5400 m below sea level at the south-eastern city limit. The most prominent of these fault systems, the Leopoldsdorf fault, is still active today (Hinsch et al., 2005).

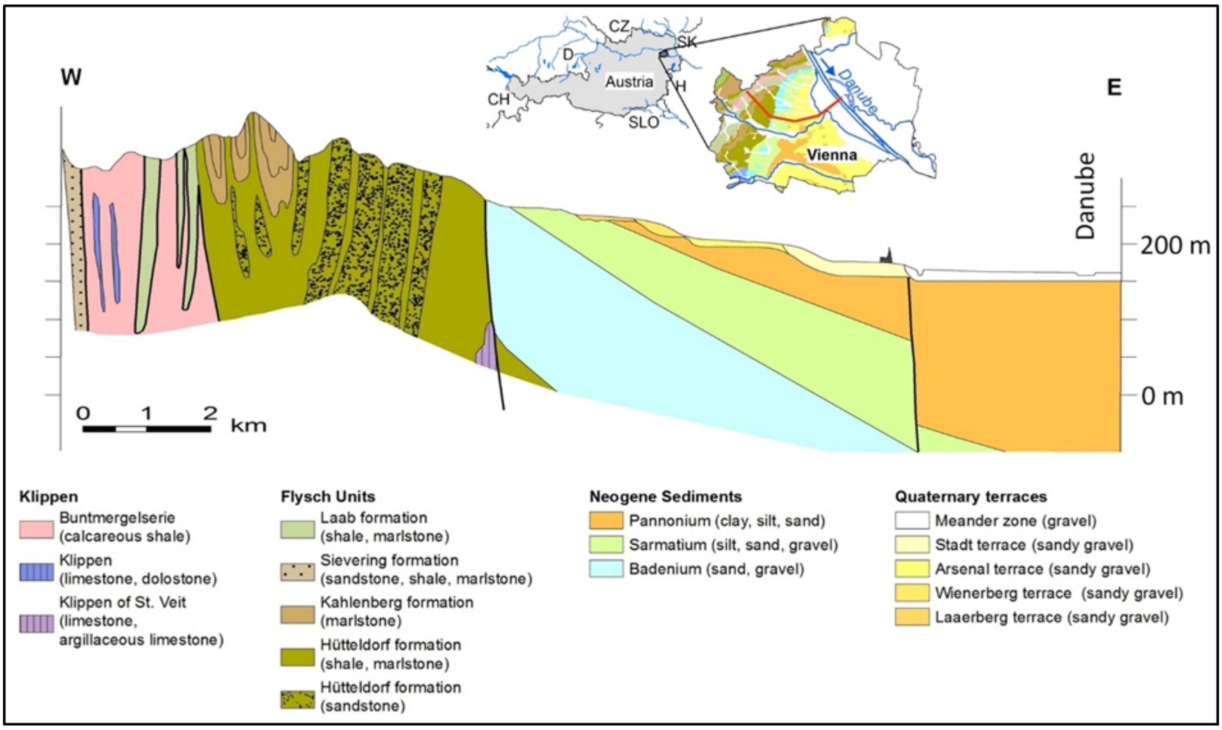


Figure 12 Cross-section of the Flysch zone and the Vienna basin (modified from Pfleiderer et al., 2012), Holocene deposits removed, 8-fold vertical exaggeration.

Input data

Borehole logs

MA29 maintains a digital database of borehole logs obtained over the last 100 years. Data include the location, elevation and depth of boreholes, date and type of drilling, as well as top, bottom and lithology of geological units. The database also contains references to samples taken for material testing. At present, the database consists of 55,600 boreholes. Digital logs are not stored as scans of reports and profiles, but numerically, which allows MA29 to select and query the database interactively. For outside users, the locations of drilling sites can be viewed online and free of charge (https://www.wien.gv.at/baugk/public/), while subsurface data of individual boreholes can be purchased for a small fee. For updating the geological map of Vienna, GBA was granted access to the complete data set (41,470 boreholes at the time).

The vast majority (80 %) of boreholes reached 2 - 20 m below ground while less than 1 % extended beyond 100 m below ground. This has obvious implications for the uncertainty of the geological model, which increases drastically with depth. Approximately 38 % of boreholes reached the top of the fine-grained Tertiary sediments, an important subsurface discontinuity for Vienna's hydrogeologists and geo-engineers.

The updated geological map (Hofmann & Pfleiderer, 2003) which is based on the Geological Map of Vienna 1:50,000 (Brix, 1972), the Geological Map 1:50,000 Sheet 58 (Schnabel, 1997) and the Geological Map 1:50,000 Sheet 59 (Fuchs, 1985), and which was updated with the data set of 41,470 boreholes, was used as surface geological map for the construction of the 3D model. In addition, the Geological Map of Lower Austria 1:200,000 (Schnabel et al., 2002) was also taken into consideration, especially major fault traces were carried over from this map.

A very valuable source of geological information in built-up areas such as large cities, represent historical maps. For updating the geological map, altogether 104 maps archived in the "Wien Museum" and dating from 1147 to 1994 were transformed to modern day topography and features such as old river courses, clay or sand pits, morphological ridges or incisions were compiled in a GIS layer. Today, these features are concealed since rivers have been channelled underground and excavation pits filled with rubble. Transferring them onto a modern map gives geological insights as to the location of river sediments, regional material distribution (sand, clay, anthropogenic material), but also provides indications of potential environmental hazards (landfills). While these features bear no information in depth and therefore cannot be modelled in 3D, they significantly improve the surface geological map.

The following structural maps were used to constrain the modelling units in the subsurface:

- Top colluvium (Nowy et al., 2001)
- Top Tertiary (Nowotny, 1998)
- Top Middle Pannonian (Friedl, 1955; Bernhard, 1993)
- Top Sarmatian (Brix, 1969; Unterwelz, 1979; Bernhard, 1993)
- Top Badenian (Bernhard, 1993)
- Base Tertiary (Kröll & Wessely, 1993)

Cross sections

Geological cross-sections were partly used as direct input for surface modelling (Nowy et al., 2001), partly only used for conceptualising the overall structure of layers and faults. The following 49 cross sections were used:

- Nowy et al. (2001): 21 North-South and 19 East-West cross-sections, constructed using the same MA29 borehole dataset as described in chapter 3.1
- Küpper (1965) – Plate 15
- Bernhard (1993) – 2 East-West and 1 North-South cross-sections (Appendices 1, 2, 3)
- Brix & Schultz (1993) – 5 East-West cross-sections (Fig. 125)
- Brix & Schultz (1993) – 1 North-South cross-sections (Fig. 132)
- Wessely (2006) – 2 Northwest-Southeast cross-sections (Fig. 168)
- Wessely (2006) – 2 Northwest-Southeast cross-sections (Fig. 335)
- Wessely (2006) – 1 Northwest-Southeast cross-section (Fig. 368)

3D surfaces

As ground surface, the digital elevation model provided by Open Government Vienna (https://open.wien.gv.at/site/open-government-data-in-vienna-2/) with a resolution of 10 x 10 m pixel size was used. In addition, both MA29 and MA45 have very recently started themselves to work with and construct 3D geological models at the scale of individual construction sites. Some of the 3D surfaces of these models were incorporated into the overall GBA model although the level of detail is vastly different. While urban geology studies at GBA are traditionally carried out at the scale of the entire city (1:25,000), the city administration departments usually investigate one subset of boreholes, an individual construction site or a small area of the city at a time albeit at a far more detailed scale.

Faults

All major fault lines published in the above-mentioned surface geological maps, depth maps and cross sections were imported into the modelling software, geo-referenced, traced and then modelled in 3D. In some areas of the city, detailed investigations by MA45 and its associated company WGM have identified faults by correlating borehole logs and sedimentary layers offset by tectonic activity. Compared to the major faults traced on maps, these faults represent information that is much more exact. They were incorporated into the model as fault sticks and then modelled in 3D.

Modelling methods

Until 2003, GBA used a set of self-programmed ArcView 3.1 Avenue scripts called "WellMaster" (Reitner, 2000) to display borehole data in 2D and to flag correlating units manually. Figure 13 shows a screenshot of such a well correlation with markers of the base of Pleistocene gravel flagged for later interpolation. The markers were subsequently interpolated to construct surfaces in ArcGIS using kriging techniques with faults as breaklines.

In 2010, GBA migrated all surfaces of the Vienna city model to the modelling software GOCAD® (Paradigm®) and refined the model by constructing fault planes and incorporating more input data. Additional geological cross-sections were imported as scans, georeferenced and vectorised. Some sections could be imported directly as GIS data sets. More surfaces were added to the model, geological bodies were defined in 3D and layers were parametrised with geostatistically-derived values of material properties such as density, plasticity, hydraulic and thermal conductivity as well as geochemical natural background levels.

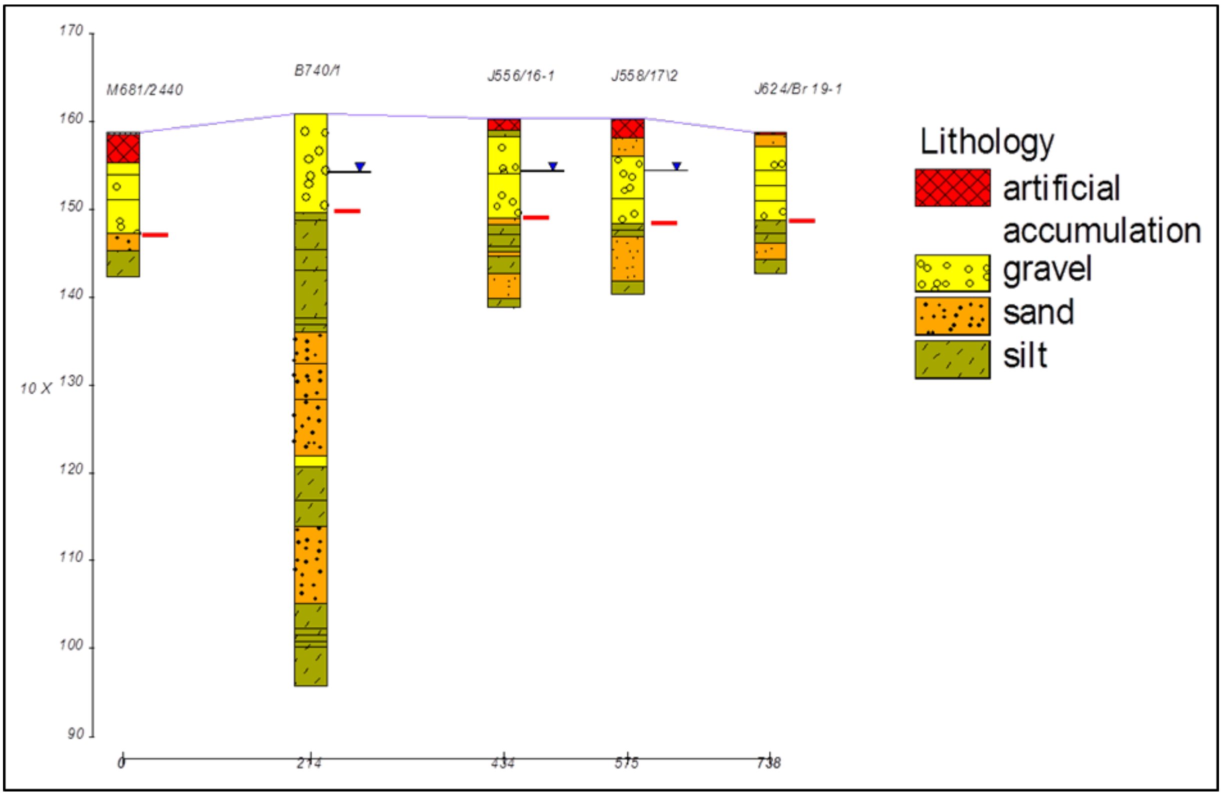


Figure 13   2D display of borehole data for manual correlation of units using ArcView scripts.

Model results and visualisation

Originally, the model consisted of five surfaces (Figure 14) which are from top to bottom

- The ground elevation (or digital elevation model) (A) ranges from 150 m above sea level at the south-eastern city limit up to 542 m above sea level in the North-West.

- The base of the Holocene, fine-grained cover overlying the gravel units (B) occurs only in isolated areas mainly in the eastern half of the city and lies on average 2 m, at most 23 m below ground.
- The base of the Pleistocene gravel unit covers the central and eastern parts of the Vienna basin and lies 10-30 m below ground.
- An intermediate (stratigraphic) surface (D) within the Neogene clay and silt unit was constructed from previously published maps to demonstrate the tectonic structure at greater depths (100 m below ground in central Vienna, descending in a step-wise fashion to 1100 m below ground in the South-East). This surface represents the base of the Pannonian sediments.
- The base of the Neogene basin (E), also constructed from previously published maps, reaches down to 5400 m below ground. The material underlying this surface constitutes flysch rocks in the north-western part and includes limestones and dolomites (carbonates) in the south-eastern part of the city area.

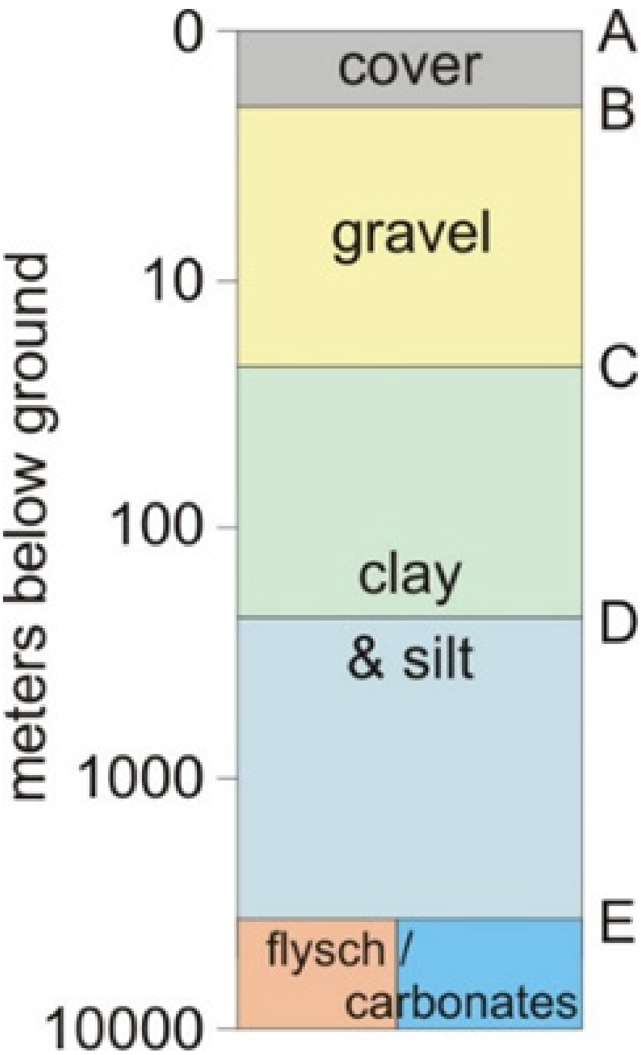


Figure 14 Schematic sequence of layers modelled in the original 3D model (Pfleiderer & Hofmann, 2004a).

In 2004, these surfaces were visualised either as contour maps in ArcGIS or using a geo-viewer developed at the Netherlands Institute of Applied Geoscience (TNO-NITG, now TNO-GSN). This viewer made use of Java 3D technology to display raster surfaces as "flying carpets". Volumes between surfaces could be filled to construct a layer model of the subsurface. Figure 15 and Figure 16 demonstrate examples of the Vienna geological 3D model visualized with the Dutch geo-viewer (Pfleiderer & Hofmann, 2004a).

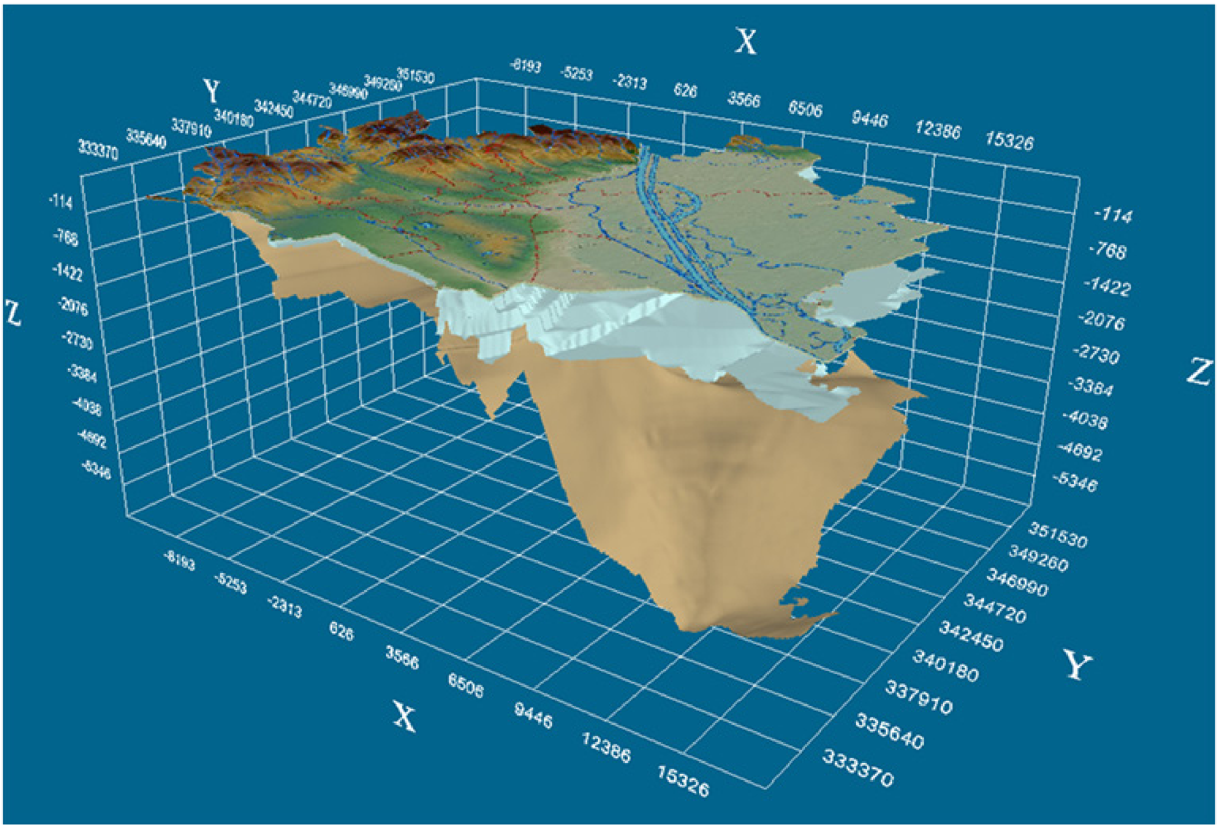


Figure 15 "Flying carpets" of the Vienna geological 3D model visualized with the Dutch geo-viewer (Pfleiderer & Hofmann, 2004a).

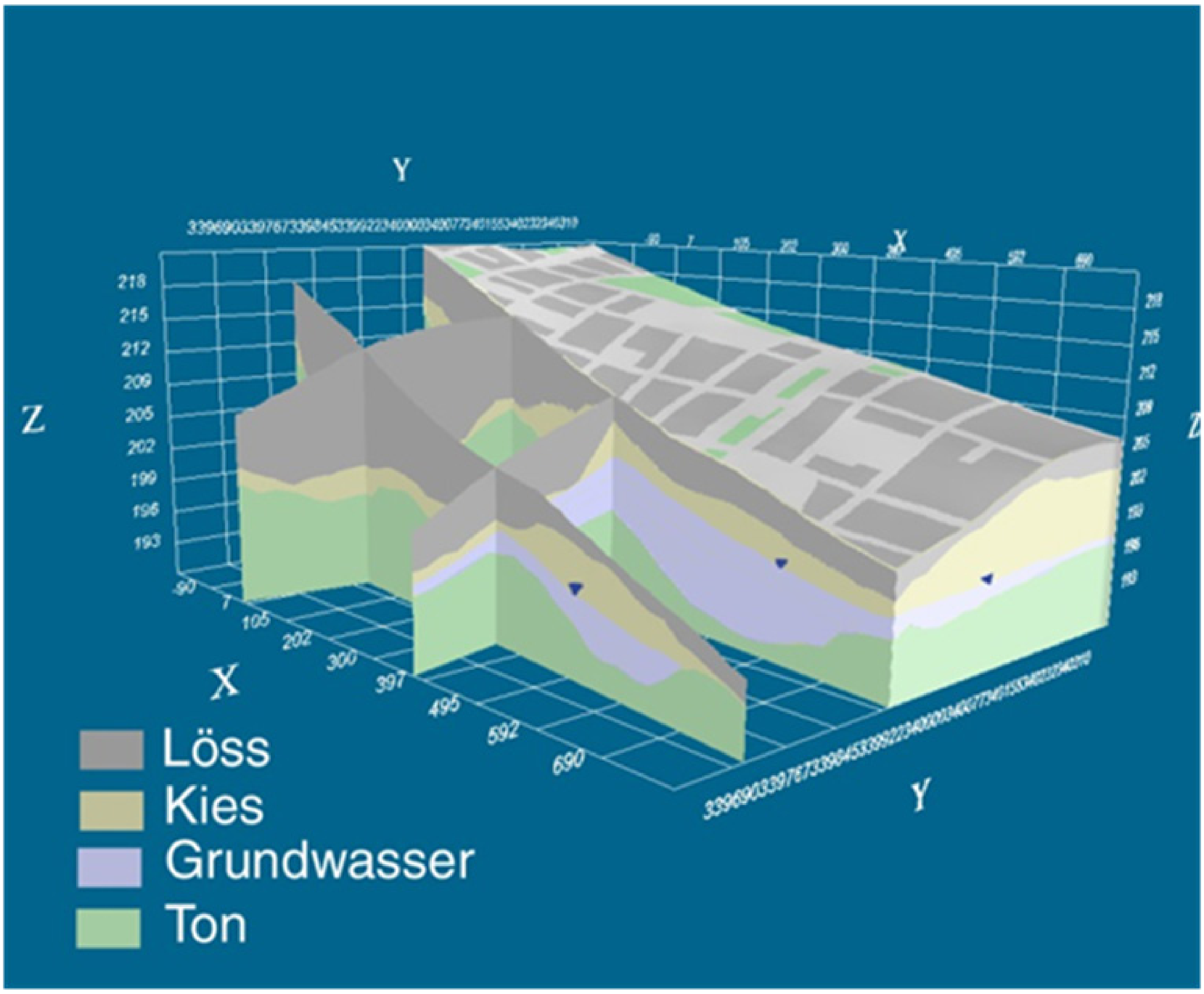


Figure 16 Fence diagram and layer model of a close-up of the Vienna geological 3D model visualized with the Dutch geo-viewer (Pfleiderer & Hofmann, 2004a).

After migrating to GOCAD® in 2010, the following surfaces were added to the five original surfaces:

- The base of the Upper Pannonian sediments
- An intermediate surface within the Middle Pannonian sediments
- The base of the Middle Pannonian sediments
- The base of the Sarmatian sediments

Since borehole logs do not contain any stratigraphic information, these surfaces are defined on the basis of lithology. Within the sedimentary column, sections containing abundant or thick layers of sand and gravel are distinguished from sections dominated by silt and clay layers.

As more and more users of the Vienna geological 3D model now have 3D modelling software, visualisation is now realised either in GOCAD® directly, or in ArcScene (ESRI) using export formats such as DXF or ASCII. However, many users still prefer taking the traditional approach of 2D map visualisation.

Model application

The 3D geological model of the city of Vienna evolved from a purely two-dimensional set of structural maps for information on subsurface geology to a truly three-dimensional model used as the basis for groundwater flow modelling, for geothermal modelling, for information on geotechnical and geochemical subsurface properties.

Hydrogeology

In the course of the study on hydrogeological applications of the 3D geological model (Pfleiderer & Hofmann, 2004b), the model was complemented with the mean, high and low water tables of the uppermost aquifer northeast of the Danube (Figure 17). These water tables were calculated using 126,847 measurements at 114 groundwater monitoring stations taken between 1966 and 2002. GBA was granted access to this data set, which is maintained by the Department of Water Management (MA45). Additionally, values of groundwater permeability were allocated to main sedimentary layers within the Quaternary und Pannonian sediments and the modelling units were parametrized with this information (Pfleiderer et al., 2005).

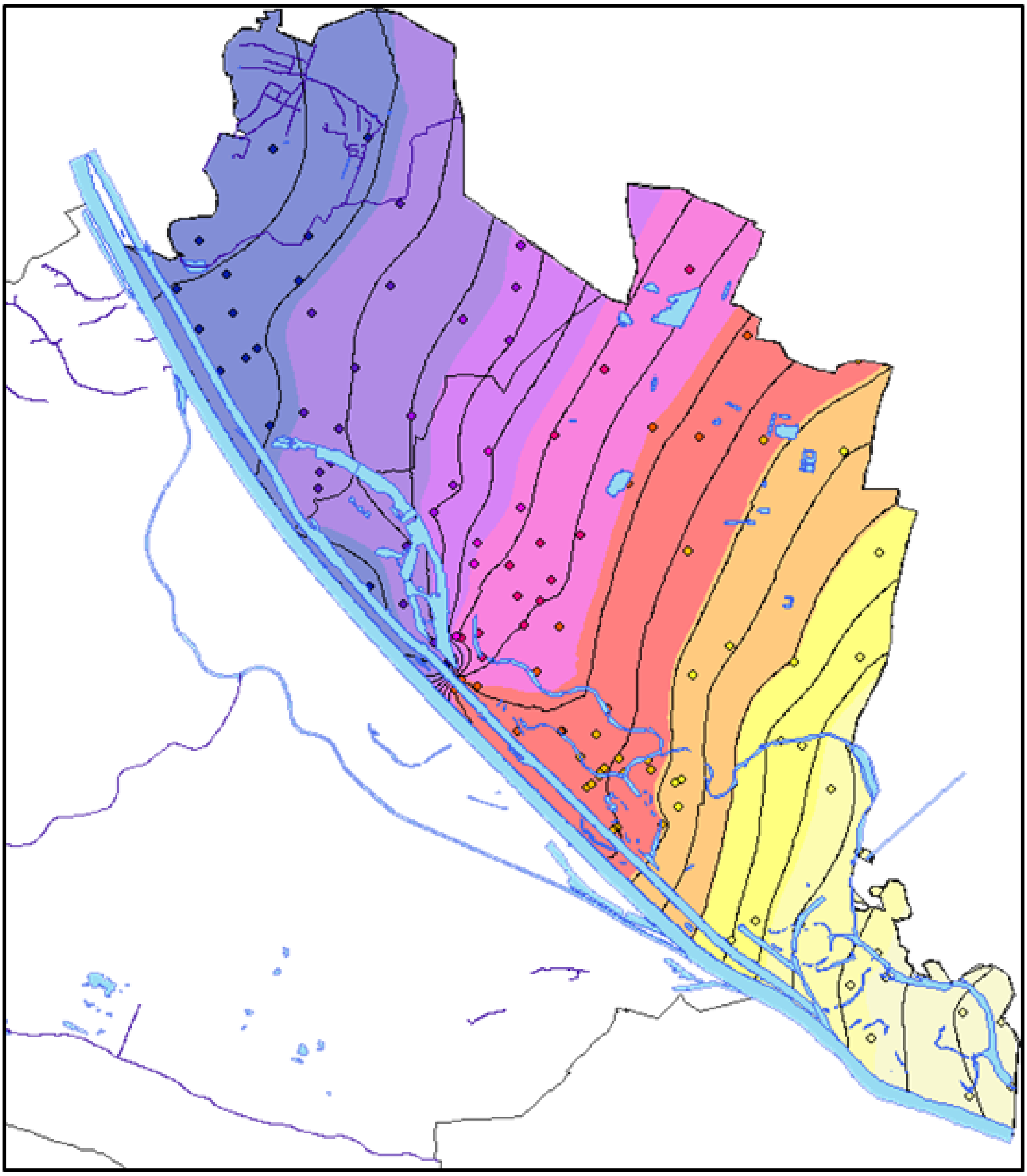


Figure 17 Mean water table of the uppermost aquifer northeast of the Danube (Pfleiderer & Hofmann, 2004b).

Geotechnical engineering

The Department of Bridge Construction and Foundation Engineering (MA29) routinely takes samples from drillings for material testing. The MA29 database of borehole logs contains references to these samples and test results are archived separately in analogue form.

Pfleiderer & Hofmann (2004b) compiled test results of 4,334 samples taken between 1951 and 2000, which contain measurements of the following parameters:

- natural water content, grain density, dry density, porosity
- yield strength, plastic limit, plasticity index
- grain size distribution (percentage of gravel, sand, silt and clay, percentiles d10, d50, d60, d90
- derived parameters: U = d60 / d10, k = f[d10, U] (Beyer & Schweiger, 1969)
- compressive strength, friction angle, cohesion

The test results were transferred into a digital database and geostatistically treated to derive typical values for the various subsurface layers. The allocation of test results to geological units was possible using x-, y- and z-coordinates of the samples and the 3D geological model. Figure 18 illustrates some results of this study.

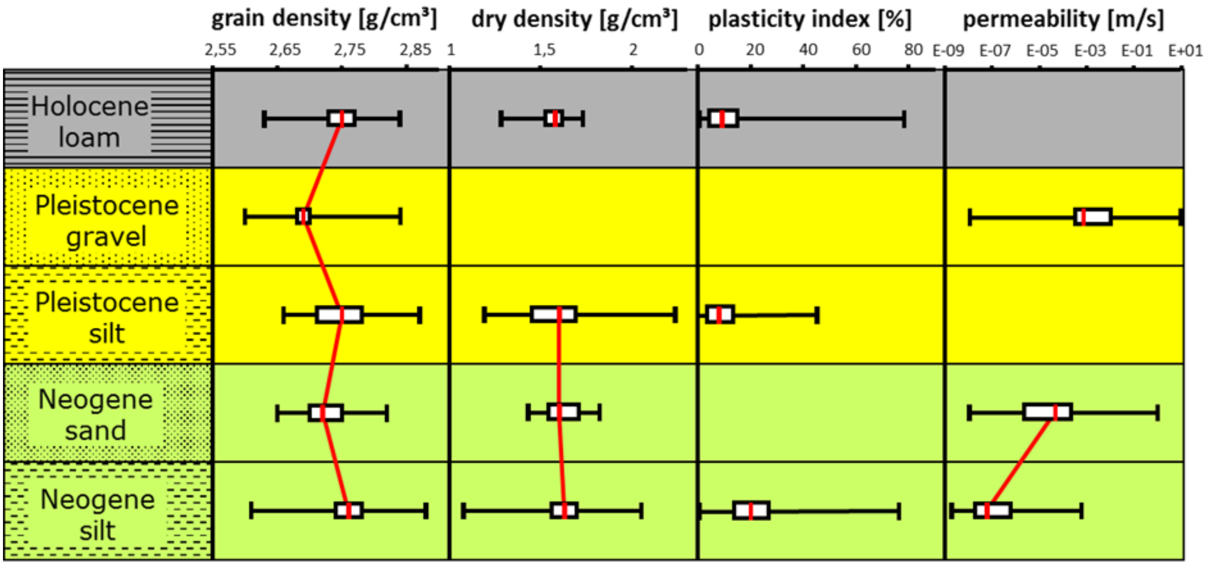


Figure 18 Boxplots of selected geotechnical properties of geological units in Vienna northeast of the Danube (Pfleiderer et al., 2005).

Geochemistry

In 2009, GBA completed an urban geochemistry study investigating heavy metal contents in Viennese soils, stream sediments, Quaternary and Neogene deposits, flysch rocks, groundwater and dust samples (Pfleiderer et al., 2010). Natural background levels were derived (Pfleiderer et al., 2012) and heavy metal exchange between e.g. sediment layers, soil and groundwater was examined. As a result of the study, the 3D geological model is now parametrised with respect to natural background levels of heavy metal contents for Pleistocene and Neogene sediments.

Geothermal potential

In 2013, the Department of Energy Planning (MA20) asked GBA to evaluate the geothermal potential of the shallow subsurface in Vienna due to increased usage for heating / cooling and seasonal heat storage. This evaluation was possible thanks to the existing 3D model, especially the knowledge of geological structures, depth to water table and hydrological properties contained in the model. As a result of the study, the modelling units are now also described by values of thermal conductivity.

According to the water usage register, kept by MA45, 1839 cases of geothermal usage are currently reported in Vienna. Approximately half of those represent closed-loop heat exchangers, half are groundwater heat pumps. Resulting from GBA’s study, the Vienna City Administration now provides maps to Vienna’s citizens indicating where the use of geothermal energy is possible and which type of usage is advisable (Fig. 8). Currently, permissions for the installation of heat pumps are granted on a first-come-first-serve basis. During the investigation, it became apparent that conflicts of use already exist as thermal plumes downstream of neighbouring heat pump locations overlap (Götzl et al., 2014). The study represented a first step towards a master plan for geothermal usage in Vienna.

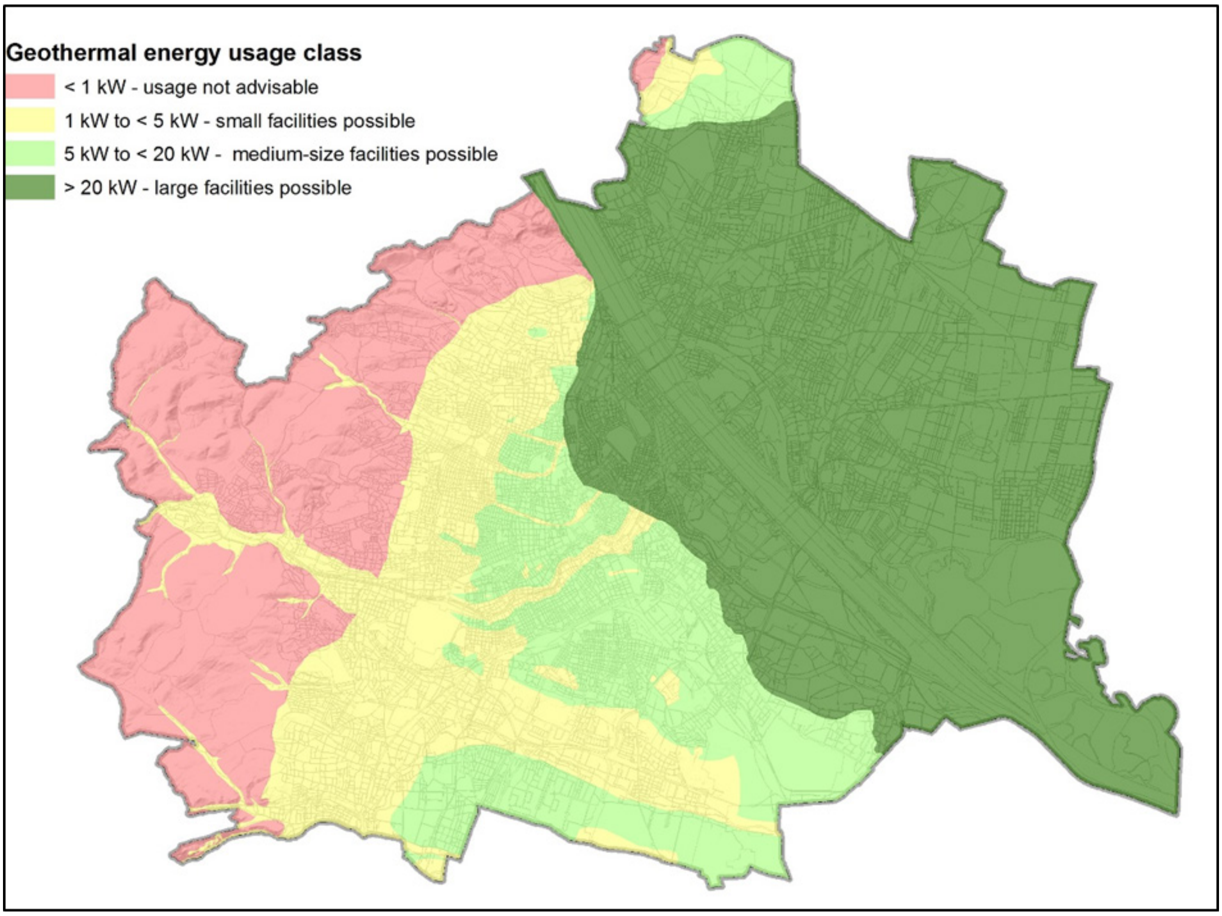


Figure 19 Geothermal energy use classes in Vienna (Götzl et al., 2014).

Appendix B: Glasgow geological model

Tim Kearsey (BGS)

Modelling rationale

The city of Glasgow is Scotland's largest city. Built around the River Clyde, during the 19th and earlier parts of the 20th centuries, it was an important area for shipbuilding. Other heavy industries also developed in the area now covered by Glasgow City and there was extensive mining for coal and ironstone, which resulted in large parts of the City of Glasgow being undermined, often at shallow levels (Campbell et al., 2010). The mining and heavy industry declined and ceased during the second half of the 20th century, and now only limited heavy industry remains. As a consequence, Glasgow has a largely post-industrial landscape with significant areas of dereliction and associated social deprivation, problems which are being addressed by local authorities and the Scottish Government (Campbell et al., 2010).

The Glasgow model was designed for the ASK Network, which was developed by the British Geological Survey (BGS) and Glasgow City Council (GCC), with support from other partners in the public and private sectors. Its main aim is to make geological data more readily available to contractors and government officials to help reduce the cost of ground investigation when delivering successful construction and regeneration projects. Therefore the models have been created to help illustrate and understand geological hazards that are a problem in the Glasgow Urban area.

The 3D model is also designed to fit within the British Geological Survey's National Geological Model (NGM) which is a multi-scalar, geospatial model of the subsurface arrangement of the rocks and sediments of the UK.

Glasgow has been identified by the Scottish Government as a major area of regeneration, both through events such as the Glasgow Commonwealth Games 2014 and their legacy, and to provide new housing and premises for business and the supporting infrastructure. Critical in this regeneration is understanding how geology controls issues that affect new developments.

Geological issues and zone of interest

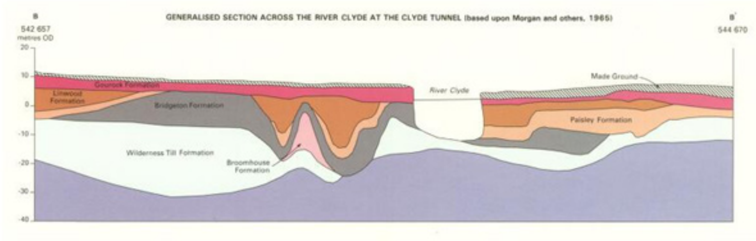
The city of Glasgow sits on fluvial, marine, glacial-fluvial, glacial and pre-glacial unconsolidated sediments which vary from 0 to 80 m thick. Below this the bedrock geology consist of faulted Carboniferous Coal field sediments and intrusions. These have been extensively mined underground for coal, often quite close to the surface (Figure 20).

Figure 20 Former underground coal workings close to surface in Glasgow (BGS © NERC).

Zone of interest

The main reason for the construction of the Glasgow model is to understand issues associated with the sighting of buildings such as shallow mining collapse and the thickness and composition of glacial units, and hazards, such as the movement of industrial contaminants through the subsurface, associated with urban regeneration in a post-industrial city. As such it was decided that the depth to which the geological model was focused on is the top 200 m below the surface (Figure 21).

Glacial and Post-glacial Geology



Bedrock geology

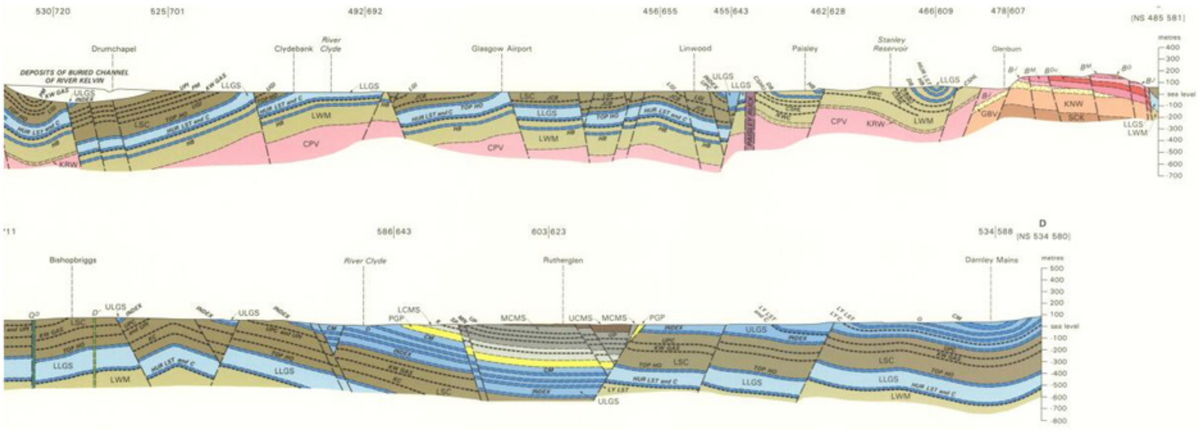


Figure 21 Cross-section from published geological maps through Glasgow (BGS © NERC).

Geological questions addressed by the model:

- With regards to the fluvial, marine, glacial-fluvial, glacial and pre-glacial unconsolidated sediments:
    - 3D geometry of geological units, to aid:
        - Identifying and investigating problematic ground conditions
        - Groundwater modelling and contaminant movement
    - Lithological variability of units within geological units
- With regards to the bedrock geology:
    - Distance to Bedrock (rock-head)
    - Depth of coal seams to aid identification of unmapped mine hazard
    - Nature of fault network

The Glasgow model was created for urban planners and geotechnical engineers who are used to using traditional geological maps. However, they are often not good at visualising the 3D geometry of geological units. The Glasgow model is primarily designed to illustrate this 3D geometry. Further stages of the work are currently undergoing to understand lithological variability and engineering properties in the model.

Available input data

There was a range of input data sources that were used in the creation of the Glasgow model:

- Digital Geological maps: 1:50,000 scale digital geological maps were used to constrain the upper surface of the model. These were imported as polygons attributed with a range of stratigraphic and lithological information derived from the BGS Lexicon (http://www.bgs.ac.uk/lexicon/).
- Digital Terrain Models: The top surface of the model was created using NEXTmap®, which is an elevation model created by Intermap Technologies for Great Britain. It is created using airborne radar survey and has an elevation reading every five metres.
- Boreholes: BGS electronically holds 11,570 boreholes in the Glasgow area. The average total depth value of the boreholes used in the model is 18.16m (min 0.7m; max 764m, Figure 22).
- Mine plans: The BGS holds mine abandonment plans for many of the major worked seams in the Glasgow area. These provide a vital source of 3D information about the coal bearing strata at multiple levels within this sequence. These plans were digitised in ArcMap® and this includes transcribing any levels recorded. To date plans of 35 different coal seams have been digitised in the Clyde Catchment area. Many of these seams represent a relatively small geographic area (Figure 23).
- Memoirs and other data: In those areas which lack borehole and mine plan information there is other geological data worth considering in the geological modelling process. These include geological memoirs and PhD theses. These can provide cross sections and structural information which may not be recorded on geological maps.

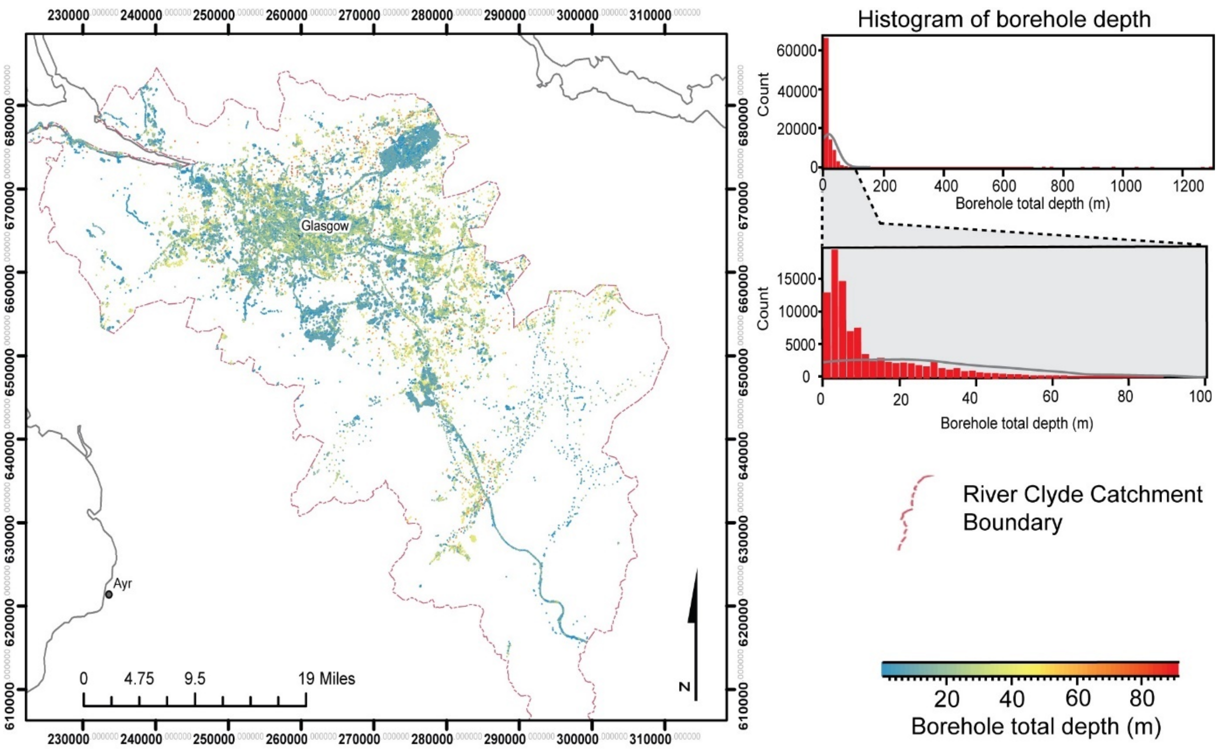


Figure 22 Map showing the distribution of all the borehole records currently held by the BGS in the study area. The borehole points are coloured based on the total depth of the borehole and show that the majority of the deep boreholes (blue) are only found in the area of the coal measures. The histograms show the frequency distribution of the depth of these boreholes (top right) and a blow up of those boreholes less than 100 m deep (BGS © NERC; OS topography © Crown Copyright).

Modelling methodology

At the time of the inception of the Glasgow 3D project there was no single piece of software available to create both the unconsolidated sediments and the faulted bedrock in the same package. Therefore different modelling methodologies were used for the unconsolidated sediments and the faulted bedrock. The base of the unconsolidated sediment model was used as the top of the faulted bedrock model. However, the two models can only be viewed together in ArcGIS and other delivery packages.

The Glasgow model volume is 10 km x 10 km wide and 80 m thick for the unconsolidated sediment model, including anthropogenic deposits (Figure 24). The faulted bedrock model has an average depth of 500 m below the surface (Figure 25).

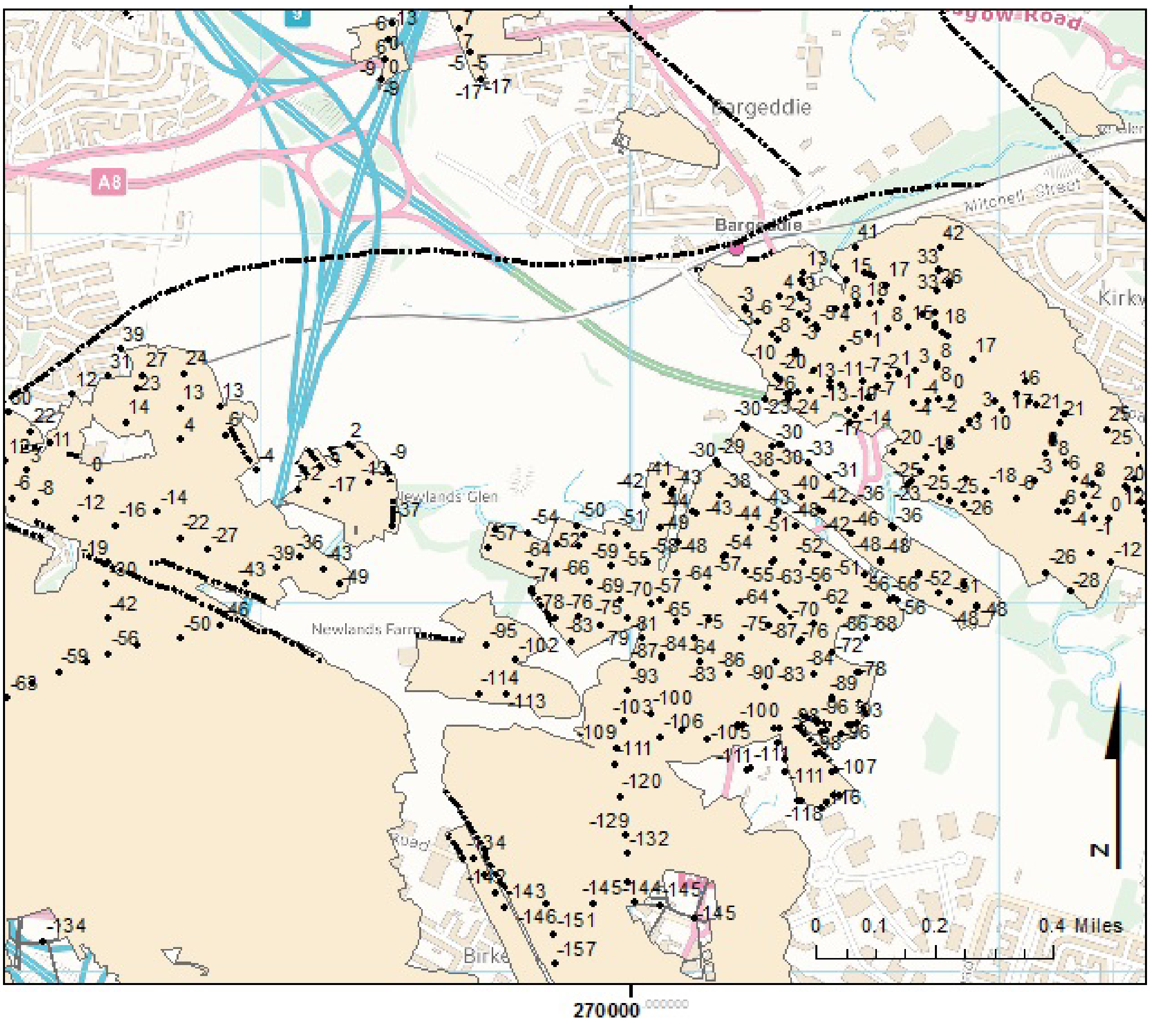


Figure 23 A detail of digitised mine plan information in central Glasgow showing the geographical area of known worked coal seam (in blue) and the depth measurements shown as point data attributed with values from the mine plans and converted to depths relative to Ordnance Datum. (BGS © NERC; OS topography © Crown Copyright).

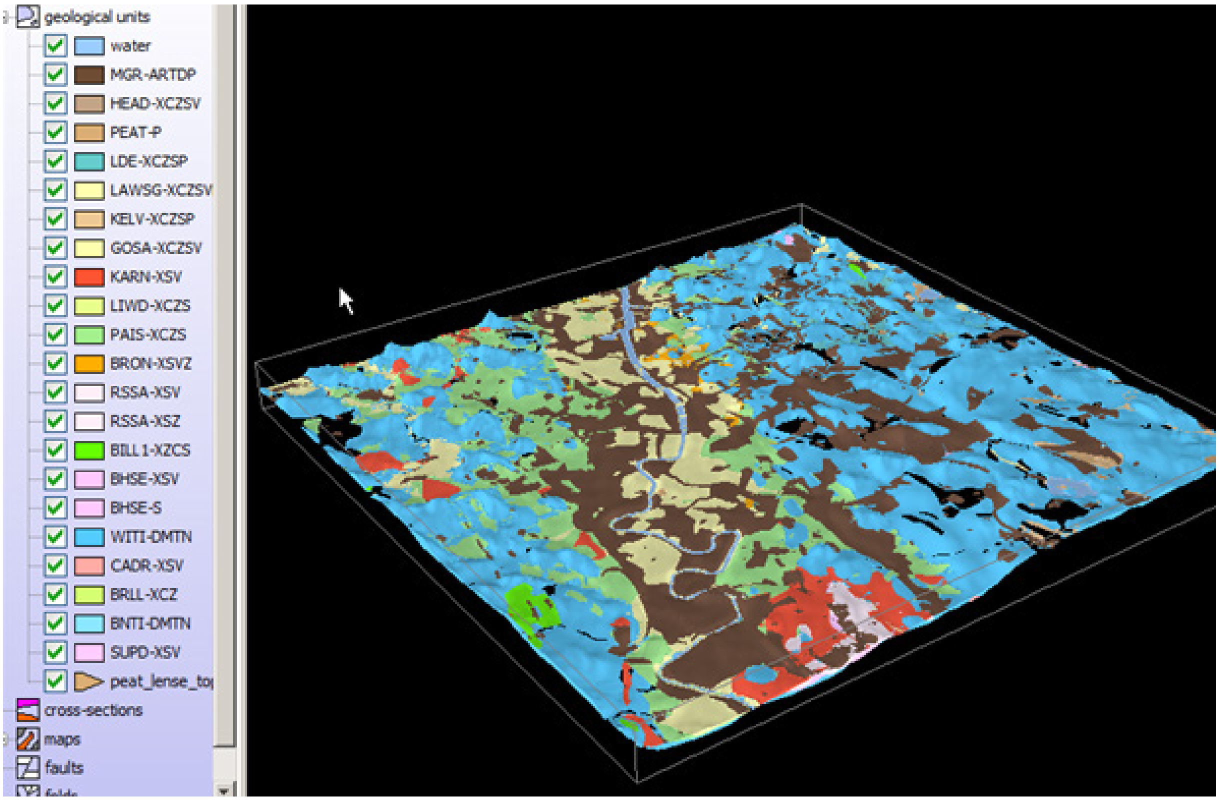


Figure 24 Overview of superficial deposits model of Central Glasgow, looking NW, ten times vertical exaggeration (BGS © NERC).

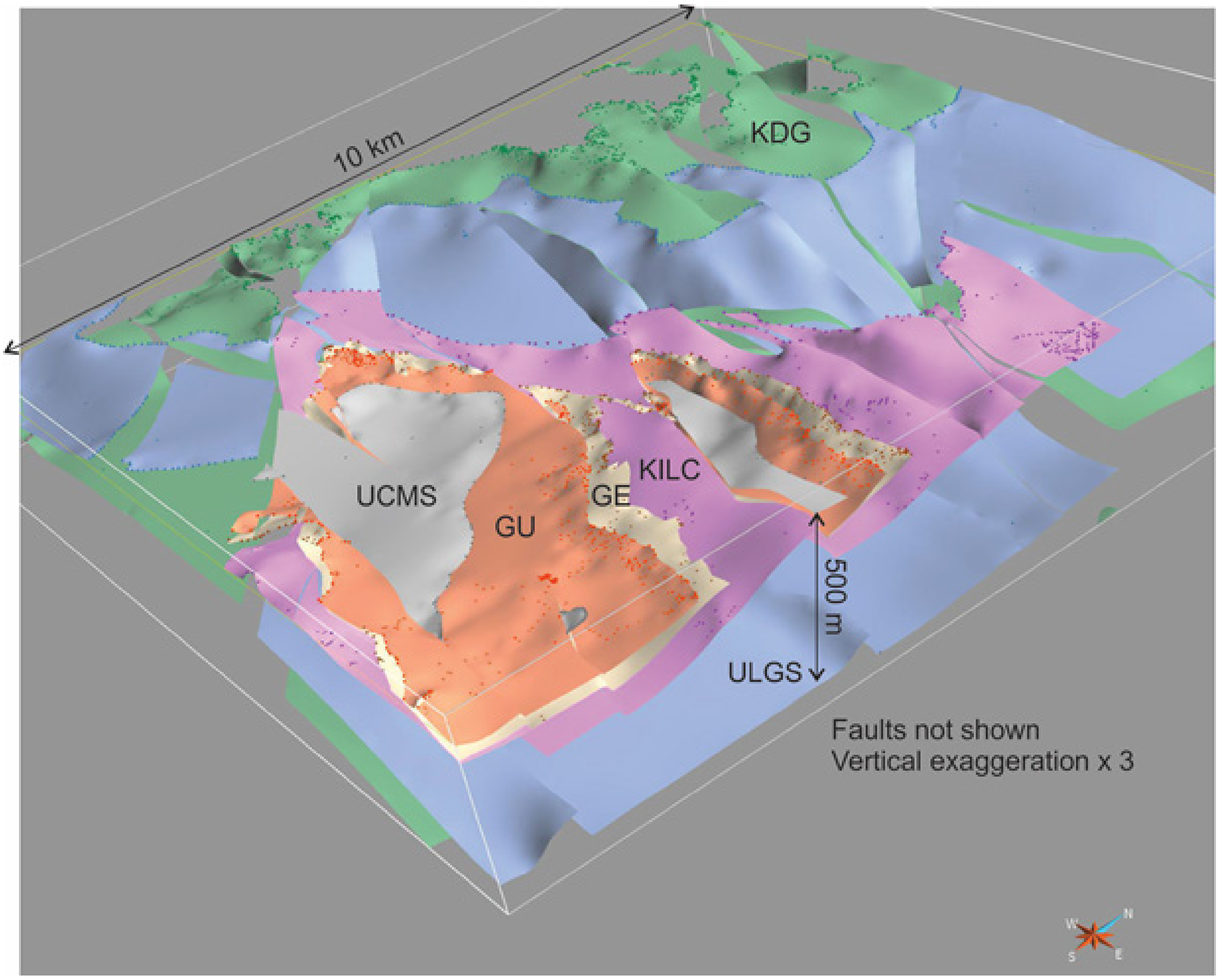


Figure 25 Overview of bedrock surfaces modelled in the Central Glasgow bedrock model with data points from boreholes, mine plans and mapped outcrop shown (BGS © NERC).

Unconsolidated sediments, including anthropogenic deposits

Anthropogenic deposits (made ground) in the 3D model represent a combination of made and worked ground including filled and partially back-filled pits and quarries. Hence it comprises all anthropogenic deposits. Areas of worked ground were primarily identified using Digital Geological Map (DiGMapGB 1:10 000) polygons. These were subsequently altered to encompass areas where boreholes reported additional areas of artificial ground. Alterations were made using the Ordnance Survey maps to identify the extent of industrial areas, housing developments and other information.

All unconsolidated sediments were modelled in GSI3D. This package has been developed by BGS and allows the geological modeller to create a 3D model using a fence diagram of cross-sections (Kessler et al., 2009). This methodology creates the boundaries between stratigraphic units as surfaces in the computer and can be termed 'deterministic' as the geologist decides where the boundaries are.

To enhance the utility of these models for land-use planners and civil engineers the stratigraphic units were supplied with lithological properties. This was done by two different approaches.

- Stratigraphic units were given bulk geotechnical and lithological properties. These properties were derived using the National Geotechnical Properties database and summarised for each geological formation (Merritt et al., 2007). These can be used to assign units with an engineering classification which incorporates the bulk characteristics of a unit (e.g. Royse et al., 2008). This characterisation is not suitable for ground investigation, but should lead to better targeting of ground investigations (Merritt et al., 2007).
- To acknowledge the internal lithological variability in the stratigraphic units a geostatistical voxel approach was used to model the lithological variation within the stratigraphic units (Kearsey et al., 2015; Figure 24; Figure 26). This was created using voxels 50 m x 50 m x 0.5 m in size.

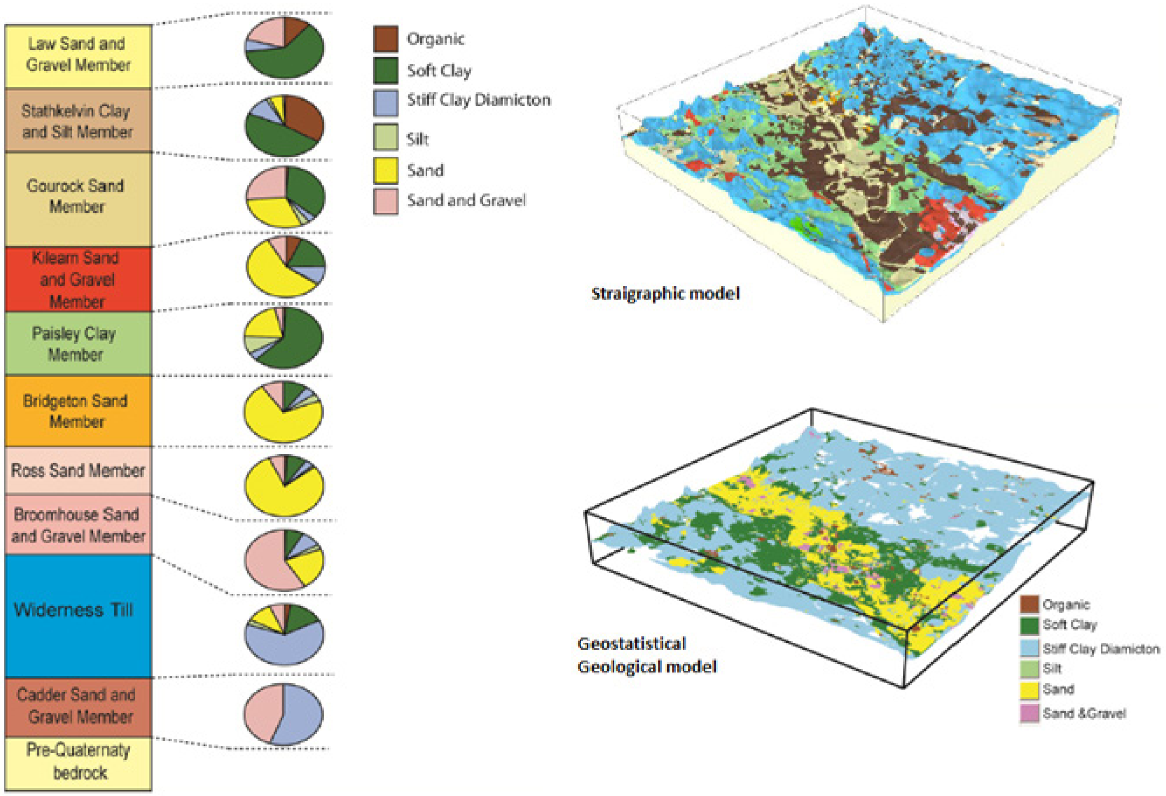


Figure 26 Lithological variability in the stratigraphic units and the stratigraphic (layer-based) and geostatistical (voxel) geological models (BGS © NERC).

Bedrock models

The faulted bedrock units were modelled in GOCAD. Only those coal seams that came to the surface within the city of Glasgow were modelled. Along with this the beds that mark the top and base of the major formations were also modelled. All the faults cut the entirety of the modelled volume and were given dips, based on their intersection with worked underground coal seams, if available. If not, values were derived from the map information (Figure 27).

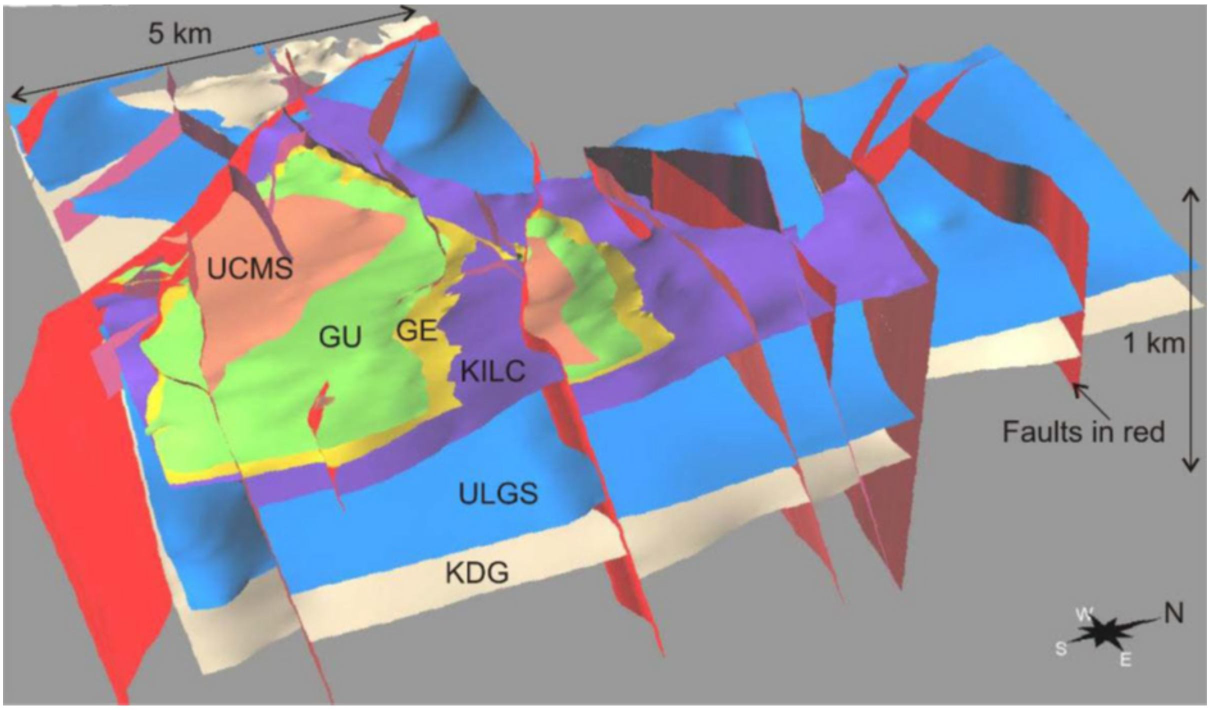


Figure 27 Bedrock model, looking west (vertical exaggeration x3); KDG– Knightswood Gas Coal (white); ULGS – Upper Limestone Formation (blue); KILC – Kiltongue Coal (purple); GE – Glasgow Ell Coal (yellow); GU – Glasgow Upper Coal (green); UCMS – base of Scottish Upper Coal Measures Formation (pink) (from Campbell et al., 2010).

Model delivery

As with most 3D models the users of the geological models do not have access to the software that the 3D model was created in. Equally the fact that different elements of the geological models were relevant to different urban issues dictated how it was delivered.

Delivery for groundwater modelling

The groundwater system is confined to the unconsolidated units within Glasgow. The geological units were exported to the ZOOM family of numerical groundwater modelling codes. A purpose-written tool built in GSI3D is used to convert data from GSI3D to ZOOMQ3D (Campbell et al., 2010).

Delivery for geotechnical properties and planning in the unconsolidated units

BGS has developed a webviewer for GSI3D models (https://shop.bgs.ac.uk/groundhog/info.cfm) which was provided free for members of the ASK Network (http://www.bgs.ac.uk/research/engineeringGeology/urbanGeoscience/clyde/askNetwork/home.html#models) (Figure 28).

Delivery for Mining hazard

The coals seams were provided as raster depth grids which can be used in ArcGIS or other software to show how close a given seam is from the ground surface (Figure 29).

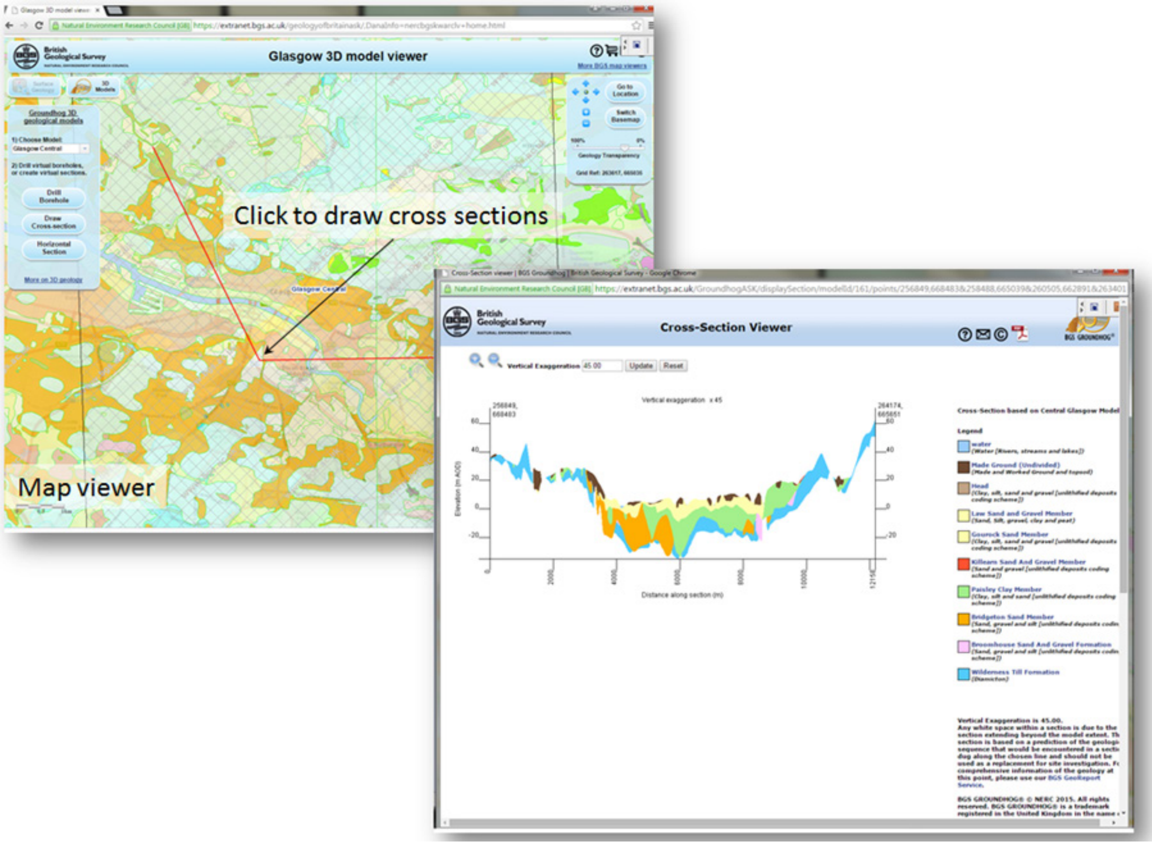


Figure 28 Example of web viewer delivery for the Glasgow model (BGS © NERC).

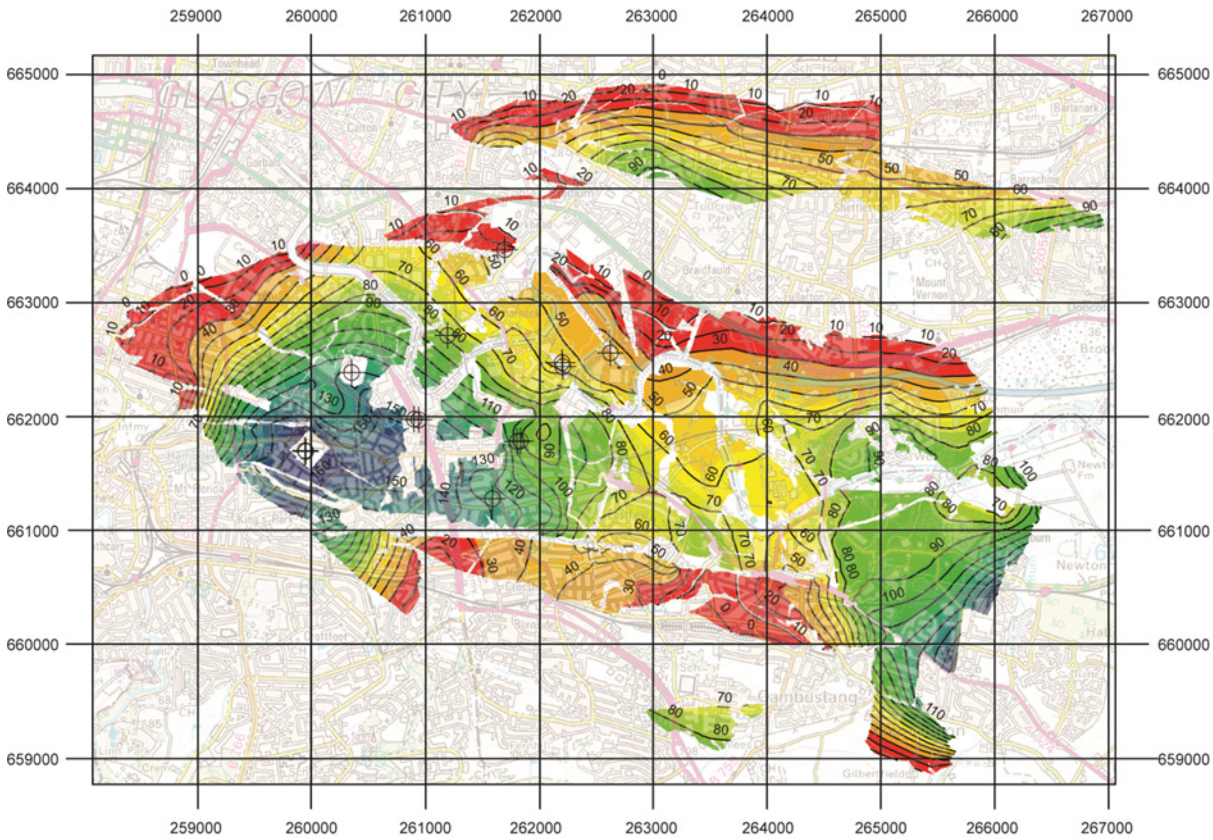


Figure 29 Raster grid of a worked coal seam from the 3D model. The contours show distance from surface with the area highlighted in red indicating where the seam was worked within 30 meters of the surface. (BGS © NERC; OS topography © Crown Copyright).

Appendix C: Odense 3D geological / hydrogeological model

Modelling rationale

Climate changes will, according to several climate models, mean more rain in Denmark in coming years and this will inevitably create increasing stress on the existing urban run-off systems (Mielby et al., 2015b). This effect will be enhanced by the constantly expanding city limits, meaning that larger and larger areas will be paved or covered with buildings, thus decreasing the areas where natural infiltration can take place. These effects are parts of a future scenario for the city of Odense (Figure 30). Added to this comes a rising groundwater table due to recent changes in the amount of groundwater abstraction, meaning that former wetland areas that for decades had been dried out and eventually urbanised, now return to their original wetland state.

Figure 30   The Municipality of Odense (source: Google Earth).

The municipality of Odense therefore needs a tool to be able to handle the water cycle in the city in the future and with it calculate probable scenarios and be able to address the changes in due time. This tool will have to encompass surface water, near-surface water and deeper groundwater which will require knowledge about surface hydrology, urban run-off systems, geology and groundwater. A vital part of this tool will be the physical framework - a 3D geological model of the subsurface that visualises the aquifers and aquitards - and this model of the physical framework will have to be constructed before the hydrological modelling is initiated. As large volumes of the subsurface have been and are being reworked and altered as part of the urban activities, the man-made parts of the subsurface play a vital role in the hydrological cycle in the cities. In realising this, the mapping and modelling of the subsurface of Odense needs to include mapping and modelling of the man-made part of the subsurface.

In 2012 the Municipality of Odense, Vandcenter Syd waterworks and GEUS collaborated with the goal to construct a 3D geological/hydrogeological model of the Municipality of Odense. The city of Odense has a population of around 150,000 and covers an area of 304 km^2 (Figure 30). In 2013 a 2-year pilot project was initiated with funding from The Foundation for Development of Technology in the Danish Water Sector (VTU Fund). Apart from the above-mentioned partners the project included participation from the private companies I-GIS and Alectia A/S.

The model project

Initially the partners agreed that the 3D geological model should cover the entire municipality and that the model should be able to be used at different scales. In addition to this the model should include the geology and hydrostratigraphy down to around 150 m below sea level (m b.s.l.) as well as the man-made layers just below the surface. One of the main challenges here was that the resolution of the subsurface as seen in data decreases with depth, because there is typically a decrease in the amount of data reaching deep levels (Sandersen et al., 2015). Another challenge was that the type of data available in the city was, roughly speaking, limited to boreholes of which many were shallow and poorly described. Finally there was the challenge of being able to zoom in and out using the same model and not having to create two (or more) separate 3D models of the same area but at different scales. Being able to use the final model at municipality scale, city scale and local construction-site scale was essential.

The hydrostratigraphic model covers the municipality area shown in Figure 31 and an example of a profile through the hydrostratigraphic model is shown in Figure 32. The man-made layers are not included in this model and the plan was to create the man-made layers and the hydrostratigraphy as two separate models, and then finally, just before model delivery, merge the models into one model. In merging the two models, the original "pristine" geology that the urban activities had destroyed, would in this process be "overwritten" by the modelled man-made layers (see sketch in Figure 33).

In the following text we will focus on the mapping and modelling of the man-made layers and therefore we refrain from thorough descriptions of the project as a whole, but instead refer to the project reports (see Mielby et al., 2015a).

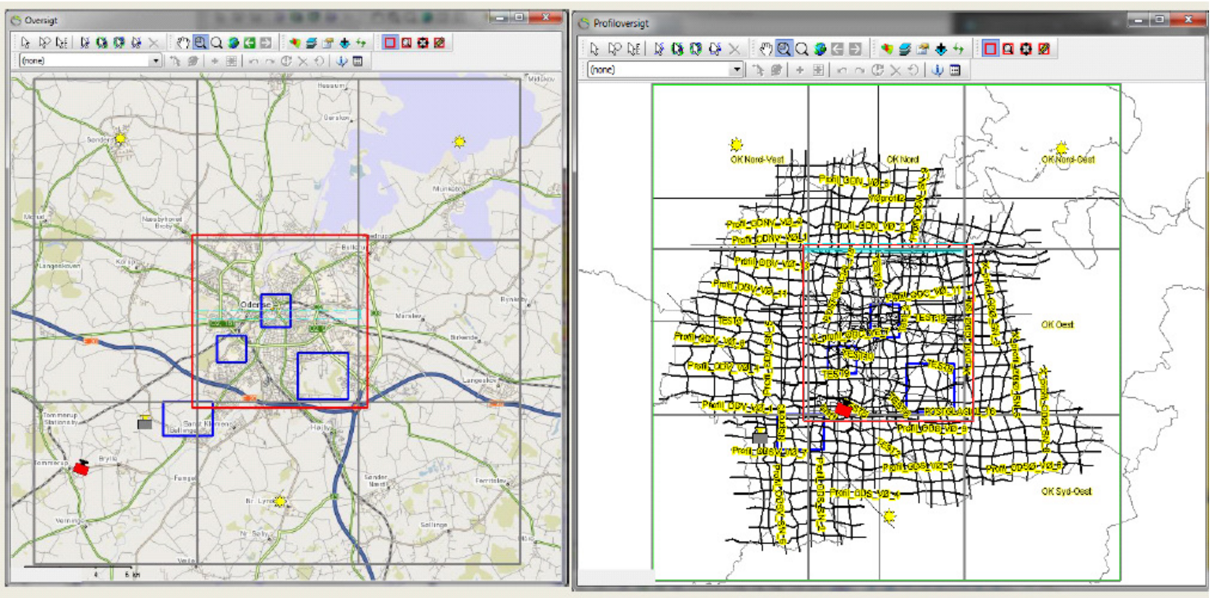


Figure 31 The 9 squares of the model area and an illustration of the coverage of the geologic/hydrostratigraphic model coverage (right).

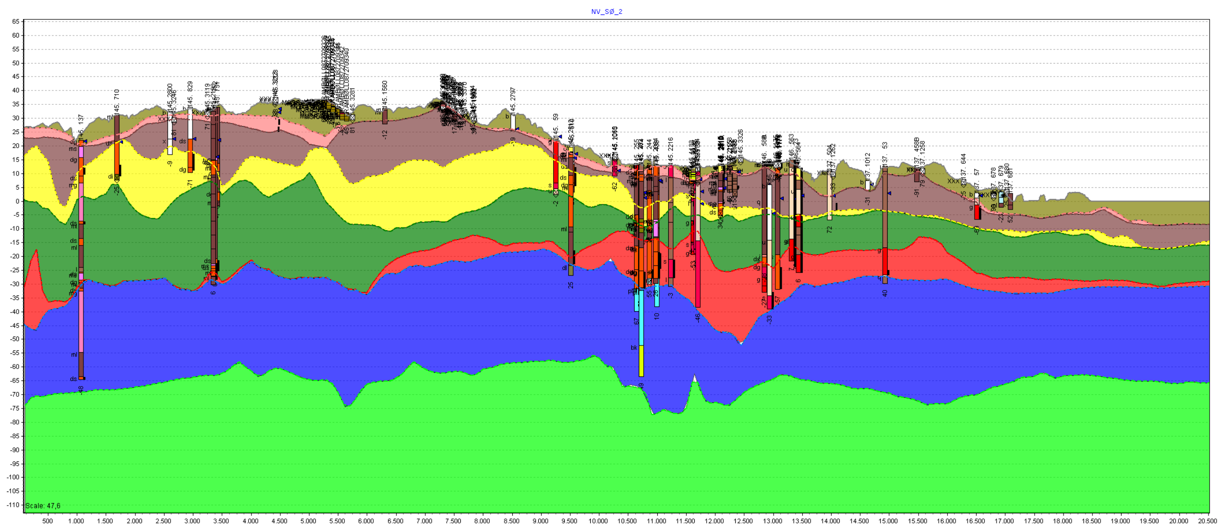


Figure 32 A selected profile through the 9-layer hydrostratigraphic model (From Sandersen et al., 2015).

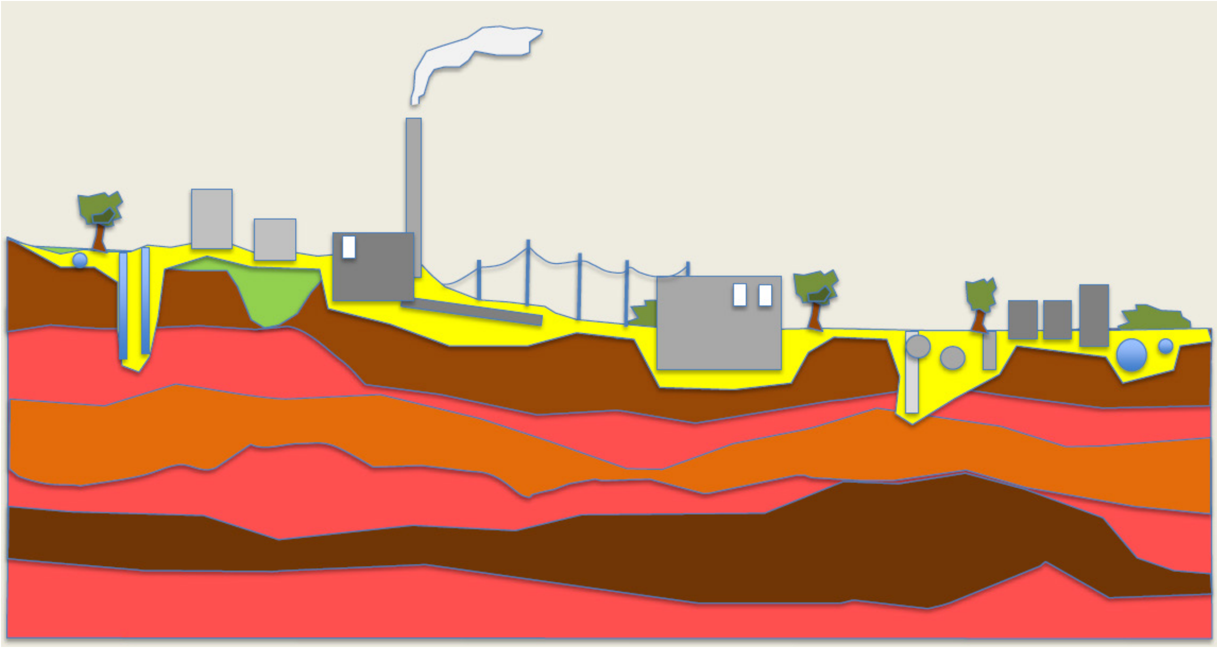


Figure 33 A sketch of merged antropogenic/man-made layers (yellow) and the hydrostratigraphy below.

Mapping and modelling of man-made layers

At a relatively early stage of the project it became clear that the ambition of mapping man-made layers in suitable detail in the entire municipality would require computer powers surpassing what is available today, so therefore it was agreed that focus should be on a local downtown area that should serve as a test area. On the basis of common discussions within the group the I-GIS company would work on mapping and modelling of the man-made layers and construct add-ons to their GeoScene 3D modelling software that could handle this specific type of modelling (see Pallesen & Jensen, 2015).

The general challenges when mapping man-made layers are, that:

- The layers are not the result of natural processes and therefore a traditional geologic approach (e.g. by using borehole data only) will not be adequate.
- The man-made layers are of a very heterogeneous nature that makes the value of interpolations between observation points uncertain.
- The physical properties of the man-made layers as they are described in boreholes are very hard to discern mainly because of the heterogeneous nature of the layers.
- The man-made layers are the result of a series of urban events affecting the subsurface in different areas at different times.

If the events that led to the creation of the man-made layers could be identified it would be easier to separate individual man-made layers and therefore give us a chance to map the layers more accurately. The approach would therefore be to try to point out at least a series of main events that could have affected the upper part of the subsurface, order these chronologically and then prioritise the events and choose which ones should be included in the mapping. These events could for instance be digging and infilling of trenches for sewers, water pipes and power cables.

As we would not have enough data from boreholes to be able to point out the spatial extent of these events, we instead approach it from the opposite direction and use the events (as we know them from the municipal activities) as proxies for the extent and physical properties of the man-made layers. This approach will therefore require data about the actual positions and construction dates of the subsurface infrastructure.

Data

The data used in the mapping and modelling of the man-made layers primarily encompass (Figure 34; see also Kristensen et al., 2015):

- Borehole data (mainly from GEUS archives)
- Supplementary borehole data (mainly from private companies)
- Geophysical data (from GEUS archives)
- 2D maps of geomorphology, soil types, etc. (GEUS)
- Digital elevation models
- Digital vector theme maps of surface/subsurface infrastructure: buildings, paved areas/roads, water supply themes, sewer lines, district heating pipes, power cables (Figure 35; from Municipal archives and water works archives)

Figure 34 Boreholes in the focus area (left) and areas affected by subsurface infrastructure (merged into one theme; showed in grey; right) (From: Pallesen & Jensen, 2015).

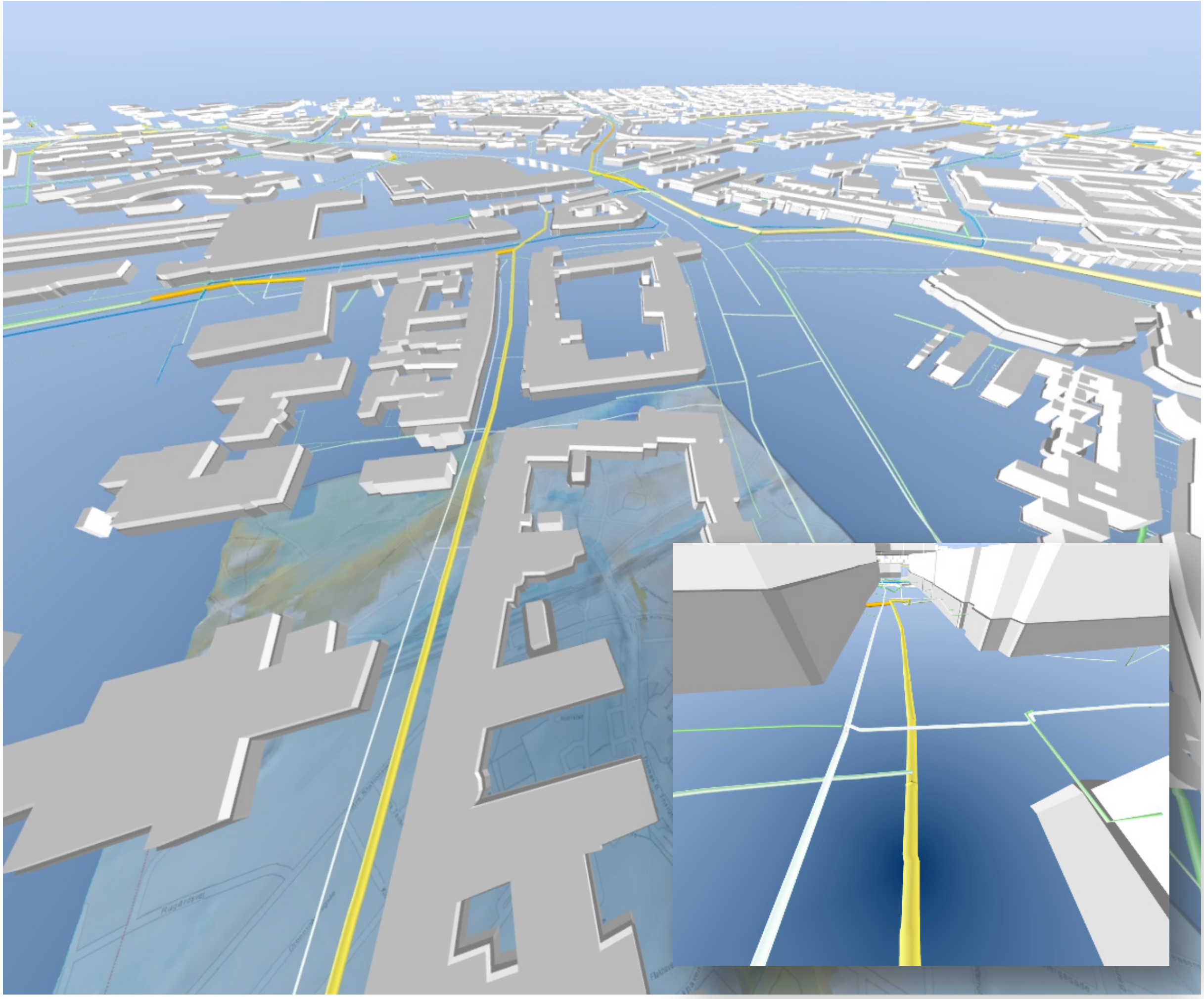


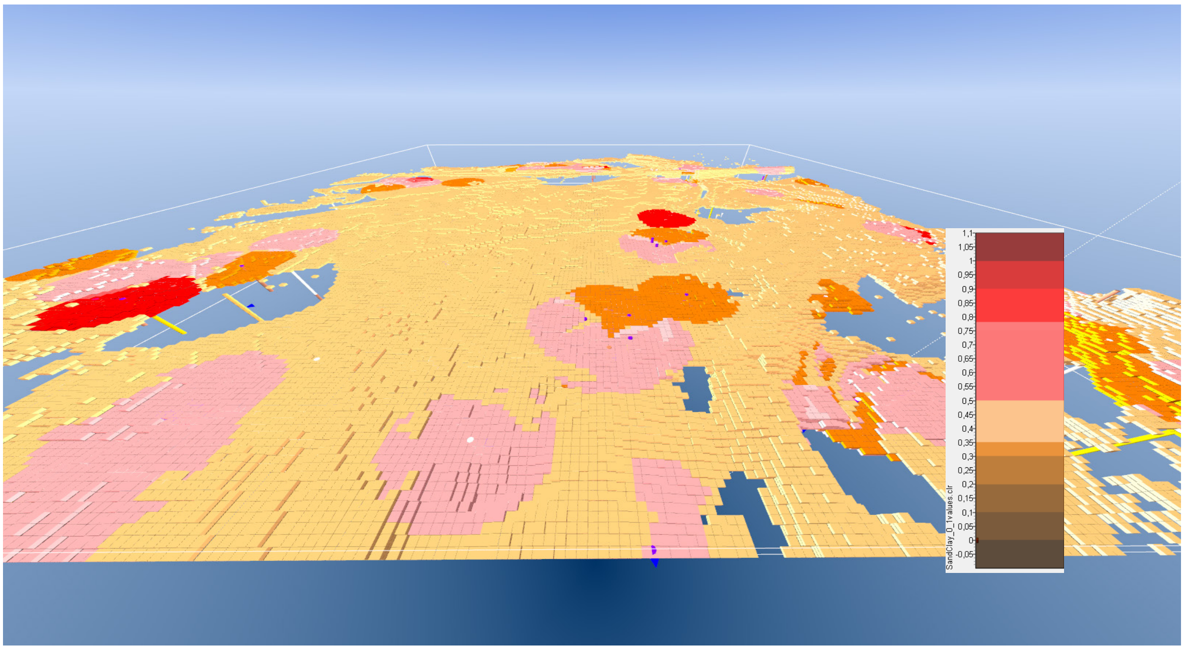
Figure 35 Example of vector themes; buildings above ground (light grey), buildings below ground (dark grey), tubes (yellow, green, white) (From: Pallesen & Jensen, 2015).

Modelling methodology

The modelling strategy has been two-fold: firstly the lithology of the infilled material as described in boreholes was created as a “background” lithology of the infill layers (Figure 36) and secondly the modelling of the infill lithology based on the subsurface infrastructure proxies (Figure 37) was superposed on the “background” lithology to create the combined model of the man-made layers (Figure 38). The last step can be repeated a number of times depending on the character and number of prioritised subsurface infrastructure themes

The modelling strategy of the man-made layers can be summarised as (Pallesen & Jensen, 2015):

- Spatial definition of the model area and definition of voxel grid size
- Mapping of the deepest level of infill-layers in boreholes. Construction of an interpolated bottom surface of the infill (see Figure 36, bottom)
- Characterisation of the infill from borehole data (lithology) and designating a hypothetical extent around the borehole
- Extrapolation of lithology information to areas without borehole data (see Figure 36, top)
- Using the subsurface infrastructure themes to construct spatial extent and infill of excavations based on specific knowledge of the standard procedures related to each theme (see example in Figure 37)
- Filling in the voxel grid with lithology (clay/sand ratio) using the "background" lithology as starting point (see example in Figure 38)
- Repetition of the last step depending on the character and number of subsurface infrastructure themes. Building elements below the surface (cellars, tunnels etc.) are considered as impermeable to water and as such they get the value "100% clay".



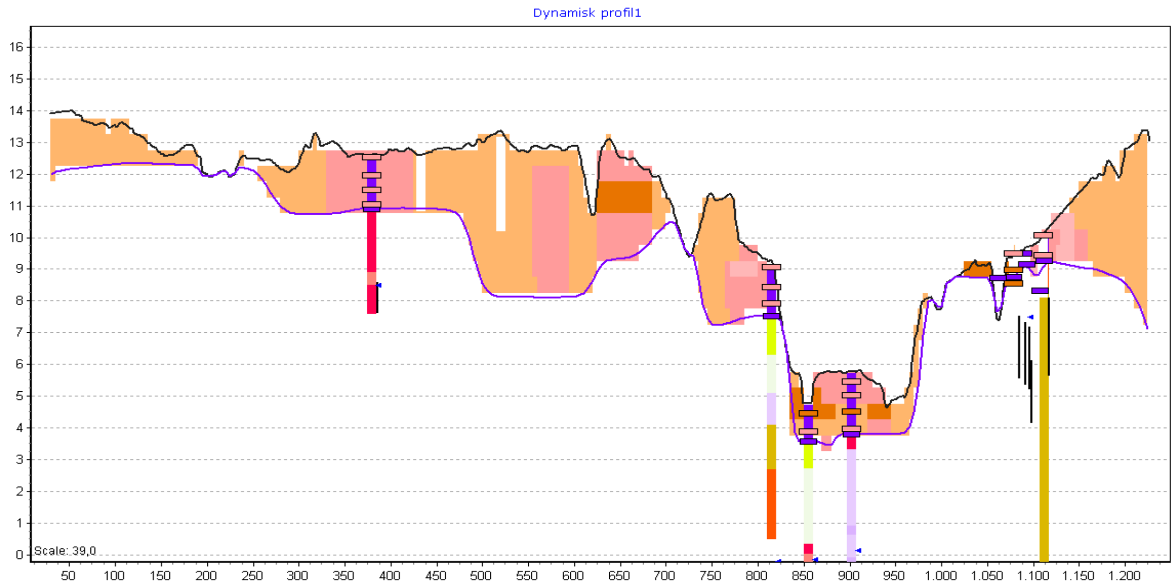


Figure 36 Mapping and modelling of “background” infill lithology based on borehole data. 3D voxels (top) and vertical profile example (bottom) (from: Pallesen & Jensen, 2015).

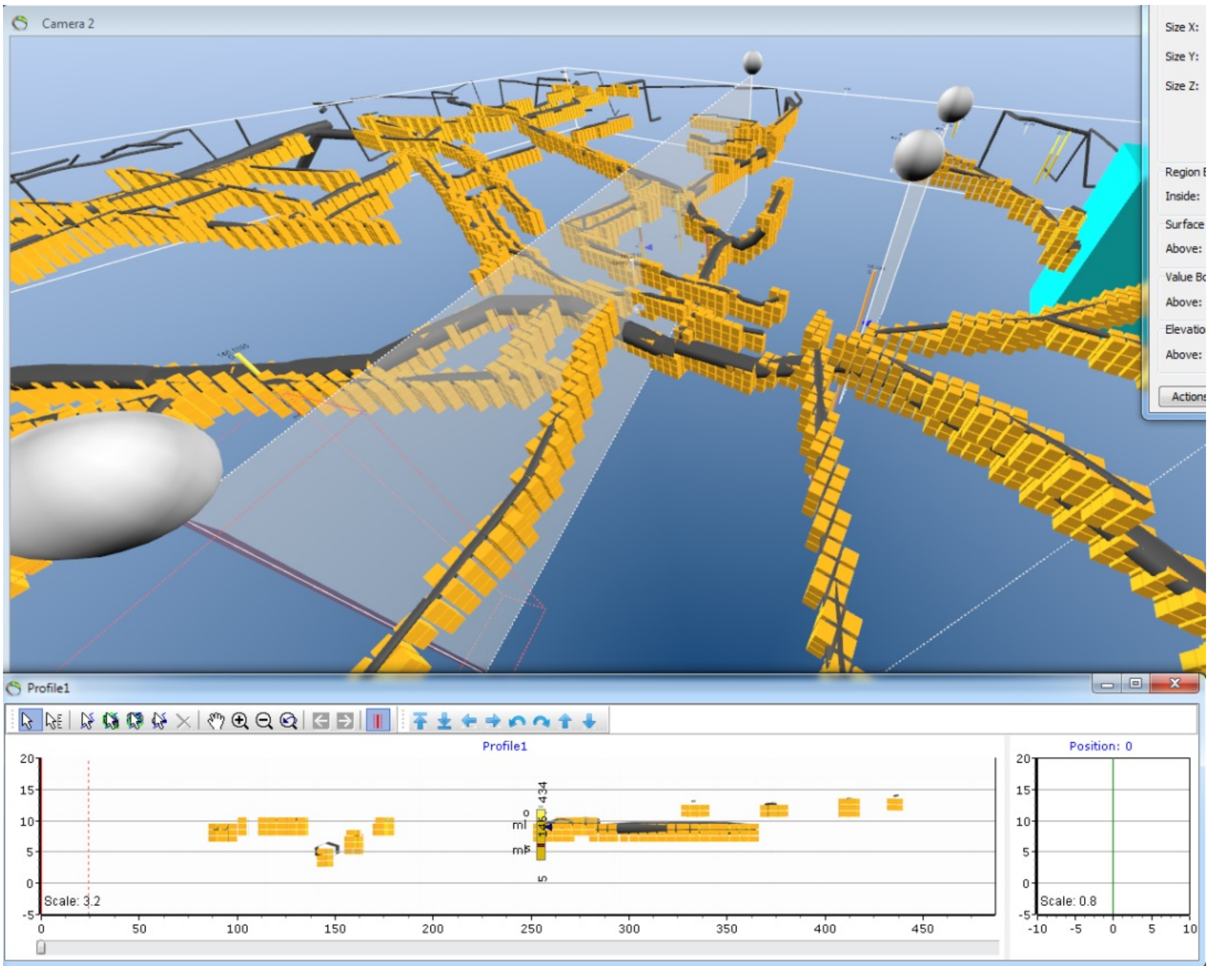


Figure 37 Example of voxelisation around tubes (From: Pallesen & Jensen, 2015).

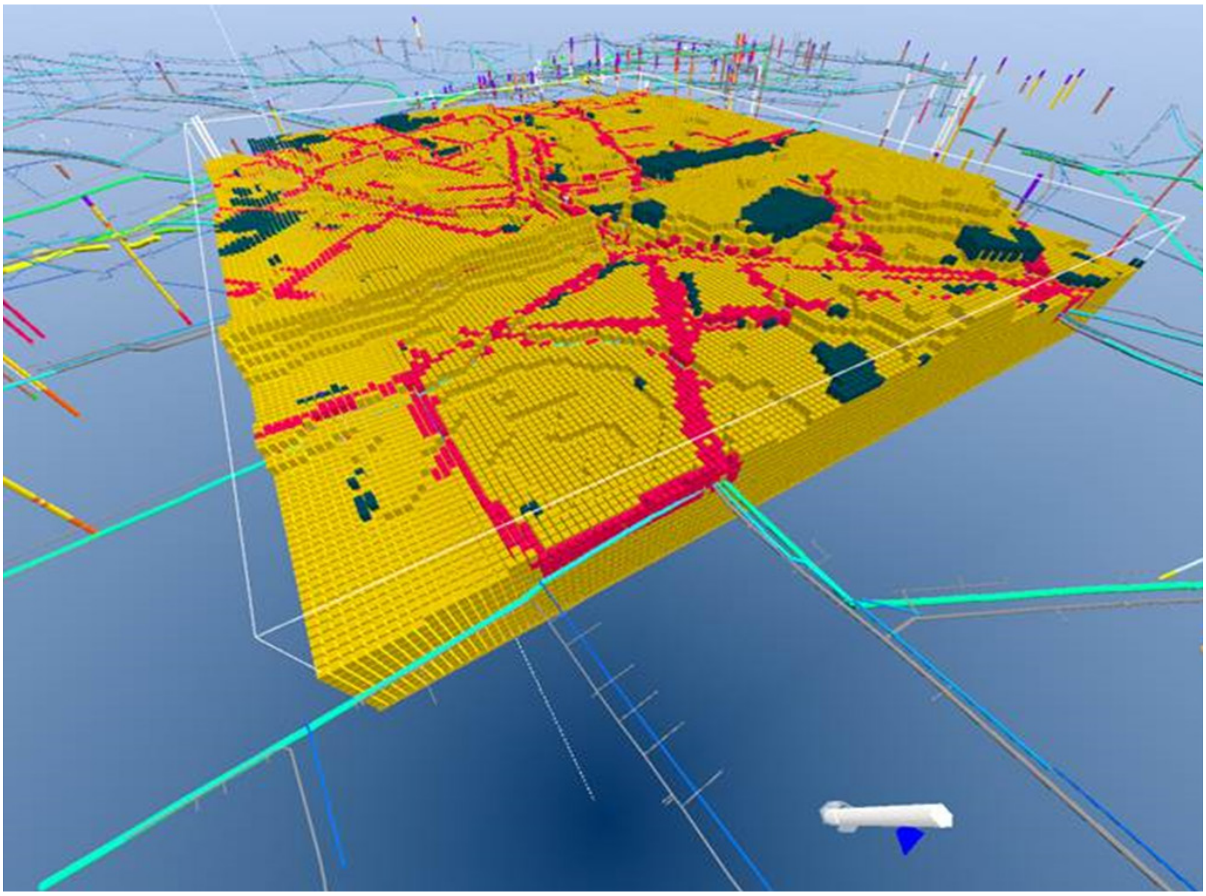


Figure 38 Example of merging of voxels from a tube theme with background lithology (From: Pallesen & Jensen, 2015).

Model delivery, future use and update

As the model of the man-made layers is intended to be part of a combined 3D model including the hydrostratigraphic model, the models will have to be merged (Figure 39). But before describing this, it is important to stress that the products of the Odense project are a hydrostratigraphic model and *a tool* that is able to produce a model of the man-made layers in a specific area for merging with the hydrostratigraphy. A 3D model of the man-made layers has not been made for the entire municipality, as this would be too big to handle with the current computational capabilities. But important in relation to this is to realise, that using a very detailed model of the man-made layers only makes sense when operating in a local area, because the meter-scale resolution of the anthropogenic model will be unnecessary in a model handled at municipality scale. On the municipality scale the overall tendencies can be modelled and visualised and potential problem areas can be pointed out and modelled afterwards in higher detail at a smaller scale.

In other words, the products of the Odense project are a hydrostratigraphic model that can handle different scales and a tool targeted at mapping and modelling of the man-made layers. The final off-the-shelf product, model-wise, is a standard hydrostratigraphic model with surfaces in a 100 m grid. In addition to this, the developed GeoScene 3D tool will make users able to perform mapping and modelling of the man-made layers in the same way as it has been done in the City of Odense.

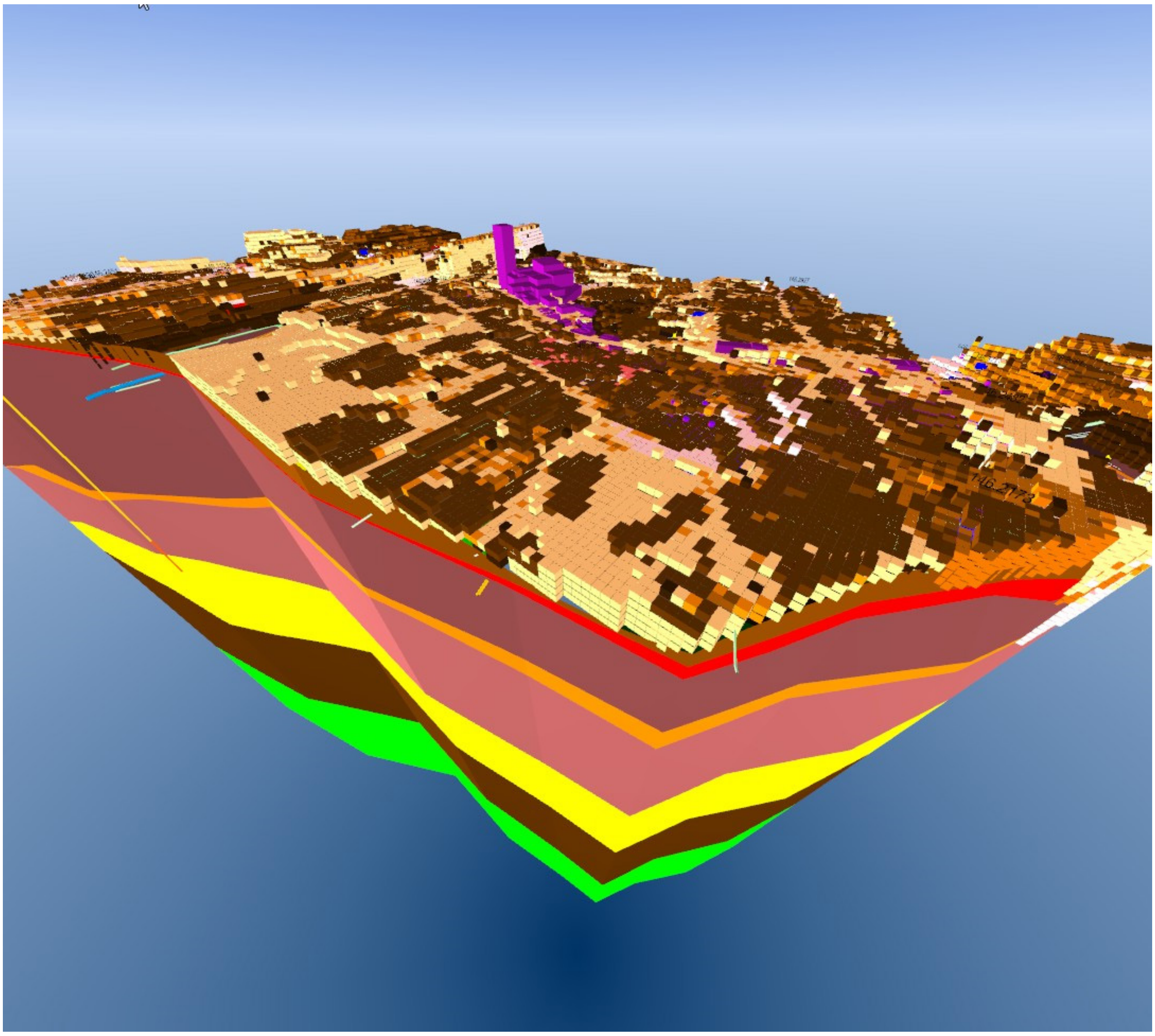


Figure 39 3D illustration of the merged anthropogenic and hydrostratigraphic models (from: Mielby et al., 2015a).

The combined hydrostratigraphic and antropogenic model therefore has to be made in a production flow as illustrated in Figure 40. The model interpretations based on the available data represent the backbone of the model (top of Figure 40) and based on this will be a series of decisions about which problems the model is intended to solve. That is, if the intention is to use the model for large-scale climate-related hydrological assessments in a large geographical area, there is no need for a model in very high resolution. On the other hand, when modelling in a very small area, there is no need to include very high detail in areas far from the focus area.

Figure 40 illustrates this flow towards producing a tailored model for a specific use. It is the intention that – theoretically – two end users working on two different projects within the same overall area will actually use two quite different models tailored for solving two specific problems. Both models will, however, originate from the same model interpretations.

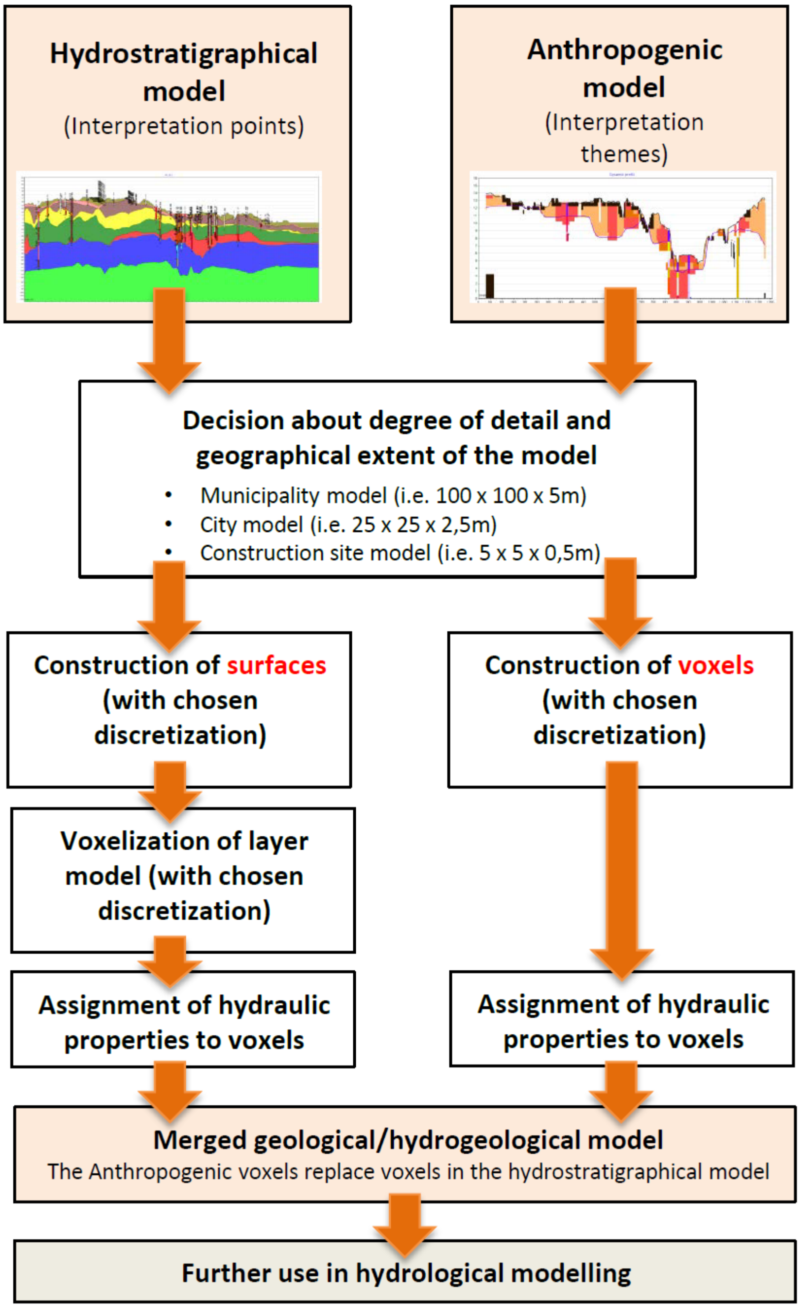


Figure 40 Flow diagram for merging of the anthropogenic and hydrostratigraphic models (English version; translated from: Mielby et al., 2015b).

Appendix D: Geological modelling the medieval city of Bergen

Anna Seither & Hans de Beer

Modelling rationale

The city of Bergen, located on the Western coast of Norway (Figure 41), has been one of Northern Europe`s most important trading ports. Founded in 1070 AD, the town gradually developed around a natural well-sheltered and ice-free harbour that proved to be an ideal location for commanding trade along the coast.

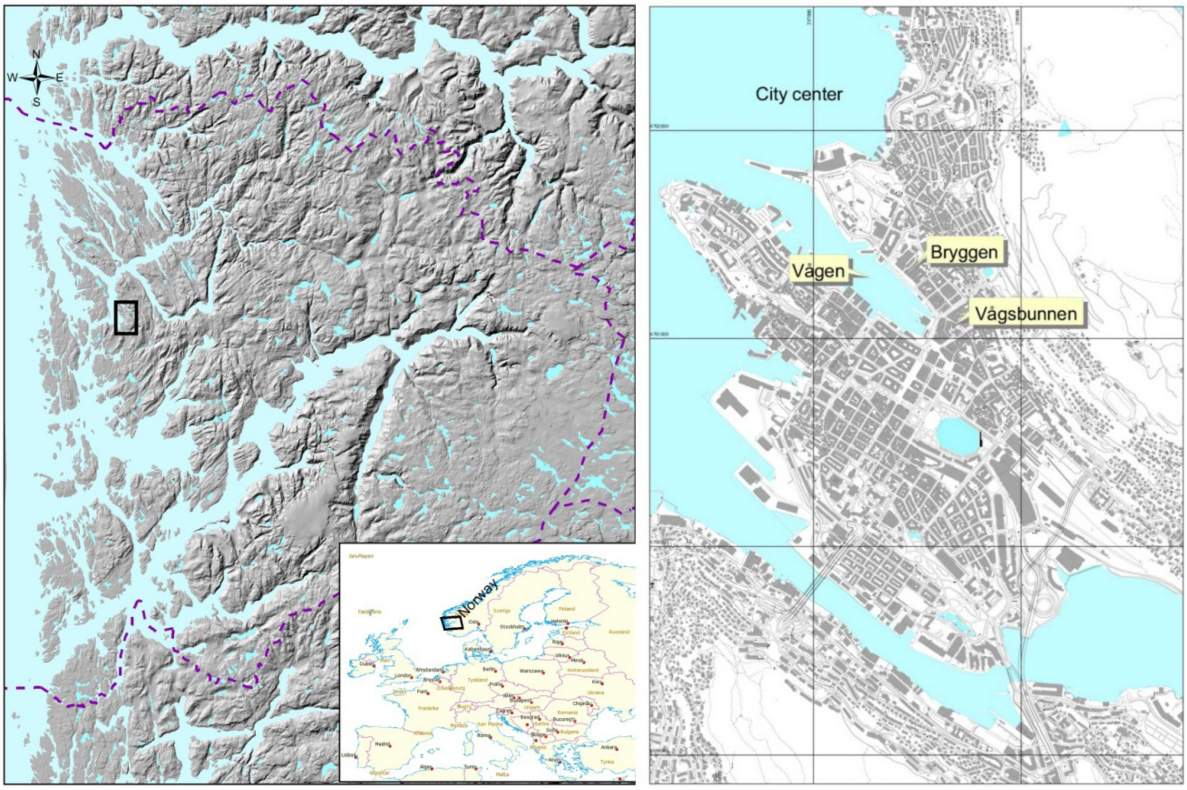


Figure 41 The City of Bergen is located in western Norway.

The landscape of a historic city such as Bergen and the character of the shallow subsurface environment are defined by a legacy of interaction between anthropogenic and geological processes. Hence, in historic cities, any geological investigation and modelling process should acknowledge the role of past and ongoing human activities (De Beer et al., 2012). Anthropogenic processes and deposits range from archaeological activities to modern urban development. The city of Bergen is an example where both buried heritage and standing monuments are of prime significance. In 1979, the medieval harbour “Bryggen” was designated a UNESCO World Heritage Site due to its outstanding testimony to past traditions. One of the main reasons for this designation were the results of extensive archaeological excavations in the period from 1955 to 1979 that revealed an extremely well preserved sequence of buried building remains since the founding of the city, basically telling the evolutionary story of the city. Today's UNESCO heritage protection not only includes the well-known historic harbour buildings from 1702 (Figure 42), but also the archaeological deposits in the subsurface. The World Heritage Site thus extends from the bedrock to the top of the roofs.

Figure 42 The World Heritage Site Bryggen in Bergen. The current timber buildings were erected after a major fire in 1702.

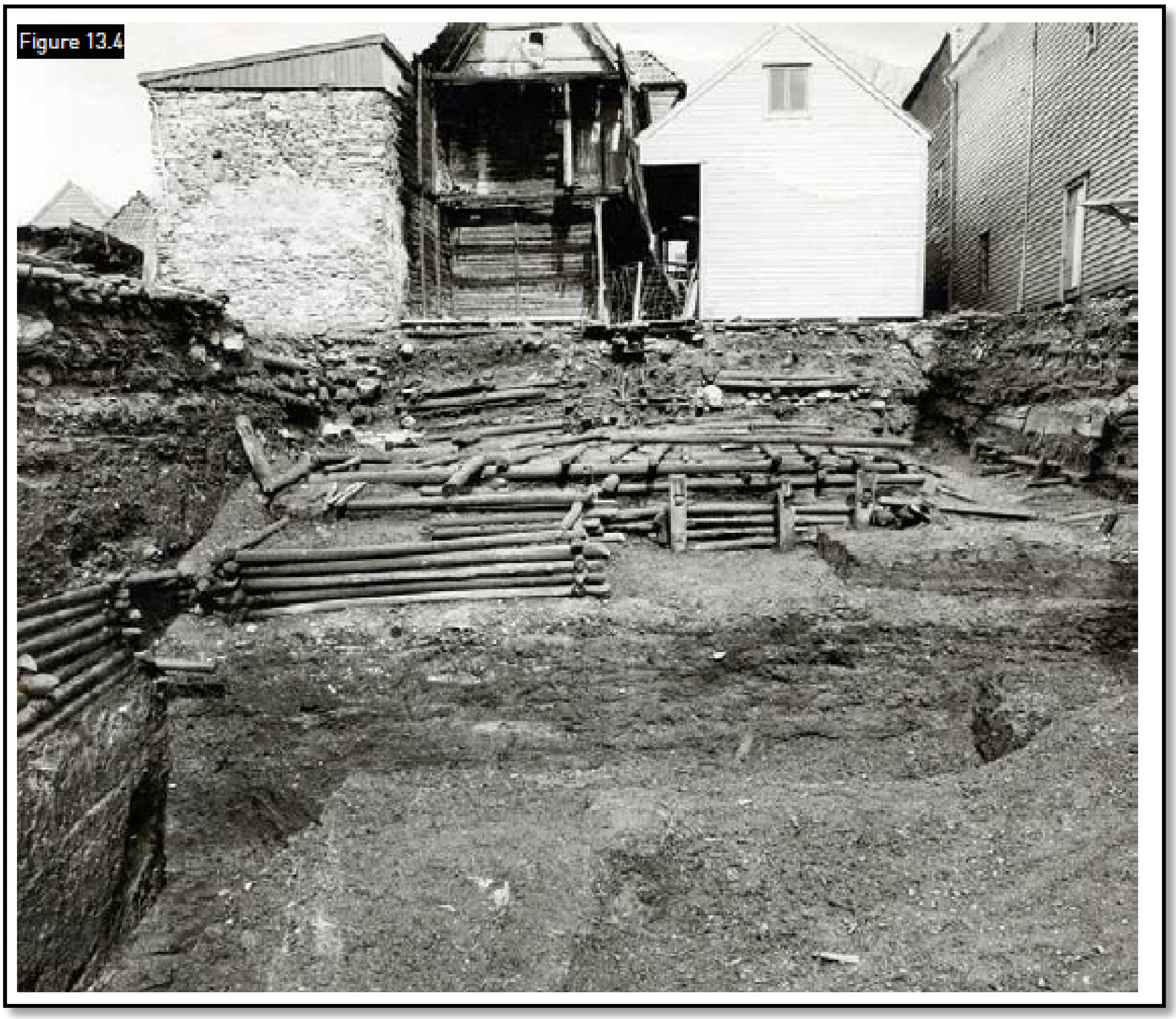


Figure 43 Buildings erected after the fire in 1702 on top of several meter-thick archaeological deposits (Photo: University museum in Bergen).

Bryggen is just a small part of the medieval city centre of Bergen. The subsurface in the remaining part of the historic centre has a similar built-up as at Bryggen, where extensive excavations took place and the subsurface temporarily was uncovered. Throughout history, Bergen has experienced many disastrous fires. Each time the houses burnt down, rebuilding took place on the old sites, on top of the building remains (Figure 43).

The subsurface in the whole city centre is characterised by significant thicknesses of anthropogenic deposits up to a 1000 years old with high archaeological value. These so-called archaeological deposits are “sandwiched” between natural geological deposits and modern man-made deposits of various compositions. The archaeological deposits in Bergen generally have a very high organic content (up to 90%) and reach thicknesses of up to 10 meters. All archaeological remains older than 1536 are automatically protected by the Cultural Heritage Act and should remain preserved *in-situ,* in line with European Convention for Archaeological Heritage. In practice, the loss of these remains should be less than 0.5% per year (www.miljostatus.no). A map of the indicative archaeological deposit thickness in Bergen centre is given in Figure 44.

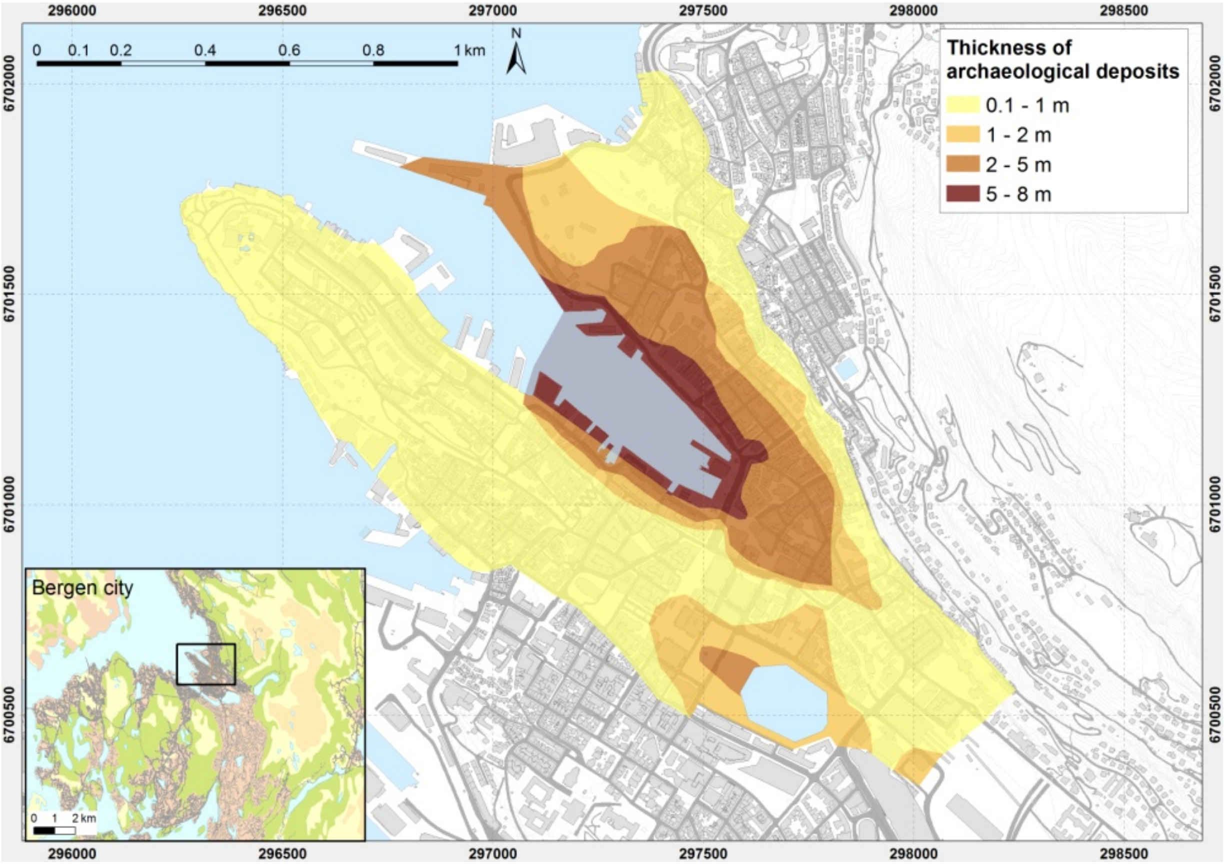


Figure 44 Thickness of the archaeological deposits (source: Riksantikvaren).

Preservation conditions for naturally degradable archaeological remains are strongly dependent on water quality and the presence or absence of groundwater in particular. Deterioration of organic material often occurs as a consequence of lowering of the groundwater level, which make archaeological deposits such as in Bergen particularly vulnerable. Both mechanical settling of the terrain and oxidisation of organic material occur, thereby not only destroying archaeological assets, but also removing the very foundation of the historical buildings, roads and infrastructure above. A main goal for the medieval centre of Bergen is therefore to establish a stable hydrological environment. This will ensure that the archaeological remains are safeguarded for posterity, while the area can be developed for modern use.

3D geological models at different scales can provide a holistic system for the management of the subsurface provided that they encompass both natural geological formations and man-made deposits. For Bergen in particular a geological model provides a framework for the integration of other spatial and process models to help assess the preservation potential for buried heritage. At the World Heritage Site of Bryggen, such a 3D geological model has been constructed in conjunction with a numerical groundwater flow model. Currently, work is ongoing to construct similar models for the whole medieval centre. Although archaeology is an important driver, the potential use of the models as risk assessment and planning tools for urban redevelopment is a decisive consideration.

This example focuses on the established local model at Bryggen and discusses the challenges posed in mapping and modelling man-made deposits in the city centre.

Bryggen

With a long-term average of 2250 mm precipitation per year, there is no shortage of water in Bergen. However, sealed surfaces, drainage systems, re-direction of rainwater into municipal stormwater facilities and pumping activities led to critically low groundwater levels in several vulnerable areas. There are also clear indications that preferential flow paths in the shallow subsurface, e.g. along pipelines, direct infiltrating rain water to surface water instead of contributing to groundwater recharge. At Bryggen, the lack of water caused increased access of oxygen into the ground, thereby initiating decay of organic materials in the archaeological deposits and leading to subsidence of buildings and infrastructure. Major efforts were and are necessary to counteract this process and to save the World Heritage Site.

In order to impede the loss of archaeological valuable materials and the destructive effects of settling, Norway`s *Directorate for Cultural Heritage* started off with a preservation programme. Since 2001 the funding for research and site remediation has gradually increased. A hydrogeological model and a framework geological model contributed to improve the understanding and visualisation of the complex coherence between natural geological deposits (till, sand, bedrock), archaeological deposits, modern man-made infillings, subsurface infrastructure and building constructions, as well as understanding of groundwater flow conditions. As such, both models contributed in improvement of monitoring measures as well as the design of mitigation measures. As a consequence of this work, in 2011, a funding of 45 million NOK became available to implement mitigation measures in order to restore the water balance at Bryggen and stop the ongoing deterioration of the site.

Modelling process

Primary focus at Bryggen has always been on groundwater flow conditions. Based on subsidence measurements in conjunction with groundwater level monitoring, it became obvious that the subsidence and loss of archaeological material were caused by locally lowered groundwater levels. Understanding the groundwater flow conditions in a highly complex geological and anthropogenic environment became essential for safeguarding the heritage site. An initial hydrogeological model was constructed using Feflow® (De Beer, 2005; 2008) The hydrogeological model was based on a geological interpretation of borehole data and included bedrock, till, beach deposits, archaeological deposits, modern man-made deposits and man-made constructions. Only at a later stage, a framework geological model was constructed using GSI3D®, as a pilot for visualisation and communication of multidisciplinary data (archaeological assessments, geology and groundwater level) in a single, relatively simple model environment (Figure 45). The GSI3D® model delivered new output for updating the hydrogeological model. In retrospect, the project could have gained benefit from construction of the framework geological model *before* groundwater flow modelling, but at that time GSI3D® software was not available to the project and the focus was on understanding the groundwater flow conditions.

The numerical groundwater flow model improved the understanding of the hydrogeological system, enabled quantification of the water balance and was used to identify the hydrological conditions that triggered degradation and subsidence. The groundwater flow conditions at the site were dependent on a complex combination of subsurface installations (e.g. constructions, drainage, leaky sewage), man-made deposits, and natural conditions such as meteorological and tidal variations, fresh/saltwater interaction, bedrock composition, fractures and natural geological variations. The following input data were used to construct the hydrogeological and framework models:

- geological maps and descriptions
- borehole descriptions (archaeological, geotechnical, hydrogeological)
- groundwater monitoring wells (incl. manual and automatic measurements of level, temperature and chemical analyses of water samples)
- historic maps and archaeological documentation
- construction drawings (incl. buildings, sheet piles, drainage, sewage, transcripts of work)
- minor excavations (archaeological and construction)
- meteorological data (precipitation, temperature, snow cover)
- tidal measurements
- water and sewage information (pipelines, depth, diameters, stormwater flow model, runoff coefficients, etc.)
- terrain and other surface composition (terrain and roof surfaces; asphalt, cobblestones, green spaces)

- digital terrain models, DTM (LIDAR and others)
- subsidence measurements (manual series on ground and buildings, at a later stage InSAR)

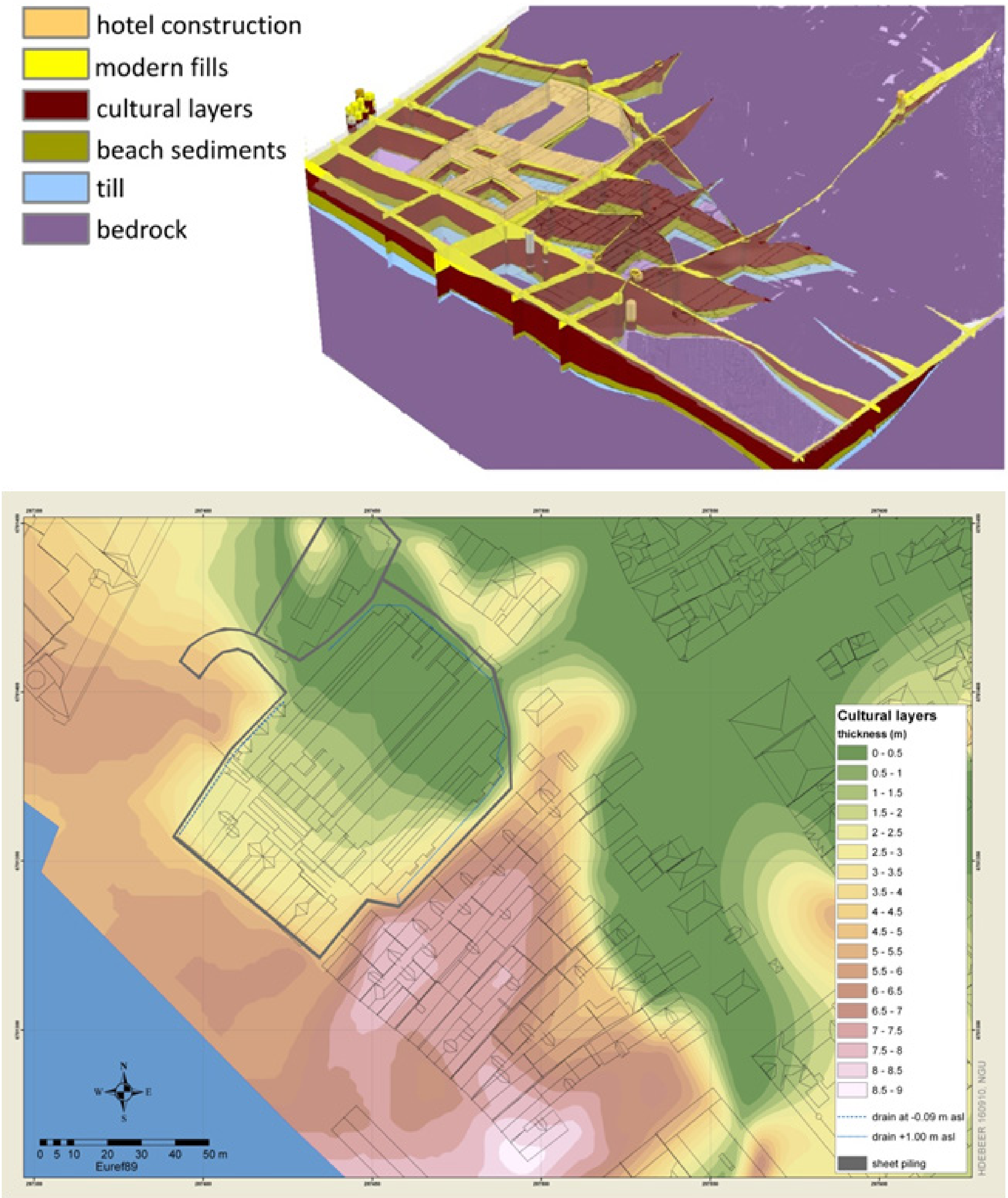


Figure 45 3D visualisation (GSI3D) of the deposit sequence underneath Bryggen`s timber buildings, extrapolated between neighbouring boreholes. The thickness of the cultural deposits as calculated from the 3D subsurface model is shown on the map (De Beer et al., 2012).

Challenges

One of the biggest challenges in describing the subsurface complexity and incorporating this into framework and hydrogeological models was the variety in information types. Including and “translating” all different types of information (e.g. archaeological descriptions, construction drawings, maps, non-standardised borehole descriptions, water- and sewage pipes, etc.) into a few holistic models, is time consuming and a process that is difficult to document. The model builder gains a conceptual understanding of the site by studying all information types. This conceptual understanding is transferred into a model with the purpose to be used by others, possibly non-specialists. A proper documentation of the conceptualisation process as well as the associated uncertainties is essential to avoid misunderstanding and erroneous use of the models once the model builder is finished.

Model use

Several of the input datasets were initially based on literature or on conceptual ideas of the modeller – and refined later on when more and more monitoring data became available. The 3D model significantly increased the understanding, not only among technical experts, but not in the least among those responsible for managing the site. Visualisation of the subsurface situation in which anthropogenic developments clearly affected natural preserving processes, was a decisive element in achieving the funds necessary to carry out mitigation work and safeguard Bryggen. The process of (hydro)geological modelling and collecting new observations through monitoring became iterative in the sense that the models were updated with monitoring data, while the monitoring network was improved by increased understanding through modelling. As such, understanding of the site was gradually improved and uncertainty reduced.

Mitigation, monitoring and management

Since 2012, various measures to locally raise the groundwater level have been carried out (Rytter & Schonhowd, 2015). Compact cobblestone pavements were exchanged with gravel, roof water was redirected to be infiltrated into the ground, and a damaged sheet pile wall and the associated drainage system were restored. Water retention and infiltration were improved considerably by the installation of swales and a rainwater garden (Figure 46). The most vulnerable area was equipped with a stepwise infiltration-transport system, which is basically a series of buried infiltration pipes, a sequence of bentonite dams, and drainage inspection wells behind each dam. This system allows regulation of the groundwater levels to a certain degree.

Even though the Bryggen quarter is secured for now, the monitoring work will continue (Figure 47). Collected monitoring data include archaeological observations, time-series of the piezometric head in about 40 monitoring wells, time-series of soil water content, temperature, oxygen content and redox potential, as well as chemical analyses and settling rates of terrain and buildings. The monitoring goals are documentation of the changes in preservation conditions, as well as supporting the maintenance of mitigation measures.

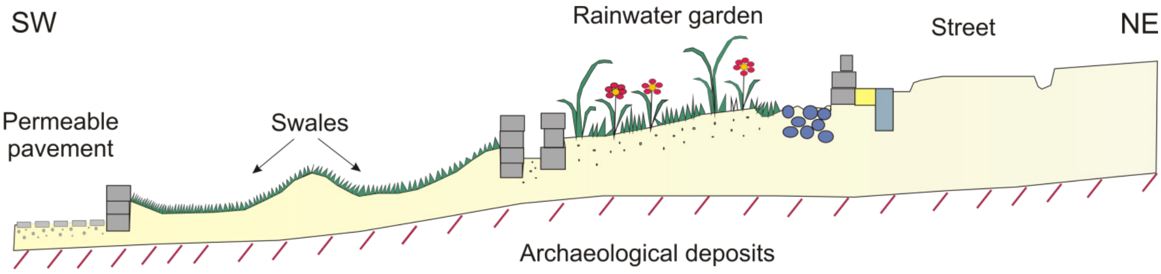


Figure 46 The rainwater garden, the swales and the permeable pavement together form an effective "treatment train". Drawing: J. de Beer, NGU (Reproduced from: Ryyter & Schonhowd, 2015).

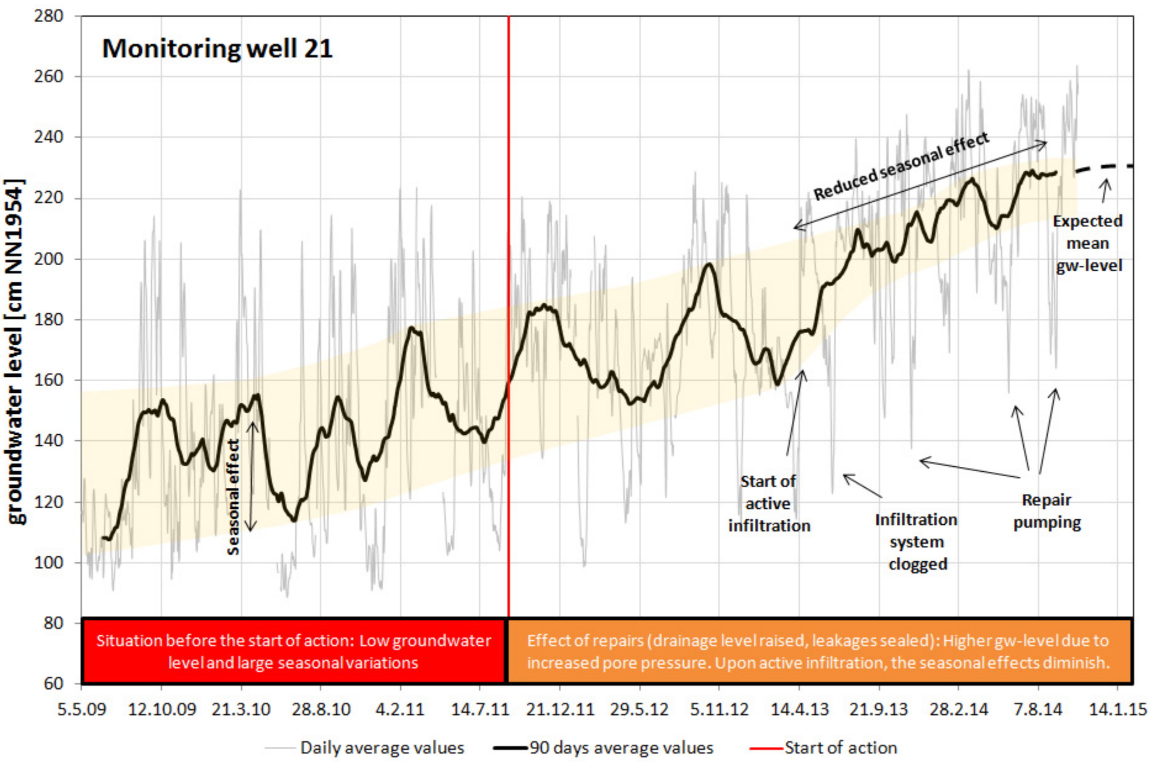


Figure 47 Groundwater level in a monitoring well. The grey line shows the daily variations of the groundwater level. The black curve gives a simplified impression of the groundwater level, by showing average values over three-month intervals. The gradual rise of the groundwater level demonstrates the success of the mitigation measures. Drawing: A. Seither, NGU (reproduced from: Rytter and Schonhowd, 2015).

Mapping and modelling in the medieval city centre

Bryggen is, due to its status as a UNESCO heritage site, an extremely well documented case of how urbanisation and changes in the subsurface may threaten archaeological heritage and cause dramatic damage to the historic buildings. But in fact, Bryggen is not a single case. Elsewhere in Norway and further afield in Europe and beyond, historic cities contain vast amounts of organic material in the subsurface, vulnerable for changes in groundwater conditions. In Bergen, the whole medieval city centre has a similar subsurface build-up as Bryggen. Therefore, the medieval city is extremely vulnerable for changes in the groundwater level, risking decay, loss of non-renewable cultural heritage, subsidence and damage to infrastructure and particular historic buildings. The medieval centre of Bergen contains important historical monuments and it is a popular tourist destination. The area is a vibrant place with coffee shops, pubs, shops, markets and living space. Modern transport and urban redevelopment are a high priority, but the consequences of not taking care of subsurface issues during the last century have become clearly visible in the streets. Streets are damaged beyond repair due to uneven subsidence and historic buildings are under threat for the same reason (Figure 48).

Figure 48 Crooked timber houses due to subsidence. Photo: J. de Beer, NGU.

There are strong indications that the subsidence is triggered by changes in the groundwater level, caused by pumps in basements and probably locally changed ground- and subsurface drainage conditions. Preserving cultural heritage and urban development do not go without conflicts of interest. The municipality has insufficient knowledge about the subsurface to use as a base for decisions on urban development projects. As a consequence, the municipality of Bergen made a temporary, but unique regulation decision for the city centre area: measures that cause increased risk for subsidence in the subsurface, including changes of the groundwater level, are not permitted.

In 2014, the Geological Survey of Norway initiated a collaborative pilot project with the municipality of Bergen and the Directorate for Cultural Heritage in Norway, the latter responsible for protection of all subsurface archaeological heritage according to the Cultural Heritage Act. The pilot project aims to systemise existing subsurface data of the medieval quarters of Bergen and to improve their availability by storing the data in public databases. The next step will be to use these data for constructing a 3D model of the subsurface and a groundwater flow model. The data and models will form the basis for evaluation of stability and risk analyses, supporting urban development and integral water management and preservation of cultural heritage.

Appendix E: Visualising construction suitability near Helsinki

Hilkka Kallio

The Geotechnical Division of the City of Helsinki ordered a construction suitability assessment from the Geological Survey of Finland (GTK) in 2011 (Kallio & Ikävalko, 2011). This assessment was part of a techno-economic review of the Östersundom master plan (Östersundom-toimikunta, 2014). The plan was introduced in 2015. Östersundom is located approximately 20 km east of Helsinki city centre and the total development area covers 45 km^2. Östersundom is today a mostly rural area with single-family homes. Once completed around 2050, Östersundom will be home to 45,000-50,000 residents and hundreds of businesses, offering jobs to thousands. The planning and implementation of ground improvement works is the responsibility of the City of Helsinki.

Methodology

The construction suitability assessment of Östersundom is based on a Digital Elevation Model (DEM), a Quaternary deposits map in scale 1:20,000 and soft soil thicknesses. Values of soft soil thickness were interpreted from a selection of prior drillings made by the Geotechnical Division of the city (all together 2446 interpretations out of 3794 drillings). The existing drillings did not cover the whole zoning area and the soft soil thicknesses of the untouched sedimentation basins were estimated based on the degree of bedrock slope and the width of the basin.

Model visualisation

The visualisation of the model was performed with ArcGIS. The point data of soil thicknesses and the construction suitability polygons were converted to an exchange format suitable for MicroStation, which is the main software of the Geotechnical Division of Helsinki. The customer requested the classification of construction suitability in three main categories: normal, demanding and very demanding ground conditions (Figure 49). The demanding ground condition include two sub-classes; soft soils thickness of 3-15 m or DEM-slope values over 10%. The location of selected drilling points was illustrated in the map, which is an approved method when the geographical distribution of data varies within the research area. Besides the requested construction suitability visualisation, GTK compiled alternative visualisations from the same input data. The alternative maps had more categories and thus gave more detail of the nature of the Quaternary material in the area.

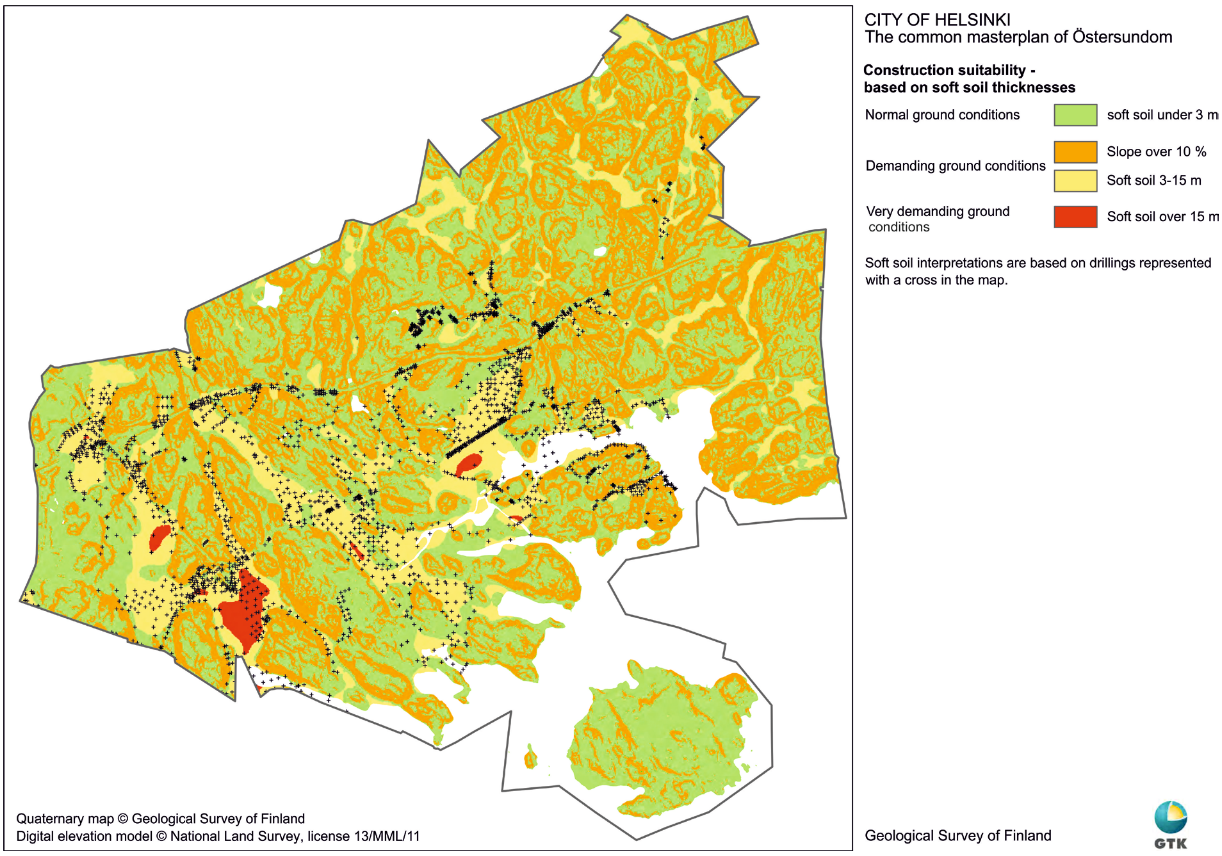


Figure 49. Visualisation of construction suitability in Östersundom. This map is based on a DEM, an existing map showing Quaternary deposits and information on soft soil thickness.

Discussion

On the basis of this assessment the planners could easily detect the demanding and very demanding ground conditions and estimate the extent of the block areas located on soft soils or on steep hills. In the common master plan of Östersundom, 30% of the block areas are planned on soft soils. The necessary ground improvement measures depend on the detailed planning of these block areas. It is difficult to say how much influence the display of ground conditions had on the land use decisions at master plan stage. An important conclusion of this example is that the planners favoured simplicity in a large scale assessment, whereas the more detailed site plans consider the precise geotechnical properties of the subsurface.

Appendix F: Visualising soil properties near Espoo

Hillka Kallio

The Suurpelto area will grow into a new urban centre in Espoo with 10,000 -15,000 inhabitants. The 325 ha large area will be gradually built and diversified for the next 15 years. The Municipal Board of Espoo approved the guidelines for the Suurpelto partial master plan in 2000 and The Municipal Council approved the plan in 2006. Based on local geology, it was known that the composition and geotechnical properties of the Suurpelto deposits make it a challenging site for construction.

Methodology

A geotechnical co-operation project was launched in 2005 with the city of Espoo, the Geological Survey of Finland, the University of Helsinki and Helsinki University of Technology as participants, with the aim to provide scientific and technical information for land-use planning and ground engineering, particularly for tasks such as construction suitability and stabilisation. The primary objectives were to identify the main sedimentary units of the Suurpelto deposits, to characterise their composition and structure, and to construct a 3D geological model of the geometry of these units (Ojala & Palmu, 2007).

The research showed that the northern part of the Suurpelto basin contains a thinner sequence of massive and varved clays with coarser (silt, sand) mineral layers representing earlier phases of the Baltic Sea Basin (BSB) than the southern part. In the southern part of the Suurpelto basin these deposits have been covered by organic and sulphide-rich sediments that represent later phases of the BSB. The soil layers containing sulphide and organic matter may have a negative effect on ground stability. In the laboratory and field tests in Suurpelto, the lowest shear strengths were attained in the sulphide-containing layer (Stapelfeldt et al., 2009).

An overall objective in the soft soil research in GTK is to perceive and classify typical sedimentation surroundings and their characteristics in the Baltic Sea Basin. With this experiment the existence of different soft soil layers can be more easily estimated and the field tests better aimed at representative locations.

Model visualisation

The GIS data handling and interpolation of sediment surfaces were done with Surfer. The map layouts were created with ArcGIS and the layout of cross sections were revised with a vector graphic editor. The visualisation of the Suurpelto sedimentation basin is made by showing the cross sections of representative locations together with the maps of individual soft soil unit distributions. A linkage between geological and geotechnical knowledge is illustrated by adding the geotechnical investigation profiles to the cross sections of geological units (Figure 50). Figure 51 shows the different periods in the evolution of the Baltic Sea Basin and thicknesses of corresponding soft soil layers.

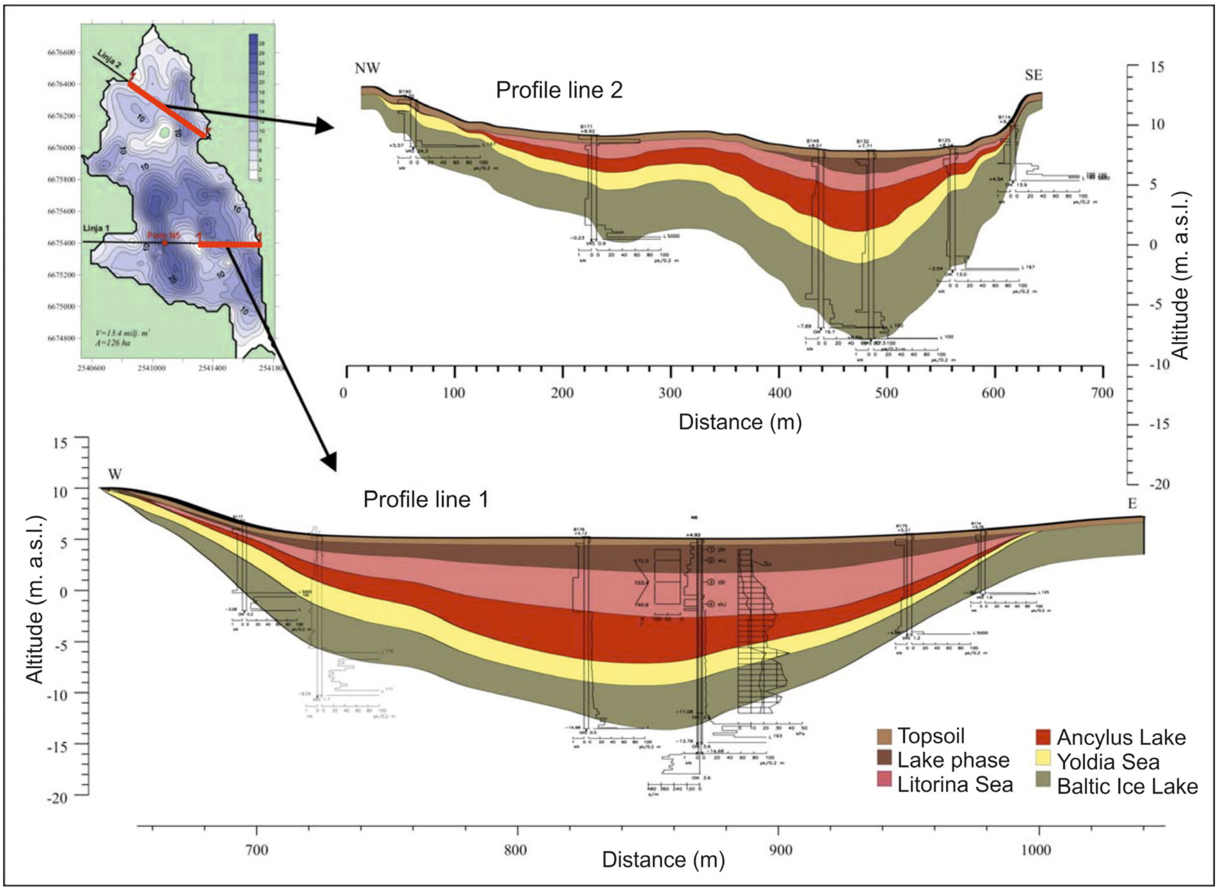


Figure 50 Cross sections of the Suurpelto quarter. A new housing area is built on a sedimentary basin. The different colours represent clay layers from both glacial and postglacial origin. Map and cross sections: GTK.

Discussion

Despite the rapid development of 3D visualisation possibilities, 2D cross sections are still an important way to visualise subsurface interpretations. A cross section ideally clarifies geometric and geologic age relationships that may be difficult or impossible to visualise solely from inspection of a geologic map, or that are difficult to perceive in a 3D scene. Cross sections through a 3D model usually require editing before they can be published in 2D. An ideal situation regarding 3D software would be an advanced cross-section construction ability that allows versatile editing.

The overall visualisation is clear and simple but still rather academic. As such, it does not highlight the characteristics that have most effect on construction suitability. Adding the geotechnical profiles to the geological cross sections is a good attempt to open up a dialogue between two, sometimes separated knowledge fields.

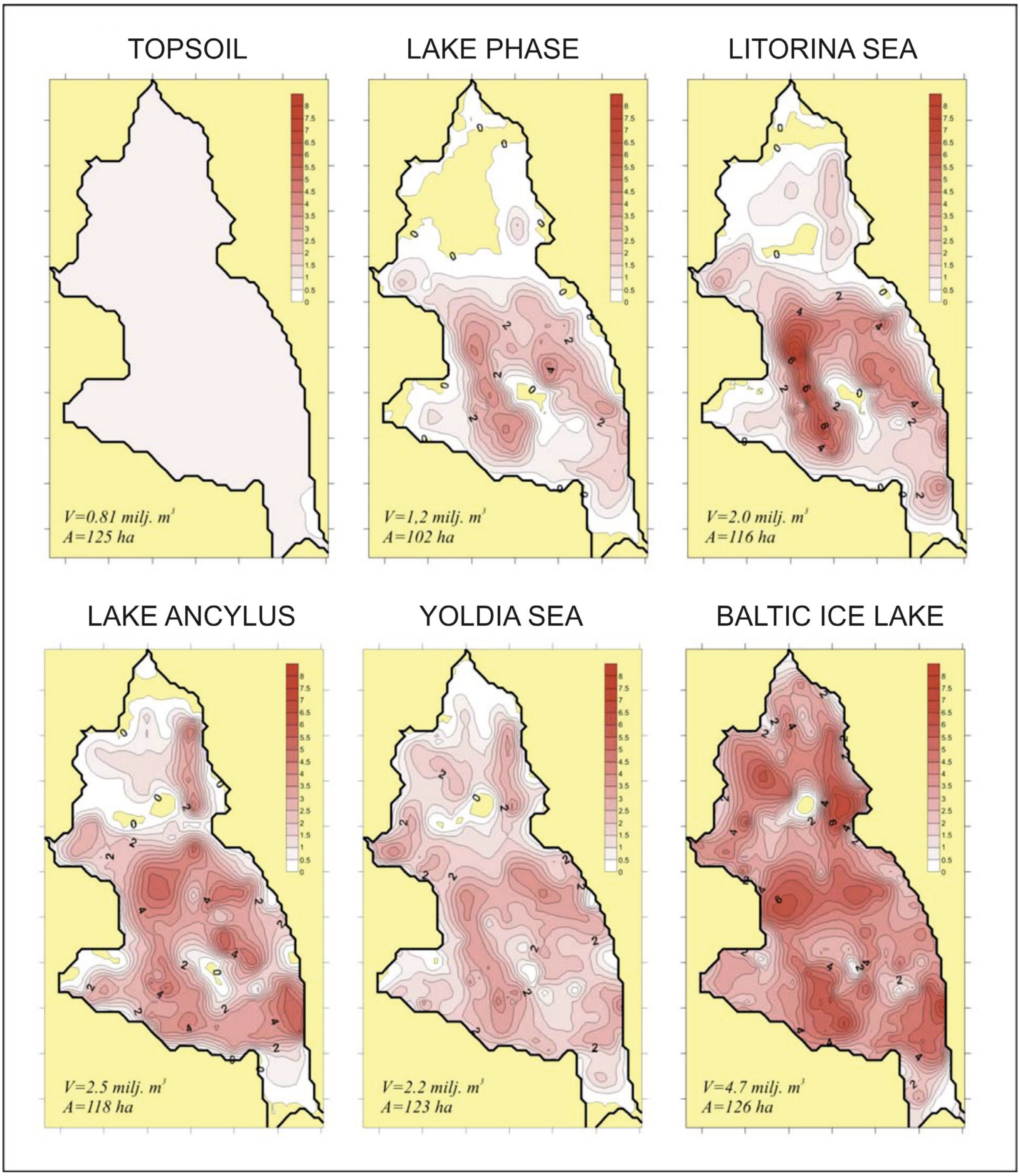


Figure 51 Different periods in the evolution of the Baltic Sea Basin and thicknesses of corresponding soft soil layers in the Suurpelto area. Map: GTK.

Appendix G: 3D modelling and visualisation in Oslo

Ingelöv Eriksson

Above-ground 3D modelling and printing is a common tool during urban planning above the surface in Oslo. It is used for visualisation and communication to the public (Figure 52).

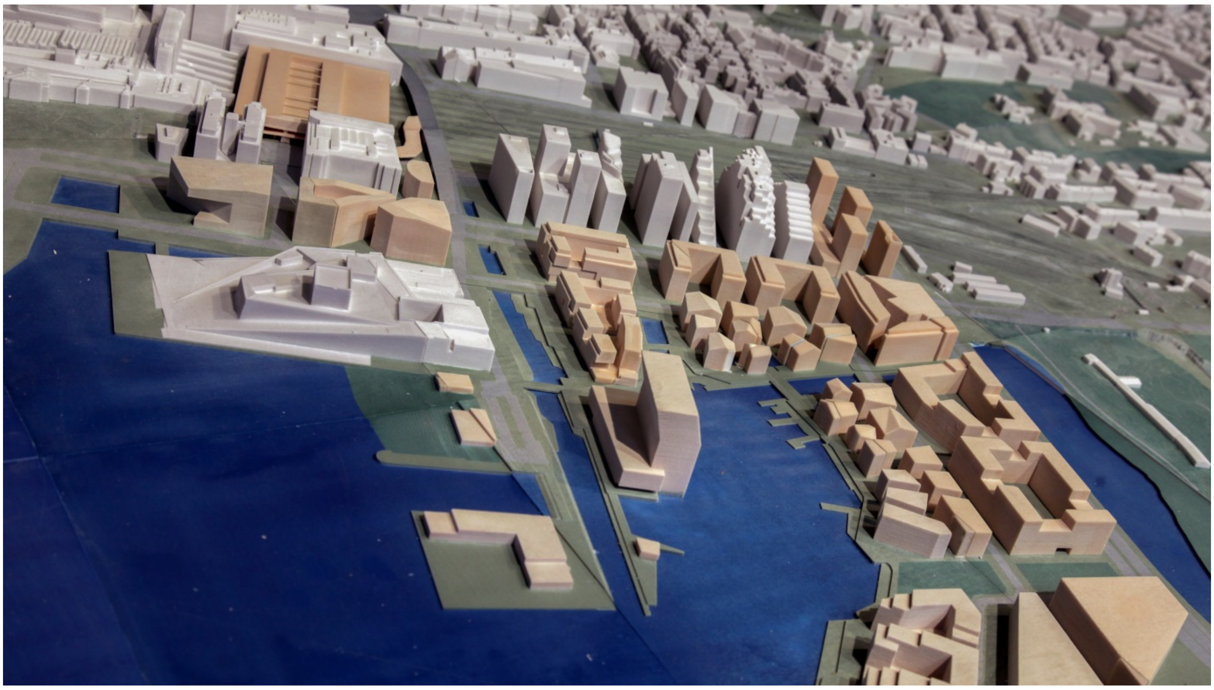


Figure 52 Printed 3D above-surface model, used for communicating future development in central Oslo to the public. Credits to Division of plan and thematic maps, Agency for planning and building services, Municipality of Oslo.

However the potential and techniques of subsurface 3D modelling are strongly advancing. One example is the BIM 3D subsurface model of the seafront area of Bjørvika that has been developed before the construction of Dronning Eufemias gate. The model has been developed by a number of parties such as the Norwegian Public Roads Administration (Statens Veivesen) and Norwegian government's agency for railway services, (Jernbaneverket). The above-ground part of the model is updated several times a year and is used for communication and sometimes during construction. The subsurface part of the model has been used during the planning and construction of a 700 m long road, built upon 1100 pillars in order to overcome difficult geotechnical properties. Detailed information about subsurface infrastructure has been used in digging machines and whilst placing out new infrastructure.

Information about sub-surface installations such as, storages, tunnels, pipes and cables is very important in Oslo. A 3D model in a test area in Oslo has been developed and the model is currently being evaluated by urban planners, the aim is to identify which level of modelling is needed in order to have sufficient background information in urban planning.

The current geological maps over Oslo are 2D maps in 1:50,000 scale. Besides that, the municipality of Oslo has an archive of geotechnical surveys, which contains thousands of boreholes with geological information.

During the summer of 2015, we took the first step to convert a small part (317 boreholes) of this archive into 3D information. The geotechnical boreholes were digitised and inserted into a geodatabase with geological layers attributes and specific depth (Figure 53).

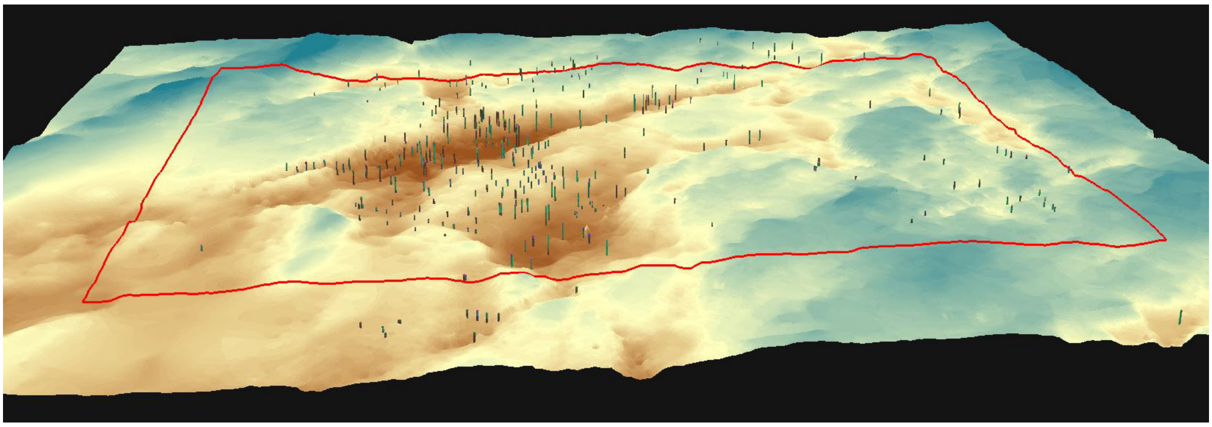


Figure 53 Depth to bedrock with boreholes used for the model. Credits to Cecilia Cerdeira, Municipality of Oslo.

Cross sections were based on the boreholes and were digitised and interpreted with a tool called Xacto, developed in Visual Basic for Applications (VBA) by *Jennifer Carrell*. With this tool we digitised (100) 2D cross sections. These were then visualised in ArcScene as 3D geological cross-sections, covering our study area (Figure 54).

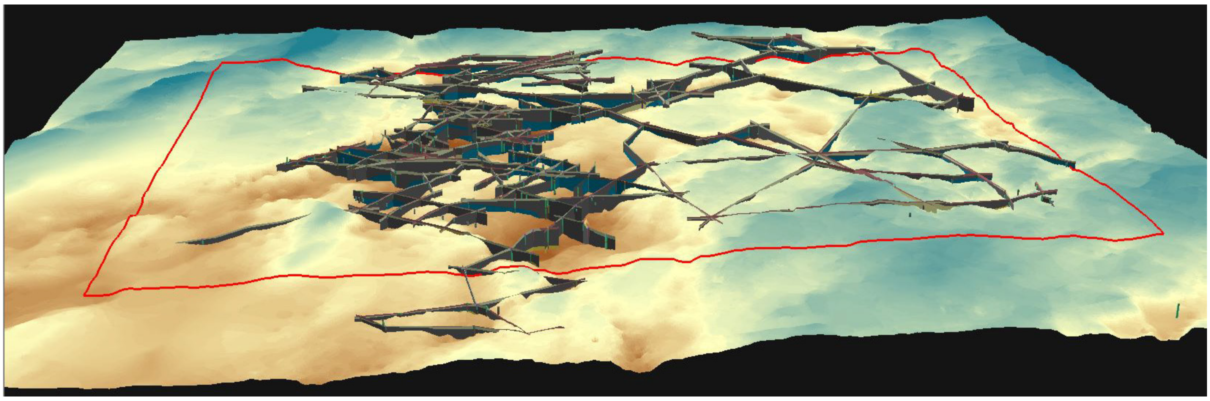


Figure 54. 3D depth to bedrock with profiles of Quaternary geology. Credits to Cecilia Cerdeira, Municipality of Oslo.

With the final 3D geological cross sections and 3D borehole information we intend to interpolate a 3D geological map for the study area. This is an important step, because it is crucial to identify how such a model will help the urban planners and to work out a product that is usable in urban planning at the right level. So far the model shows that there are quick clays present at several areas. Some areas with clayey sands and clayey gravel have also been identified, as well as artificial soils (man-made deposits).

Apart from the above, it is difficult to discuss the use and need of 3D subsurface modelling without discussing the Planning and Building legislation in place. According to Norwegian legislation the constructor is responsible for a building project, therefore they most likely take most profit from the development of detailed subsurface models. Establishing standard formats and ways to digitally collect, store and reuse such models is of great importance.

In Norway, the calculation of risks in areas prominent to mass movements (mainly quick clays in the Oslo area) is requested by law. In a planning process so-called ROS analyses, (Risk and Vulnerability Studies) are generally carried out by consultants and are a necessity to get a plan approved by the Planning and Building authority. The ROS analyses are rarely effectuated within the municipality itself. The results are generally presented as a report and not visualised.

So far, it has been concluded that a more detailed subsurface mapping of Oslo can help in the building control process, as well as in the evaluation of the ROS analyses. At the same time, we are distinguishing between 3D information and 3D visualisation. We are aware that 3D visualisation can be a great help, but it can also be confusing. It is therefore important to visualise as simple as possible without leaving out important information. 2D visualisation of 3D information can therefore be a solution.

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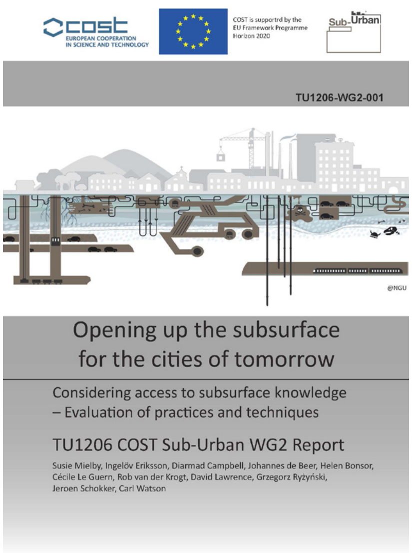

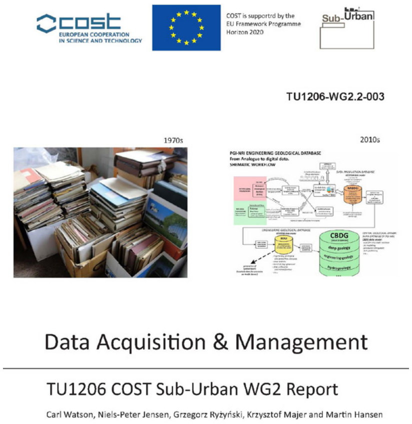

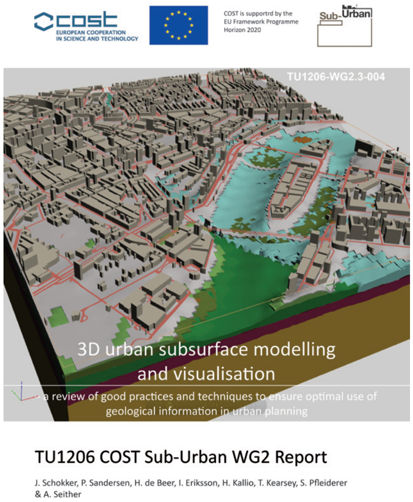

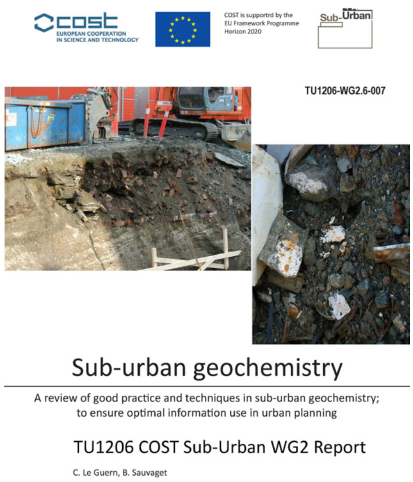

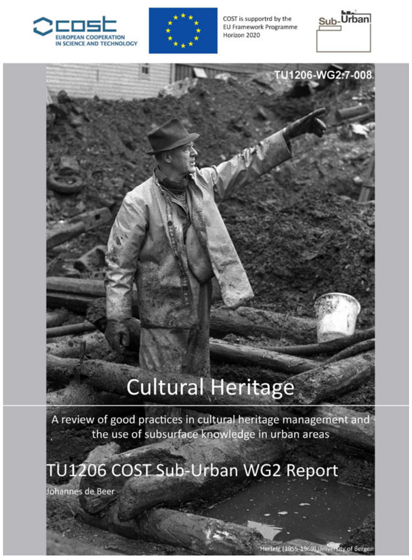

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