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Construction and usage of geological near-surface models with GSI3D – applied (hydro-)geological information for land sites and urban areas

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KEYWORDS

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Abstract

The GSI3D-software (Geological Surveying and Investigation in 3D; © INSIGHT Geologische Softwaresysteme GmbH), which is a powerful software-tool for 3D mapping of land sites and urban areas, generates dynamic digital 3D models from existing data sets. The spatial distribution of each geological unit is defined by an internally consistent net of intersecting cross-sections, based on lithological and stratigraphical characteristics and geological structures. The dynamic 3D models can be supplemented by artificial ground distributions and man-made modifications of the subsurface, such as infrastructure lines, tunnels and building foundations. Further processing of the 3D models allow each individual geological unit, sub-unit or lens to be attributed in terms of engineering conditions or hydro-geological parameters.

For the distribution of digital 3D models, a platform independent software-tool, the subsurface viewer, is used. This stand alone system enables the end-user to customise the visualisation and analysis of the subsurface, optimising it for individual tasks and providing planning and decision support for a sustainable management of natural resources.

GSI3D (Geological Surveying and Investigation in 3D) ist ein leistungsfähiges Softwarewerkzeug zur 3D Untergrundkartierung in urbanen und ländlichen Regionen. Mit GSI3D lassen sich die geologischen Verhältnisse auf der Basis von bereits existierenden Datensätzen über kreuzende Profilschnitte unter Berücksichtig von lithologischen und stratigraphischen Eigenschaften konstruieren. Die geologischen 3D Modelle können mit strukturellen Informationen zu anthropogenen Strukturen, wie Infrastruktur-Einrichtungen, Tunnelbauwerke oder Gründungsbauwerke, ergänzt werden. Dadurch, dass die geologischen Einheiten, Untereinheiten und Linsen beliebig, mit z.B. geotechnischen Parametern oder hydrologischen Größen, attributiert werden können, lassen sich die 3D Modelle variabel weiterentwickeln.

Zur Weitergabe, Publikation und Präsentation der mit GSI3D erstellten Untergrundmodelle wird eine eigenständige Software, der subsurface viewer, eingesetzt. Dieses plattform-unabhängige Werkzeug ermöglicht dem Endanwender eine interpretationsfreie Analyse des Untergrundes zur Planung nachhaltiger Maßnahmen der Untergrundbewirtschaftung.

1. Introduction

In 1815,William Smith presented the first detailed regional illustration of the subsurface, with E-W oriented cross-sections through his “Geological Map of England and Southern Scotland”. Smith’s sections recorded the three dimensional geological setting, its chronological evolution and the spatial distribution of unit strata. Since then, geologists have been trying to image the geological environment and its setting by drawing geological maps, supplemented by cross-sections and 3D block diagrams.

In general, a precise view of the geological environment can only be obtained by high resolution field mapping based on a large number of natural or man-made exposures supported by data from either drill-cores or geophysical investigations. Where field-data are limited or absent, drill-core and geophysical data are the only way to establish the subsurface geology.

Advances in digital visualisation and modelling techniques enable geologists to document their knowledge of subsurface conditions in easy-to-use and -understand digital 3D models. One such tool for 3D mapping of land sites and urban areas is the GSI3D (Geological Surveying and Investigation in 3D; © INSIGHT Geologische Softwaresysteme GmbH) method. With this, dynamic digital 3D models are compiled from existing data sets, such as geological and soil maps, historical maps, digital terrain models and drill-logs, as well as from geo-technical and hydrogeological data, and geophysical measurements. With GSI3D, the geologist can use down-hole drill data and outcrop information to construct a net of internally consistent cross-sections, defining the spatial distribution as well as the top and base of each geological unit present. These geological units are defined according to lithological and stratigraphical characteristics, with the geometry of geological structures based on genetic and morphological rules and perceptions. By using an iterative modification and fitting of the cross-sections, subsurface structures, such as channels, basins and swells can be generated. The dynamic 3D model can be supplemented by artificial ground distributions and man-made modifications of the subsurface, such as infrastructure lines, tunnels, and building foundations.

Further processing of the 3D structural model allows each individual geological unit, sub-unit and lenses to be defined in terms of engineering conditions or hydrogeological parameters. The resulting models can be distributed by a platform independent software-tool, the subsurface viewer, which enables the end-user to customize the visualization and analysis of the subsurface, optimising it for the individual tasks in the fields of mineral resources exploration, engineering-geology, hydrogeology, or environmental geology.

The present paper documents the GSI3D methodology, together with aspects of the application of 3D models to hydrogeology, in two areas of interest:

- a 4,000 km² regional model in northern Germany, constructed for the Oldenburgisch-Ostfriesische Wasserverband (OOWV water agency) and
- a 160 km² model of urban Cologne, compiled for the Rhein Energie AG.

2. GSI3D Methodology

A geoscientific investigation aims to depict the geology of the surface and subsurface in as much detail as possible. In addition to geological maps, hand-drawn cross-sections, fence diagrams and block models have also proven to be valuable methods. The spatial 3D image of the subsurface is usually supplemented by borehole information or sections from geophysical investigations.

The GSI3D program allows the geologist to create a net of intersecting cross-sections, by merging these datasets and combining them with surface data and data sets from other geo-scientific disciplines (Hinze et al., 1999; Kessler and Mathers, 2004). This geological 3D 'map' is then used to produce a dynamic digital 3D model of the geological environment, based on the unit distributions of outcropping and subcropping geological units.

A GSI3D mapping project (Kessler et al., 2004a) requires a Digital Terrain Model (DTM) in grid format, which forms the cap of the geological succession, a generalized vertical section file (resembling the stratigraphic order of the geological units) and a legend file (defining the colour coding for borehole information and stratigraphic units). In addition, geo-coded topographic maps and shape files of the geological line work (geological, engineering, hydro-geological and soil maps) can be loaded into GSI3D, visualised in their spatial context, and used during the 3D mapping process as information sources for reconstructing the geology. The digital information package can be supplemented by unit or groundwater information in varying grid and tin (triangulated irregular network) formats, as ASCII or Surfer, and goCad tin's. Digital images of outcrops and geophysical horizontal and vertical data can be geo-coded with GSI3D tools and integrated into the 3D mapping procedure.

For visualising borehole data, GSI 3D can display large amounts of down-hole drill log information in its spatial distribution (Fig.1). Individual boreholes can be visualised according to stratigraphy, lithological main or minor components, fossil content or chemical parameters, or any other given attribute. Borehole information sets are loaded as character separated value (csv) files, allowing data exchange with most common database applications, using x,y,z-coordinates for the drilling starting point and geo-scientific down-hole descriptions. In contrast to other 3D modelling packages, GSI3D does not require time consuming pre-processing of geological data sets (e.g. interpretation of each borehole in terms of stratigraphy). Instead, GSI3D enables the operator to interpret each borehole in the spatial context of all other geo-information during the 3D mapping process.

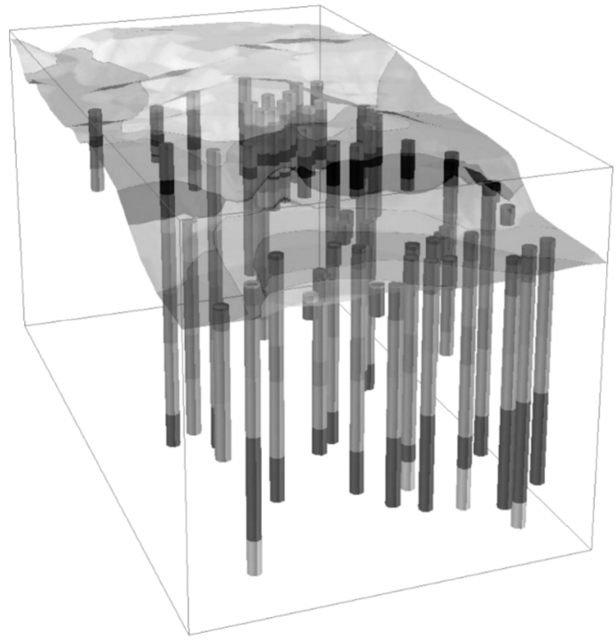

Figure 1: Common 3D visualisation of geo-data. Geological map plotted on DTM and drilling down hole data. Colour coding of drillings according to lithological major components: greyish colours in the upper part of the drill-logs = sand and clay, black = gravel; greyish colours in the lower part of drill-logs = limestone and sandstone. Vertical exaggeration: 2x

After data homogenisation and visualisation, the surface and subsurface information is used to set up the net of intersecting cross-sections (Fig. 2). Each geological unit or individual lens is defined in the cross-sections according to lithological and stratigraphic characteristics derived from the borehole data. Unit outcrops are constructed according to the geological line work or the morphology given in the DTM. An iterative modification of the intersecting cross-sections enables the geological subsurface structures to be constructed.

Whilst constructing cross-sections, all modifications are visible

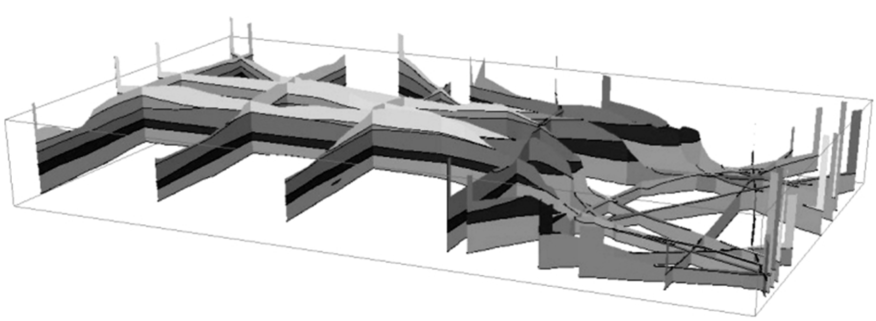

Figure 2: 3D visualisation of consistent mesh of cross-sections. Colour coding according to litho-stratigraphy: greyish colours = aeolian sediments and fluviatile deposits, black colour = glacial loam and sand, lower most greyish unit = tertiary clay. Vertical exaggeration: 2x

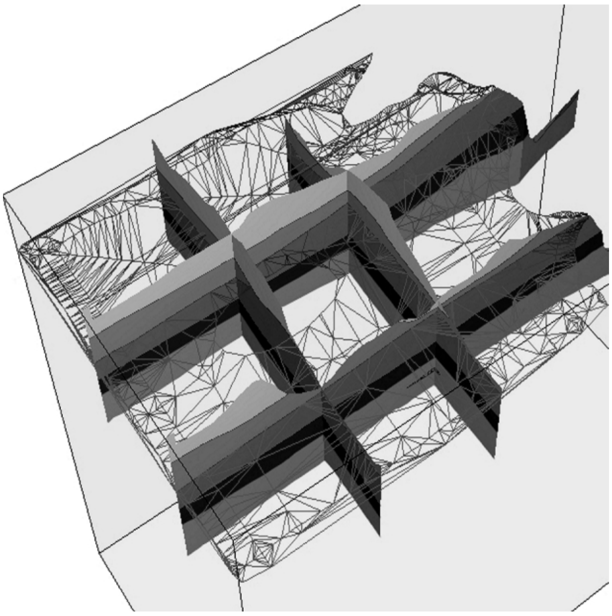

Figure 3: 3D visualisation of cross sections and triangulated mesh of unit distribution, defining the base of a glacial sand. Vertical exaggeration: 4x.

in their spatial context in the 3D window of GSI3D (Fig.3). This interrelated view of all basic and constructed data sets enables geologists to view the surrounding geo-information interactively, influencing the section construction and the side effects of section modifications on already existing sections. As a result, it is possible to work on cross-section meshes comprising several tens of sections, based on hundreds of boreholes. This enables the geologist to incorporate large amounts of data into the 3D mapping procedure and also to cover extensive areas during one mapping campaign.

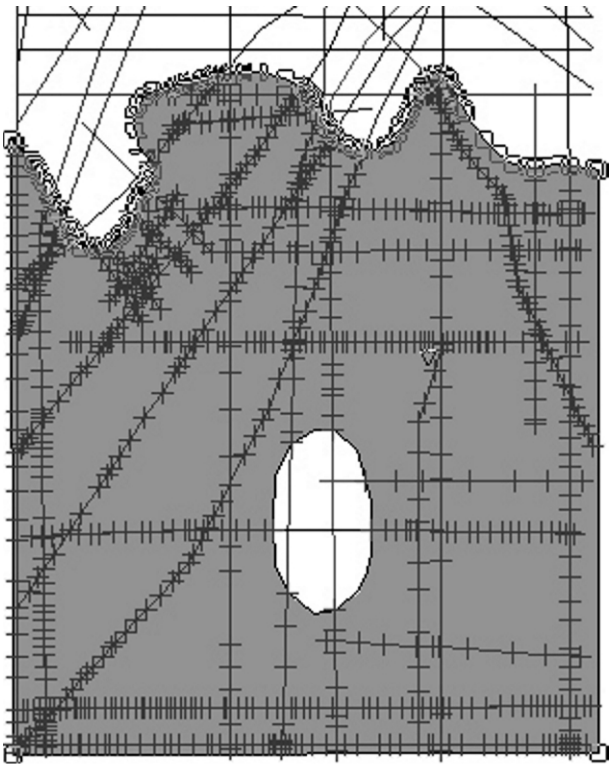

Figure 4: 2D view on cross section mesh and constructed envelope of a glacial outcropping and sub-cropping sand. Crosses on section outlines mark defined nodes of the respective unit in cross sections.

Once the cross-section net has been set up, the lateral distribution of outcrop and sub-crop units, the so-called envelopes, have to be defined (Fig. 4). After the distribution and base of each geological unit has been defined in the cross-sections and the unit envelopes, the 2D and 3D correlation lines are triangulated into unit distributions, giving the lateral extent and the depth of the base of each geological unit (Sobisch, 2000). Volume bodies of each geological unit are subsequently calculated by stacking the base of each unit to the base of the overlying unit, defining the thickness of each geological unit as well as the elevation of the upper surface. Volume body calculation commences with the youngest unit and moves downward, with the top of outcropping units defined by the DTM (Fig. 5). In addition, it is possible to visualise the model colour scheme to show variations in applied geological parameters, such as hydraulic conductivity or geotechnical values.

GSI3D based 3D structure models are distributed in the digital format of the subsurface viewer (Fig. 6). This operator-friendly software-tool allows users to visualise and analyse the subsurface-models without requiring any other GI-System or allied software products (Neber, 2006a). The subsurface viewer has functions to create digital thematic maps, contour lines and distribution plans of individual geological units, horizontal und vertical slices, estimates of the geological succession (synthetic drill-logs), perspective 3D visualisations, and stereo imaging of the 3D model.

Together with these features, the GSI3D methodology allows the user to incorporate all the available field data and experience into the resulting subsurface 3D model, explaining complex geological settings in a format easy for non-geologists to understand without further need for interpretation (Kessler et al. 2004b).

3. Applications

Geo-scientific data from previous investigations, especially borehole data, has mostly been stored in analogue formats, such as written reports, and in extensive archives. Although an increasing amount of surface geo-information is being stored and used in GI systems, geological maps, for example, are not always available in digital formats for further use in GI systems. Even more often, subsurface data is simply neglected. Although the primary costs for data collection are substantial, representing a high economical input, the vast amount of borehole data collected are often not used by decision-makers and other endusers. This is due to the heterogeneous distribution and description of the data; frequently it has to be re-interpreted by experts for each single purpose.

In many cases, drilling campaigns have been undertaken to collect 'new' field data in areas previously investigated, rather than concentrating on the interpretation of already existing information packages. In addition, to develop sustainable management strategies, decision making and planning requires a detailed, but nevertheless understandable view of complex subsurface conditions in order to evaluate required and suggested protection activities of the subsurface and planned modifications of the natural environment.

This can be done by setting up a digital data collection, comprising all the available data, and to provide this in a ready-to-use format that does not require further interpretation. Essentially this would be a dynamic 3D subsurface information system established within, for example, a city council.

Previously used by the mining and oil industries for reservoir modelling, digital 3D geological models are now being used more often for groundwater studies and for urban management. By implementing integrated investigation strategies and visualising the geological environment in 3D, the gathered and interpretation free data pool can be used to develop management strategies for a wide range of sustainable ground-related issues, such as:

- assessment of location, thickness and capacity of aquifers and aquitards,
- monitoring of water quality and all related environmental issues,
- protection of groundwater dependent eco-systems,

and in urban planning for:

- risk assessment of geogenic hazards,
- construction planning,

and during on-site investigations to develop:

- integrated investigation strategies of contaminated (mega-) sites.

In comparison to analogue storage methods, 3D subsurface information systems, based on homogeneous data sets, offer considerable advantages to decision making in visualising the subsurface.

GSI3D is also a powerful tool for visualising the geological setting of former high energy sedimentary environments, documented by rapidly changing facies and small-scale variations in lithology and stratigraphy, as well as manmade modifications of the environment (Price et al., 2004; Classon et al., 2005). The result of the 3D mapping is a dynamic 3D model which displays the geological setting in more detail than a 2D geological map.

3.1 Northern Germany

The first GSI3D based regional model was part of a research project, supervised by the service for water management, coast and environment protection of Lower Saxony (NLWKN), in co-operation with the University of Cologne (Department of Quaternary Geology), the cities of Emden and Norden and the Oldenburgisch-Ostfriesische Wasserverband (OOWV). The main focus of the initial research, which covered 1,200 km², was to establish a dynamic 3D model combining all the available geo-scientific data-, with a special emphasis on the 3D mapping of the main aquifers and their overlying geological units, as well as the distribution of the acquired data in a format compatible with the daily needs of the water agency. Following this initial project phase, the 3D model has been expanded in the past three years into a consistent and detailed 3D subsurface model, covering all the major catchment areas of the local water agencies over a 4,000 km² area.

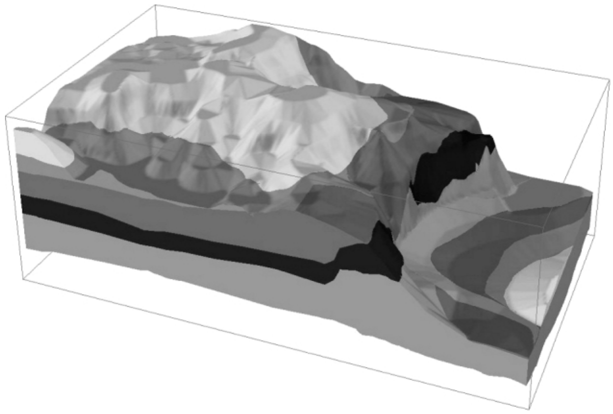

Figure 5: model of geological volume bodies. For legend see Fig. 2. Vertical exaggeration: 4x.

3.1.1 Geological Setting

The geological basement is mainly composed of mica-rich glauconitic fine sands with intercalated clay and silt lenses of Miocene to Pliocene age. This Neogene sequence is covered by Lower Pleistocene to Elsterian, sands, partly gravely, forming the main aquifer in the region (Fig. 7a, b). The top of the Elsterian sequence is composed of sub-glacial deposits of the Lauenburger clay facies, deposited in irregular erosional channels formed by melt water from the retreating ice-caps. The clays and silts of this facies form one of the main aquitards. Saalian deposits are represented by a glacial loam and associated covering sands; the former lies in discontinuous horizons which also act as aquitards. Eemian sediments are

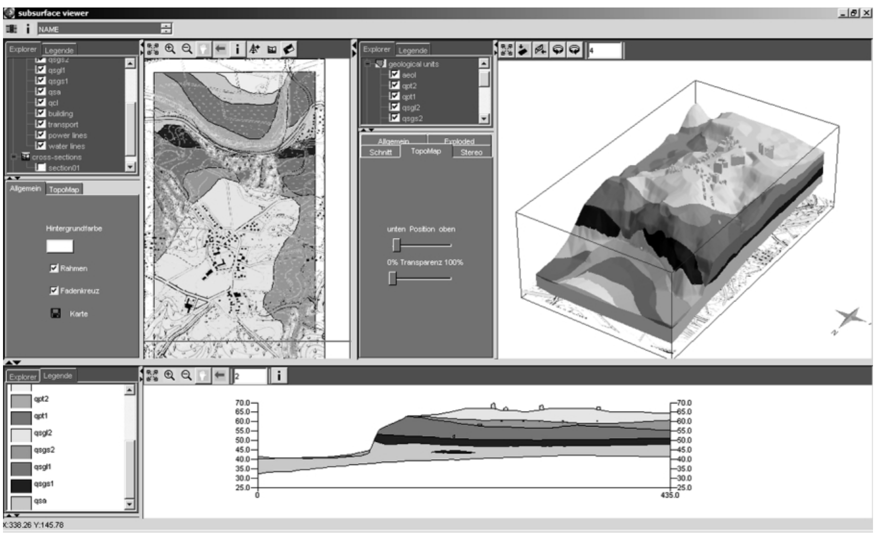

Figure 6: subsurface viewer, 2D map view (upper left), 3D model view (upper right), 2D cross-section view (bottom).

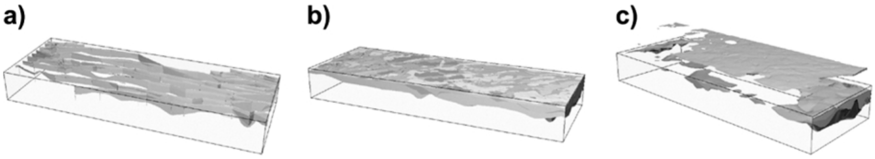

Figure 7: Litho-stratigraphic model, Northern Germany. a) Mesh of EW oriented cross sections. b) 3D model of geological volume bodies. c) Exploded view of main aquitards, note hydraulic windows in the upper left area. Vertical exaggeration: 15x.

restricted to sporadic clay to silt and peat lenses. The overlying Weichselian to Holocene deposits are generally fine sands, of either periglacial, fluviatile or aeolian origin, and peats.

The main focus of interest of the regional water agency was to assess the location, thickness and capacity of aquifers, especially the Pleistocene to Elsterian sands, and their natural protection by the overlying Lauenburger clay facies and Saalian loam horizons (Fig. 7c).

The geological 3D model compiled comprises up to 36 lithostratigraphic units and lenses, defined by processes of landscape evolution and deposition/erosion. Altogether, the total area has been mapped in 3D to a general depth of 200 m, documented by 14,000 drill logs and 1,500 geophysical measurements, together integrated into a net of 930 intersecting cross-sections.

3.1.2 Hydro-stratigraphy and customised outputs

Each geological unit or subunit in the model can be attributed with any given geo-scientific parameter. The main interest of the OOWV water agency, for example, is the distribution of the major lithological units, their hydraulic conductivities and the monitoring of ground water quality. For these applied tasks, complex and scientific explanations with an analysis of the subsurface in terms of stratigraphy are not needed. Instead, a relatively straightforward 3D models displaying the required data was presented (Neber, 2006a). For this, the scientific lithostratigraphic model has been visualised in an understandable, non-scientific language, referring only to clay and silt distribution, gravel horizons and sandy sediments, as well as the allocation of aquitards and aquifers in the region (Fig. 8). To evaluate the respective hydraulic conductivity values, a modified standard hydro-stratigraphic table (after Manhenke et al., 2001) wasused, providing standard conductivities for the major lithological units.

Using the subsurface viewer publication format, the OOWV can run independent queries and visualisations of the subsurface setting and to produce animated GIFs and video formats, for communication with administrative bodies whenever necessary; for example, during applications of water rights or disputes over concurrent usage, such as peat exploitation and groundwater protection. Unit distribution is also given in ASCII grids, defining the top and base, as well as the thickness, of each unit. These grids are subsequently integrated into the existing GIS infrastructure of the OOWV water agency for further use in surveys to define areas where groundwater dependent ecosystems are protected by underlying glacial loams (Petersen and Sütering, 2003), to characterise conceptual models for flow and transport path modelling, and the planning of drilling campaigns for further well galleries. The subsurface information provided also offers basic data for contamination accidents, giving possible transport paths for contaminants, allowing a more accurate and effective response to possible threats of the natural environment.

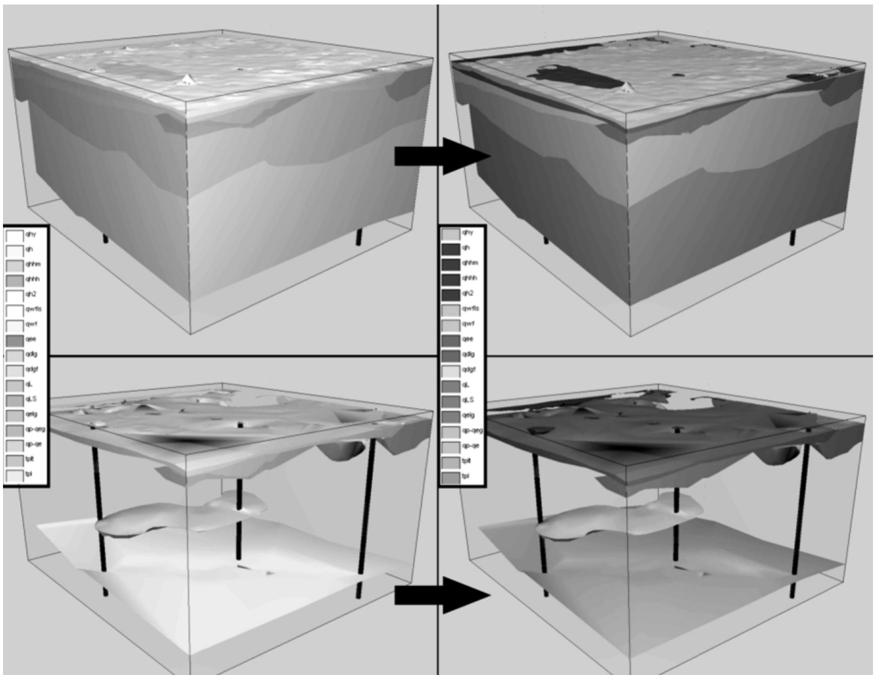

Figure 8: a) Lithostratigraphic 3D model of volume bodies. b) Reattributed Hydro-stratigraphic 3D model of volume bodies. c) 3D visualisation of present aquitard units, according to lithostratigraphy, and base of aquifer. d) 3D visualisation of present aquitard units, according to hydro-stratigraphic attributes (hydraulic conductivity), and base of aquifer. Hydro-stratigraphic classification after Manhenke et al. (2001).

3.2 Cologne

Initial 3D mapping projects in the eastern parts of Cologne focused on the landscape evolution and the geological and/or anthropogenic setting of four individual study areas, altogether covering 200 km². Each study concentrated on distinct aspects of the natural and/or man-made environment and established best practice guidelines for the specific 3D mapping procedures. The research was conducted by the Dept. of Quaternary Geology and the Institute of Applied Geomorphology (University of Cologne) in cooperation with the Office for Soil and Groundwater Protection (Cologne) and the local water agency, RheinEnergie AG. The Geological Survey of Northern Rhine Westphalia provided approx. 9,000 borehole logs for the study, the Roman German Museum of Cologne gave archaeological site descriptions from excavations, and 6,000 drill logs from the archives of the Office for Soil and Groundwater Protection were digitised and integrated into the 3D mapping.

By combining these data and other data such as engineering- and hydrogeological maps, the geological setting as well as the tectonic structures from the Lower Devonian up to the Holocene were reconstructed in detail. Man-made ground was mapped in 3D based on an improved classification system for anthropogenic features and sediments (c.f. Price et al., 2004). In this, man-made deposits are handled with a hierarchical, multi-level scheme, using subdivisions such as class, group, type and unit, each giving progressively more detail. The scheme not only takes the landform of man-made objects and/or deposits into account, but also its functional origin, to systematically address, quantifying and qualifying the anthropogenic influence on the environment.

Subsequent 3D mapping, initiated by the local water agency, focused on a 70 km² catchment area on the west hand side of the Rhine and the initial research areas have been integrated into a consistent and comprehensive 3D structural-model, completely covering the eastern parts of Cologne.

3.2.1 Geological and anthropogenic setting

Cologne is situated on the Cologne Block east of the margin to the Rhenish Massif, in the SE of the Lower Rhine Basin. This NW-SE orientated tectonic basin is divided by major faults parallel to the basin margins. Subsidence started in the Early Oligocene and resumed in the Pleistocene. The Lower and Middle Devonian basement of the Lower Rhine Basin is covered by Palaeogene and Neogene sediments, represented by marine sands and terrestrial clays with intercalated lignites. The overlying Quaternary sequence, predominately gravels, sands and clays, are of fluviatile origin, deposited by the Rhine-Maas river system.

Due to its long and intense settlement- and occupation-history, with prehistoric, classical, medieval and modern landscaping eras, the shallow subsurface of Cologne exhibits a complex and heterogeneous structure, with man-made deposits like waste, building rubble and war-wreckage. Artificial changes on the surface and subsurface configuration are recorded, for example, by deposits filling a trench which surrounded a former Roman fort (Fig. 9).

Detailed interdisciplinary 3D mapping of the natural strata and man-made ground units, as well as anthropogenic land forms, not only led to a better understanding of the complexity and heterogeneity of the shallow urban subsurface but also provided best-practice guidelines of both a conceptual and practical nature (Classon et al., 2005), such as:

- suggestions on how to systematically address artificial deposits, qualitative requirements for digital elevation data and artificial down hole data information,
- techniques for data-processing in the management of a large amount of drill-log data and analysis of digital terrain data,
- combining spatial subsurface data with surface data, deriving from time-lapse analysis, itself focusing on the 'excavation and aggregation history' of man-made ground (Fig. 10).

3.1.2 Management systems and customised outputs

The usage of multidisciplinary approaches in the 3D mapping of urban areas has shown that even diverse and heavily artificially covered, modified or reworked geological systems can be visualised in detail (Kessler et al., 2004a; Classon et al. 2005). The established 3D structure-models allow future engineering-, hydro- and environmental geology investigations to be planned in advance of field surveys. The geological/anthropogenic setting can be addressed directly from the previously established 3D model (Fig. 11). This allows focussed field surveys to be undertaken, reducing cost intensive field work to a minimum (Neber, 2006b). The optimised GSI3D workflow ensures that the project manager has the latest version of the 3D structure-model in the field, allowing a direct analysis of the geological/anthropogenic

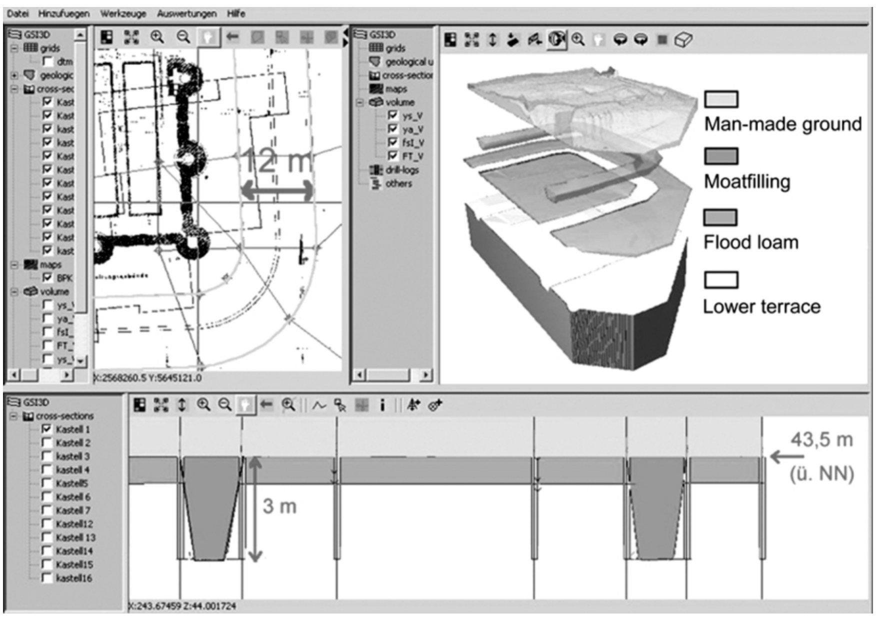

Figure 9: Structural-model of the surface and subsurface features in the area of a former Roman fort. The subsurface feature is covered by several dm to m of post-Roman man-made ground and was reconstructed by incorporating geological borehole data with data from archaeological excavations, giving the elevation, depth, size and wall angle of the trench.

setting, reducing office-work time.

4. Conclusions and outlook

A detailed geoscientific knowledge of the natural and man-made environment, especially in highly populated areas, is essential for a sustainable subsurface management and its strategic planning. In the past, individual surveys and drilling programmes led to the acquisition of an extensive data set on the subsurface. Unfortunately, this data is generally of a heterogeneous nature and stored in an analogue format. By applying the GSI3D methodology, these expensive collections can now be transformed into a homogeneous data set and used to establish a comprehensive 3D model of the subsurface. Customised outputs of 3D subsurface models guarantee a time and cost efficient saving in the planning of future investigations and help decision making and planning, by providing easy-to-use analytical functions to explore even complex geological settings.

The establishment of GSI3D based 3D information systems follows a straightforward methodological approach and workflow, allowing the geologist to map the natural environment by distinguishing lithostratigraphic characteristics for each geological or anthropogenic unit. Available bore logs and other geoscientific outcrop and subsurface information, can be used in the construction of the iterative set-up of a mesh of consistent and detailed cross-sections. This defines the lateral distribution and thickness of each unit present and also displays the genetic aspects of landscape evolution envisaged by the geologist (Kessler and Mathers, 2004).

In addition, it is possible to visualise the 3D model units according to distinct applied geological parameters, such as hydraulic conductivity or geotechnical values. This attributing process allows thematic maps on engineering conditions and mineral resources, to be produced, generating the basis for further geoenvironmental analysis, monitoring and forecasts.

In summary, the integrated approach and the usage of the GSI3D methodology and software-tool to visualise and map the geological and anthropological environments in 3D offers the following advantages:

- one software-tool for assessment, management and monitoring of the shallow and medium deep environment and its man-made modifications,
- cost reduced planning and investigation due to efficient usage of multidisciplinary archive material prior to and during field work,
- the ability to add to existing data bases in task orientated and optimised work flows,
- spatial information data management and export capabilities to existing IT-infrastructures and of thematic maps to GIS systems,
- distribution of digital 3D geological maps via the subsurface viewer with analytical functions for further processing,
- visualisation and analysis of the subsurface in order to deliver an easy to understand decision support system for policy and decision makers for a sustainable regional planning.

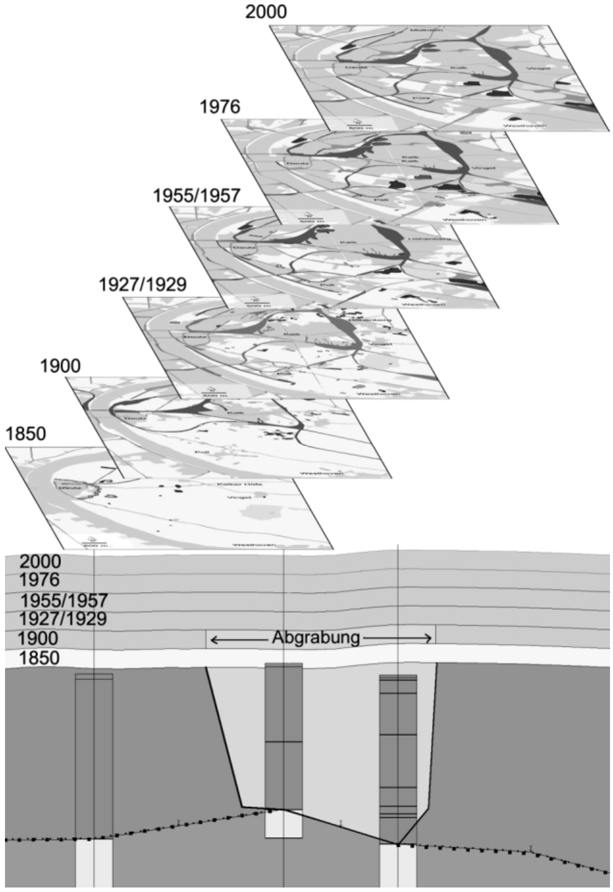

Figure 11: Technogenic land-use sequences from 1850 to present: Reconstructed from topographic maps. The structures and distribution of man-made ground deriving from the cartographical work provides potential boundaries and outcrops of artificial ground units. Multiple data sets, in combination with borehole information, are integrated into the structure-modelling process.

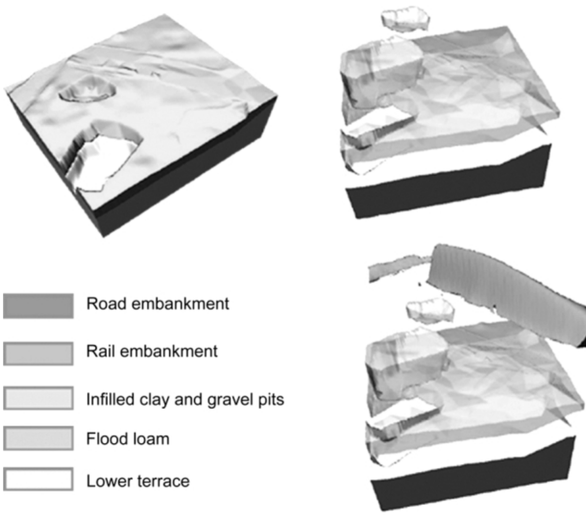

Figure 10: Structure-model of the surface and subsurface features in the area of a former mining area.

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