A Concept for 3D Geological and Urban Subsurface Modeling with a Unified Voxel Model Examined by a Case Study for the City Center of Stuttgart (Baden-Württemberg), Germany

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Keywords: Geological 3D modeling, Urban subsurface modeling, Voxels, CityGML, Case study Stuttgart.

Abstract

Geological data provide an essential source of information for space planning in the subsurface. Three-dimensional geological models make this information about the subsurface available for various users and use cases. There is a significant demand for subsurface information in city planning, including the modeling of buildings and infrastructures. This demand arises from the interaction between geological processes and the (potential) use of the underground. The paper introduces a concept of a voxel model that includes buildings, traffic infrastructure and the geological structure of the subsurface. The voxel modeling approach aims to provide a unified visualization of geological and urban modeling elements. Furthermore, an analysis of the interaction between buildings and their environment, characterized by geological properties, such as strength of the construction ground or hydraulic and heat conductivity should be feasible. Finally, this paper discusses the feasibility of the concept, based on a case study for the city center of Stuttgart, Germany.

1. Introduction

Geological structures can extend across areas with a size of several thousand square kilometers and depths ranging from hundreds to thousands of meters. Geological Surveys create geological 3D models with the purpose of modeling these large-scale structures for regional, statewide or national territories. Berg et al. (2009 and 2011) and MacCormack et al. (2019) summarize the most important 3D modeling activities of the Geological Surveys worldwide in recent years.

In Baden-Württemberg, a German state located at the southwestern border with France and Switzerland and covering an area of 35.750 km², the responsible Geological State Survey is the State Authority for Geology, Mineral Resources and Mining – Dept. 9 in the Regierungspräsidium Freiburg (LGRB). The LGRB provides a statewide geological 3D model of the lithostratigraphic classification of the subsurface in Baden-Württemberg (Geologisches Landesmodell) at a target scale of 1:500.000, including geological features such as large scale tectonic elements, Cenozoic volcanic structures and impact craters (Rupf and Nitsch, 2008). Moreover, the LGRB supply a site assessment tool for the planning of shallow geothermal probes in Baden-Württemberg (ISONG). ISONG evaluates the subsurface regarding its suitability for energy production with shallow geothermal energy based on a geological 3D model at the target scale of 1:50.000. The ISONG model comprises 24 lithostratigraphic units with similar geothermal and geotechnical properties occurring in the subsurface up to a depth of 400 m (Rupf and Armbruster, 2008).

Geological 3D models on a district or city scale are typically smaller in dimensions compared to 3D models of geological structures. Most urban subsurface models encompass unconsolidated rocks up to a depth of several hundred meters (Albarrán-Ordás and Zosseder, 2022; Lehné et al., 2018; Mielby and Sandersen, 2017) and are primarily based on geoscientific investigations of anthropogenic subsurface layers, such as building ground investigations, construction tests of underground infrastructure, or the monitoring of groundwater systems. Rogowski (2017) describes the building ground of Stuttgart with a digital map, which serves as fundamental database for the concept presented in this paper.

City models can encompass individual buildings, urban districts or entire cities. Over the last few decades, Building Information Modeling (BIM) has become an essential methodology for the interdisciplinary information management of all processes related to a building. BIM can be used throughout the entire lifespan of a building—from its planning, through the design and construction phases, operation and maintenance, to eventual demolition (Chapman et al., 2020). Moreover, BIM, based on an object-oriented modeling approach, which can be applied for the entire building down to the smallest elements, such as doors, windows, or wires (Sacks et al., 2018).

Urban planning applications make use of 3D city models at a district or city scale. Bao et al. (2021) and Santhanavanich et al. (2020) describe some of these applications with the purpose of planning the heating demand and a safe traffic routing in a city district. The OGC standard data model CityGML is often used to store and manage such 3D city models.

This study introduces a concept of a voxel model that merges information from various types of 3D geological models and urban underground models. The concept aims to describe a voxelization pattern for the unified visualization of large- and small-scale model elements. Furthermore, the conceptualized voxel model should empower users to analyze the interaction between buildings and their environment, considering several geoscientific subsurface properties, and visualize this information for participants in city planning without geological expertise. Based on the state of the art in research on common city planning with urban and geoscientific datasets this paper introduces a concept for 3D geological and urban subsurface modeling with a unified voxel model. In the case study for Stuttgart, data regarding geological features, buildings and traffic infrastructures in the underground of Stuttgart are gathered, and prepared for initial superficial analysis, validating the concept. The paper concludes with further insights into the planned future work.

2. State of the Art

2.1 Geological Modeling

A stepwise construction of 3D geological models starts with the acquisition and preparation of various datasets like well log data, geoscientific maps, geological cross sections and previous 3D models. Following the best practice a review and standardization of this datasets based on the correlation to lithostratigraphic horizons.

A visualization of the sequence of geological strata can be achieved by constructing the borders between its layers. For modeling of lithostratigraphic horizons, results from drillings, geological mapping and other geoscientific investigations, such as geophysical and geotechnical measurements, are commonly used. The LGRB utilize well log data, thickness distribution maps of the lithostratigraphic horizons and structural geological maps for the development of the statewide geological 3D-model and ISONG (Rupf and Nitsch, 2008; Schmidt, 2015).

For volumetric visualization, it is necessary to construct volume elements such as grid cells or voxels. Lehné et al. (2021) and Panteleit et al. (2013) describe 3D modeling workflows based on this approach for the cities of Darmstadt and Bremen, specifically tailored to address hydrogeological issues in these urban areas.

2.2 City Modeling

Several European and German cities aim for a standardized use of BIM in all construction projects. The State Capital of Stuttgart (2023) plans to implement BIM in all construction projects until 2030. The underground car park 'Villa Berg' serves as a pilot project for the use of BIM in underground infrastructure projects. The primary objectives for employing BIM in municipal construction projects encompass achieving climate neutrality, enhancing profitability, and advancing project digitization.

Modern 3D city models utilize data models to manage information about geometries, topologies, and semantics of objects in the city, such as buildings, vegetation, or water bodies (Kolbe, 2009). CityGML is a widely used open data model based on the Extensible Markup Language (XML), capable of describing model elements in five Levels of Detail (LoD) (Padsala, 2021a; Padsala, 2021b). Various municipal surveyor's offices, including the City Office of Surveying Stuttgart, provide 3D models, which can be applied for various city planning applications as mentioned in the introduction. A web-based 3D visualization of city models in a specific tile formats can enable hierarchical representations of model elements depending on the scaling of the model view in the web browser (Cozzi, 2015). Figure 1 illustrates an example of an aboveground 3D city model with building geometries for the City of Stuttgart.

Moreover, city planners can enhance their city models with Application Domain Extensions (ADE`s). An ADE is a built-in mechanism of CityGML, which extends the existing data model for specific use cases and applications (Biljecki et al., 2018). Betz and Coors (2021) and Padsala et al. (2021a) have developed ADEs for storing validation results of CityGML structures and for the management of food, water, and energy resources in a city.

Figure 1. Excerpt from the 3D city model of Stuttgart for the main square "Schlossplatz". (© Stadtmessungsamt Stuttgart, 2024)

The development of voxel-based 3D city and infrastructure models is implementable too. Gorte (2023) has highlighted the advantages of voxel modeling. Persistent features in urban spaces, including the underground, buildings, and spaces filled with water and air, can be investigated and visualized. A large amount of laser scanning and other sensor data is necessary for generating voxel datasets. An issue in 3D city modeling on a district or city scale is the management of this database. Dado et al. (2016), Gorte (2023), and van Oosterom et al. (2015) use octree-based data structures to reduce the storage requirements of a voxel model. In an octree-based data structure, it isn't necessary to save all data values at every hierarchical tier of a database. Homogeneous values can be removed, following the principle illustrated in Figure 2.

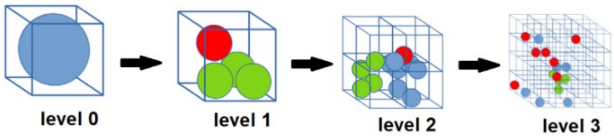

Figure 2. Schematic illustration of an octree data structure for storing voxel models. From a geometric perspective, an octree represents the subdivision of a cubic volume into eight subsets. Subsets with the same value at higher levels (illustrated here with the same colour) can be removed at those higher levels (based on Gorte (2023)).

2.3 Use Cases in Urban Geology

An analysis of the interaction between buildings and their environment, characterized by geological properties, is possible through the combination of geological models and urban underground 3D models in a unified voxel model. Moreover, in 3D models addressing questions related to urban geology, the voxel-based modeling approach is often chosen to join the fundamentally different model types used in geological and urban 3D modeling. Geological 3D models consist of interpolated surface and volume elements that depict geological features at too large scale and with too low resolution to be used in urban geology models without adjusting the scaling. Drilling data and results from geological mappings and investigations are usually available in large quantities only for the unconsolidated rock layers of the shallow subsurface. Depending on the data foundation, it must be assessed to what extent geological model elements can be reliably modelled at a high resolution. Building models are created based on detailed plans, which can be represented in extensive object-oriented models. For city planning models, buildings are simplified to basic geometries, representing, for example, building volumes, foundations or roofs.

Both geological and urban subsurface models consist of model elements of various geometric types (points, curves, surfaces, solids). As some use cases demonstrate, the conversion of these geometries into a voxel model and the parameterization of individual voxels are common modeling approaches. The conversion of semantic-rich CityGML and IFC datasets can only be achieved through time-consuming and computationally intensive workflows (Heeramaglore and Kolbe, 2022).

In a voxel model, the scaled geological and urban model elements can be constructed as well-matched voxel geometries. Issues that still need clarification include the conversion of CityGML datasets into voxels datasets as well as their visualization and their analysis, especially for large datasets.

Mielby and Sandersen (2017) have developed a workflow for merging a hydrostratigraphical model with an anthropogenic model in a unified voxel model. Both models are created at predefined scales and extents. The anthropogenic model is constructed in higher level of detail with the purpose of modeling the anthropogenic ground fill layers in interaction with subsurface infrastructure. The hydrostratigraphical model serves as a geological background model, contributing information about the classification of the bedrock into established hydrogeological units. Lehné et al. (2021) provide a hydrogeological 3D model with integrated geometries of underground infrastructures and foundations for urban planning applications. This case study focuses on the interaction between subterranean sewage systems, building foundations and groundwater. Soriano-Cuesta et al. (2024) created a 3D model of the geotechnical underground layers in the urban area of Seville, including their variations in essential mechanical resistance properties. Furthermore, a methodology was developed to process extensive geotechnical data for urban environments.

3. Concept

This study aims to delineate the concept, illustrated in Figure 3, for a unified voxel model, incorporating geological and urban data. The model serves as a basis for the visualization and analysis of various artificial and geological structures beneath the surface, along with their pertinent properties. The model is composed of three parts:

1. Buildings and infrastructures (above- and underground)
2. Anthropogenic and unconsolidated rock layers
3. 3D model of geological bedrock horizons

The development of a standalone model for anthropogenic and unconsolidated rock layers of the topset beds, as well as for buildings and infrastructure, can be realized at a higher level of detail than a voxel model for the bedrock, thanks to a more comprehensive database for the topset beds. A well-matched voxel size for topset beds and above- and underground buildings is necessary for the integrated modeling of building and geological data. Modeling processes should be based on parameters derived from building data and geological features with the purpose of assessing the impact of buildings and infrastructure on the underground.

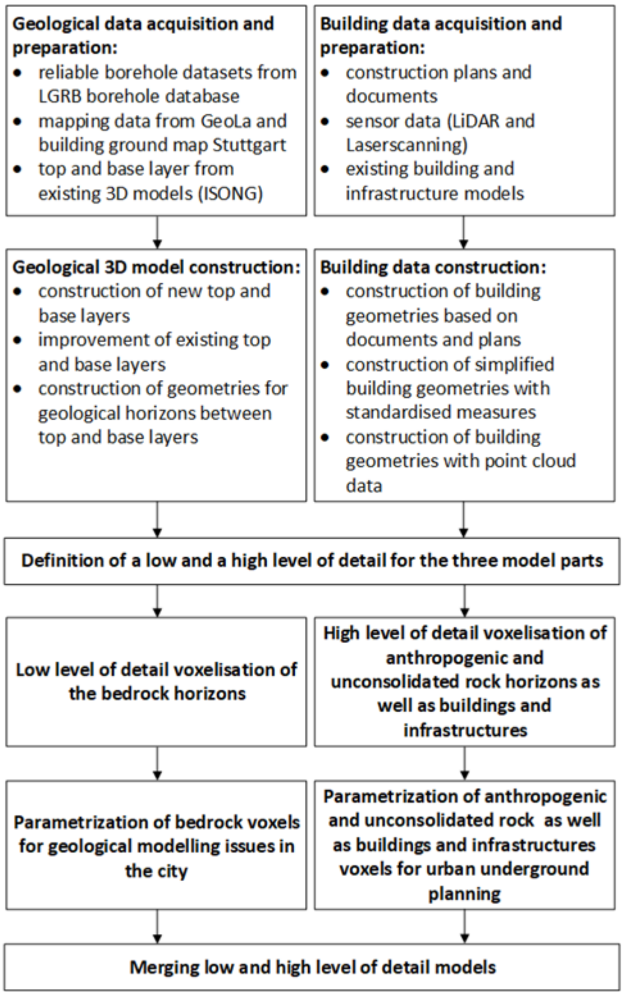

Figure 3. Diagram of the model workflow based on input data described in Section 5.

A geological horizon model of the bedrock is intended to be constructed following the stepwise geological modeling workflow described in Section 2.1. A voxel model with a lower level of detail, resulting from a larger voxel size, is deemed sufficient due to a limited database. For visualization purposes, the uppermost horizon should be replaceable by a unconsolidated rock model.

The research focus of the work is intended to be a comprehensive integration of subsurface infrastructure into geological 3D modeling for application in urban planning issues. Extending the approach of Lehné et al. (2021), Mielby et al. (2017) and Soriano-Cuesta et al. (2024) the modeling concept for the case study in Stuttgart utilize comprehensive building data from several city planning authorities of Stuttgart in order to generate a detailed voxel model for buildings and infrastructures in the city center. Based on the state of the art, urban data for subsurface modeling can be incorporated more extensively. Non-existent 3D data, such as building data or of the subway tunnels can be generated in a simplified manner with standardized geometries. Available comprehensive base data, such as laser scanning data for street tunnels, should be evaluated for the construction of building and infrastructure geometries. The large amount of data should be efficiently organized in a octree-based data model. The model datasets are intended to be converted into the 3D Tile format for a web-based visualization. Through the tiling pattern, it will be determined when the unconsolidated rock model as well as buildings and infrastructures should appear in the model view.

The voxel modeling approach was chosen for the study because voxel data structures significantly facilitate common 3D spatial analyses of different data types. Furthermore, the standard workflow for voxelization is to be extended to allow the transfer of different data types into a voxel model without loss of relevant semantic information. The accuracy of modeling results can be validated based on the LGRB models and the building ground map. The performance of visualization can be compared with the visualization of the aboveground city model for the city of Stuttgart.

4. Case Study Stuttgart

The city of Stuttgart, situated in a basin in the southwest of Germany, is the capital of the state of Baden-Württemberg. Figure 4 depicts the study area, which is intended to be 700 meters long in the north-south direction and 900 meters long in the east-west direction. Accordingly, the study is intended to be conducted for an area covering 630.000 m². The 3D model is planned to extend to a depth of 100 meters.

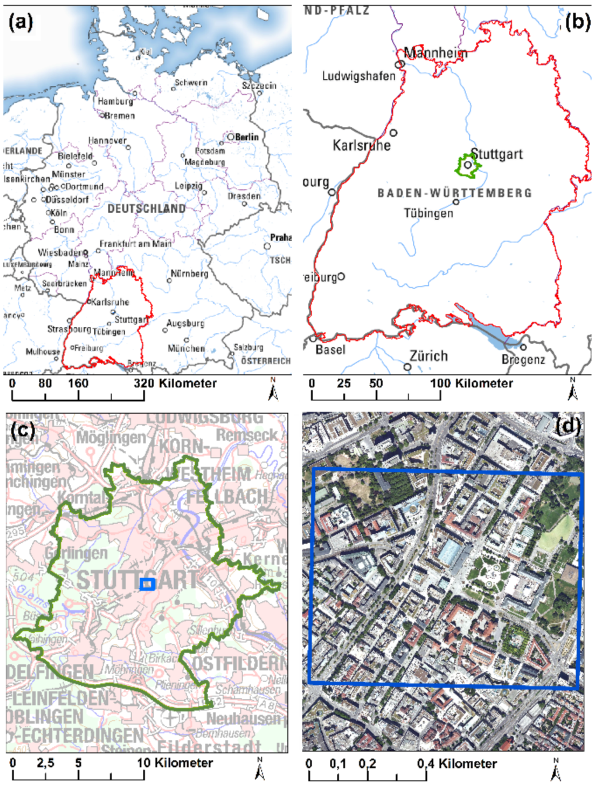

Figure 4. The study area is situated in Germany (a), within the red outlined region of Baden-Württemberg (b), specifically in the green marked city area of Stuttgart (c). The aerial photograph of the study area (d) depicts the significant diversity of urban infrastructure in the study area (see blue rectangle). (Spatial base data: © Landesamt für Geologie Rohstoffe und Bergbau (top left and right) , © GeoBasis-DE / BKG 2015 (bottom left), © Landesamt für Geoinformation und Landentwicklung Baden-Württemberg, www.lgl-bw.de, Az.: 2851.9- 1/19 (bottom right))

4.1 Geology of Stuttgart

Most wells and geotechnical investigations describe two bedrock horizons. The bedrock horizons are composed of Triassic sedimentary and carbonate rocks. As illustrated in Figure 5, quaternary topset beds cover the bedrock over a large area with varying thickness. Additionally, a complex structure of anthropogenic deposits and buildings shapes the unconsolidated rock layers.

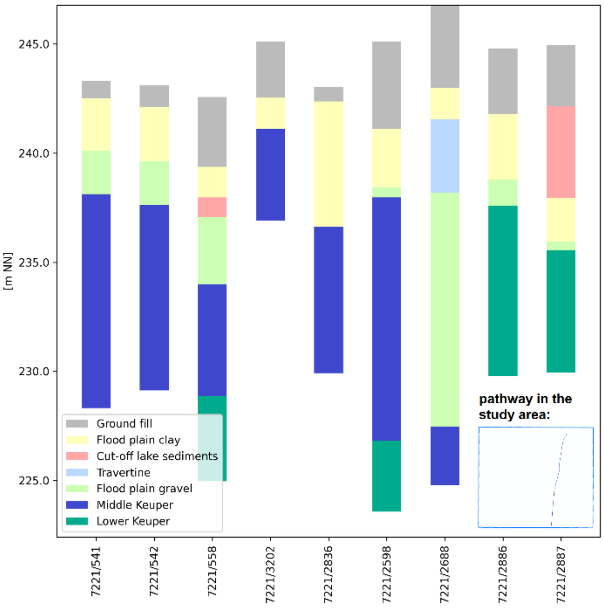

Figure 5. Stratigraphic logs of the unconsolidated rocks and bedrock horizons along a north-south profil in the study area (see blue rectangle). The stratigraphic logs are arranged on the Y-axis according to the elevation above sea level. A identification number (X-axis) of the stratigraphic logs is derived from the map sheet and archive number.

The Middle Keuper and Lower Keuper are intended to be incorporated into the 3D model as geological bedrock horizons. Below the Quaternary topset beds, a gypsum- and anhydrite-bearing Middle Keuper horizon is usually present. The Middle Keuper horizon can reach a thickness of up to 100 meters in the Stuttgart urban area. In the study area, the upper part of the Middle Keuper was eroded. Bedrocks from the Lower Middle Keuper, such as the Grundgipsschichten, are still commonly present in the study area. The reduced thickness of the Middle Keuper horizon in the study area is approximately up to 20 meters. Below the Middle Keuper horizon are the bedrocks of the Lower Keuper. The Lower Keuper horizon is variable, consisting of clay, sand, and dolomite rocks, and reaches a thickness of up to approximately 20 meters. In the southern study area, the Lower Keuper is directly beneath the Quaternary topset beds.

The Middle Keuper horizon is important for mineral spring water protection, as it separates the Quaternary aquifers from the mineral water-bearing aquifers. In areas without a Middle Keuper horizon with sufficient protective function, protective measures are necessary to avoid endangering the quality of mineral waters. A 3D model of Lower and Middle Keuper horizons aims to support the verification of mineral water protection zones.

The 3D model of the unconsolidated rock layer in Stuttgart aims to represent a typical floodplain sequence for Quaternary topset beds in the city center, encompassing anthropogenic features such as construction or disposal sites covering the naturally deposited sediments. Refilled sinkholes are intended to be part of the unconsolidated rock model.

The engineering use of the building ground of the City of Stuttgart is associated with some geotechnical challenges. Swelling processes caused by gypsum formation lead to uplift in the subsurface, which can damage buildings and infrastructure. Later, the dissolution of gypsum-bearing horizon induce subrosion processes. A well-known geological hazard in Stuttgart is the formation of sinkholes and caverns as a consequence of the subrosion of carbonate Middle Keuper rocks. In the valley of the Stuttgart city center area, the gypsum- and anhydrite-bearing layers have been almost completely dissolved, but six sinkholes in the study area indicate the locations of collapse events (Rogowski, 2017). Another challenge is the prevention of landslides, which can particularly occur situated on slopes in Stuttgart basin.

A geological and urban 3D model can be of great benefit for the study area. The subsurface affected by subrosion processes can be assessed in a more detailed and efficient manner for construction projects. Additionally, competition for underground use, such as transportation infrastructure, urban and private buildings, or geothermal utilization, can be assessed and taken into account. The compliance with protection regulations, such as the existing mineral spring protection in the study area, can also be coordinated in such a 3D model.

4.2 Underground Traffic Infrastructure in the City Center of Stuttgart

A diverse underground traffic infrastructure is planned to be part of the building and infrastructure model. This includes subway tunnels and stations, a road tunnel, and a pedestrian subway located in the study area, as illustrated in Figure 6.

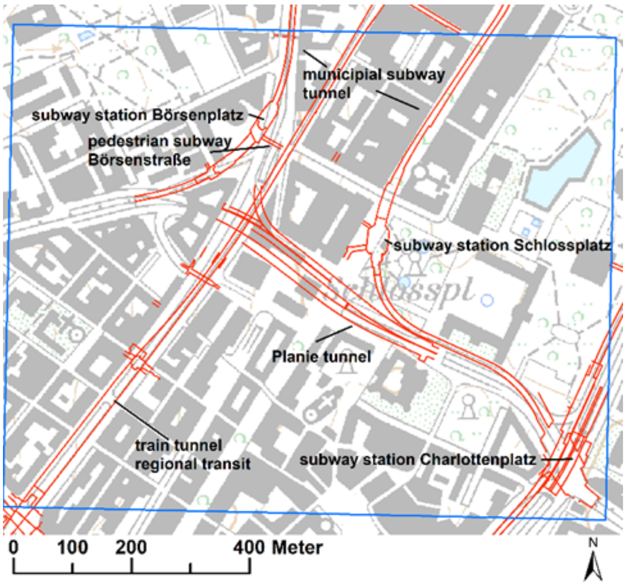

Figure 6. Urban map of the study area, showcasing underground traffic infrastructure proceeding through the city center of Stuttgart. The study area is marked by the blue rectangle. (Spatial base data: © Landesamt für Geoinformation und Landentwicklung Baden-Württemberg, www.lgl-bw.de, Az.: 2851.9- 1/19)

There are two municipial subway tunnels and a underground train tunnel of the regional transit in the study area. Beside the tunnels, three underground train stations are located beneath Schlossplatz. Börsenplatz and Charlottenplatz. The street tunnel, called Planie Tunnel, passes beneath Schlossplatz A pedestrian subway at Börsenplatz leads to the nearby subway station and passes beneath Friedrichstraße. In addition to the primarily considered traffic infrastructure, it will also be tested to integrate other subsurface objects such as the sewer system and building foundations or basements.

5. First Results

5.1 Assessment of Geological Data

An analysis of the database for the working area in Stuttgart allows a first estimation of the feasibility of the concept. The borehole database (ADB), statewide geoscientific mapping data (Geologische Landesaufnahme, GeoLa) and the digital building ground map Stuttgart from the Geological State Survey of Baden-Württemberg are a fundamental database for modeling the unconsolidated rock and bedrock layers for the study area. An ADB dataset based on 24269 stratigraphic log data could be assembled for the urban area of Stuttgart. Table 1 underlines that a considerable number of well log datasets with depth information are located in the study area. Well informations about sinkholes are available for every sinkhole in the study area.

Sediments	**Number of well log datasets**	**Distribution of well log datasets**
Ground fill (qhy)	501	local
Flood plain clay (qhta)	228	local
Travertine (qsk)	73	local
Cut-off lake sediments (qha)	130	local
Flood plain gravel (qu)	199	entire study area
Middle Keuper (km)	207	local
Lower Keuper (ku)	216	entire study area

Table 1. Overview of number of well log datasets for topset beds and bedrock horizons in the study area.

GeoLa provides interdisciplinary geological data in the scale of 1:50.000 harmonized for the state of Baden-Württemberg. The GeoLa datasets are a comprehensive collection of mapping results from the LGRB in the fields of geology, hydrogeology, engineering geology, economic geology, and soil science. The results of the state mapping are provided in form of statewide mapping units for Baden-Württemberg and regularly updated based on latest constructed datasets. The data from mentioned fields of geology are well-matched and can be used together for analysis in GIS systems or geological modeling programs. For city- and district-wide projects, more detailed datasets in higher resolution are required.

The building ground map of the city of Stuttgart provides data on a regional lithostratigraphical classification of the Quaternary topset beds as well as the Jurassic and Triassic bedrocks including information about hydrogeological conditions in the subsurface in a scale of 1:5000 for the map sheets of Stuttgart. This classical geological survey data are provided in combination with geoscientific investigation data about the building ground and underground infrastructure.

Rogowski (2017) adjusted the resolution of the model data for urban planning and urban geology issues such as building ground investigations in slope and plateau areas or in groundwater protection zones.

The building ground map is the most detailed mapping dataset available for the construction of the 3D underground model. However, due to the different subdivision of mapping units for state- and city-wide maps, there are discrepancies in the geological description of the subsurface that need to be verified. The GeoLa dataset for the study area, through its statewide harmonization, enables a better comparability with mapping data from other cities and regions in Baden-Württemberg. Furthermore, the direct comparison of GeoLa data with the building ground map of Stuttgart illustrates the effects of reduced resolution of the model data on the modeling results.

Figure 7 shows the distribution of wells in the study area. Moreover, the location of unconsolidated rock layers based on ADB stratigraphic log data coincides with the areal extent of the interpolated surfaces from Rogowski (2017). The ADB borehole information about the location of ground fill horizons differs significantly from the interpolated areal extent by Rogowski (2017). These differences between the regularly updated stratigraphic log dataset and the interpolated surface from 2017 were expected, as the shallow subsurface of a city undergoes constant changes. Such changes are intended to be gathered, visualized, and made usable for urban modeling.

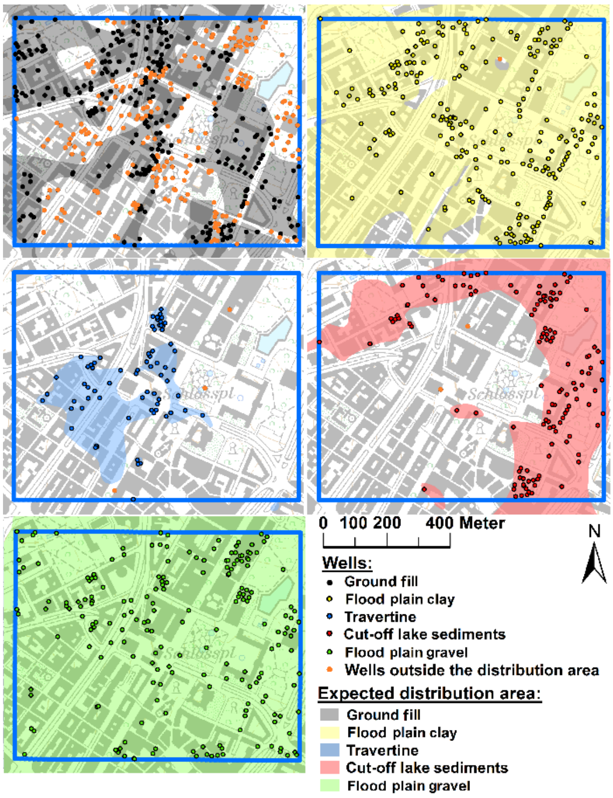

Figure 7. Comparative evaluation of the location of wells and the interpolated areal extent of anthropogenic and unconsolidated rock layers. The study area is marked by the blue rectangle. (Spatial base data: © Landesamt für Geoinformation und Landentwicklung Baden-Württemberg, www.lgl-bw.de, Az.: 2851.9- 1/19)

Several geological information crucial for urban planning could not be derived from the low-resolution GeoLa data. Quaternary topset beds consists only of widespread flood plain sediments in the GeoLa data for the working area. Locally occurring sediments such as Stuttgart travertine or cut-off lake sediments are only modeled in the building ground map. Based on the stratigraphic log datasets and geological maps constructed by Rogowski (2017), an area without a Middle Keuper horizon is expected in the working area. In contrast to this, a missing part of the Middle Keuper horizon has not been identified in GeoLa for the study area.

5.2 Assessment of Urban Modeling Data

An aboveground city model is available in CityGML for the City of Stuttgart. For initial modeling, a simplified city model with Level of Detail 2 (LoD-2), including a terrain model, will be provided. LoD-2 describes all buildings with standardized roof forms, aligned according to the actual ridge line. The building footprints are taken from the official cadastral map. Based on street LiDAR measurements geometrical objects can be generated and provided for the Planie tunnel. The LiDAR dataset is a point-cloud representation of the inner building surface of the tunnel in LAS format. Figure 8 illustrates the 3D geometry models for the subway station “Schlossplatz” and the pedestrian subway “Börsenplatz”, which are available in CAD file formats. Subway tunnels must be constructed directly as 3D objects. However, detailed 3D modeling of the tunnel system based on construction documents and plans is very time- and labour-intensive. Therefore, it was decided to represent most tunnel elements as cylinders with standardized dimensions. This described data is provided by the city of Stuttgart and made available by the Civil Engineering Department of Stuttgart.

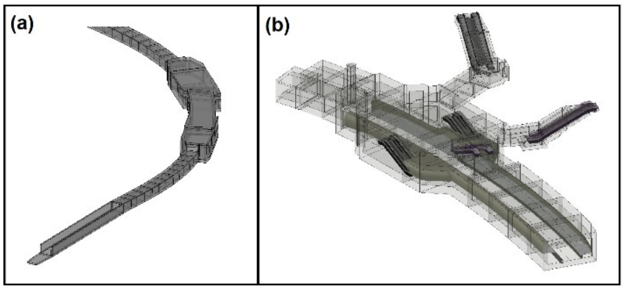

Figure 8. Examples of geometry models of the civil engineering department of Stuttgart for the subway station Börsenplatz with adjacent subway tunnels (a) and for the subway station Schlossplatz (b) (© Tiefbauamt Stuttgart, 2024).

Further underground building elements for a city model have to be generated from construction documents and plans. 3D objects of the sewer system in 3D-DXF format are originated from the association for sewage treatment Stuttgart. A detailed modeling of all known building elements is to be omitted at the beginning of the project. For example, only the data of the main sewer channels should be provided, as all other pipeline data would be require a building model in a much higher level of detail compared with described building data.

5.3 Estimation of Model Size

Based on the definition of different voxel sizes and arrangements, the number of required voxels for a model with the extent described in Section 4 was estimated. Here, it is assumed that the complete subsurface model space (730 m x 915 m x 100 m) is represented by voxels. The 3D model is divided for the depth range up to 30 m in the topset bed section and for the depth range from 30 m to 100 m in the bedrock section.

The depth of the topset beds was determined based on the well log informations about Quaternary sediments obtained from wells, which are located in the study area. If Quaternary sediments in sinkholes are excluded for defining the model dimensions, then the base of the topset beds is 20 m below the Earth's surface. Gorte (2023) use in his study on large voxel models cubic voxels with a edge lengths ranging from 20 cm to 120 cm for subsurface models. With this assumed voxel size, a total of 7.73 million to 2.50 billion voxels is required for the topset bed section in the study area. Mielby and Sandersen (2017) describe cuboid voxels with an edge length of a few meters for construction side models. An voxel model of the topset bed consisting of voxels of an area from 2 m to 5 m edge length and a depth of 0,5 m size would comprise 1.07 to 10.02 million voxels. For citywide modeling, Mielby and Sandersen (2017) use larger voxels with an area of 25 m to 50 m and a depth of 2.5 m to 5 m. In this study, voxels with this described edge length are intended to be used to model the bedrock section. Consequently, an expected number of voxels is between 935 and 34199.

When selecting the voxel size, it is important to consider that model elements can be represented by voxels in the required level of detail for planned modeling and visualization. Extensive datasets of buildings and unconsolidated rock horizons are intended to be represented by a large number of voxel elements in a small space in order to depict the data in a high level of detail in the model space without oversimplification or distortion. The datasets for the bedrock horizons are less detailed and homogeneous for larger parts of the model space. A smaller number of voxels is sufficient for 3D modeling of these datasets. The avoidance of a voxel model with unnecessarily high level of detail is of great importance in order to achieve low storage requirements and fast performance of modeling processes.

6. Conclusion and Outlook

This paper introduced a concept of a unified 3D voxel model for geological and urban underground modeling in the city center of Stuttgart. A description of acquired dataset highlights potential uses and interactions between available datasets. A unconsolidated rock model, a bedrock model until 100 m depth and a building and traffic infrastructure model serves as basis for constructing a three-part voxel model. Well-known urban issues like the determination of mineral water protection zones can be reconstructed through a unified modeling approach.

After acquiring the database and conducting an initial review, the construction of the voxel model can commence for the working area in the city center of Stuttgart. The stepwise model construction will proceed as outlined below:

1. Development of lithostratigraphic horizon models for the unconsolidated rock and bedrock layers
2. Generation of geometries for the subsurface and bedrock horizons
3. Assembling of geometries for above- and underground buildings and infrastructures in a unified 3D model based on CityGML
4. Construction of a high level of detail voxel model, respectively, based on the geometries for the unconsolidated rocks as well as for buildings and infrastructures.
5. Construction of a low level of detail voxel model based on the geometries for the bedrock horizons.
6. Parametrization of voxel with relevant properties for urban underground planning.

During the development of the voxel models, particular attention should be paid to the estimation of an appropriate voxel size for each part of the model. It is also necessary to plan for the efficient generation and management of large-scale voxel datasets with an appropriate data structure (e.g. octree-based).

Acknowledgement

We extend our sincere gratitude to the Civil Engineering Department of Stuttgart (Tiefbauamt Stuttgart), the association for sewage treatment Stuttgart (Eigenbetrieb Stadtentwässerung Stuttgart (SES)) and the City Office of Surveying Stuttgart (Stadtmessungsamt Stuttgart) for their invaluable contribution to this research. We would like to express our personal thanks to Mr. Claus-Dieter Hauck and Mrs. Silvia Deist, who organize the central provision of data by the Civil Engineering Department of Stuttgart. By providing building and infrastructure data for the underground of the city center of Stuttgart, they have significantly support the development of this concept.

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