INCREASING SIGNIFICANCE OF 3D TOPOLOGY FOR MODELLING OF URBAN STRUCTURES

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ABSTRACT:

Demand driven growth of construction activities in the rapidly expanding urban areas has become a global phenomenon. With the advancement of technologies, expectations are increased where valid 3D volumes can be calculated with least errors. Can 3D topology and topological data structures help in achieving better accuracy and facilitate the maintenance of 3D models?

Complex constructions get immense support if the data structures are 3D compatible and thus can be visualized in a 3D environment. It is important to have accurate alignments of the adjoining objects in 3 dimensions since errors will not only affect the horizontally adjacent objects but also the objects on the surface below or above it.

The paper aims to highlight the significance of 3D topology for the applications where we need to work with spatial datasets of above and under surface. We illustrate with a small example that current practice of creating 3D models is insufficient to validate their objects consistency.

1. INTRODUCTION

Demand driven growth of construction activities in the rapidly expanding urban areas has become a global phenomenon (Urbanization and Global Change, 2006; Lu et al, 2007). The fact is we are doing construction activities at an unprecedented rate in all spatial dimensions which can be below, on and above surface. With high technology involved, humans are successful in constructions of complex nature on a large scale. Our city space is shrinking not only in horizontal terms but also vertical extents (Godard, 2004). The competing demands for the vertical and horizontal space by different types of objects is throwing new challenges to the professionals involved in such activities (Pearlman et al, 2004). Expectations have increased where valid 3D volumes can be calculated with least errors.

To achieve this goal, it is important to understand the elements involved in such types of processes and their interaction in the limited space available. Indeed the subsurface information should be matched with what is on the surface. So these surfaces representing underground objects cannot intersect with the terrain or with the 3D Buildings on the terrain. All these issues can be regarded as topological inconsistency. Therefore it is important to understand the necessity of 3D topologically correct models for all the objects above, on and below the surface. Currently, the research on 3D topology is disperse and domain-oriented. Therefore, often 3D topologically correct data created for different domains appear to be inconsistent when integrated in one environment.

The paper aims to highlight the significance of 3D topology for all objects above and below the ground. The applications where we need to work with spatially valid datasets are increasing and 2D topology or even domain 3D topology is insufficient to validate their objects consistency. The paper is organised as follows. The next section (Section 2) elaborates on the complexity of construction works in large projects and motivates the need for topologically valid 3D data. Section 3 provides an overview on 3D topological data structures developed for above and below surface objects. Section 4 highlights the common characteristics of the models in order to allow match between subsurface and surface models. Section 5 introduces a case study of a large civil engineering project to illustrate the problems of data integration and discusses possible solutions. Section 6 concludes with recommendations for further research and developments.

2. 3D DATA IN CIVIL CONSTRUCTIONS

Modern day constructions require high precision alignments and valid volumes to be calculated. Modelling the increasingly complex urban scene, including subsurface land use, multi-layer buildings and their corresponding usage and ownership cannot adequately be undertaken using 2D systems (Ellul et al, 2006).

Houses with basements, building complexes with multilevel underground parking, multi-level underground train and metro stations, dams are some of the most common examples where we see the objects interacting in different levels of surfaces. It is important to have accurate alignments of the adjoining objects in 3D since errors will not only affect the horizontally adjacent objects but also the objects on the surface below or above it. Future cities conceptual designs are increasingly focused to create entire cities as part of one single large multi-dimensional structure. Such structures will include utility networks wiring through the entire framework alongside the residential and other commercial space usages. Such a large multi-functional city will thus require tight integration of objects to allow the maximized usage of available space in horizontal and vertical directions (de Vries and Zlatanova, 2011).

3D data visualisation and information consistency is critical for large civil projects. Such projects have time span of 5-10 years. In this period huge amounts of data are exchanged between companies involved in the project. Within the Dutch program Ruimte voor GeoInformation, 2004-2009 (RGI, Space for Geographical Information) several projects have dealt with 3D data modelling (www.rgi.nl) and many of them investigated this problem. For example the study performed within the project GeoInformation management for civil infrastructure works (GIMCIW) in the period 2006-2007 has clearly revealed low efficiency in data management and data exchange. The interviewed large companies have acknowledged numerous challenges: much of the design information is 2D CAD drawings (although 3D features are presented), much of the subsurface information is given as measurements (Excel sheets) and not as 3D models, various different files formats, limited re-use of data, difficulties in obtaining a general overview of the project, etc. (Tegtmeier et al 2009). The companies have recognised the importance of 3D information partially due to increased complexity of construction works and partially due to technology developments. An increasing number of 3D City Models are becoming offered freely by municipalities and other data providers. Various BIM models are progressively produced by designers, architects and constructors (Stoter et al 2011). However, the integration of 3D data sets exhibits even large problems compare to 2D. The available 3D data sets are either not validated or validated within a given domain.

In this paper we argue that 3D topological structures will help in this process and should be extended for all objects above and below the surface. Such a 3D topological data structure will force validity checks prior exchange or storage of data. Development of such 3D topology for the built environment is a complex task. As mentioned previously, 3D topological structures have been developed independently and have been largely influenced by characteristics of the domain. For example, under surface objects have largely been modelled as solids, while above surface objects tend to be represented by surfaces. The following section reviews several of these models.

3. 3D TOPOLOGY

Although 3D models are getting used increasingly in many areas, they mostly have been used without using topological structure or semantic information (Jun et al, 2010). 3D entity-based data models for geospatial representation are based on the concepts used in 2D vector GISs (Lee et al, 2008). In 3D, to provide a comprehensive overview of relationships, frameworks need to examine relationships not only between 3D objects but also between the primitives constructing the 3D objects (3D, 2D, 1D or 0D). This may require 2D and 1D topological requirement to be accomplished first. Many visualisation engines require the presence of topological primitives (nodes, edges and faces) to support the display of 3D objects (represented as meshed closed surfaces), with the data currently being stored primarily in proprietary file formats for efficiency. It may therefore be possible to provide support for visualisation in 3D as part of the implementation of topology, by modifying and enhancing the topological structure to support visualisation (Ellul et al, 2006). 3D topology can be useful in three different processes (Ellul et al, 2006):

- Data modelling (construction and validation) relating to the processing and structuring of data into topological primitives and according to topological data models.
- Standard analysis relating to the analytical querying of data once it has been structured in topological format.
- Other custom analysis relating to applications utilising the data structured into specific topological models.

3.1 Topological models for above surface objects

Presently many 3D topological models have been presented as data structures (schema's) with the purpose of storing and maintaining topologically correct data and little attention has been paid on processing and 'cleaning' the data sets according to the rules of the topological models or for performing spatial (topological) analysis. 3D topological models have been developed as individual models (Molenaar, 1989; Pilouk et al, 1994) or as an addition to geometrical models supported by present Database Management Systems (DBMS) such as Oracle Spatial and PostGIS (Penninga et al, 2006; Brugman 2010). An overview of 3D Topological models has been made in many studies (Ellul et al, 2006; Zalatanova, 2004). Early 3D topological models differ significantly in number of primitives, explicitly managed relationships (also related to the allowed singularities) and subdivision of space. The primitives managed can be 0D (node, which contains the coordinates), 1D (arc, composed of two nodes), 2D (face, which can have 3 and more nodes) and 3D (body, which can be polyhedron or tetrahedron). The explicitly maintained relationships and singularities are closely related to the type of the allowed primitives. For example, if only triangles and tetrahedrons are allowed, the model commonly does not maintain explicit relationships. Most of the models are based on a full subdivision of space, which means that an extra object 'air' should be defined. To illustrate the differences, few of the models will be described here with their main characteristics.

- 3D FDS: The formal data structure (FDS) was introduced by (Molenaar, 1989) and is first data structure to consider spatial objects as an integration of geometric and thematic properties. The fundamental rule of 3D FDS is the concept of a single-valued map; i.e., the node, arc, face or edge can appear in the description of only one geometric object of the same dimension.
- TEN: Tetrahedral Network (TEN) introduced to overcome the storage of explicit relationships encountered by 3D FDS. Introduced by (Pilouk et al, 1994), further developments of this structure were presented by Peninga et al 2006. This research has showed an interesting storage of the coordinates together with the tetrahedrons. The

performed tests revealed that such approach does not increase drastically the storage space and allows for fast query of the coordinates for visualisation and metric operations

- SSM: The Simplified Spatial Model (Zlatanova, 2004) was the first topological structure that focused on visualization aspects of the queries. It was designed to serve web-oriented applications where spatial queries need to be visualized on the screen as 3D models.
- CityGML Model: One of the newest developments in 3D is CityGML (Open Geospatial Consortium, 2008). CityGML is an open data model and XML-based format for the storage and exchange of virtual 3D city models. CityGML defines the classes and relations for the most relevant topographic objects in cities and regional models with respect to their geometrical, topological, semantical, and appearance properties. Theoretically the model can support topology as defined in GML, however a simplified approach using links between common faces of adjacent solids is utilized. The model does not maintain relationships between 0D, 1D and 2D primitives.

These and other topological data structures are based on explicit representation of objects. Other data structures may consider the explicit representation of relationships, in which the description of the objects has to be derived from the structures. The 3D topological model presented by Brugman (Brugman 2010) is a typical example of extending the geometrical model of DBMS with topological relationships. The model keeps the geometry data types of DBMS (point, line, polygon and polyhedron with their rules for validity) and introduces additional relationships, which represented the neighborhood and containment relationships between the objects. The models therefore allow for fast query of geometry of objects and at the same time allows for maintenance of spatial relationships.

3.2 Topological models for geological models

All the models listed above have been developed with the idea of managing 3D objects above the ground. Topology has been considered of great importance also for geological objects (Wahl, 2004). The 3D topological models for subsurface (geological) objects have been created separately and focused on objects with indiscernible, continuous boundaries. In these models the subdivision of space is by definition complete. The objects of interest are predominantly bodies and 3D surfaces although line (breaklines, boreholes) and points are also included in the models. Spatial relationships like neighborhood and containment are of specific interest. Another critical characteristic of geological objects is uncertainty of objects. As described by Tegetmeier et al, 2009, the uncertainties could be spatial (unclarity about boundaries), temporal (changes in time) and semantic (unclarity in classifications or values). To represent best the objects and to provide the most suitable operations to perform certain operations different data models have been investigated. Lattuada, 2006 and Breuning and Zlatanova 2011 discuss the differences of geological models compared to on and above surface objects. In all models however, the spatial topology description on subsurface objects as well as on the spatial relations between subsurface engineering and surface spatial objects is semantics dependant (Wu et al, 2004).

Wu et al., 2003 present a classification for 3D models for geosciences modelling which focus the geometry. The authors subdivide the geological model in three large groups facial, volumetric and mixed models. The facial models comprise models that are based on surface representations such as Grid, Boundary representations–, Freeform surfaces, Wire framework or Linked slices, TINs, DEMs, etc. Volumetric models are further subdivided into Regular volume (CSG, Voxel, Octree, needle, Regular block) and Irregular (Tetrahedron Network, Pyramid, Tri-Prism, geocellular, Irregular block, Solid, 3D Voronoi volume). Examples of mixed models are TIN-CSG, TIN-Octree, Wire framework-Block, Octree-TEN, etc.

Some of the models are described which follow the above mentioned classification for 3D models for geosciences modelling:

- G-GTP model for subsurface geological bodies: GTP (Generalized Tri-Prism) for modelling geological bodies. Generally, GTP model is based directly on sampling data and without data interpolation to model the basic pattern of strata interfaces in the form of TIN. The basic element of the model is the tri-prims. The tri-prism has 2 triangles as at the bottom and top, three side faces, 3 side edges, up and bottom TIN edges, and up and bottom TIN nodes. Each tri-prism must have these five primitives unless the side faces are not planar. They can be subdivided then with another primitive, i.e. diagonal. Pyramid and TEN are the degradation of GTP if a side-edge or a TIN-face shrinks to a node. Consequently, the GTP model can be seen as the common 3D model of tetrahedron model, pyramid model and TP model.
- 3D Vector Topology Model in the Visualization System (Yan et al, 2000): A 3D geological entity is a collection of a series of thematic and relations in the geological domain. In a 3D vector topological model, there is only polyhedron class which has both thematic and geometric characters. Abstractly belonging to polyhedron class, volume and out-surface area of a point object is equal to zero. Line object cannot be existed in the geological domain. Fault object i.e. fault, disconnection, etc. is regarded as the body object having the characters of zero-volume, some zero-area faces and some zero-length lines.
- 3D OO- Solid Model (Deng et al, 2008) The OO-Solid Model is an object-oriented 3D topologic data model based on (geological) volumes with fully considering the topological relations between geological objects and its geometric primitives. It requires split into sections, which can be parallel and vertical sections.

4. COMPARISON OF MODELS

Table 1 is an overview of the characteristics of the discussed models. As it can be seen all the topological structures are based on boundary representations. Further primitives and relationships between them are defined. Nodes, Arcs and Faces are the most common primitives used by the 3D topological and 3D geological models. Faces are used to define sometimes as 3D object. However, in some models the basic three primitives are used to create complex classes or 3Dprimitives such as Polyhedron or Tetrahedrons. Explicit relationships can be preserved as well. As mentioned, the geological models are commonly based on full subdivision of space, which can also be found in above surface data structures.

Table 1: Overview of above and under surface topological models

3D Model	Supported Primitives	Constraints on primitives	Relations between primitives	Representation of objects	Subdivision of space	Thematic Semantics (yes, no)
3D FDS	Node, Arc, Edge, Face	node has unique coordinates Arc is straight lines Face is planar	arc has two nodes arc has left and right face ace has left and right body. Singularities: node-on-face, arc-on-face, node-in-body and arc-in-body.	Point: node Line: arcs Surface: faces. Body: faces (closed volume). .	Full	Theme Classes
TEN	Node. Arc, Triangle, Tetrahedron,	Node has unique coordinates Arc is straight lines	Arc has two nodes Triangle has three arcs Triangle has left and right tetrahedron Singularities are not permitted.	Point: nodes Line: arcs Surface: triangles Body: tetrahedrons	Full	Theme classes
SSM	Nodes, Faces,	Node has unique coordinates Arc is straight	Faces are described by nodes Singularities: node-in-face and face-in-body	Point: nodes Line: nodes Surface: faces Body: faces (closed	Embedding (single-valued)	Not Discussed

		lines Face is planar and convex		volume)		
CityGML	Point, Curve, Surface, Solid	Primitive is described by set of coordinates (GML3 compliant geometry).	Xlinks for topology implementation between solids. Xlinks performs aggregates to components directional topology.	Point: point Line: curve Surface: surface. Body: surface/volume	Embedding (single valued)	Yes
Integral Real -3D Spatial Model *G-GTP*	Generalised tri-prism (GTP)	Side-face is planar (subdivision to prism or tetrahedron with diagonals)	GTP has: 6 nodes, 6 TIN-edges, 3 Side-edges, 2 TIN-faces, 3 Side-faces, 3 diagonals	Body: GTP	Full	Not discussed
3D Vector Topological Geological Model	Point, Line, Face, Polyhedron	Polyhedron must be valid.	Face in a multi-hierarchic network. Node connects more than two edges or arris Face has arris.	Body: polyhedron	Full	Yes
3D OO-Solid Model	Node, Arc, Polygon, Region, Solid	Node has coordinates (6types of nodes) Polygon must have orientation	Arc has 2 nodes Polygon is composed of arcs Region has polygons	Line: arc Surface: regions Simple volume: regions (closed) Composed volume: simple volume.	Full	Yes

These similarities give indication that an integrated topological model for above and under surface could be designed. Practically all the mentioned topological data structures can be used to integrate object from above and below surface as they allow representation of 3D volumes, but some of the structures does not provide robust mechanism for validity of volumetric objects. 3D volumetric primitives are therefore advantageous, because they ensure validity and facilitate calculation of 3D volumes. TEN data structures are very good candidate for such an integrated modelling. CityGML has also the potential to become such a model since it offers options to link to the OGC Topological complex model. CityGML was used in our study as integrated data model.

5. CASE STUDY- DELFT: CHALLENGES AND OPORTUNITIES

As mentioned above CityGML was designed only for above surface information, Within the national funded project 'Geoinformation management for large infrastructure works' it was extended with geo-technical information (Emgård,and Zlatanova, 2008). This solution was selected after a careful consideration of several international and national standards and considering mostly the semantic and geometric properties of the models (Tegtmeier et al 2009, Tegtmeier et al 2008, Tegtmeier et al 2007a, Tegtmeier et al 2007b). As can be seen from the table, CityGML provides means to describe (thematic) semantics, geometry but also a kind of topology of 3D objects. Furthermore, the model can be extended applying the mechanism of Application Domain Extension (ADE). CityGML model was extensively investigated and tested within the 3D pilot project (Stoter et al 2010, Verbree et al 2010). Stoter et al 2011 presented an extension of CityGML to fit the needs of the large topographic map of Netherlands. Applying ADE mechanism BelowSurfaceObject was created, which allows specification of geological and geo-technical objects (Figure 1). In addition to the geological formation, geo-technical information of measurements and lab tests is also maintained (not shown in the Figure). Further specialisation of the top-level classes is presented in Tegtmeier et al, 2009.

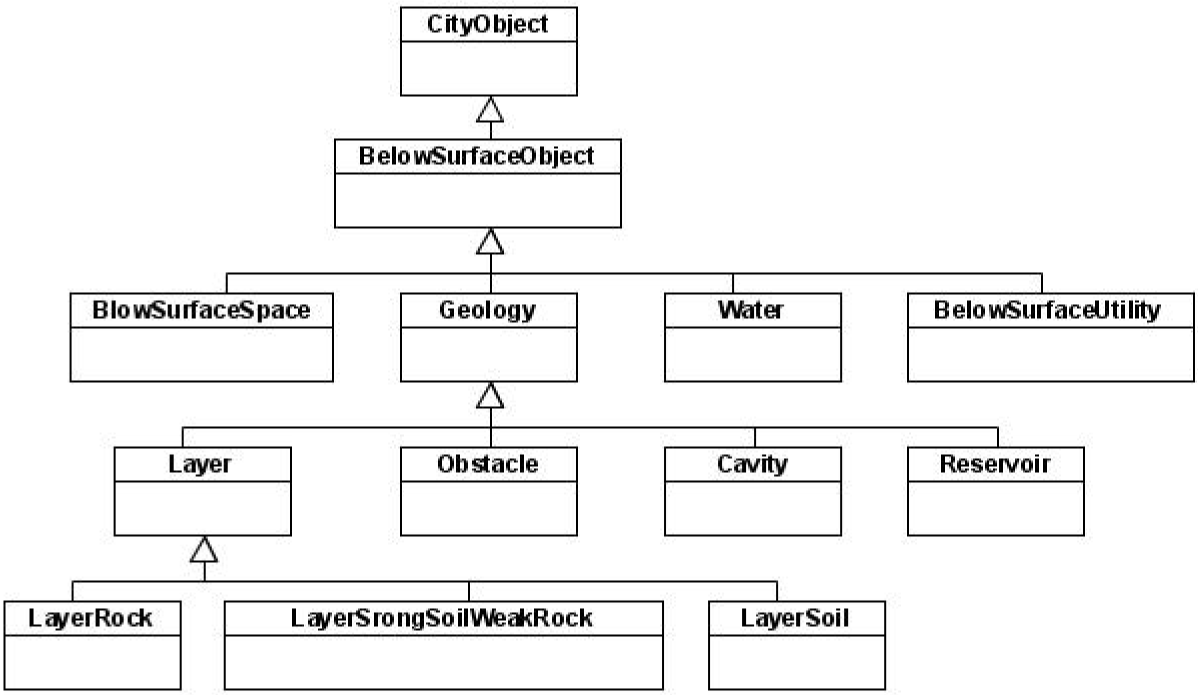

Figure 1: Top level classes of the *BelowSurfaceObject* hierarchy (courtesy of Tegtmeier et al 2009).

The model is very extensive with respect to the semantic information, but it does not elaborate sufficiently on the topological relations between the objects. The geological objects are described by geometric primitives, i.e. surfaces and solids.

For the test of the model, data from Delft Railway Station Reconstruction project (http://www.spoorzonedelft.nl/) were made available. The railway track is to be moved underground. The construction area is in densely populated area, close to the old city and poses many data integration challenges to the constructors (Figure 2). The test data were mostly 2D maps and images complemented with geo-technical measurements. To be able to create the 3D representations according to CityGML and the geo-technical ADE extension, all the data sets had to be processed. During this processing we have used software tools which are readily available in the market such as ArcGIS and RockWorks. The measurements (boreholes and soundings) were processed in geological software RockWorks to create the geological surfaces. These surfaces were lately integrated with the above surface information. To integrate all the data in one 3D model the following steps were taken in ArcGIS:

Figure 2: Railway station Delft: a) old situation and b) new situation

1. Under surface objects: We have used the subsurface model obtained from the boreholes in RockWorks (as set of surfaces) and exported as a 3D polygon shapefile. We have used ArcScene software to show the subsurface data in a 3D environment. A sink hole into the south-west side of the sub-surface indicates the area of reconstruction. (Figure 3).

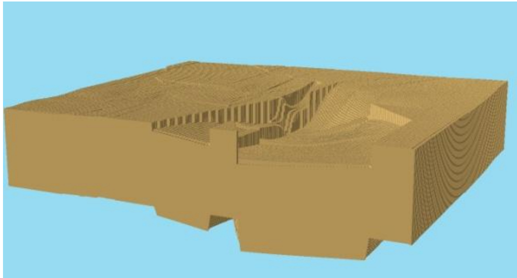

Figure3: LayerSoil represented as subsurface model

2. Surface features: To show the surface features, we have used a 2D high resolution satellite imagery which is basically a non-interactive raster image. A Triangulated Irregular Network (TIN) depicts the surface variations (0 – 1.07 m). The TIN is created from the point geometry elevation spots which store the height (NAP) values in a separate column in an attribute table. These elevation spots are used to interpolate surface as TIN using 3D analyst extension of ArcGIS. This TIN also serves as base height for the satellite imagery of the area in the 3D environment. The image shows clearly the different landcover/landuses in the area covered. Majority of the area is covered by building complexes. Railway track could be seen dividing the area covered broadly in two parts. Trees and some green patches are also visible on the surface.
3. Buildings LOD1: A two dimensional polygon layer of building footprints is used to extrude the buildings in ArcScene. This extrusion uses height values stored as a separate column in its attribute table. For this purpose, under Extrusion property of the layer, Height column is used as Extrusion value or expression. This extrusion is added to each feature's minimum height. However, this extrusion is only for the display purpose and does not change the geometric characteristics of the layer to 3D primitives. It is simply a case of using corresponding values stored in attached data table as a column (Figure 4).

Figure 4: Terrain features with Buildings

In our case study, we have used geometrical models based on the basic primitives of point, line and polygons. None of the datasets used have true 3D geometrical shapes such as Polyhedrons or tetrahedrons as their base shapes which are mentioned in the 3D topological and geological models earlier. As a result, the integration resulted in some differences between surface and subsurface objects (Figure 5), which could not be checked while creating the model. The base primitives of our surface and subsurface model are simple 2D geometry primitives and not topological primitives.

Using topological primitives and populating a 3D topological model would have help to avoid these problems.

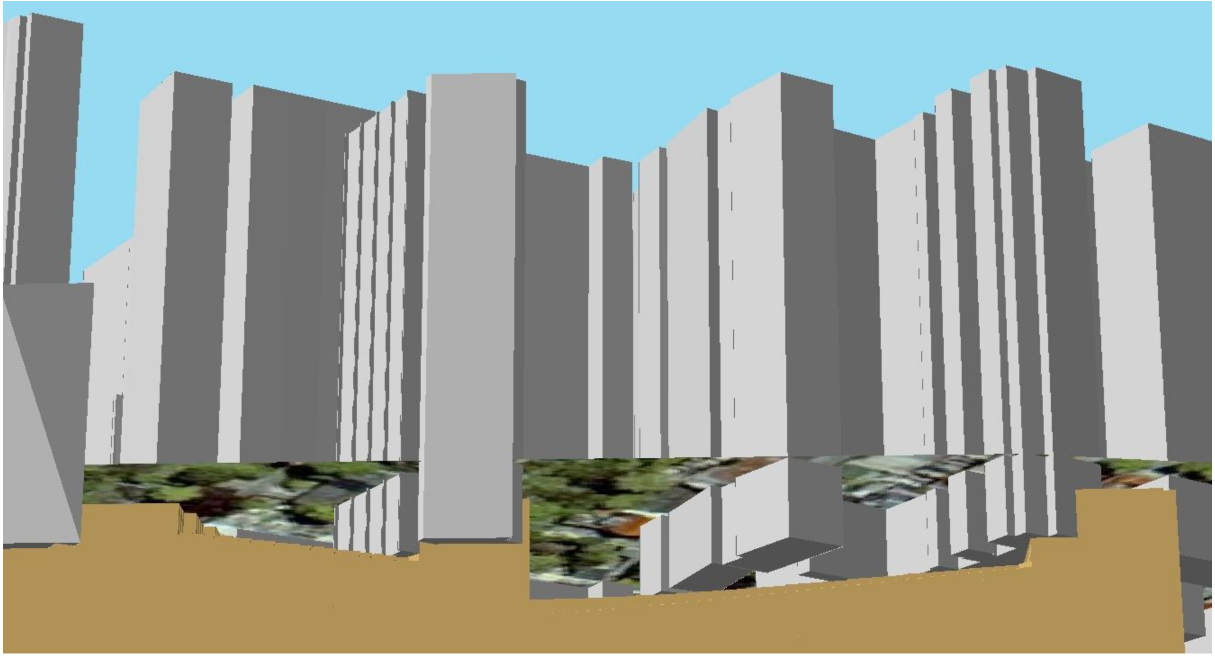

Figure 5: Integration of above- and under surface objects. The discrepancies between the different object are apparent

6. CONCLUSIONS AND RECOMMENDATIONS

The complexity of tasks to be resolved in urban areas require the generation of true 3D datasets which are valid and can fulfil the 3D topological requirements. A very important aspect of 3D data sets is the validity of the objects. Our case study highlighted the discrepancies which can occur if topologically valid approach is not used. The validity of objects was not checked at any level: per objects, between the objects in one layer or between the objects of different layers. At the moment no software package can provide 3D validation and repair of individual objects, not to speak of validation of layers. In this respect, a good first step for validation of extruded objects is proposed by Ledoux and Meijer 2011.

Much more efforts are need for the implementation and use of data model that maintains 3D topology for above and under surface objects. The reviewed 3D topological models for above surface and under surface confirm that such datasets can be created, but the most appropriate 3D topological data structures still have to be investigated and agreed upon. 3D topological data structures that are based on tetrahedrons such as TEN are very promising start and need to be further studied for their applicability for an integrate data model. Another approach is use of polyhedron data type. A polyhedron data type has some advantages since it will not require subdivision of solid objects into tetrahedrons, but the topological data structure will be more complex to maintain. The topological model then can be linked to the semantic classes of CityGML and the geo-technical ADE. Concluding, we firmly believe that the research on integrated above/under surface 3D models have to be dealt together with 3D topological models. Maintenance of topology in any stage, i.e., creating, storage and analysis of 3D models will ensure their validity and consistency.

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