Integrated data processing and simulation platform for mechanized tunneling – Showcase application on the "Wehrhahn-Linie" project in Düsseldorf

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ABSTRACT: In the mechanized tunneling process a vast amount of data is collected, processed and stored in various locations and formats. An integrative strategy supporting the processing and visualization of data from different sources in connection with simulation based prognosis is becoming more and more important, especially when considering the complexity of interacting tunneling processes in association with increasing quality standards. In the collaborative research center 837 "Interaction modeling in mechanized tunneling" an integrated product model, which not only incorporates machine and project data, but can also be used for setting up simulation models in mechanized tunneling, is currently being developed at the Ruhr-Universität Bochum. This presentation describes the approaches used for generating the integrated product model, including various sub-models. Furthermore, its performance is demonstrated by applying the product model to the "Wehrhahn-Linie" subway project in Düsseldorf, Germany.

1 INTRODUCTION

The multitude of processes and interactions involved in mechanized tunneling makes the tunneling operation basically equivalent to a non-stationary manufacturing plant. This includes not only the material logistics, but also the collection, storage and processing of (measured) data and information gained from the entire production process. In addition, more data and information is collected from accompanying fields, such as geotechnical engineering (geotechnical reports, preliminary exploration), surveying (settlements, navigation) or from construction operations (shift protocols, quality management, additional studies). However, these data units are usually neither stored in consistent formats nor in a central repository. The temporal and spatial synchronization of the data thus forms the basis for a qualitatively adequate data management and process controlling.

Existing data management systems are primarily designed for the storage of the raw data obtained during tunneling operations. The data is mainly in the form of documents and spreadsheets that provide, if necessary, standard two-dimensional visualization options in the form of charts. Yet, without a sufficient 3- or 4-dimensional visualization of data, relationships are often difficult to interpret or to recognize. Furthermore, a holistic and comprehensive view of the construction process and the various measurement data, along with employed simulations, are often not provided. In a tunneling project, however, consistent and complete data management throughout the full duration of the project is essential, not only during the planning or execution phase.

For mechanized tunneling, it is suggested to use numerical simulation tools to guarantee quality assurance and to ensure a safe construction (Guglielmetti et al., 2012). Performing these simulations, however, can be a time consuming task, as the information needed to properly model a realistic tunneling process is usually present in different file formats. For this reason, it is rare to find project data from the planning and execution phases presented side by side. With an integrated product model, it is possible to obtain the required data quickly and efficiently to automatically generate working models.

To be able to view and analyze the wide range of available data, all relevant data must first be compiled into a consistent and structured form, for example, in an integrated product model. In this way, 4-dimensional representations of data are possible, as well as couplings to numerical simulation tools for interactive use.

A research approach for such an integrated product model is being developed in the collaborative research center 837 “Interaction modeling in mechanized tunneling” at the Ruhr-Universität Bochum, Germany. In particular, the concepts presented in this paper are applied to the subway project “Wehrhahn-Linie” in Düsseldorf, Germany.

2 DATA LANDSCAPE IN TUNNELING

The “data landscape” in tunneling is very diverse. Files are stored not only in different formats and structures, but refer to different reference values, dates and locations. Moreover, accessibility is limited depending on the role of a user in a project. Data access and processing can be complicated, depending upon the release protocol. Often, needed data and plans are not even available in digital form. Based on a selected view of essential tunneling concepts (ground, machine, tunnel, surface/building structure), the range of data diversity will be presented by selected examples.

2.1 *Ground*

Information on the ground is typically obtained from field and laboratory tests that are mostly performed in advance of a tunneling project, or gathered from existing local experience. From geo-referenced boreholes, exploration drilling and groundwater monitoring wells positioned along the tunnel route, geological soil layers and hydrogeological boundary conditions can be determined. The soil mechanical parameters of each layer are determined in laboratory experiments or estimated by experts having local experience. In general, the data of the ground investigations are stored and recorded in tabular form (including test and measurement protocols, evaluations, mechanical and hydrogeological soil parameters) and graphically (including measurement and evaluation charts, drilling and exploration profiles, geological longitudinal and cross sections as CAD plans). The relevant ground information is summarized in a geotechnical report, which is usually available in digital form.

2.2 *Machine*

The tunnel boring machine considered as a construction method continuously produces a large amount of data obtained from various measurements. The data are distinguished between so-called instantaneous machine data, which are recorded at intervals of typically 10 seconds, and average values, for each advance cycle (ring). These values are logged for about 200 to 400 different measuring systems leading to about 1.7 to 3.5 million accumulated data items per day (Maidl et al., 2011). The collected data include, for example, thrust forces, the torque and the rotational speed of the cutting wheel, the advance speed, supporting pressures, grouting pressures, temperatures, oil pressures, flow rates, system alarms, etc. The measured data are stored as numbers in tables for each ring. Furthermore, a variety of protocols pertaining to the operation of the machine or accompanying logistics are created (documents, spreadsheets).

2.3 *Tunnel*

The geology of the underground site is one determining factor on the planning of the tunnel track, but at the same time, topographical and procedural aspects (minimum curve radius, tunnel diameter), environmental aspects, traffic conditions (links to existing infrastructure, safety, driving dynamics for vehicles), legal aspects (property ownership) and, of course, economic factors play an important role in the decision-making process. The final route is made up of curves, straight lines and clothoids, which are ultimately geo-referenced. The coordinates are tabulated and the alignment is stored in CAD files. Documents, resolutions, etc., that have contributed to the final selection of the route are usually stored in document format.

In addition, material compositions, production and installation protocols for annular gap grout and segmental lining must be stored, along with structural analyses for the tunnel lining and calculations of the necessary support pressure.

2.4 *Surface / building structure*

A self-contained monitoring of displacements during mechanized shield tunneling provides a basic tool for risk control. The present state of science and technology is a deformation monitoring using conventional terrestrial measurement techniques, such as tube water levels, leveling or measuring with (fully automatic) tachymeters. By increasing the performance of satellite-based remote sensing systems, terrestrial measurements are being supplemented with these new techniques. Without any on-site installations, the method of radar interferometry can track, depending on the topology of the surface and the technique used, approximately 25,000 measurement points per km² (Mark et al. , 2012). Thus the amount of data grows even greater. Crucial for the use of satellite based data is, on the one hand, a proper geographic referencing of all data points and, on the other hand, recording all measured values (terrestrial and satellite based) with respect to a common reference measurement. Since the latter is not logistically feasible in general, all measured points must be transformed by a post-process to a common reference measurement afterwards. With an online connection, data can be stored directly in digital form, for example as table values. Further information, such as geographic positions, can be added to files as meta-data. The brief measurement intervals of terrestrial methods provide up to several thousand measurement values per hour. In addition, there are still a number of measurement points to be recorded by hand. These must first be digitized and can be further processed as described above.

For a holistic view of a final tunnel acceptance, the acquisition of building data, including geometric parameters, is also required. Thus, an assessment of the risk of damage can be made based on settlement data. The building location, the number of floors, the building materials used, the proportion of window area or the progress of degradation are just a few factors that need to be captured in a database. Usually, for large areas of influence of a tunnel, capturing the necessary topology from laser scans is helpful. The point cloud data thus generated can be used for a vector-based representation of the above-ground buildings. In particular, not only can the amount of raw data be reduced, but also a very accurate height model of the surface be made, useful for the evaluation of radar images. Since data records are available in digital form for only very few buildings, a manual evaluation of original (analog) plans is usually required.

2.5 *Numerical simulations*

The ever-increasing power and efficiency of modern computer technology and the considerable progress in computational mechanics have stimulated the developments of modern computer based data collections, numerical models and visualization methods. Numerical models, in particular, need continuous improvements in order to be used as useful tools for tunnel design and for the prediction of the soil behavior during the construction processes especially with respect to surface settlements. These developments concern the quality of the models as well as their ease of use. Furthermore, a high quality of the input data (geometry, geological data, building stiffness, soil parameters, etc.) is a prerequisite for a realistic numerical model and more accurate simulation results. In a numerical simulation for tunneling, the generation of the model is the most time consuming task starting by information about tunnel geometry, geological data, and construction sequences/method to the mesh generation of the finite element analysis. Therefore, more attentions are dedicated recently to the automatic generation of the simulation models.

In order to generate these models automatically, several input files in various formats are provided. As an example, a volumetric CAD model in ASCII format can be provided for the representation of the geological domain including all layers and boundaries of the simulation domain (Li & Zhu, 2009). Furthermore, the material parameters, geometry of the shield and the tunnel alignments can be provided as a text file that is automatically read and used to generate the simulation model. Also, the simulation results are stored both in results files and within a database, such that they can be extracted and evaluated upon user request. The result files, i.e. formatted as ASCII or binary output, can be read and visualized by any post-processing module.

3 METHODS FOR DATA MANAGEMENT IN CONSTRUCTION

3.1 *Existing data management systems*

Currently, there are various data management systems that are used to manage and process data for large construction projects. These systems are used by construction companies, engineering consultants and equipment manufacturers mainly for process controlling accompanying the construction process. The focus of these systems is structuring the large amount of raw data that is generated during the tunneling process. An overall analysis of data and the coupling with numerical simulations is generally not available in these programs. The aim of the research in this paper is to develop a holistic and interactive data platform in the form of a product model with an integrated visualization that has an additional interface for the automatic inclusion of data for simulations.

3.2 *Basic IT concepts of product data models*

The modeling of data structures for building infrastructures has been widely studied. Especially the Building Information Modeling Framework (BIM) has been found to be suitable to define a methodology for product modeling in construction. BIM provides a semantically coherent exchange of information and models in standardized exchange formats, such as the Industry Foundation Classes (IFC, Building Smart, 2013). The use of standardized exchange formats is particularly helpful in the planning phase, when many project participants work together simultaneously on different topics. Information can then be exchanged quickly and uniformly. Through visualization capabilities using BIM complex relationships can also be easily identified.

IFC is based on an object-oriented data model and is therefore both versatile and easily extendable. Using IFC, objects are first modeled based on spatial regions such a building floors before including physical elements, where an element consists of a combination of a graphical representation and semantic information. Originally, IFC has been developed to model buildings, but has been now extended to other fields of applications in civil engineering, such as bridges and roads (Arthaud & Lebegue, 2007; Rebolj et al., 2008; Hegemann et al., 2012; Lee & Kim, 2011; Ji et al., 2013). The modeling of shield tunneling is presented in (Borrmann & Jubierre, 2013) using an IFC-based multi-scale product model. This product model provides a minimum number of required new IFC classes to represent the tunnel and also offers the possibility of the modeling additional components, such as work spaces, as part of the tunnel interior in a hierarchical manner.

To model large spatial data related to technology infrastructures, the Geographic Information System (GIS) is used. The focus of GIS lies more on the management of spatial and geographical data, rather than the modeling of individual structures in detail, as done in BIM. GIS uses the Open Geospatial Consortium (OGC) standard GML as a data model. Since 2012 the extension of GML to CityGML (Groeger et al., 2012) has been accepted as an international standard by the OGC. CityGML has been developed for the storage and interoperable access of 3-dimensional models of cities, which now also includes tunnels, along with geometric, semantic and topological aspects (Kolbe et al., 2005). The approaches mainly deal with the modeling of structures and the spatial planning in building construction. A methodology for modeling the soil and underground structures is presented in (Zobl & Robert, 2008). A distinction is made between geological features, such as layers of soil or groundwater, and underground structures, such as sewers or tunnels.

The research presented here often considers only the planning phase. Although methods already exist to model soil or tunnels, the modeling is usually based on distinct individual models that represent only one particular aspect of tunneling. For the modeling and data management of an entire tunnel project, the individual models must be coupled to allow the necessary interaction that exists between models to be handled by computer systems.

4 INTEGRATED PRODUCT MODEL FOR TUNNELING

4.1 *Modeling of data in mechanized tunneling*

Based on the experience gained with modeling building structures, the BIM concept has been extended to tunneling projects, taking into account existing proposals such as (Kymmell, 2008). To structure the large amount of data and information obtained during the planning and operation phases of mechanized tunneling, it is necessary to first classify all available data. To realize this, a holistic product model consisting of four sub-models has been developed, namely: a ground (subsoil), machine, tunnel and construction environment sub-model, as natural components of mechanized tunneling (see Figure 1). To generate these models, the standardized exchange format IFC BIM was used.

Subsoil model

The subsoil model is based on (Zobl & Robert, 2008) and includes two main components: soil and groundwater. In a preliminary step, a 3-dimensional subsoil model is generated with corresponding layer sequences based on the engineering geological classification (see Section 2.1). The generation can be done for example by using a Delaunay algorithm (George & Borouchaki, 1998) connected to a triangle mesh. To characterize each soil layer (dependent on the depth and stress state) corresponding semantic information, such as soil and hydrological parameters, are assigned to it. In addition, all available raw data obtained by ground investigations will be integrated into the product model. The 3-dimensional representation of groundwater, based on the data of groundwater monitoring, is generated dynamically to create a time-dependent groundwater model.

Machine model

The model of the tunnel boring machine (TBM) is spatially divided into the TBM head and the back-up system (Hegemann et al., 2012). The dimensions of the machine can be adjusted via an appropriate scaling with respect to project constraints. The spatial areas are defined by machine elements containing additional units of relevant semantic information, such as the effective excavation diameter of the cutting wheel. In addition, measurement data collected during operation can be associated with individual elements. The visualization of the machine is set at the end of the tunnel.

Tunnel model

The tunnel model was developed in cooperation with the Technische Universität München (Amann et al., 2013). It immediately connects to the model of the machine. The

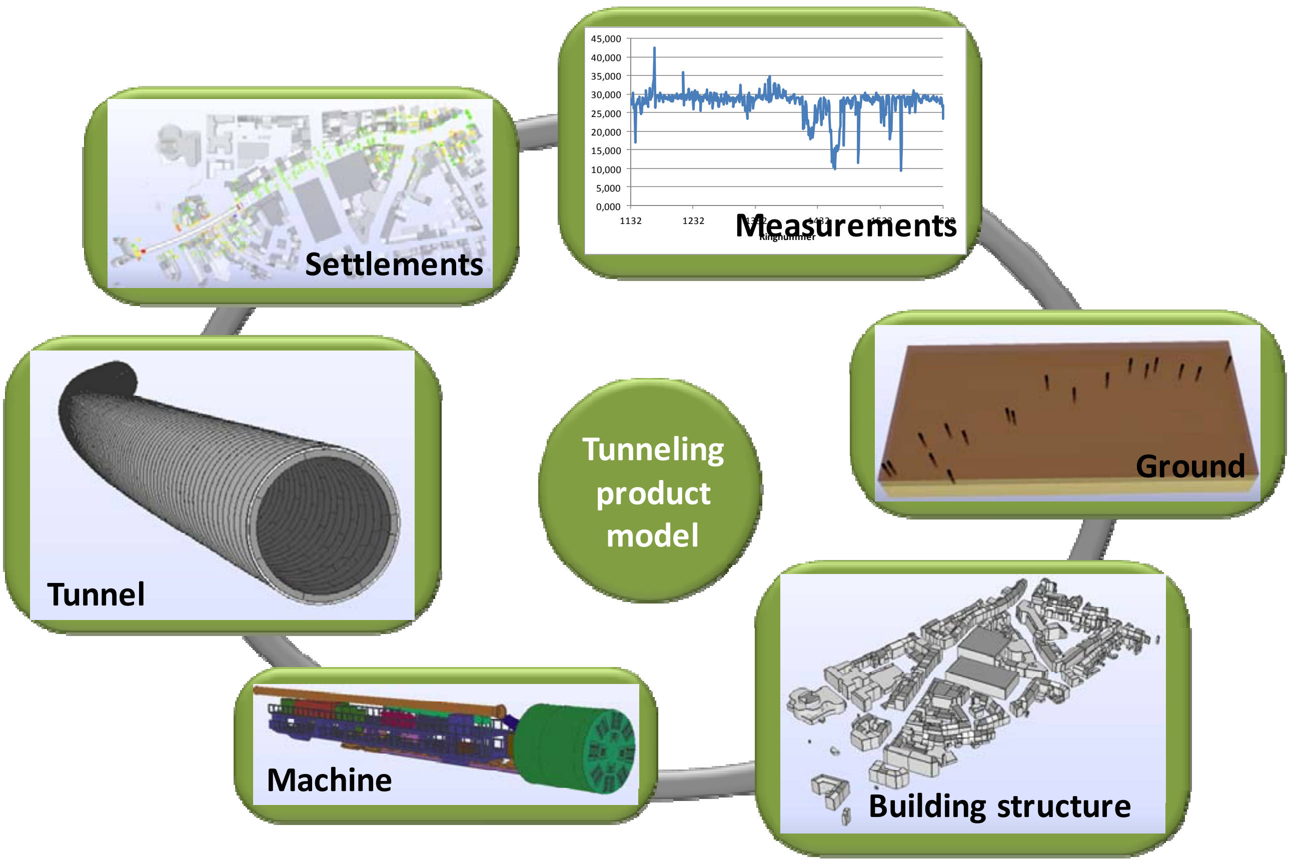


Figure1.Concept of the product model

tunnel itself is represented by traverse or polygonal line, where a single polygonal section corresponds to a single ring. The tunnel can be displayed in a time-dependent manner and loaded at different stages of the construction process, that is, all rings constructed up to a given date will be extracted. The extracted tunnel consists of two parts, the tunnel lining and the annular gap, where each part has a specific IFC representation and, therefore, a specific visualization and semantic component. The visualization is generated dynamically based on the number of selected segments. The tunnel lining is divided into individual rings with their respective segments. Each ring is associated with semantic information, such as the outside diameter or the segment thickness, including also process information such as the date of installation or downtimes. The annular gap is also specified by each ring and has semantic information like the composition of the mortar and the injected grout volume.

Building model

The (surface) building model includes the overlying buildings in the influence area of the tunnel. The buildings, especially their stiffness and mass, have a great influence on the size and shape of the settlement trough. These and other information, such as indicators to describe the vulnerability to subsidence, will be integrated into the building model. Additional information, such as the area and the position of a building, can be easily determined by visualization.

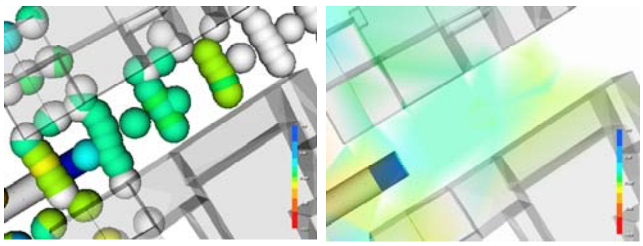
Apart from the four sub-models described above, the product model can also capture additional data, such as individual settlements. Settlements are usually measured as point data, meaning that time-dependent measurements are made for one single point. Accordingly, for each point there is a set of measurements over a specified time period, where the data can result from either terrestrial measurements or from numerical simulations. Of course, using visualizations can be very effective in the evaluation of subsidence effects.

4.2 *Visualization capabilities in the product model*

Geo-referencing plays a major role in the visualization of data, since all elements must be displayed in a uniform and consistent coordinate system. A unified visualization is critical to identify relationships and dependencies between different data sources and components, for example, determining the effects between the position of the TBM, the jacking pressure and the observed settlements. Trying to spot these correlations from spreadsheets or other documents is almost impossible. Further, a high degree of interoperability is enabled by animations that can show how values change over time in predefined time steps.

For the visualization of subsidence, several methods have been found to be suitable (Falkner et al., 2012). Basically, the methods are distinguished as being either point-wise or planar, whereby a variety of user-specific variations exist for each approach. For presentation of the settlement trough, it is advantageous to visualize the level of settlement by using a color scheme, which can be project-specific and adjusted according to the amount and the distribution of the occurring or anticipated settlements. The settlement points can be displayed either using geometric objects (such as spheres) or in a triangle mesh.

The advantage of geometric shapes is the ability to illustrate the settling by changing the color or position of the geometric object. In a triangle mesh, on the other hand, gradients can be visualized well, making the planar settling behavior easy to interpret. Both visualizations are shown for comparison in Figure 2.



a) b)

Figure 2.Visualization of settlements as spheres (a) and as triangle mesh (b)

4.3 *Automatic access to data of the product model*

To access the data of the product model, an interaction platform has been developed that provides a unified interface in the form of a web service. In particular, the web service processes incoming requests, reads data from the corresponding product model component and produces results in a compact form. By providing a unified interface, various applications, such as data processing software or simulation components, can access the web service to retrieve needed data.

The system described also can be used for the automatic configuration of numerical simulation models. In mechanized tunneling, numerical simulations are often carried out with commercial software applications. Because proprietary software packages typically lack standardized interfaces for input data, input files need to be created specifically for each application. The problem here is that parameters required for an input file can be associated with completely different identifiers, although they might have identical semantic meanings.

In order to provide a universal interface, an ontology is required that describes both the name (identifier) of an individual parameter in the various software applications as well as the (canonical) location of the parameter in the product model for automatic extraction. Thus, the product model can be passed a number of parameters required during a simulation run. Each parameter is then read from the product model and the results automatically returned to the simulation. This allows the designers to easily perform many simulations based on different scenarios to find an optimal solution. Furthermore, the results of the simulations are continuously improved since they have access to updated information from previous simulations or other information sources in the product model.

5 CASE STUDY: VISUALIZATION OF SETTLEMENT DATA FROM THE WEHRHAHN-LINIE METRO PROJECT DÜSSELDORF

The “Wehrhahn-Linie” is a subway construction project in the city of Düsseldorf, Germany, and will connect the southern district “Bilk” with the district “City Center”. A total of 7 new stations will be built by a shield machine (hydro-shield) along a 3.4 km long track (Blome, 2010). The outer diameter of the tunnel (D_o) is 9.50 m; the average overburden is 1…1.5x D_o. The twin-track tunnel section is constructed with a 45 cm thick reinforced concrete segmental lining. During the approximately 1 km long advance of the east branch (“Ostast”) of the project, comprehensive settlement measurements were carried out. For this case study, a tunnel section between the subway stations “Schadowstraße” and “Jacobistraße” is examined. Here, a total of

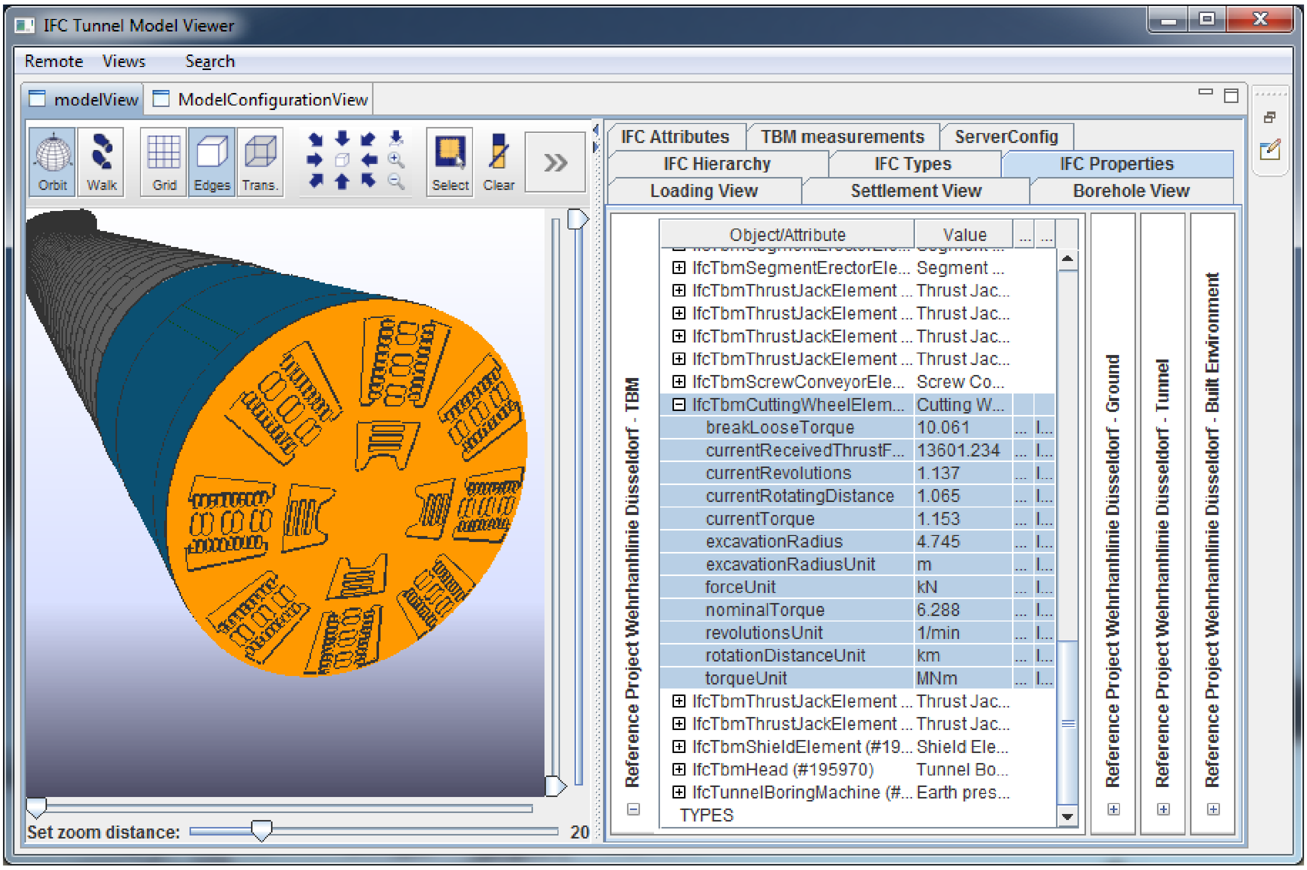


Figure 3.Access software to data stored in the product model

approximately 6,000 settlement data points is available, gained from both terrestrial measurements using classical methods such as tube water levels (550 points) and from satellite measurements (5,500 points).

As noted above, the exact geo-referencing of data points is essential. Here, the Gauss-Krüger coordinate system has been used consistently. By transforming all the terrestrial subsidence measurements to the common reference measurement used in the satellite-based displacement measurements, a direct comparison of the data is possible.

The three-dimensional representation of the buildings was taken from laser scan data sets and a 3D city model of the city of Düsseldorf.

All elements of the shield tunneling machine have been taken from the provided original records of the construction company. Due to the temporal and spatial synchronization, a visualization and animation of the shield tunneling advance is possible. Figure 3 shows a screenshot of the data management software that can access the data stored in the product model. In the picture the model of the TBM is displayed together with the generated tunnel. In addition, on the right hand side data pertaining to the cutting wheel is shown. The characteristics of an element are thus directly available and current data corresponding to the selected time step is presented.

A significant advantage of the integrated model is the capability to view data from various sources to a time-consistent (synchronous) manner. For example, in addition to settlement measurements, operation data of the TBM can be displayed and used for further analysis. The settlements measured on day 146 after the beginning of the construction process of the case study section are shown in Figure 4 as an example. Figure 5 shows the same section one day (or 9 rings) later. At this time, a small heaving occurred at the surface.

To explain these heaves, various machine data can be extracted from the product model, here the thrust forces. The thrust forces of the hydraulic jacks in the area of the heaving and immediately before show, that they are comparatively high in comparison to the considered part of the Wehrhahn-Linie. A look at the position in the tunnel alignment shows that there is a subway station just before the location, where the heaving occurred. The stations in this project are constructed by the cut-and-cover method (diaphragm cases with roof). Prior to excavation, the TBM drives through the stations. Thus, the high thrust forces most likely result from the TBM cutting the diaphragm walls used to build the subway stations. Upon exiting the diaphragm walls, the thrust force is suddenly too high for the pure ground to excavate, which must be subsequently reduced by the TBM operator.

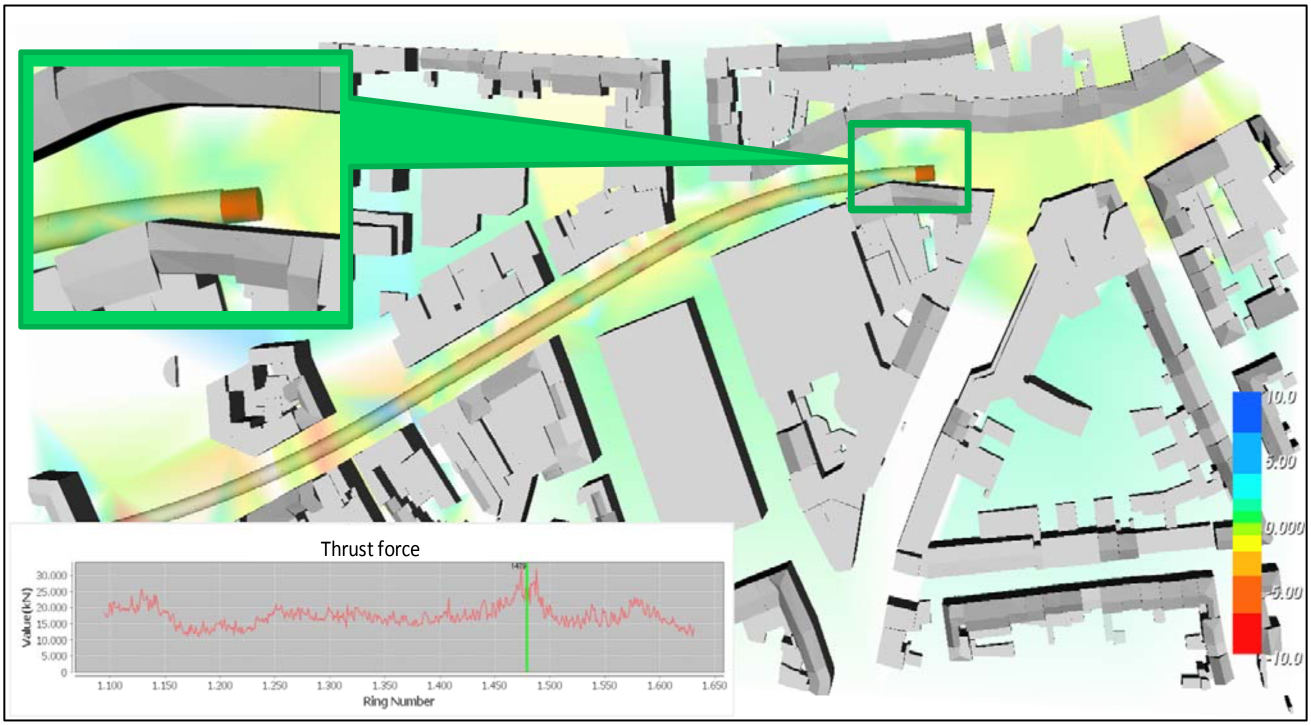


Figure 4.Visualization of settlements measured on day 146 in connection with TBM data (thrust force)

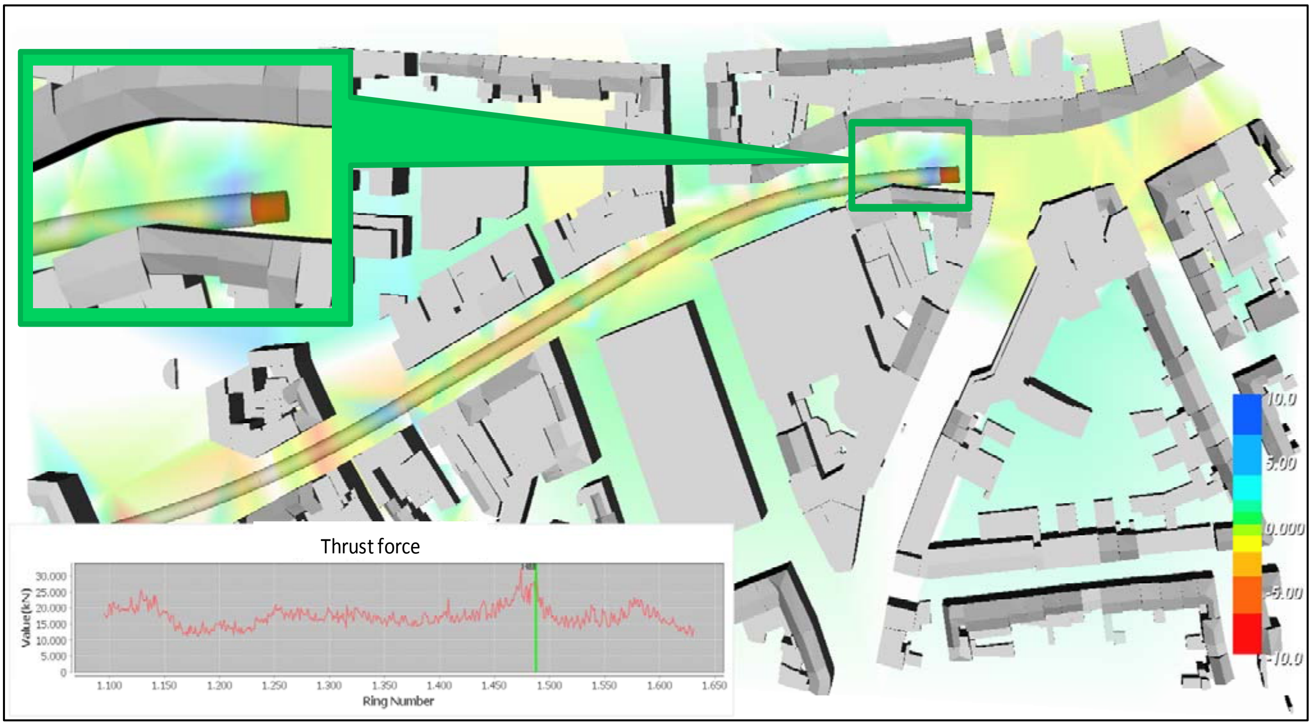


Figure 5.Visualization of settlements measured on day 147 in connection with TBM data (thrust force)

6 SUMMARY

The three-dimensional visualization of settlement data coupled with other project data (here, machine data) simplifies the analysis of causal relationships within project data. The basis for this is a sufficient homogeneity of data in modeling and storage. The example presented here could now be coupled in a further step with numerical simulation components to perform settlement calculations involving realistic data for a model generation.

The use of a product model can support project phases ranging from the initial design stage to the final planning stage to significantly increase the transparency and structure of a tunneling project.

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