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Parametric multi-level tunnel modelling for design support and numerical analysis

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Abstract: In this paper, a concept for parametric multi-level modelling of shield-bored tunnels within urban environments using Building Information Modeling (BIM) tools, in particular Revit and Dynamo, is presented and employed as the basis for structural analysis on different Levels of Detail (LoDs). To this end, a parametric representation of each system component on three LoDs is developed in the information model and used for automated generation of the numerical models for the tunnel construction process and soil-structure interaction. Our platform (called SATBIM) enables flexible, user-friendly generation of the tunnel structure for arbitrary alignments based on predefined structural families for each component, supporting the design process and at the same time providing an insight into stability and safety of the design.

1 INTRODUCTION

Complex infrastructure projects such as shield-driven tunnels in urban areas require demanding data management as well as analysis during planning and construction. In the past years, extensive research has been conducted, leading to sophisticated simulation models for numerical predictions of tunnelling-induced effects and steering of the construction process in real time [12]. A different, until now mostly independent line of research is Building Information Modeling (BIM) for infrastructure, allowing for multi-level information representation of the built environment with the adequate Level of Detail (LoD) to support planning and analysis tasks of large tunnel projects [4]. Considering the fact that each project from the early design stage over construction to the operation phase requires both information management and numerical analysis on different LoDs, the need for a unified approach becomes evident. The link between information and numerical modelling has recently been addressed in [10, 1].

During the design and analysis of major infrastructure projects such as shield-driven tunnels, different scales have to be considered: from the kilometre scale for the general alignment of the track down to the centimetre scale for detailed design of connection points. Moreover, both the planning and the design phase require analysis, modelling, visualization, and numerical analysis. These tasks are supported by Geographic Information Systems (GIS), BIM tools, and software for numerical simulation. To carry out the above tasks with high consistency when changing scales, a sound foundation for handling multi-scale representations is required. Multi-scale modelling is already well-established in the GIS field [14] and for modelling of buildings [15, 3]. However, there is only a very limited number of examples where the multi-level approach is used to support planning, design, and analysis of large tunnel projects [4]. Nevertheless, multi-scale concepts would be extremely useful in the context of numerical analysis for such projects: The planning process typically provides only rough information in the early stages, but increasingly detailed and fine-grained information in later stages. Still, the proof of design has to be conducted throughout all those phases. To enable information and numerical modelling preserving the consistencies of data on different LoDs, this paper presents SATBIM, a comprehensive platform for incorporating multi-scale representations into a BIM, with a particular focus on the geometric-semantic modelling of shield tunnels in a form suitable for direct usage of the information model for further numerical analysis. Multi-scale representation in numerical models usually refers to modelling on micro, meso and macro scale. Here, we consider different representations only on the macro scale. Therefore, in the following, we refer to this approach as *multi-level modelling*.

2 SATBIM: MULTI-LEVEL INFORMATION MODELLING AND ANALYSIS FOR TUNNELLING

Following the state-of-the-art in engineering practice, the design of a tunnel is assessed by analytical, empirical, or very complex numerical models. The generation of such numerical models based on the tunnel design and reports requires demanding manual intervention of experts and high computational costs [9, 11, 6]. On the other hand, in recent years, BIM has gained increasing attention in infrastructure projects, simplifying planning and analysis. Still, manually generating a simulation model based on the BIM (or vice versa) is time-consuming, costly, and error-prone.

In the remainder of this paper, SATBIM, a unified platform for information and numerical modelling is proposed. The central goal of SATBIM is to develop a multi-level simulation model for tunnel-structure interaction integrated in the framework of BIM. The platform support the design process and design optimizations, and allows to minimize the risks on existing infrastructure, therefore increasing the safety (see Fig. 1a). SATBIM provides an integrated

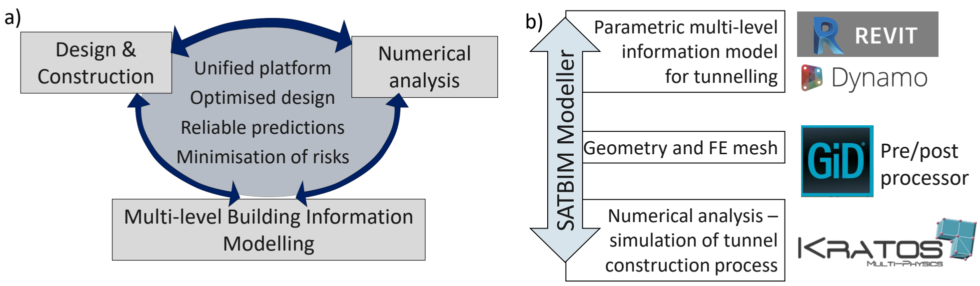

Figure 1: a) Concept for integrated SATBIM platform for design and numerical analysis on different LoD; b) tools used in SATBIM

platform for structural analysis, visualization and optimization of the mechanized tunnelling process from early stages of the design over to the construction and the operation phase. To perform those tasks, different tools are developed and integrated into a user-friendly platform with a high level of automation. For BIM, the Autodesk tools Revit and Dynamo [2] are employed. For numerical simulations, we use the pre/post-processor GiD [5] together with the open-source Finite Element (FE) platform for high performance computing KRATOS [8]. These software packages are connected through the newly developed `SatBimModeller` to enable the tasks of modelling, analysis and visualization (see Fig. 1b) in a unified way. `SatBimModeller` is mainly written in Python, using a modular architecture that allows for easy extension and adaption of the platform. Furthermore, we developed a number of Dynamo programs, which allow to parametrically generate the BIM for the tunnel project in Revit.

2.1 Multi-level approach

As mentioned, in the design phase of tunnelling projects, decisions have to be made on wildly differing scales: from the kilometre scale for tunnel alignment to the centimetre scale for modelling the tunnel structure and its details. Those scales have to be consistently connected in order to avoid spatial conflicts (see Fig.2a). In SATBIM, for each component of the shield tunnelling process further described in Section 2.2, three LoDs are defined: *Low*, *Medium* and *High*, also referred to as LoD 1, 2, and 3 in the following.

In general, on the lowest LoD 1, non-volumetric representation of the component is assumed, since in the corresponding numerical model, the respective component is not represented with actual structural models, but instead with an empirical model realized through a set of boundary conditions. On the medium LoD 2, for each component, a volumetric representation is established, where the component is "occupying" the exact volume, however, the geometry is simplified, i.e. approximated. Finally, on the highest LoD 3, we include more details about the actual geometry of the component.

For each component and on each LoD, a so-called "Revit family" for the corresponding component is created. In order to keep consistency between different LoDs, parametric consistency between families is defined as shown in Fig. 2b: the full set of parameters defining a component is needed for definition of the highest LoD, while only a subset of the parameter list is used on lower LoDs. This way of handling parameters allows for automated preservation of the consistency of the multi-scale model.

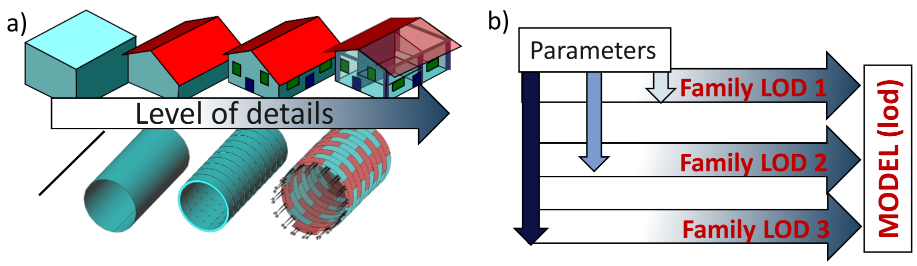

Figure 2: a) Multi-level representation of geometry; b) parameter consistency between different LoDs for individual components

2.2 Components of the information model

A realistic model to be applied during the construction and the design phase needs to represent all components of the tunnelling process relevant for the prognosis of the response of the surrounding soil during excavation. These components include the soil, the TBM with the hydraulic jacks, the segmental lining with support measures applied at the tunnel face and at the tail void, and existing infrastructure (see Fig. 3a). Apart from geometric data, semantic

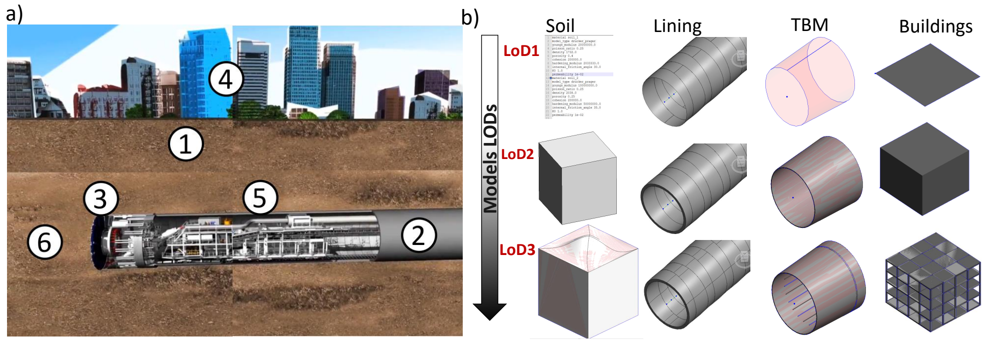

Figure 3: a) Main components of the urban tunnelling process: 1) soil, 2) lining, 3) TBM, 4) existing infrastructure, 5) grouting, 6) alignment; b) tunnel information model with components modeled on different LoDs: soil, lining, TBM and buildings

data can be represented on different LoD. Process parameters such as face pressure, grouting pressure or TBM advance rate are represented with a different LoD in terms of (i) the discretization of time steps for the TBM advance and (ii) negligence/consideration of time-dependent effects occurring during the tunnelling. The parametric families on different LoDs established in Revit are manipulated with custom nodes implemented in Dynamo, resulting in the BIM model as shown in Fig. 3b.

Combining all individual components (lining with its alignment and grouting, soil with excavation, TBM, and buildings), the complete Tunnel Information Model (TIM) is generated as shown in Fig. 4a and b. For each component, individual local parameters (characteristic for each individual component) are defined, however, there are also a number of parameters which are common for multiple components. Those parameters, such as ring length L_r, excavation radius r_{exc}, number of steps/slices, overburden, etc., are defined as global parameters (see Fig. 4a). Based on this data, the simulation model is generated subsequently. In order to generate the simulation model for tunnelling with identical geometry, material and process parameters, the generated TIM is exported by newly developed Dynamo nodes. The geometry of all individual components is exported in ACIS format. Each volume of each individual component is exported separately, in order to enable flexible manipulation with those volumes when assigning custom layer entities needed for numerical simulation. The semantics are exported to text files for each component separately, containing the local parameters, together with one main file containing the global parameters.

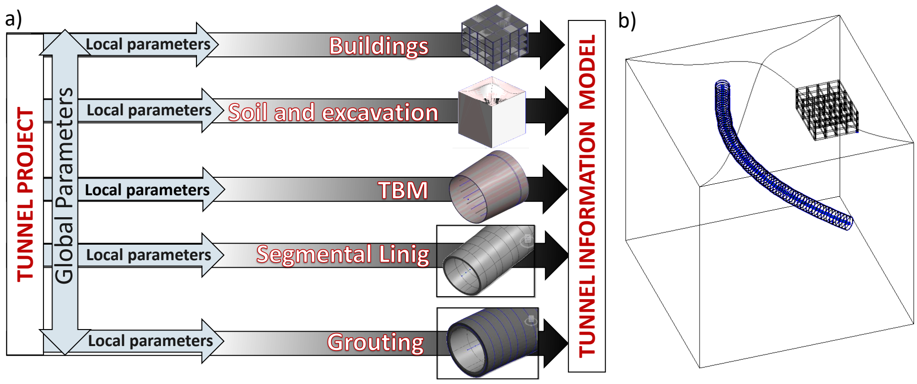

Figure 4: Tunnel information model: a) combining sub-models and their dependency on local and global parameters; b) complete tunnel information model

3 MULTI-LEVEL SIMULATION FOR THE SOIL STRUCTURE INTERACTION IN TUNNELLING

3.1 SATBIM Modeller

Based on the multi-level parametric TIM, numerical models for each component on each LoD are developed, considering proper geometric and material representation, interfaces, as well as the representation of the construction process. For the generation of numerical models, the fully automatic `SatBimModeller` for arbitrary tunnel alignment has been developed in Python. The modeller provides a high degree of automation for generation, setup and execution of the simulation model, connecting the multi-level TIM with the simulation software KRATOS and the GiD pre/post-processor. All information about the geometry, process parameters and material parameters obtained from TIM are used for the generation of numerical simulations for soil-structure interaction. The core of the `SatBimModeller` is a Python program, which reads all defined specifications of the model from ACIS files together with model, material and semantic parameters, and automatically generates an FE simulation model and a simulation script for KRATOS (see Fig. 5).

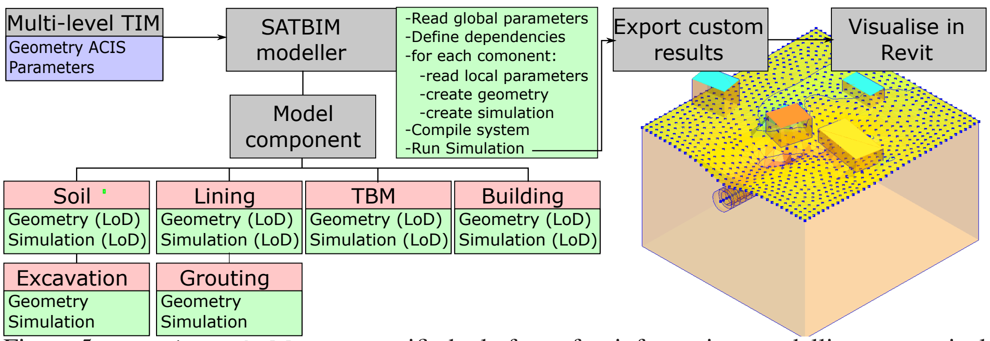

Figure 5: `SatBimModeller`: a unified platform for information modelling, numerical analysis and visualization of tunnelling-induced effects in Revit

The SATBIM software is organized in a highly modular way to provide high flexibility not only for further extensions, but also adaptions to any changes in the simulation software.

Moreover, the `SatBimModeller` allows to generate simulation output in a form which can be imported back into Revit for visualization of the soil-structure interaction effects induced by tunnelling. By doing that, the simulation results (e.g. settlements) and their impact on the existing environment (e.g. risk of damage) can be visualized within the TIM to enable a comprehensive, intuitive and quick understanding of effects of design actions on the stability and safety of the existing environment (see Fig. 5).

3.2 Numerical examples

In this section, simple numerical examples are presented to demonstrate the feasibility and the importance of our multi-level approach. In all examples, the numerical models are generated based on the TIM, i.e., make use of the complete SATBIM workflow. The first example (cf. Fig. 6) shows the difference in deformation of the tunnel lining between LoD 2 and LoD 3, using a subgrade reaction model, the simplest possible representation (LoD 1), for the soil. In both cases (lining LoD 2 and LoD 3), the same insitu soil dead load is applied,

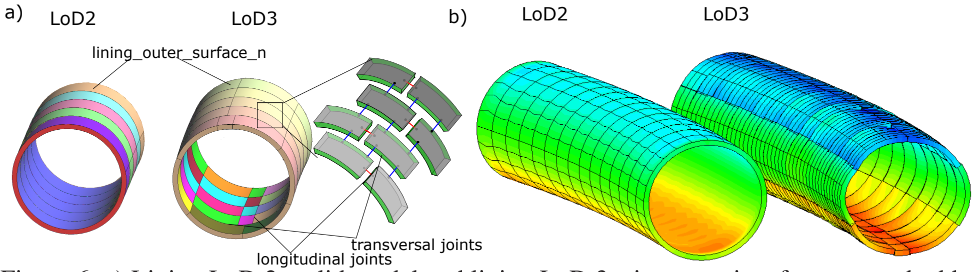

Figure 6: a) Lining LoD 2: solid model and lining LoD 3: rings consist of segments, bedded on elastic springs (soil LoD 1 in both cases); b) vertical displacements for the two different models

however, as expected, the response (Fig. 6b) of the lining modelled as a solid shell (LoD2) is much stiffer than of the lining modelled with segmented rings (LoD3).

In the second example, the LoD of a building is varied form LoD 1 (dead load from building weight acting on the soil surface) over LoD 2 (reduced models with a substitute elastic stiffness E, height H and weight ρ computed according to an approach proposed in [13]) to LoD 3 (full structural frame model), cf. Fig. 7a. For the simple representation of shield tunnelling, i.e. confinement and and support by lining structure without explicit modelling of the lining structure, the volume loss method is implemented, where the confinement is described with the volume loss coefficient $V_l = (V_0 - V_{def})/V_0 \cdot 100\%$. In this implementation of the volume loss method, after the deconfinement, the deformed area of the tunnel is continuously calculated at each computation cycle and deformations of the excavation boundaries are fixed when the volume loss value of the tunnel boundary is reached [7]. Figure 7b shows the effect of the choice of the LoD for the building, where the maximum settlements are obtained for building LOD 1 due to the negligence of the building stiffness in soil-structure interaction. In contrast, for building LoD 3, this effect is overestimated.

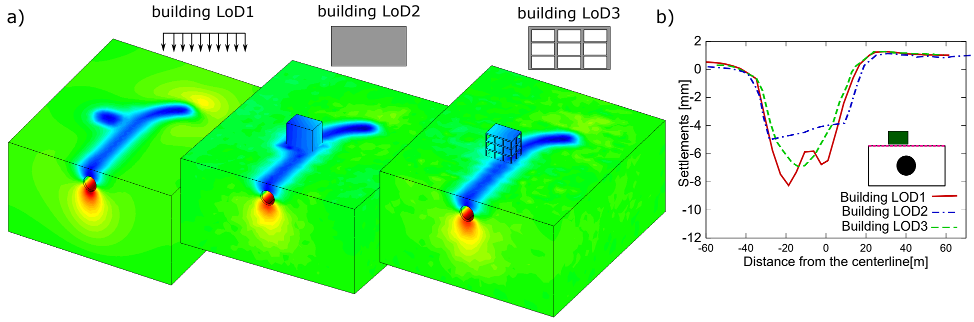

Figure 7: Effect of different LoDs of building on surface settlements combined with the volume loss method: a) geometry and vertical displacements; b) surface settlements

4 CONCLUSIONS

The current state-of-the-art tunnel design process is cumbersome and involves significant manual, time-consuming preparation and analysis as well as excessive computing resources. To ensure a seamless workflow during the design and the analysis, in this paper we proposed a novel concept of multi-level numerical simulations enabling the modelling on different level of LoDs for each physical component of tunnel construction process. We present SATBIM, an integrated platform for information modelling, structural analysis and visualization of the mechanized tunnelling process for design support. SATBIM enables practical, yet flexible and user-friendly generation of the tunnel structure for arbitrary alignments on different LoDs, supporting the design process and providing an insight into soil-structure interactions during construction. The multi-level information model for tunnelling is developed using the industry-standard tools Revit and Dynamo, allowing for consistent parametric modelling on different LoDs. The resulting TIM serves as a basis for the generation of numerical models for soil-structure interaction in tunnelling using the developed `SatBimModeller`. The numerical models are subsequently simulated in KRATOS, an open-source platform for finite element simulation. The simulation results can then be imported back and visualized in Revit. The numerical examples presented in this paper show the difference in the numerical predictions for different LoDs, and demonstrate the new possibilities offered by our unified platform.

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