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An integrated platform for design and numerical analysis of shield tunnelling processes on different levels of detail

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ABSTRACT

Building and construction information modelling for decision making during the life cycle of infrastructure projects are vital tools for the analysis of complex, integrated, multi-disciplinary systems. The traditional design process is cumbersome and involves significant manual, time-consuming preparation and analysis as well as significant computational resources. To ensure a seamless workflow during the design and analysis and to minimise the computation time, we propose a novel concept of multi-level numerical simulations, enabling the modelling on different Levels of Detail (LoDs) for each physical component, process information, and analysis type. In this paper, we present SATBIM, an integrated platform for information modelling, structural analysis and visualisation of the mechanised tunnelling process for design support. Based on a multi-level integrated parametric Tunnel Information Model, numerical models for each component on different LoDs are developed, considering proper geometric as well as material representation, interfaces and the representation of the construction process. Our fully automatic modeller for arbitrary tunnel alignments provides a high degree of automation for the generation, the setup and the execution of the simulation model, connecting the multi-level information model with the open-source simulation software KRATOS. The software of SATBIM is organized in a modular way in order to offer high flexibility not only for further extensions, but also for adaptation to future improvements of the simulation software. The SATBIM platform 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.

1. Introduction

Building Information Modelling (BIM) enables the design and analysis of complex, multi-disciplinary systems as often encountered in infrastructure projects and, in particular, tunnelling. Complex projects such as shield-driven tunnels in urban areas require demanding data management as well as analysis during the complete life cycle (design, planning, and construction).

Following the state-of-the-art in engineering practice, the design of a tunnel is assessed by analytical, empirical, or very complex numerical models. In recent years, extensive multi-disciplinary research has been carried out to promote the development and implementation of underground construction. Special focus has been put on the development of numerical models and design concepts to deal with the manifold complex interactions of the components and processes in mechanised tunnelling in urban areas. This allowed to move from empirical models for prediction of tunnelling-induced effects, which neglected the soil-structure interaction effects [1–3], to modern numerical strategies for the modelling of 3D interaction effects [4–6]. Combining sophisticated simulation models with machine learning tools enables predictions of tunnelling-induced effects and steering of the construction process in real-time [7].

On the other hand, in recent years, BIM has gained increasing attention in infrastructure projects, simplifying the planning and analysis and increasing productivity in design and construction. Although BIM was initially developed for managing building data during the building's life cycle, recently, the concept has been extended to enable the representation of subsurface construction and geo-related data, such as geological, hydrogeological and geotechnical objects and properties [8]. Moreover, the BIM concept has been used to create a tunnel information modelling framework that creates and interlinks a ground model, a tunnel lining model, a tunnel boring machine model as well as a built environ-

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ment model [9]. The most recent advances in BIM for infrastructure allow 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 [10].

Considering the fact that each project from its early design stage over construction to the operation phase requires both information management and numerical analysis, the need for a unified approach becomes evident. Currently, in engineering practice, the generation of numerical models based on tunnel design and reports (even when those are part of a BIM) requires demanding manual intervention of experts and is thus error-prone. In addition, the resulting simulations can incur substantial computational effort. Recently, the link between information and numerical modelling for modelling of structures has been addressed in [11,12] where the Finite Element (FE) method is used for the analysis of the structural behaviour of design alternatives generated in the BIM framework. Another example is the Analysis in Computer Aided Design (AiCAD) concept for integrated design and analysis of structural membranes, where Isogeometric Analysis (IGA) [13] is applied to non-uniform rational B-Splines (NURBS) surfaces, i.e. unmodified CAD geometry [14–16]. This approach fully exploits the benefits of geometrical definitions in design tools (NURBS surfaces) and makes use of basis functions from CAD for representing the geometry as well as the solution fields in IGA. Yet, for geotechnical problems, there is no generic link between BIM and numerical simulations. Some initial research in this direction has been presented in [17, 18], where data obtained from a Tunnel Information Model (TIM) [19] is applied for the generation of the numerical model for a real-world tunnelling project, namely the Wehrhahn metro line in Duesseldorf.

A unified integration of all information in one multi-level model not only facilitates technical design and construction aspects, but can also be employed in cost estimates, accounting, quality controlling, production management and, last but not least, in claim management for the project. For these economically important aspects, every investment in the configuration of the model and the supply of suitably processed data pays off as soon as any technical or contractual problem occurs and information needs to be retrieved fast and reliably. A seamless documentation along with clear definitions of times, locations and components of the tunnel are a prerequisite for that. To this end, the here proposed BIM can be linked to a process controlling system [20] in the construction phase of the project to allow for a real-time update of the project information.

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, as illustrated in Fig. 1. Moreover, both the planning and the design phase require data analysis, modelling, numerical analysis, and visualisation. These tasks are supported by Geographic Information Systems (GIS), BIM tools, and software for numerical simulation.

To carry out those tasks with high consistency when changing scales and modelling the components on different LoDs, a sound foundation for handling such multi-level representations is required. Multi-level modelling is already well-established in the GIS field [21], where most often the "bottom-up" approach is used, generalizing detailed models to more abstract ones [22]. Besides, multi-level modelling has become standard for modelling buildings [23,24] as well as an integral part of CityGML [25]. However, there is only a very limited number of examples where the multi-level approach is used to support the planning, design, and analysis of large tunnel projects [10].

Multi-level concepts naturally arise from the information quantity and flow at different project stages (planning, design and construction), allowing to build different LoDs from a low to high-detail representation. For example, the planning process typically provides only rough information in the early stages (low LoD), but increasingly detailed and fine-grained information in later stages (high LoD). The proof of design has to be conducted throughout all those phases. Nowadays those analyses are usually conducted using different models and software on different stages, and therefore the link between them is not generic and may suffer from inconsistencies. Therefore, multi-level concepts would be extremely useful in the context of numerical analysis for such projects.

To enable information and numerical modelling preserving the consistency of data on different LoDs, this paper presents SATBIM, a comprehensive platform for incorporating multi-level representations into BIM and numerical analysis. A particular focus of this paper is the link between *(i)* the geometric-semantic modelling of shield tunnels on different LoD, *(ii)* the numerical analysis and *(iii)* the visualisation of central results of the numerical analysis.

This paper is organised as follows: Section 2 introduces the concept for parametric multi-level information modelling as a basis for numerical analysis, giving an overview on the software architecture and the data flow. Section 3 presents the automatic modeller `SatBimModeller` for the generation of multi-level numerical simulations for soil-structure interaction in tunnelling based on the multi-level information model. Moreover, in Section 3, the visualisation of simulation results within the BIM design environment and our strategy for real-time design optimisation is introduced. Section 4 gives examples of integrated information and numerical modelling, demonstrating the capabilities of the proposed concept. In Section 5, we conclude, summarizing the central findings of this paper.

2. Integrated multi-level information and numerical modelling for design support

2.1. Multi-level parametric information and numerical modelling

2.1.1. The concept

Nowadays, large infrastructural projects require both information management and numerical analysis on different LoDs throughout the complete project life cycle. To facilitate the tasks of design, analysis and assessment of different design solution, SATBIM provides a unified platform for information and numerical modelling (see Fig. 2a). The central goal of SATBIM is to develop a multi-level simulation model for the tunnel-structure interaction integrated in the framework of BIM to support engineering decisions in the planning and design phase. This allows for the subsequent evaluation and minimisation of risks on existing infrastructure. Our approach also enables the general evaluation of the efficiency of such a multi-level simulation approach in other fields related to engineering design and risk assessment.

The appraisal of different design alternatives is essential for ensuring an optimal design alternative. The current state-of-the-art process for dealing with alternatives involves repeated manual changes of the simulation model, re-simulation of the complete model, and manual evaluation of the results. This is cumbersome, error-prone, and requires significant computing resources and time. Note that in the conceptual phase, a designer often only needs approximate estimations for many different scenarios, e.g. tunnel track alternatives. Moreover, different design objectives require different approaches for assessing the safety and stability. For example, minimising the overall risk of damage to buildings needs high LoD for structures and low LoD for lining, while estimating stresses in the tunnel structure needs high LoD for lining, while low LoD for buildings is sufficient (see Fig. 2b).

To ensure a seamless workflow, the analysis time should be minimised, i.e., the simulation model should be configured such