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Building information modelling based ground modelling for tunnel projects – Tunnel Angath/Austria

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ABSTRACT

The trend for digitalization in geotechnics and tunnelling of the past decade has been spearheaded by developments in building information modelling (BIM) within these disciplines. While many advances have been achieved, BIM ground modelling remains a challenge since the inherent heterogeneity and uncertainty of the underground are difficult to describe and to model. This paper presents a new concept and framework for ground modelling in BIM. A split of the BIM ground model into several "sub models" is proposed: the "factual data model", a "geotechnical model" and the "geotechnical synthesis model". The proposed BIM ground modelling concepts are based on – and in line with current international developments (e.g., DAUB / German ITA branch, or IFC Tunnel) and should serve as an example of how to approach BIM ground modelling for future projects. After presenting this theoretical context, the case study of the Austrian Tunnel Angath is given where state of the art BIM ground modelling was done in the planning phase of the project. Although the modelling for this project is seen as a success, it has highlighted several deficits that hamper the industry wide adoption of BIM in ground modelling: e.g., permanent data storage, editable model transfer and easy visualization of BIM ground models. It is nevertheless concluded that BIM ground modelling is beneficial for the tunnelling industry as it contributes towards more standardized and comprehensible working processes and an enhanced base for decisions.

1. Introduction

Being part of the global trend of digitalization, the past decade has seen a rapid increase in the interest in digital techniques for geotechnics and tunneling. Developments range from augmented reality, an increased use of scanning technology (laser-scanning / photogrammetry) and artificial intelligence to applications of robots and unmanned aerial vehicles inside tunnels (Marcher et al., 2020; Huang et al., 2021). One of these topics is building information modelling (BIM) and for example Borrmann et al. (2019) define it as "… a comprehensive digital representation of a built facility with great information depth. It typically includes the three-dimensional geometry of the building components at a defined level of detail. In addition, it also comprises non-physical objects, such as spaces and zones, a hierarchical project structure or schedules. …". BIM is therefore a way of modelling buildings digitally before their construction to detect flaws as soon as possible.

While the development of BIM is already far advanced in structural engineering, BIM in geotechnics and tunneling is currently seeing a rapid development and a transition from academic and pilot use cases to "real-world" applications and common practice. Despite general publications on BIM in tunneling (Daller et al., 2016; Berdigylyjov and Popa, 2019; DAUB, 2019, 2020; Kapogiannis and Mlilo, 2020; Huang et al., 2021; Ninic et al., 2021), several recent publications address specific aspects of BIM in tunneling such as "BIM to FEM" approaches (Alsahly et al., 2020; Fabozzi et al., 2021), settlements (Providakis et al., 2020, Providakis et al., 2021) and others (Ninić et al., 2020). Published case studies on applications of BIM for tunneling projects are for example

Abbreviations: BIM, Building Information Modelling; BIMGM, BIM Ground Model; IFC, Industry Foundation Classes; LOD, Level of Development; TA, Tunnel Angath; UAFm, Unterangerberg Formation.

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Cudrigh-Maislinger et al. (2020); Weichenberger et al. (2020); Wenighofer et al. (2020); Mitelman and Gurevich (2021); Wang and Zhang (2021).

Whereas there is extensive literature on different aspects of (engineering) geological 3D models from the past decades (e.g., Gong et al. (2004); Caumon et al. (2009); Horner et al. (2016); Erharter et al. (2021)), the specific literature about BIM ground models (BIMGM) is rather sparse with few examples (Kessler et al., 2015; Daller et al., 2016; Weil, 2020). While the above given publications mostly address specific technical tunnel related topics, the goal of the present paper is to focus on the geotechnical ground model as a part of the overall BIM coordination model of a tunneling project. We first present background information on the state of the art and current developments in BIM ground modelling on which the presented concepts are based (Section 2). In accordance with these developments, we then contextualize the BIMGM within a construction project's overall BIM structure and also within a project's life cycle (Section 3). Beyond that Section 3 addresses different possible use cases of the BIMGM. In Section 4, we present the concepts of selected "sub-discipline models" of a BIMGM which are then applied to the real-world case study "Tunnel Angath" (i.e., "Rohbaustollen Angath", Section 5). The paper is closed with a discussion of the presented BIM framework, its limitations and an outlook to future developments in Section 6. Supplementary material can be found in the end of the paper, where an example BIMGM is included as an.ifc file with a corresponding exemplary attribute list.

The concepts about BIM ground modelling presented in this publication were developed in the context of the herein described example and other real-world projects and the authors' involvement in two working groups on BIM ground modelling that are further described below (DAUB and IFC tunnel).

The rapid development of BIM in the past years has produced a vast amount of (sometimes redundant or even conflicting) terminologies and definitions. On the one hand this paper aims at using consistent and clear terminology but on the other hand an extensive glossary of definitions would be out of the scope of this study. References to synonymous terms are given throughout the text, but the reader is for example referred to Borrmann et al. (2019, pp. 575–578) for general BIM glossaries and to DAUB (2019, pp. 40–41); buildingSMART (2020, pp. 51–52); Molzahn et al. (2021) for BIM ground modelling / tunneling specific glossaries and terminology definitions.

2. Background

2.1. State of the art

Digital ground models became state of the art in infrastructure projects in the last decade, as an additional or alternative way to represent ground conditions. Databases and digital data exchange formats replace hard-copy documentation of factual data, i.e., observations and measurements that describe the conditions at certain locations. Several countries established a common practice and standardized formats, e.g. AGS (Bland et al., 2014) in Great Britain and several other countries or DIGGS (Cadden and Keelor, 2017) in the US. Conceptual data models e.g., by OGC (GeoSciML (OGC, 2017), GroundWaterML (OGC, 2021)) are frequently used in national geological surveys, infrastructure owners or other larger organizations that need to work with extensive geoscience-related datasets. The general application of"Engineering Geological Models" has recently been described by a guideline of the IAEG Commission 25 (see Baynes and Parry (2022) and Parry et al. (2014)) and can include digital 3D models (observational models), describing the expected distribution of relevant aspects in the model space, based on geological conceptual models and are used to derive geotechnical models for specific use cases. Traditionally, these models were described by reports, maps and sections which can now be linked to- and extracted from digital models.

Nevertheless, there are no commonly agreed standards for the digital exchange of geological and geotechnical data in infrastructure projects. In the last two decades, 3D ground models were implemented as a helpful and efficient tool, and many examples around the world are described in literature, e.g. for alpine tunnels (Cudrigh-Maislinger, 2018), Metro projects (Huang et al., 2022) and hydropower (Weil et al., 2019) and further developed in ongoing research projects (e.g. Gächter et al. (2021)) However, solutions and data structures for these projects were mainly developed independently by their authors and users of the models and do not follow detailed definitions of requirements by project owners. This implies frequently enormous efforts for digitalization, transformation and mapping of information between different formats and software.

In the "DACH countries" (Germany, Austria, Switzerland), the BIM method has been applied for many infrastructure projects in the recent years which was pushed by government agencies (BMVI, 2022) and large infrastructure owners, with the intention to establish the method as"common practice". Even though ground models were not a main focus in most cases, this development triggered a transition towards digital methods and 3D modelling being applied in the field of engineering geology and geotechnics.

With both the BIM method and digital ground models becoming more and more accepted, the demand for standardization and clear definitions is getting obvious. Many national and international work groups have formed to address these requirements and publish recommendations. Several initiatives are mentioned below, selected because the authors are personally involved, or their output was considered in the approach of the here presented exemplary project.

2.2. Current developments and standardization

All initiatives described below started with definitions of requirements and have different backgrounds: From focus on specific needs in tunneling (DAUB, IFC Tunnel) over the general field of geotechnics and earthworks (DGGT, IFC common schema covering geotechnics in IFC 4x3) to a more global scope considering interfaces to mining and resources, oils and gas, environmental and other geosciences (OGC). Work groups are formed by participants from federal agencies, infrastructure owners, consultants, contractors and software developers. The developed concepts vary from more general description of model structures, object catalogues and example property sets to detailed data models (e.g. in UML) and definition of extensive attribute lists representing the definitions in nation, EN and ISO standards for ground characterization and geotechnical testing.

- The German branch of ITA released recommendations for BIM in tunneling (DAUB, 2019) and model requirements (DAUB, 2020) that have been well-adapted by the industry. The latest recommendations in this series was published in autumn 2022 and covers geotechnics and ground models, with definitions of use cases, model structure and typical property sets elaborated by a work group of geologists, geotechnical- and tunnel engineers (DAUB, 2022). The model structure described below (Section 4) was developed based on work within this group.
- The German DGGT published detailed recommendations and concepts for model structures of geotechnical models. Data catalogues with definition of attributes and property sets have been published recently (DGGT, 2022), covering both factual and interpreted models (homogeneous areas (German: "Homogenbereiche") according to (DVA, 2016))
- The IFC standard format for the exchange of BIM models in OpenBIM environments is currently being extended to infrastructure models (buildingSMART, 2022), including tunnels. The latest released version IFC 4x3 already included a simple schema for interpreted geotechnical models and boreholes. In the course of the development of conceptual models for IFC tunnel, an extension of this schema is planned. This extension shall cover factual data (observations and

measurements) with links to existing exchange formats for factual data as well as different types of interpreted models, several concepts to treat uncertainty in the model and an extension of the IFC format to realize voxel representations. A focus is on the concepts to link the definition of expected ground conditions to the tunnel alignment/ design model as realized in the example model (described in Section 4). The German section of buildingSMART recently published literature and a similar schema in German language (Holsmölle, 2022).
- The Open Geospatial consortium (OGC) just launched an initiative to extend OGC schemas to geotechnical models (OGC, 2022), mainly driven by the French MINnD group. This initiative is coordinated with buildingSMART international and intends to maintain a common concept for the geology/geotechnics domain that is implemented by both IFC and OGC standards in the future. In addition, a collaboration with the International Society for Soil Mechanics and Geotechnical Engineering is expected, that has recently formed "Technical Committee 222 Geotechnical BIM and DT", as "a forum to ISSMGE members to disseminate and exchange knowledge and practice on BIM and Digital Twins in Geotechnics" (ISSMGE, 2022).

Based on so far published materials and discussions, it can be concluded that the above-mentioned groups developed similar concepts for ground models, even though differences in terminology, focus and presentation of the results exist.

3. Contextualization of the BIM ground model

Whereas the previous section presented background literature, state-of-the-art industry applications and government guidelines, this section sets the BIMGM into a hierarchical context within a project's bigger BIM model structure (Section 3.1) and within a building's life cycle (Section 3.2). Based on this, typical expectations for a BIMGM from the client's perspective are defined (Section 3.3).

3.1. Integration within the overall BIM structure

Following the proposed structure of DAUB (2020), the BIMGM is a "discipline model" and "contains specific information from the single specialist designer in charge of their discipline" (the discipline model of DAUB (2020) corresponds to the "Partial Model" of Borrmann et al. (2019)). It has to be noted, however, that a "BIM discipline model" does not necessarily contain all the available information but is rather a filtered and specifically prepared model to be integrated in the overall BIM (coordination) model. This can be compared to typical plan preparation, where finalized plan documents do not contain all "working data" that was necessary and gathered for their creation. The working model which is used by the modelling personnel shall only be called the "domain model" and it is usually not included in the final BIM model. The amount of information that goes from domain model to the BIM discipline model must be defined individually for each project based on necessary requirements of all involved parties and the long-term application of the BIM model.

The BIMGM represents one beside other discipline models in a tunneling project, such as excavation and support and systems. Hierarchically, the discipline model is located below the "Coordination Model" and above the "Object Groups" (Fig. 1). The discipline model itself can be subdivided into "sub-discipline models" which refers to a separation into contextually specific models (e.g., a factual data model, a geotechnical model, a hydrogeological model etc.) and into "sub models" which refers to geographically separated parts of one sub-discipline model (e.g., multiple sub-models for multiple construction lots of one bigger project).

3.2. The BIM ground model within the building life cycle

The BIMGM is subjected to constant change and update throughout a

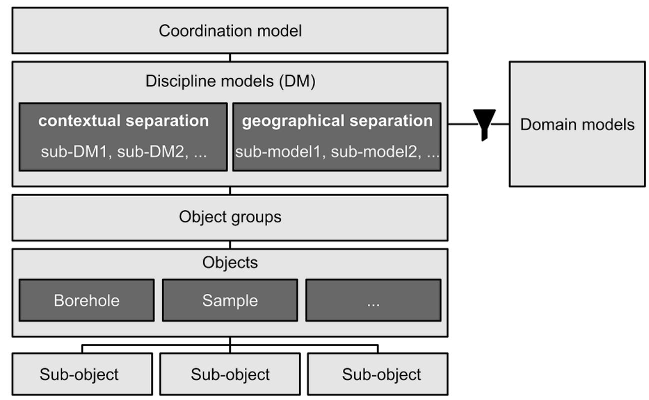

Fig. 1. Overall BIM Model structure (modified after DAUB (2020)). The BIM ground model is a discipline model which gets its input from domain models and can either be separated contextually into sub-discipline models and / or geographically into sub-models.

tunnel's life cycle and consequently also serves different use cases. Use cases in the design phase of a tunnel are for example: compilation of existing data and knowledge within one model, route selection, visualization and communication of complex ground conditions, coordination of different disciplines that address ground-related topics, estimation of excavation quantities, providing input for geotechnical assessments (e.g., numerical modelling), preparation of tender documents.

However, the BIMGM is not only a tool for the design phase of a project but should also serve different purposes throughout the rest of its life cycle. During construction, the BIMGM can be further used as a database for the collection and combination of the digital geological-geotechnical documentation from the excavation. It enables model-based comparison of expected vs encountered conditions with a "single source of information" and thus increases the efficiency of keeping and overview of the excavation progress.

During the maintenance and operational phase, both a BIMGM from the planning phase and one that documents the "as-built" state from the construction phase should be available to help identify, possible ground related damages that occur on the building with a time delay (e.g., long term settlements, fractures, unforeseen water ingress etc.). A future use case of BIMGMs is discussed in Erharter et al. (2022), which concerns knowledge derivation for future projects based on bigger BIM databases. Several of the here given use cases for a BIMGM are based on DAUB (2022) and further information on use cases can be found therein. A graphical representation of use cases of the BIMGM throughout a building life cycle is given in Fig. 2.

3.3. Expectations for the BIM ground model

The basic requirement for the BIMGM is that its information content (geometrical and metadata) is at least the same as in conventional / non-BIM based planning and in accordance with all current standards and guidelines. BIM based planning should not be an end in itself but create an actual benefit for the tunnel. The main purpose of the BIMGM in the planning phase of a tunnel is to ease the communication between different parties as it can serve as a central source of geological information. Based on that, every-one should be able to derive information as desired and lengthy coordination between planning companies with iterative generation of error-prone plans should be avoided (a discussion on the current limitations of visualization of geological data is given in Section 6).

Although geological 3D modelling has been done for several decades (see introduction) the uprise of BIM has pushed geological and geotechnical 3D modelling in civil engineering. Therefore, BIM ground modelling is often expected to increase the quality of the geological prognosis. In reality, the geological 3D modelling and 3D visualization

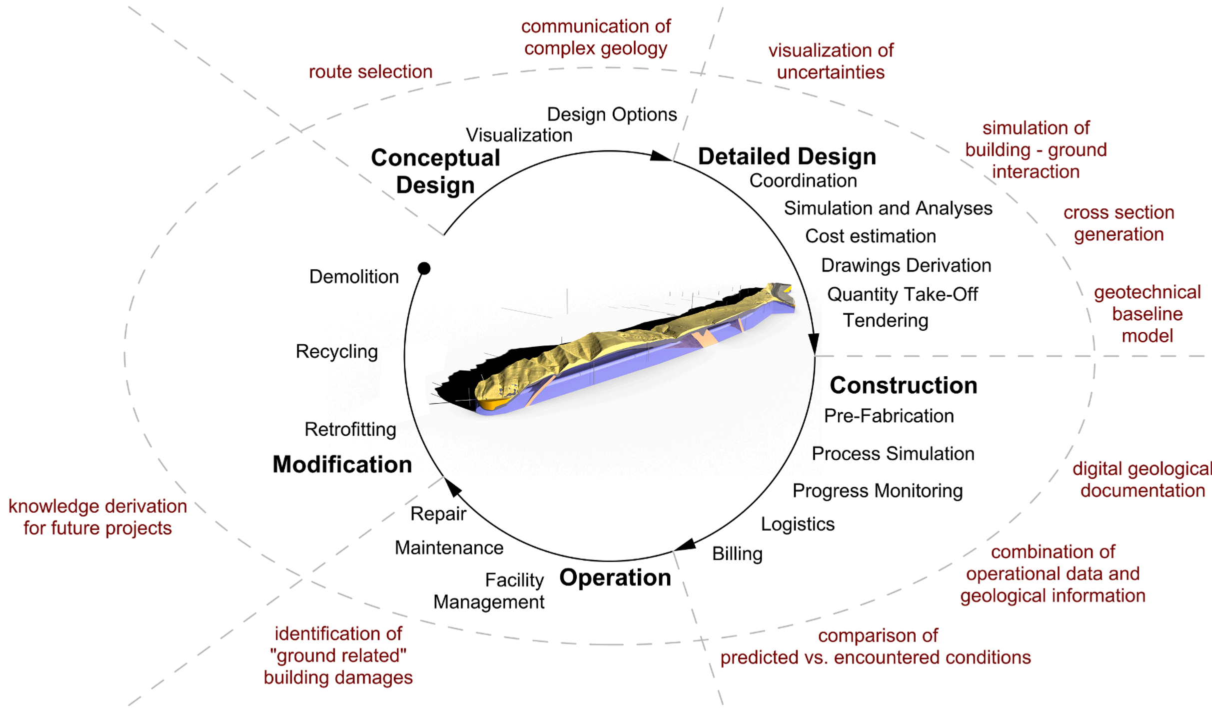

Fig. 2. Inner circle: BIM – lifecycle modified after Borrmann et al. (2019, p. 5); Outer circle: possible applications of the BIM ground model throughout the whole lifecycle of a building.

of buildings within the geology help all involved parties to get a better understanding of complex conditions and thus increase the value of the geological model. On the other hand, it must be noted that geological 3D modelling can only improve the previously mentioned aspects of a geological prognosis, but it is as dependent on the quality of the engineering geological investigation as conventional geological planning.

In the context of modern tunnel construction contracts like design and build contracts or alliance contracts (Deutschmann, 2021; Karasek, 2021) BIM based planning has the advantage that it can help to communicate the totality of complex ground conditions better to potential contractors than classical 2D based planning does. Geotechnical baseline conditions and the included uncertainty/expected variations that are described e.g. in a "geotechnical baseline report" according to FIDIC Emerald book can be represented in a ground model. With delivering a BIMGM as well as domain models (native formats and software – see Section 3.1 and Fig. 1) the complete geotechnical and geological information can be included but also represented in a well manageable format.

4. BIM ground model – Sub discipline models

4.1. Overview

As given in Section 3.1, the BIMGM can be separated into several sub-discipline models. In this section, three selected sub-discipline models are presented: the Factual Data Model, the Geotechnical Model and the Geotechnical Synthesis Model. It has to be noted that the three presented sub-discipline models do not represent the overall best approach to a BIMGM but are the models that were created for the planning phase of the case study of "Tunnel Angath" (TA) which we will present in Section 5. For the TA the chosen approach fitted the requirements, but different projects might call for a different choice of sub-discipline models.

The basic distinction between not-interpreted or "factual" models (here the factual data model) from interpreted models is supported by all work groups mentioned in Section 1.1 and is in line with the classical approach of data exchange and reporting (e.g. Geotechnical Data Report vs Geotechnical Interpretive Report and Geotechnical Baseline Report according to FIdIc Emerald Book (FIDIC, 2019)). In addition to the sub-discipline models mentioned above, several others – especially interpreted models – are conceivable in the context of BIM ground modelling (e.g., a hydrogeological model, material recycling model etc.). For example, it is recommended to have a geological model ready before a geotechnical model is created (Parry et al., 2014), but in the project reality it is not always necessary to implement each sub-discipline model as a BIM model (even though it may exist in the native domain model).

A BIMGM must always be accompanied by a geotechnical report that describes its purpose, concept, modelling approach and classification that is represented by it. It can either replace other documents like longitudinal- or cross sections or can be used to extract them. Technical details of the implementation of the BIMGM should be given in the BIM Execution Plan – BEP.

In this paper's supplementary material, an exemplary BIMGM is given as an.ifc file (IFC 4X1) including all three sub-discipline models (factual data model, geotechnical model, geotechnical synthesis model). The BIMGM is accompanied by an exemplary list of model objects and attributes, defining the BIMGM's semantics as given in the begin of a project in the BEP. An overview visualization of the exemplary BIMGM is given in Fig. 3 and further information on this is given in the subsequent subsections and Section 5. The content of the exemplary model is only for representative purpose and not directly based on the real BIMGM of the tunnel Angath.

4.2. Factual data model

The factual data model represents the BIM version of the content of a "Geotechnical Data report". In the planning phase of a project, the factual data model contains the information that has been collected during site investigation (e.g., borehole data, results from in-situ and lab testing, geophysical investigations, documented outcrops). During construction, the scope of the factual data model is extended to serve as a database for documented geotechnical observations (e.g., tunnel face mapping, collected samples from the investigation etc.). The exact line

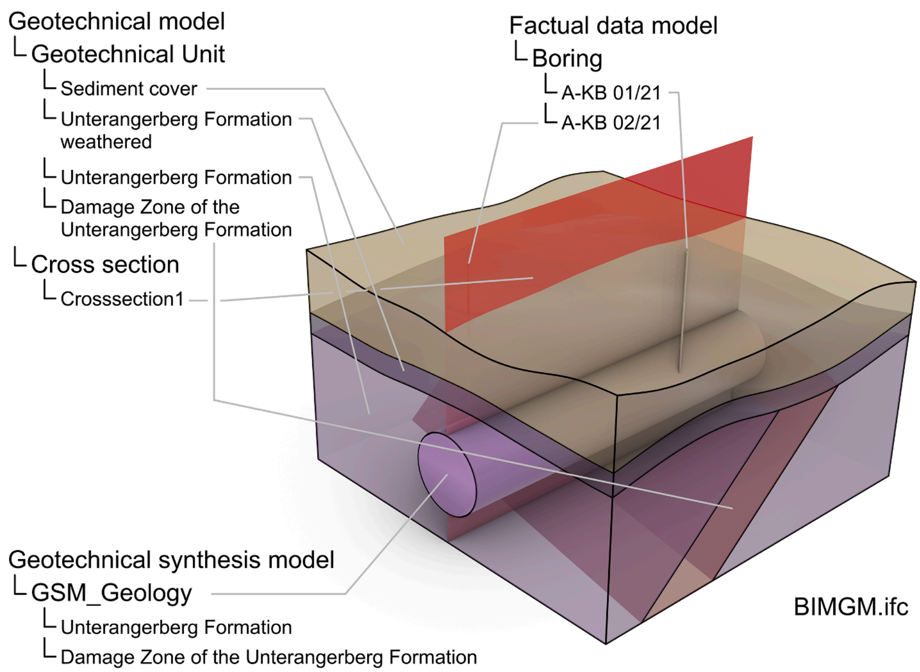

Fig. 3. Visualization of the exemplary BIM ground model that is provided as supplementary data to this publication (BIMGM.ifc). The model contains all three sub-discipline models: Geotechnical model, factual data model and Geotechnical synthesis model including an object specific attributation.

between "factual" and "interpretation" is not clear, as any description of natural material implies a certain degree of interpretation. The same applies to deriving geotechnical parameters from measurements during tests. In this context, the limit is usually set according to data exchange points like submitted information from laboratory, contractor for drilling and in-situ testing or field geologist.

4.3. Geotechnical model

In contrast to the factual data model, the geotechnical model is an interpreted sub-discipline model as its content is fully based on processed information from the factual data model and interpolation between points of confirmed information. The geotechnical model is derived from an engineering geological, conceptual model for a specific purpose, like e.g., tunnel design in a certain project phase. It represents volumes of homogeneous properties which are called geotechnical units. These geotechnical units can be separated from each other with volumes or with boundary surfaces only. In the latter case, however, it has to be specified exactly if the boundary surfaces represent upper or lower boundaries for the respective geotechnical unit (see also buildingSMART (2020, p. 67)).

In cases of high investigation densities, well-known ground conditions and / or high-resolution models, the attributes of the geotechnical units can comprise specific information concerning for example the general geology (geological formation, lithological characterization etc.) or mechanical properties of the ground (e.g., density, friction angle,

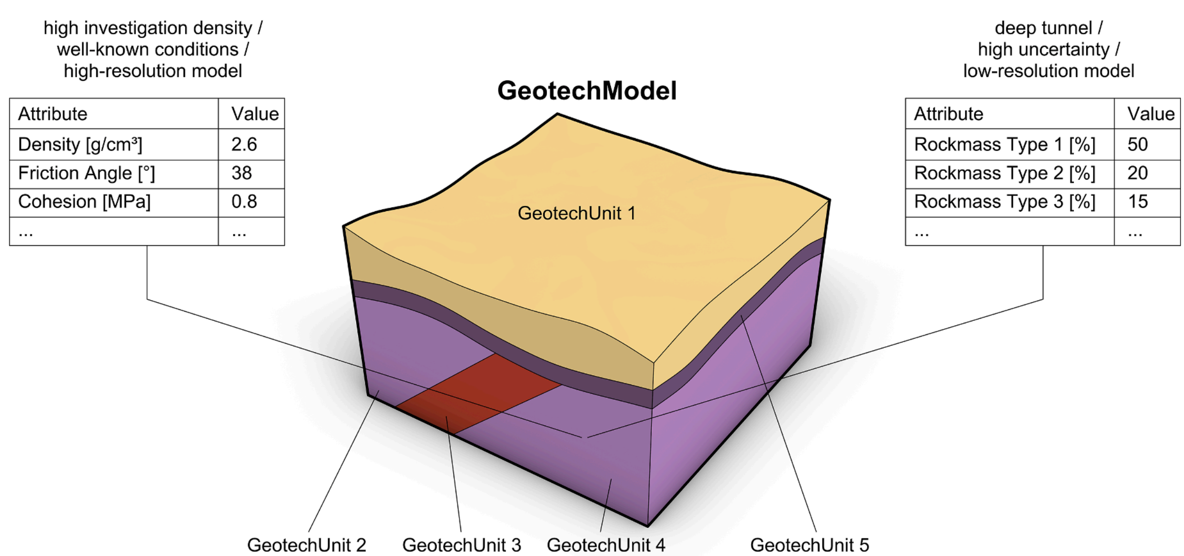

Fig. 4. Concept of the BIM-geotechnical model with five exemplary geotechnical units. The left attribute box shows exemplary attributes for a geotechnical model with well-known ground properties; the right attribute box shows exemplary attributes for a geotechnical model without exact knowledge of the distribution of ground properties.

cohesion etc.). In case of deep tunnels, where an exact localization of geotechnical properties is often not possible (ÖGG, 2021), a high degree of uncertainty and / or a generally low resolution model has to be produced, the geotechnical units' properties can be made up of distributions of ground classifications (e.g., rock mass types, Q-classes, etc.). In Fig. 4, the concept of the geotechnical model with multiple geotechnical units is visualized and also two examples of attributes are given.

Uncertainty related to geological investigations or interpretations can be represented within the model either via attributes (i.e. qualitative or quantitative description) or also via the geometry itself by e.g. modelling different likelihoods of boundary surfaces between geological units. Dealing with the topic of uncertainty itself is however in principle not different in BIM ground modelling in comparison to conventional engineering geological modelling (Weil, 2020).

4.4. Geotechnical synthesis model

The geotechnical synthesis model contains all the 1D information along the tunnel that is usually communicated with longitudinal sections (Fig. 5). The geometry of it can be as simple as a tube along the tunnel axis, that is split into multiple sections of homogeneous properties. The name "Geotechnical Synthesis model" was developed in the IFC tunnel work group as a working term and is used for a sub-model that contains the essence of the other sub-models in relation to a certain building or design structure, like e.g., a tunnel tube and its alignment. Developed during the design phase of a tunnel, it is used as an interface to the model of the planned building, especially the planned excavation and support structures that interact with the ground.

One important function is to consider the uncertainty in the prediction of geological structures and geotechnical conditions to be expected along the alignment. It follows a common approach in tunneling: the definition of "homogeneous sections" along the alignment with characteristic, similar geotechnical conditions and expected ground behavior; usually defined for certain chainage intervals and documented in a longitudinal section (Fig. 5). Such plan documents are commonly used as the basis for definition of excavation methods, support types, ground improvement and other measures, and the estimation of quantities, advance rates etc.. This is a common way to document the contractual basis of expected ground conditions.

The intervals of the "Geotech Synthesis model" quantify or rate the relevant geotechnical aspects. These aspects can be described in the other sub-discipline models (geological, geotechnical, hydrogeological model) which allows to extract the relevant information from there. This can comprise e.g.:

- the expected distribution of geotechnical ground types
- discontinuity properties
- groundwater conditions
- geogene hazards, contaminations and other aspects

Based on this condensed information with reference to the tunnel, the designer can define solutions and "answer" with a design-prognosis model, including:

- planned excavation methods
- expected distribution of support types
- expected additional measures for ground improvement, health and safety, logistics etc.

Explicit geometric modelling of complex geological structures such as discrete fracture networks (see e.g. Pan et al. (2019)) can be valuable for specific use cases (e.g., finite element modelling) with high resolution models for local-scale building structures and surrounding ground. For long and large buildings like kilometers of tunnel, it is considered more appropriate to include the information on typical discontinuity orientation and conditions in the attributes of the model. For this reason, discontinuities like joints and faults are characterized in the subject example model by special attributes of the geotechnical synthesis model, describing the typically expected conditions for each individual tunnel section.

5. Case study tunnel Angath

In this section, a discrete project implementation of the above given BIM concepts will be presented. The case study concerns the BIMGM of the "Tunnel Angath" (TA, in German: "Rohbaustollen Angath"), which is located in the "lower Inn valley" in the Austrian federal state of Tyrol. The TA runs through the "Unterangerberg", which is a smooth plateau that rises around 150 m above the valley bottom and has a maximum elevation of ~ 680 m.a.s.l.. The river "Inn" confines the Unterangerberg to the South and the nearest city to the project is "Wörgl".

The TA is part of route section "Schaftenau – Radfeld" within the *trans*-European railway connection Berlin – Palermo and is also part of the northern access to the Brenner Base Tunnel. Within this route section, the TA is a side tunnel South of the main railway tunnel and will be

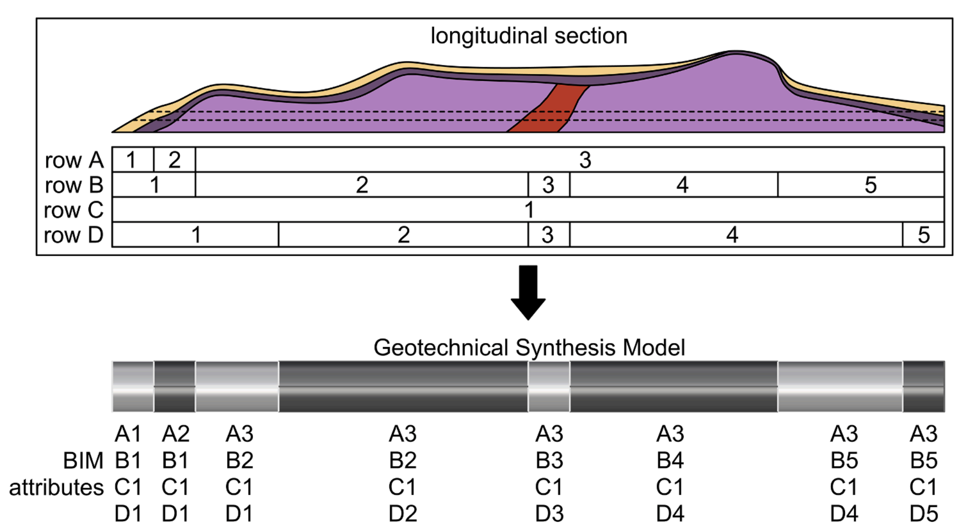

Fig. 5. The concept of the Geotechnical Synthesis Model as the BIM based version of a "classical" tunnel longitudinal section. The rows A-D in the longitudinal section stand for real properties such as rock mass types, permeability, lithology etc.

constructed in advance to the main tunnel tube. There are planned to be six connecting tunnels between the TA and the main tunnel. A special access road to the construction site has to be built for the project. An overview of the tunnel project, the BIMGM model extent (see subsection 5.2) and locations of nearby exploratory drillings are given in Fig. 6.

5.1. Engineering geological overview

The Unterangerberg, where the TA is to be excavated, comprises geological conditions that are demanding for the planning phase (Erharter et al., 2019) and for the excavation. The tunnel will be excavated in the bedrock of the "Unterangerberg Formation" (UAFm), that features a rugged bedrock surface with pronounced WSW-ENE striking gullies and ridges that are covered by glacial sediments (Poscher et al., 2008; Sommer et al., 2019). The UAFm is part of the "inneralpine Molasse" and is made of prodelta sediments, deposited into marine basins which are also affected by synsedimentary deformation (Ortner and Stingl, 2001; Ortner, 2003). The lithology of the UAFm consists of an alternation of claystone/marl and sandstone with layer-thicknesses between few millimeters and several centimeters. The rock is therefore highly anisotropic due to the low uniaxial compressive strength of around 25 MPa. It can be classified as a "hard soil – soft rock" material (Kanji, 2014). The rock mass of the Unterangerberg is intersected by several zones of tectonic disturbance with increased occurrence of fault zones. Located between the bedrock and the glacial cover is a zone of heterogeneous weathering up to 35 m thick (Erharter et al., 2019).

The cover of glacial sediments above the UAFm consists mostly of fine to coarse grained glaciofluviatile to glaciolacustrine deposits (Ilyashuk et al., 2022). In the area of the portal of the TA, there are mostly fluviatile sediments of the Inn valley, consisting of sandy to gravely river deposits under a layer of topsoil with high organic content. The portal is also located in close vicinity to the highway "A 12 – Inntalautobahn", which is why extensive anthropogenic deposits and remodelling of the landscape is expected in this area.

5.2. Structure of BIM ground model

In order to meet different use cases of the BIMGM, three sub-discipline models were created as they were presented in Section 4. An overview of the three models is shown in Fig. 7.

For the 3D modelling and attribution of the BIM elements of this case study, a combination of different software packages was used (Table 1) in the example project of TA. Similar ground models can be created with alternative software products that are available on the market and commonly used by the industry.

Export and data exchange are done in the.ifc data format in the latest available version at the time of modelling (IFC 4x1). Since there are no suitable classes (BIM Types) for ground modelling yet, all objects are classified as "BuildingElementProxy". To still be able to have some classification of the object types and to ensure more clarity in the IFC viewers when examining the BIMGM, and to differ between the three sub-discipline models, the objects have been assigned to "buildings" and "stories" similar to structural engineering projects. Three "buildings" were created for the three sub-discipline models, as seen in Fig. 7, with the individual objects assigned to their own "stories". Table 2 shows the applied allocation of the "story" to the corresponding "building". It must be noted that this is a workaround, as a result of the current state of technology which does not allow for the creation of custom classes / object types.

Some IFC viewers allow additional sorting by using classification systems. For the TA project, a user defined classification system was created with classes analogue to the previously defined "stories" and

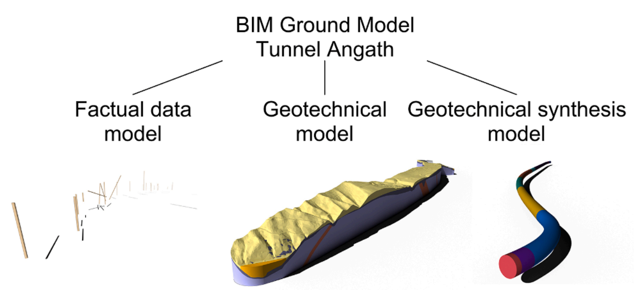

Fig. 7. Structure of the BIM Ground Model of Tunnel Angath.

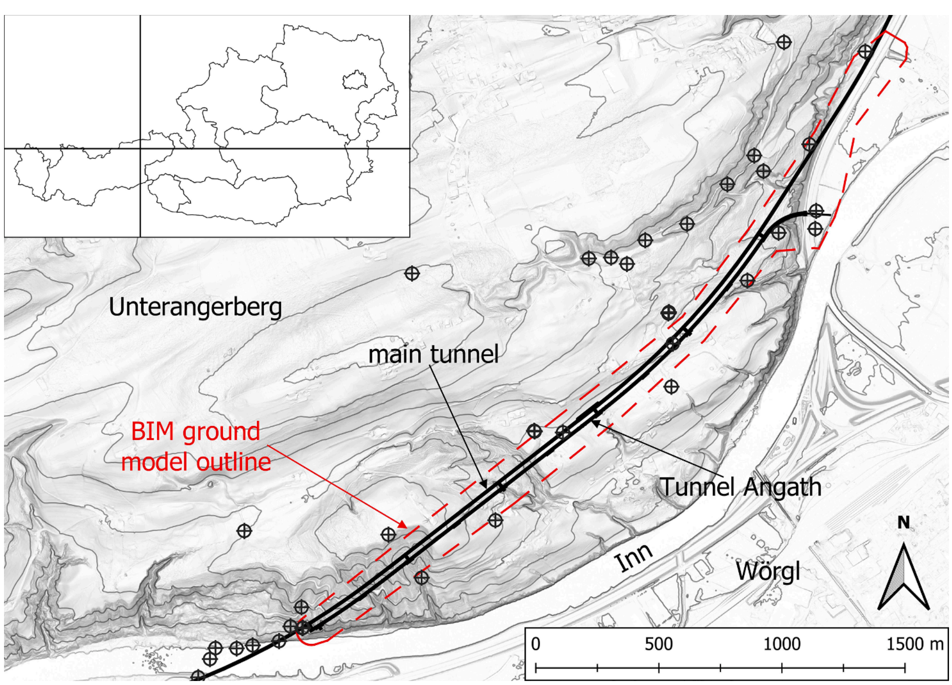

Fig. 6. Geographical overview map of the planned Tunnel Angath. The minimap in the upper left corner shows the project location within the Austrian Federal State of Tyrol. Crosshairs show locations of exploratory drillings.

Table 1
Used software for the BIM Ground Model of the Tunnel Angath.

Software (developer)	Version	Use-case
MOVE (Petroleum Experts)	2020.1	Geological 3D modelling
Rhino (Robert McNeel & Associates)	6.34/ 7.8	Computer aided design and platform for parametric modelling with Grasshopper
Grasshopper (Robert McNeel & Associates)		Parametric modelling of volumes and boreholes
BricsCAD BIM (Bricsys NV)	22	Data modelling and attribution of the final geometries

Table 2
Classification of the BIMGM into "Building" and "Stories".

Building	Associated Stories/Classes for the Classification System
Geotechnical model	Geotechnical unit
	Cross section
Geotechnical synthesis model	GSM_Geology
	GSM_Discontinuity
	GSM_Water
	GSM_Gas
	GSM_Swelling
Factual data model	Boring

each object was assigned a class. An exemplary BIMGM with the described classification methods can be found in the supplementary material of this paper.

The three sub-discipline models of the BIMGM consist of objects that are modelled from geometries with associated attributes. To ensure that the information content / semantics of the BIMGM are fully understandable for other involved companies, an attribute list was developed from the start of the project that assigns attributes to each object. These attributes were created as user defined PSets with the data modelling function of BricsCAD BIM. A simplified attribute sheet for exemplary purposes can be found in the supplementary material of this paper.

To fulfill all requests from the client and other planning companies it was agreed that the BIMGM should horizontally cover an area of at least 60 m around the TA, the connecting tunnels to the main tube and the access route to the construction site (see red dashed line in Fig. 6). The lower boundary of the BIMGM was set to 440 m.a.s.l., as the lowest point of the TA is at 473.75 m and it was the goal to have the model extend at least 30 m below the lowest point of the tunnel. Considering a possible application of the BIMGM for numerical / finite element modelling, the model extent was based on the suggestions of EANG (2014) who recommend a model extent around the tunnel of 4–5 tunnel diameters horizontally and 2–3 tunnel diameters vertically.

5.3. Sub discipline models

For the geotechnical model (GM), homogeneous areas with the same geotechnical properties were modelled as 3D volumes. The volumes are provided with the percentage distribution of individual rock mass types (see Section 4.3) as well as further geological information. For each volume, 5 rock mass types with associated attributes can be defined. The following attributes can be added to each rock mass type in the GM:

- Identification of the rock mass type
- Volumetric percentage of the rock mass within the volume
- Associated description
- Link to a data sheet with further geotechnical parameters

To link the geotechnical units of the geotechnical model with associated data sheets of the rock mass units, relative paths were given in the attributes of the volumes. The datatype of these relative paths is a "string", but – depending on the used IFC-viewer – the paths can be directly used to access further.pdf files from the BIM model. To create these, relative paths are inserted starting from the location of the IFC file to linked files or folder paths. An example for a relative path to a linked drill log is shown in Fig. 8. In addition, an example of how to access a superordinate folder is shown.

Fig. 9 shows an exploded view of the geotechnical model. The model consists of 17 volumes which represent individual geotechnical units of the TA. The topmost geotechnical units comprise the following sediments: anthropogenically modified sediments, top-soil and deposits from the river Inn, quaternary cover of the Angerberg (yellow, white and orange colors in Fig. 9 and Fig. 10). Below these several geotechnical units represents either weathered or unweathered Unterangerberg Formation (purple and dark-purple in Fig. 9 and Fig. 10) or different zones that are subjected to tectonic deformation (orange in Fig. 9 and Fig. 10).

Additionally, 10 cross sections were generated to provide a convenient view for pre-defined longitudinal, transverse or horizontal sections through the tunnel. In the attributes of the cross section relative paths to 2D section plans are added.

According to Section 4.4, the geotechnical synthesis model is the representation of a classical tunnel longitudinal section. For the representation, a model is created which is modelled as a segmented 3D model with a simplified, representative tunnel shape. In individual tunnel sections, information about gas or water ingress, interface information, etc. is represented. If varying information (e.g., A, B, C, D from Fig. 5) are combined within one synthesis model, many small sections result in the model. To avoid excessively small and complex sections, several geotechnical synthesis models are created for the different data. Doing this is a trade-off between having as few models with a maximum of information as possible vs user friendliness and readability of the whole geotechnical synthesis model which is increased if there are multiple models for different categories of information. For the TA, 5 such models were created:

- Geology: consisting of 9 sections with distributions of different rock mass types.
- Discontinuities: consisting of 4 sections with the prediction of discontinuity properties such as their orientation.
- Water: consisting of 12 sections with water ingress forecasts and predicted water pressures.
- Gas: consisting of 3 sections with forecasts of gas inflows.
- Swelling: consisting of 2 sections with forecasts of swelling phenomena.

In the respective geotechnical synthesis models, different attributes are added depending on the type of information. For example, the type, azimuth and angle of interfaces are defined in the model "discontinuities".

The factual data model represents uninterpreted facts - see Section 4.2. For the TA project, 36 boreholes were modelled. For better visibility, the boreholes were modelled as cylinders with a diameter of 1 m. In the attributes, further information such as start and end of drilling, water level and a link to drilling log files were given. Fig. 10 shows a rendering of the BIMGM with all three sub-discipline models. The volumes of the geotechnical model correspond to the exploded view that is given in Fig. 9.

6. Conclusion and outlook

In the previous sections, a new concept of BIM ground modelling was presented that is based on - and in accordance with recent developments from different international working groups. The BIMGM of the TA was shown as a case study for a "real world" implementation of these concepts. For this case study, the concepts worked perfectly fine and also the chosen software pipeline has proven to be sufficiently versatile and flexible to produce the desired products.

We want to emphasize, however, that on the one hand the presented

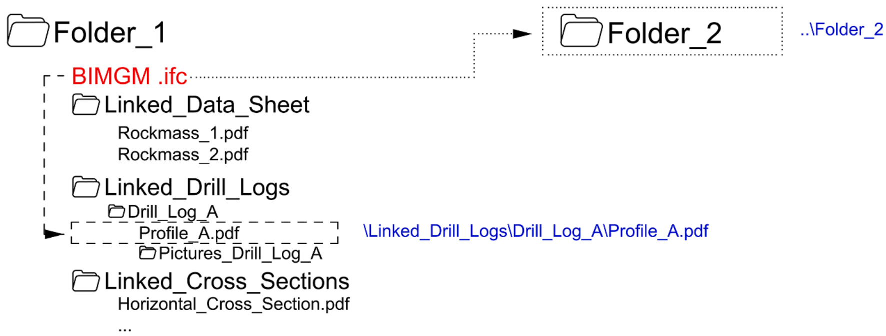

Fig. 8. Examples of relative links to folders or files (blue) from outgoing ifc (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

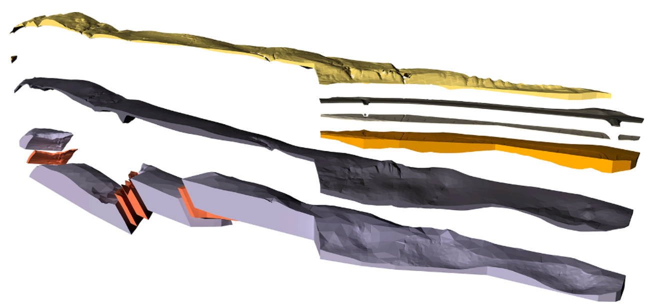

Fig. 9. "Exploded" view of all Geotechnical Units of the Geotechnical Model of the "Tunnel Angath". Fig. 10 shows a "non-exploded" version of the model.

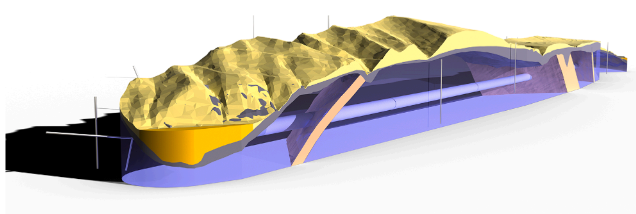

Fig. 10. Rendering of the BIM ground model of the "Tunnel Angath" with all three sub-discipline models: geotechnical model, geotechnical synthesis model, factual data modell. For an "exploded view" of the geotechnical model see Fig. 9.

concepts and their implementation should be understood as a "snapshot" of the currently ongoing, fast developments in this field. On the other hand, the paper should also serve as a guideline and example to ease the entry into the world of BIM ground modelling for practitioners with little BIM experience.

Despite many current efforts to push the boundaries of BIM ground modelling, there are several topics that need improvement which can also be seen as limitations of the current approach. While there are first attempts to establish the concept of the Level of Development (LOD; see for example Borrmann et al. (2019, p. 10)) for the tunnel (DAUB, 2019), there are currently no accepted standards that propose a LOD for the ground model itself. DAUB (2022) presents certain granularity levels for ground modelling but this also has yet to proof its practicability. This deficit might be connected to the comparably high degree of uncertainty in ground models and also to the fact that every ground model is unique and project specific. Nevertheless, general guidelines on this topic are desirable from a client's perspective (to be able to come up with clear and assessable calls for BIMGM bids) but also from the perspective of the modelling company which can benefit from comprehensible descriptions that explain well what the client wants.

Another challenge is seen in the IFC format for ground modelling. In the current state of IFC, custom properties have to be manually defined for every project which is laborious and error prone. Furthermore, BIMGMs that are saved as IFC files are not usable for further modelling as few geological / geotechnical software packages can deal with it directly but still rely on their own proprietary file formats. This is also problematic when BIM models should be connected to geographical information systems, which are widely used in geology and the infrastructure sector but hardly ever fit for BIM implementations. Considering the (often highly praised) application of BIM models throughout the whole life cycle of buildings (Section 3.2), it is especially questionable for infrastructure projects with planned life times of more than 100 years, if models from the planning phase will be usable several decades later when long term – possibly ground related – damages occur on the building.

Owed to the current state of technology, easy visualization of geological information based on a BIMGM is a challenge today. Although a BIMGM can contain the exact same information as a conventional 2D geological tunnel section, the information on the 2D section literally "catches one's eye" and is easily readable, whereas the information in the BIMGM must be looked for and found. This might be a minor visualization problem but can be the source of miscommunication and errors and should be solved by more advanced viewing technology that is specialized on displaying tunnel-related geological information.

We also identify another challenge in the required level of software skills that BIM ground modelling demands. Standard university education hardly ever involves applied courses on geological 3D modelling, or even BIM modelling. The demand on the personnel is therefore increasing as knowledge of a whole set of software packages and possibly different programming languages is required to produce state of the art BIMGMs. The shown case study demonstrates well how one has to be able to establish a whole software pipeline as there is not one single program that can fulfill all requirements.

Whereas current developments of BIM for ground modelling are often focusing on the planning phase (as in this study), the next years will show how well BIMGMs can be integrated into the construction phase of a project. It has yet to be proven that economic benefits arise when BIM models are used for automatic "as-planned" vs "as-built" comparisons and that the model of the "planned geology" can easily be updated with information from the excavation.

Lastly it should be noted that although there are several needs for improvement, BIM ground modelling has benefits for the whole field of geotechnics as it forces people to establish standardized procedures for things that have been solved by "in-house" or custom solutions for many years. The high degree of standardization that BIM demands should be seen as an opportunity to make geotechnics internationally more transparent and comprehensible and thus improve this industry's standard as a whole.

CRediT authorship contribution statement

Georg H. Erharter: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Jonas Weil:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Lisa Bacher:** Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing, Visualization. **Frédéric Heil:** Resources, Supervision. **Peter Kompolschek:** Resources, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

A link to the data was shared at the "Attach Files" step and within the "Supplementary material" section of the paper.

Appendix A. Supplementary data

"Attribute_list.pdf" and "BIMGM.ifc" can be downloaded from: Link to TU Graz Repository.

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