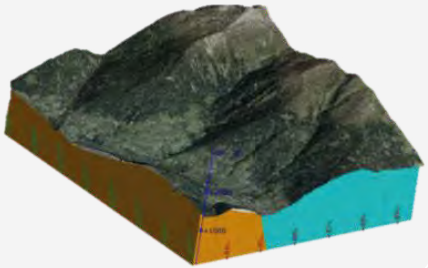
Digital
Ground Model



Recommendation
Digital Design, Building and Operation of Underground Structures

Model requirements – Part 3

Ground Model

Supplement to DAUB recommendation BIM in Tunnelling

DAUB-Working Group

Deutscher Ausschuss für unterirdisches Bauen e. V.
German Tunnelling Committee (ITA-AITES)

Recommendation
Digital Design, Building and Operation of Underground Structures. BIM in Tunnelling
Model requirements – Part 3: Ground Model
Supplement to DAUB recommendation BIM in Tunnelling (2019)

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For reasons of readability, the simultaneous use of feminine, masculine or neutral forms of language is dispensed with in the following and the generic masculine is used.

All references to persons apply equally to all genders.

Preamble

To ensure sustainable use of the many sources of information in infrastructure construction, it is necessary that attention is also paid to digitalisation in underground construction.

Recommendations of the German Tunnelling Committee DAUB usually provide „best practice" solutions for underground construction in Germany and/or projects with German involvement. Digital applications are just beginning to be implemented in underground construction projects. Thus, recommendations given in this document reflect the experts' practical experiences in early usages and are meant to foster standardization in construction.

The DAUB recommendation „Digital Design, Building and Operation of Underground Structures – BIM in Tunnelling" **[1]** published in May 2019 was produced with the objective of providing a basic understanding of the application of BIM in tunnelling. Based on this recommendation the Model requirements Part 1 **[2]** were released in the following year explaining a basic understanding of the model structures and providing uniform descriptions for typical objects in tunnelling and the associated object information.

While elaborating further model requirements the current paper describes, as Part 3, the specification of ground conditions by using a digital ground model, whereby particular requirements of tunnelling works are considered accordingly. The recommendation comprises both structural reflections for organizing the model including related information and insights into initial usages of digital ground models in practice.

Even a positive return of investment can hardly be quantified by balancing costs and benefits of implementing BIM, this paper is additionally meant to show potential savings and a related return of invest when using digital ground models.

The recommendation starts with an introduction and a short survey of the current situation in practice. The following reference is made to the first recommendation, issued in May 2019, by describing the contribution of the ground model to the listed use cases there. "Requirements of Ground Model Authoring" (cf Chapter 4) can be seen as the principal chapter of the recommendation. This is followed by fields of action for further developments and a short outlook on different aspects of the role of the ground model.

It is to be expected that this recommendation will be successively revised in the coming years to suit further developed experiences and requirements.

This recommendation is published together with additional recommendations (Part 2, Part 4 and Part 5). Reference is mostly made to part 2.

For overview purposes all recommendations published thus far are listed as follows:

BIM in Tunneling	**05/2019**
Model requirements Part 1: Object definition, coding and properties	06/2020
Model requirements Part 2: Information Management	08/2022
Model requirements Part 3: Ground Model	08/2022
Model requirements Part 4: Derivation of model based Bill of Quantities	08/2022
Model requirements Part 5: Allowance of tolerances and superelevation	08/2022

1 Introduction

1.1 Initial situation

The advantages of using the BIM method, as they are highlighted in various publications on BIM in infrastructure construction, have thus far been mainly projected onto the planning and construction of buildings. However, in underground construction, one cannot focus solely on the structure itself, since the ground or subsoil, including the groundwater conditions, must always be seen as part of the entire structure. When using BIM, the recording and description of the ground leads to the digital ground model, which has recently attracted more and more attention. For its implementation, different boundary conditions and rules must be considered compared to building modelling **[7]**.

The classification of the ground model as part of the “Survey of existing situation” use case, as most recently done by the “Masterplan BIM Bundesfernstraßen” from Autumn 2021 **[7]**, and the assignment of this use case exclusively to service phases 1 and 2 (according to HOAI) do not adequately reflect the importance of the ground. In every consideration, all project requirements must always be kept in mind over the entire project life cycle.

The need for a conscientious exploration and modelling of the ground is obvious, as this data has a significant influence on the location of the structure, its possible dimensions and manufacturing processes. The expenses incurred during the implementation of the structure in terms of costs and construction time are directly related to the (hydro)geological and geotechnical conditions in the project perimeter and must be taken into account over the entire duration of the project.

The digital, object-based ground model should be structured in the same way as the building model in order to be able to use both models, along with other models, as separate domain models when creating a coordination model for an underground construction project.

Therefore, it is advisable to set up a structure with (partial) objects, including the associated properties for the geometric and informal representation of the ground, which is compatible with the structure of the building model or the coordination model.

The following two figures (**Figure 1-1**) clearly compare the requirements on modelling the ground in comparison to the structure. The two images can be used to compare different aspects of the object classification and object structure, as known from building modelling (**Table 1-1**).

Another important aspect to note is that the initial ground model (preliminary design) is created at a point in time when the project space is known, but there are still no defined building alignments for the planned construction.

There are also differences in the description of the properties of the objects depicted in the model. If the properties of the building, such as material properties or load limits, can be specified with sufficient accuracy, the characteristic values for describing the ground are subject to certain scatter ranges.

1.2 Scope and Target Audience

With the present recommendation, all project participants in underground construction should be addressed. With respect to the recording of the ground, it is a good idea to already apply the presented fundamentals in the first considerations of the planning of an underground construction project. The generated

Figure 1-1 *Comparison of modelling requirements – building on the left (photo: Implenia/Bernd Schumacher), ground on the right (photo: Implenia)*

Table 1-1 *Comparison of the object structures "Building" and "Ground"*

Aspect	Building model	Ground model
Geometry	clear geometric shapes (even though the portal entry is a bit more complex)	geometries with irregular structures that are difficult to define
Expansion	it is known after how many meters the tunnel resurfaces at the other portal	it is difficult to define how far a geological unit actually extends
Number	the number of objects can be determined (handrail, side walls, tunnel blocks, shoulders, ...)	it is unclear how many faults or fissures occur in the observation area and, thus, describe the geological units
Localization and orientation	objects can be clearly located along the tunnel/track axis	georeferenced arrangement of objects; selectively distributed or spatially extended, irregularly arranged

ground model will provide an essential contribution for decisions and documentation during the project execution for all further project phases, from planning to construction and the operation phase. The conscientious maintenance of the ground model should be carried out consistently throughout all phases.

1.3 Delimitations

The statements in this recommendation focus on the special requirements for the description of the ground during the construction of underground structures. These high requirements require a very extensive and detailed recording and description of the (hydro-) geological/geotechnical conditions and can, therefore, require more effort to draw up a ground report compared to constructions from the special civil engineering.

2 Current Implementation

2.1 Traditional method

Traditionally, to describe the geology, a baseline survey is carried out by using existing data (e.g. geological maps, comparative sections) and by collecting new information gained from project-related exploration. These results are submitted as geotechnical and geological baseline reports – including appendices. The scope and the level of details correlate with the design phase. To summarize and visualize the information and insights, geological longitudinal sections are used.

2.2 Purpose of digital ground description

The traditional method causes problems if the data exchange is not performed digitally. "Digital" encompasses not only the exchange of reports but primarily the administration of information and models via a document management system throughout the construction lifecycle.

With the growing digitization in underground construction, interfaces and adjustments are required for a more efficient and transparent use of ground information – for all parties involved. An information and collaboration platform is unavoidable from start to finish of the project. This platform functions as a so-called "single source of truth".

This in turn leads to the following advantages from the engineering geologist perspective:

- Improved overview of available data
- Less effort of data processing
- Better understanding of the ground due to simultaneous consideration of all information in the model
- Simplified creation of high quality and consistent 3D interpretations allowing for blurring (see **Chapter 4.7**).

In addition, the project and all stakeholders benefit from the following advantages:

- Improved communication of complex geometry via 3D modelling
- Simplified variation studies
- Improved predictions
- Multi-phase information and collaboration platform (single source of truth)

However, to achieve these benefits, there are still challenges to be addressed when managing the project:

- Lack of experience in applying the method (e.g., increased effort to set up systems)
- Using existing software solutions for target-oriented task processing
- Establishing the necessary acceptance by stakeholders (keyword "change management")
- Identifying existing solutions and how they can be applied to the current task

These aspects may involve additional work during the transition phase. But as BIM training progresses and with the development of a routine, this extra effort will decrease in the long term.

3 BIM use cases involving the ground model

Various BIM uses cases are described below for specific project phases, for which the ground model makes a contribution. The enumeration is based on the uses cases already listed in the DAUB recommendation "BIM in underground construction" **[1]**. Currently, 2D planning is still the basis of most construction projects, especially with regard to the approval phase, and is taken into account accordingly in the following. A selection of future use cases is presented in the outlook. For an overview, the applications are listed in **Table 3-1** with the corresponding chapter number.

It is explicitly pointed out that standards, guidelines, and classification schemes have the same validity for BIM use cases as in non-BIM-based planning. The appropriate sets of rules must therefore be selected on a case-by-case basis.

3.1 Design preparation

The ground model is one of the central models in the planning preparations, because it shows the existing geological conditions and thus significantly supports the decision-making process for the location, design (geometry, technology) and the manufacturing process of the structure to be realised.

Table 3-1 *BIM use cases overview*

Chapter	Project phase/BIM use case
3.1	**Design preparation**
3.1.1	Survey of existing situation
3.1.2	Digital ground modelling
3.2	**Design**
3.2.1	Investigation of design variants
3.2.2	Visualisation
3.2.3	Geotechnical evaluation and dimensioning/ verification
3.2.4	Coordination of specialist's design
3.2.5	Progress control of design work
3.2.6	Production of preliminary design and design approval
3.2.7	Health & safety and environmental protection
3.2.8	Design approval
3.2.9	Cost estimation and cost calculation
3.3	**Construction preparation**
3.3.1	Bill of quantities, tendering, award
3.3.2	Partially automatic production of bill of quantities
3.4	**Construction**
3.4.1	Construction scheduling
3.4.2	Logistics planning
3.4.3	Production of construction drawings
3.4.4	Construction progress control
3.4.5	Change management
3.4.6	Invoicing of construction works
3.4.7	Defects management
3.4.8	As-built documentation
3.5	**Operation**
3.5.1	Use for operation and maintenance

3.1.1 Survey of existing situation

Description	▪ Acquisition of existing ground models ▪ Model-based preparation of ground-relevant documents displaying existing conditions (e.g., boreholes, inventory models, geological maps, etc.) ▪ No existing artificial structures are included in the ground model. Other parts of the existing conditions model include present cavities, buildings, soil improvement measures, embankments, etc. as well as contaminated sites and explosives
Goals	▪ Creation of the basis for further ground-related project work ▪ Creation of input variables for subsequent use cases (e.g., planning variant analysis)

3.1.2 Digital ground modelling

Description	▪ Collection and presentation of all (hydro)geologically and geotechnically relevant data over the entire course of the project ▪ Use of the data as an input variable for further applications ▪ Continuous updating of the model as knowledge is acquired
Goals	▪ Creation of a model-based, consistent database of the current information status for all project participants for transparent and cooperative project management ▪ Recording and visualisation of possible or actual (hydro)geological and geotechnical units, taking into account interpretative uncertainties

3.2 Design

3.2.1 Investigation of design variants

Description	▪ Definition of exploration programs or their supplement ▪ Analysis of variants based on ground models ▪ Conflict analysis geometrically and across different domain models - e.g., with underground infrastructure - e.g., protected areas
Goals	▪ Comparison of different planning variants based on the ground model for decision-making purposes ▪ Definition of variants for further detailing in the following planning phases

3.2.2 Visualisation

Description	▪ Visualisation of the geological conditions to support planning ▪ Presentation of the explorations on which the ground model is based (locally verified findings) and the geological/geotechnical units (continuum) derived from them
Goals	▪ Visualisation of the spatial relationship between structure and ground ▪ Public involvement ▪ Optimisation of coordination with internal and external project participants ▪ Display of forecast uncertainties ▪ Visualisation of probes and probing results

3.2.3 Geotechnical evaluation and dimensioning/verification

Description	▪ Transfer of geometric boundary conditions and input parameters from the ground model for the structural design of underground structures ▪ Calculation and visualisation of various (hydro)geological/geotechnical scenarios using the respective sub-discipline model
Goals	▪ Increase in the effectiveness and support of the structural engineer, considering geotechnical boundary conditions ▪ Feedback of new insights into the model to sharpen the forecast security

3.2.4 Coordination of specialist's design

Description	▪ Merging the respective sub-discipline models (e.g., geological model, hydrogeological model, etc.) together with the building model in a coordination model ▪ Examination of the assignment of tunnelling classes to the homogeneous areas (cf. **Chapter 4.3.2** and **Chapter 4.3.4**) ▪ Examination of the uniform use of the information from the ground model by the individual domains (consistency of the design basis and construction methods)
Goals	▪ Risk minimisation through early coordination of all domains ▪ Minimisation of design and construction conflicts with special consideration of the interaction ground – structure ▪ Increase in transparency

3.2.5 Progress control of design work

Description	▪ Status of the exploratory work and description of the ground ▪ Checking of the exploration phases (preliminary, main investigation according to Eurocode 7) and model versions
Goals	▪ Illustration of exploration and modelling progress ▪ Use in project management to compare with the project schedule

3.2.6 Production of preliminary design and design approval

Description	▪ Design and approval documents (e.g., geological longitudinal sections, profiles, reports) are derived from the ground model ▪ Creation of 3D views to support the approval process
Goals	▪ Ensuring consistent design documents ▪ Ensuring design that conforms to standards and quality

3.2.7 Health & safety and environmental protection

Description	▪ Consideration of safety-relevant aspects in the ground model, in particular geogenic influences (e.g., gases, temperature, quartz content, heavy metals, etc.) ▪ Analysis of working conditions ▪ Protection against contamination ▪ Consideration of aspects relevant to environmental protection (restricted areas, hazardous substances) in the models
Goals	▪ Identification and illustration of spatial and temporal dependencies of security-relevant aspects ▪ Basis for the development of security concepts ▪ Definition of treatment and disposal concepts (soil and water)

3.2.8 Design approval

Description	▪ Enhancement of 2D documents with 3D views, as long as plan reviews are still done “on paper“. ▪ Use of 3D models at public hearings ▪ Ideally, checking on the model
Goals	▪ Simplified approval through illustrations on the model

3.2.9 Cost estimation and cost calculation

Description	▪ Model-based and structured determination of quantities ▪ The ground model provides the relevant information for estimating the production effort (geometry, tunnelling classes, construction methods, material, difficulties, risk profiles, etc.)
Goals	▪ Identification or illustration of geometric and temporal dependencies or boundary conditions (ground – structure interaction) ▪ Improved analysis of project risks

3.3 Construction preparation

3.3.1 Bill of quantities, tendering, award

Description	▪ Determination of relevant quantities based on model-based design and geological forecasts that are shown in the ground model ▪ Creation of the ground model as a contractual basis ▪ Visualisation of the ground conditions for the group of bidders (illustration of the ground report)
Goals	▪ Development of the ground model with a realistic assessment of the likely interactions as a contractual basis and basis for future target/actual comparisons ▪ Determination of tunnelling classes and other boundary conditions to describe the tunnelling process (e.g., difficulties)

3.3.2 Partly automatic production of bill of quantities

Description	**Direct application:** - Model-based determination of quantities of excavated or excavated volumes **Indirect Applications:** - Delivery of the basis for the creation of BoQ-items of tunnelling works (excavation, securing means, obstacles, etc.) - Addition of items that cannot be derived directly from the model (e.g., hardship allowances)
Goals	- Provision of information from the ground model for the creation of bill of quantities items including quantities

3.4 Construction

3.4.1 Construction scheduling

Description	- Use of the information from the ground model to validate the excavated tunnelling areas, taking geological synthesis described into account - Extrapolation of the findings to future excavation sections
Goals	- Creation and refinement of tunnelling forecasts and durations, considering the naturally caused scattering of the soil parameters on which the ground model is based

3.4.2 Logistics planning

Description	- Basics for planning the professional treatment or disposal of the excavated material and any ground and process water (technology, space requirements, transport routes, …) - Derivation of possible geological/geotechnical scenarios underground that have an impact on the working conditions (rock burst, gas, temperature, dust, etc.) and for the control of which special logistic measures may be required
Goals	- Provision of information from the ground model relevant to logistics planning (transport and disposal concepts (soil and water), occupational safety) and localisation in the respective excavation sections

Due to its relevance the use case “logistics planning“ is explained in more detail at this point.

The ground not only has a decisive influence on the construction of the underground structure, but also on how the structure is constructed and how the excavated material is processed. These aspects specify the substantial boundary conditions for the logistics to be set up and must therefore be taken into account when planning them. The consideration of the feasibility of the logistics concepts and their effects on time and costs can be decisive for the project.

The information from the ground model should enable a statement to be made as to which working conditions are to be expected underground and which measures must be planned for and implemented to control them. Forecasts of the temperature and the expected dust development relate, for example, to the concepts for the ventilation (pressure, suction) including any cooling to be used or the use of machines and conveyor belts or additional equipment required. In the same way, any possible occurrence of gas must be considered and will require further measures for the usage of machines and occupational safety.

The ground model provides information about the excavated material to be expected and its properties. This information can be included in a disposal and recycling concept that may have to be drawn up. This concept then determines which material can be processed and reused. The remaining material is to be disposed of/deposited. In this context, there are tasks related to storage capacities, transport routes and landfill sites, which should or must be solved by the time a project is approved at the latest.

These aspects can be recorded by one or more separate sub-discipline model(s) (see also **Chapter 4.3**).

3.4.3 Production of construction drawings

Description	▪ Illustration of the expected ground conditions in longitudinal and cross-sections when creating construction drawings ▪ Construction drawings for carrying out special soil improvement measures
Goals	▪ Ensuring consistent planning documents

3.4.4 Construction progress control

Description	▪ Documentation of the actual geology to update the “Bauzeitenmodell” (construction period) ▪ Comparison of the forecast and actual excavated tunnelling or drilling classes for each section to validate future tunnelling progress
Goals	▪ The immediate and transparent identification of deviations between the anticipated and encountered ground conditions (if not immediately, then in a timely manner) ▪ Validation of projected completion dates

3.4.5 Change control

Description	▪ Recording of the excavated ground conditions that have been encountered and a comparison with the anticipated rock parameters
Goals	▪ Documentation of deviations in the ground for forecasting ▪ Delivery of the basis for any necessary technological adjustments and measures

3.4.6 Invoicing of construction works

Description	▪ Using the model to document the ground conditions that have been encountered as a basis or to check the plausibility of the billing of excavation services, taking into account the associated time-dependent costs
Goals	▪ Increase in transparency and cost certainty ▪ Clear documentation on the model

3.4.7 Defects management

Description	▪ The occurrence of defects can be related to the existing ground conditions (interaction ground – structure)
Goals	▪ Supplying background information for the assessment of defect incidents

3.4.8 As-built documentation

Description	▪ Creation of the ground model after construction with the help of all technical documentation (e.g., photographs of the tunnel face, water ingress, etc.) ▪ Updating the forecast model
Goals	▪ Compilation of the current status in a complete documentation model (= fact model) ▪ Adaptation of the interpretation models according to the ground conditions encountered ▪ Handover of the documentation and interpretation models (geometry and/or information on rock parameters) to the client, if necessary, the operator and the responsible authorities

3.5 Operation

3.5.1 Use for operation and maintenance

Description	▪ Documentation of the existing ground conditions ▪ actual data of existing conditions for other adjacent projects ▪ If necessary, adapting the content to the information required for the operating phase and maintaining it
Goals	▪ Fast and intuitive access to available digital information

4 Requirements of ground model authoring

The digital ground model serves as a visualisation and as an information storage for the knowledge gained in the process of project development and updating. It does not replace the geotechnical report or the structural tunnelling report but provides the necessary descriptions and explanations. Other documents (analogue/digital) can be referenced to the model and its objects (e.g., borehole photos, laboratory reports).

Since the model provides a variety of bases for the further planning steps, it should be created with an appropriate lead time.

4.1 Structure of the ground model

The general structure of the model shall provide an understanding of how the main content that makes up the ground model is organised and how it is divided between different sub-models and how these relate to one other.

According to the DAUB recommendations **[2]** (Model Requirements Part 1) the ground model is to be understood as an independent domain model which is situated in the hierarchic level below the BIM-Coordination Model and above the Object Group.

It is composed of several sub-discipline models, each representing different contents and aspects of the ground in terms of underground construction **(Figure 4-1)**. These sub-discipline models can be generally distinguished into the Geological Documentation Model or GeoDocu Model, which is a factual model, and into several interpreted models such as the Geological Model, Geotechnical Model, Hydrogeological Model, and the Geotechnical Synthesis Model. Data collection for the factual model is mainly done during the ground investigation phase and later during the construction phase as part of the regular ground verification and documentation process. The interpretation of factual data is required for the design and the prediction of the expected ground conditions and is continuously updated with the gathering of as-built as well as the data actually encountered during execution. The different varieties of models will be described in the following chapters.

Thematical structuring of the different models allows for differentiating the information contained in the model between factual information and interpretative data. This reflects the approach that is followed in the German speaking countries' (D-A-CH region) normative regulations and standards for the preparation of geotechnical interpretative reports, where a strict differentiation between factual and interpreta-

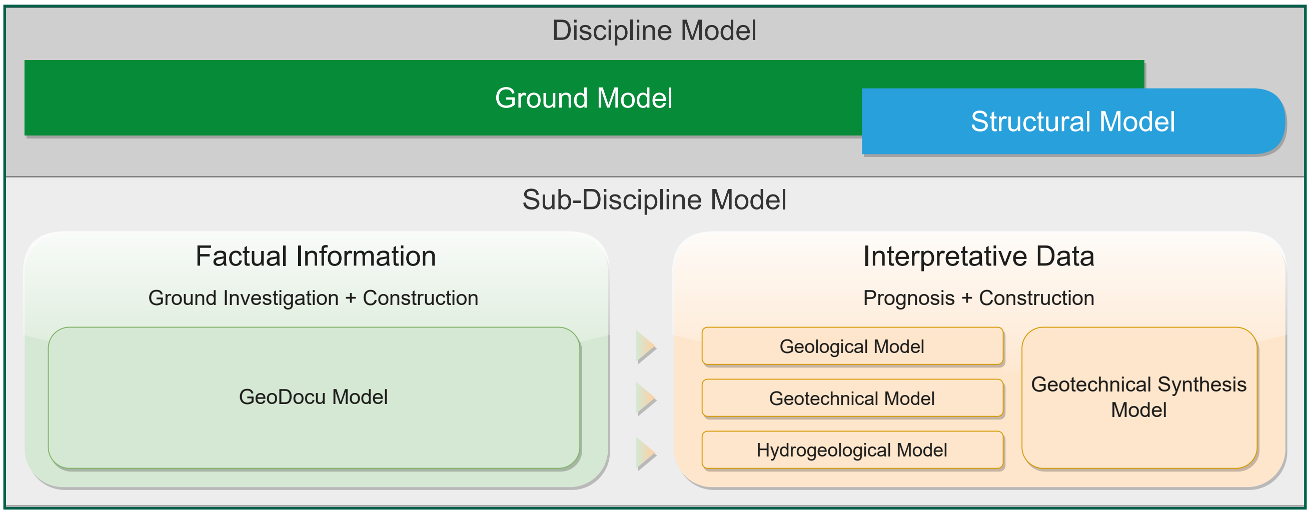


Figure 4-1 *Structure of the domain model "Ground"*

tive data is mandatory (see DIN 4020 **[8]**, SIA 199 **[9]**, ÖGG-Guidelines **[10]**.

4.2 The GeoDocu Model

This sub-discipline model (**Figure 4-1**) includes all utilised data and measurements which are typically considered as factual data and which form the basis for the ground modelling process. They are composed of legacy and published data from different sources, e.g., official maps or data collected during construction or operation of existing underground structures. The major source though, is data arising from geotechnical investigations for the project at hand (mapping, boreholes, laboratory and in-situ testing). Further input and upgrade to the GeoDocu Model is not restricted to pre-construction phases because the ongoing data collection and documentation during the construction phase provides additional data.

In reality, though, the utilised data is not entirely factual in a strict sense. A basic amount of interpretation is often required during construction, data processing, and documentation of ground investigation campaigns. Moreover, ground related data that is collected by geologists during investigation campaigns or qualitative rock mass ratings and characterization of the ground are inevitably subjected to a certain degree of interpretation.

Therefore, the qualitative and textual information of this sub-discipline model is composed of basic interpretative assumptions (e.g., allocating the encountered borehole lithology and sections to a geological unit).

For easier differentiation between data that is allocated to the factual GeoDocu Model and data that will be added to the interpreted models a definition shall be applied. Factual data is considered to be all data that is acquired or described as a value or characteristics in the sense of a measurement or identification of a property at a given location and time. Following this definition, the data and descriptive information that is gathered during the mapping of a tunnel face shall be added to the GeoDocu Model. Accordingly, there is substantial data added to the factual model during the construction phase. Main sources for this data come from surveying and monitoring, regular geological documentation and other ongoing measurement campaigns undertaken during construction.

The factual information should be linked to the interpreted models (see **Figure 4-2** and **Chapter 4.3**) by adding a certain interpretative property to an object at the factual side (e.g., the interpretative property "Geotechnical Unit" is added to the object borehole or tunnel face area). The relationship applied between the GeoDocu Model being the factual model and the interpreted model is exemplarily shown in **Figure 4-2**.

4.3 Interpreted models

While preparing the interpretated models, the engineering geologist evaluates, summarises and interprets factual data and extrapolates it to the continuum underground space. Within the domain of interpreted models, the Geological Model, Geotechnical Model, and the Hydrogeological Model are the most commonly used or considered mandatory parts of a ground model. Each of those models characterises and assesses the project underground space within the model's boundaries and according to the specific topic. They are referred to as sub-discipline models and shall be outlined with respect to sub-models which are delineating a specific area or location.

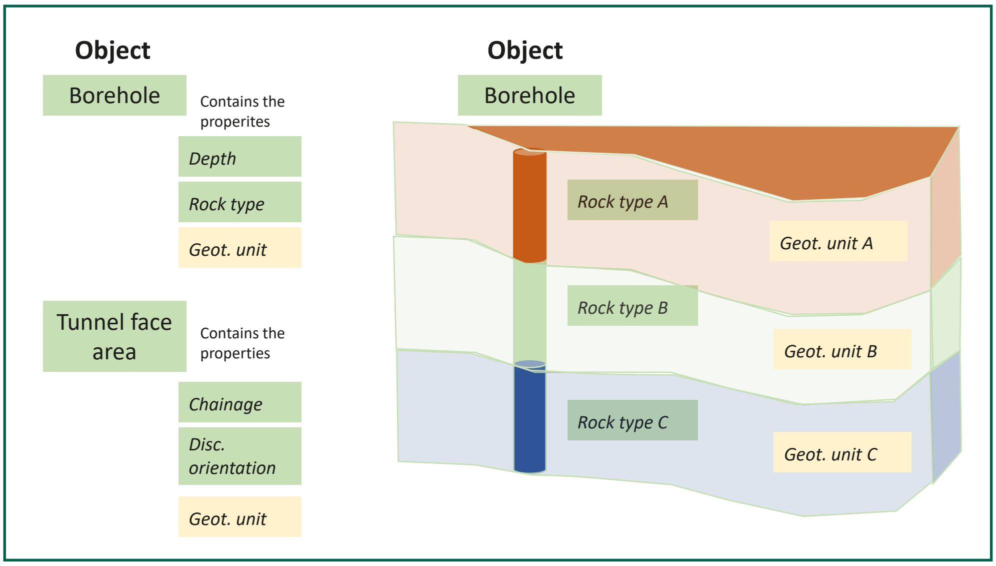


Figure 4-2
Correlation of actual objects out of the GeoDocu Model (green) and the interpreted geotechnical model (yellow)

The different aspects and content contained within each interpreted sub-discipline model will be elaborated in the following chapters. Depending on specific project requirements they shall be prepared, modelled, and handed over separately in accordance with the relevant standards and norms for preparation of geotechnical interpretative reports. The interpreted models are to some aspect depending and building on each other and share common information. Nevertheless, their information data and purpose should be clearly outlined towards the other interpreted models. **Figure 4-3** shows how the ground classification through development of different sub-discipline models and their subsequent overlaying can be achieved.

Additionally, there is a Geotechnical Synthesis Model introduced (refer to **Figure 4-1** which represents the interface between ground model and structure (**Chapter 4.3.4**).

As a spatial representation of the different interpreted models, 3D volumetric bodies are widely used. However, in principle, 3D surfaces outlining underground space volumes and structures, or voxel models can also be used as well.

A crucial aspect of interpreted models is the comparison between predicted vs. actually encountered ground conditions and thus the deviation between the predicted conditions from the design phase to the conditions encountered during the construction phase according to **Figure 4-1**. Based on the encountered ground conditions and data acquired during execution of the project, the predicted model is adapted and corrected. This 'as encountered' or actual model will then serve for the direct comparison with the original interpreted model and identify the deviations between predicted vs. actual (refer to **Chapter 4.10**). As per project requirements, other sub-discipline models may be necessary (e.g., disposal class model, geochemical model, re-usage of spoil). The ground model may thus be enhanced and added with other sub-discipline models, if deemed necessary.

4.3.1 The Geological Model

The Geological Model reflects the interpretation of the geological framework and structure of the ground within the model space. Depending on the project phase and the use case, the degree of detail is variable. One of the key aspects concerning the detail of a model is certainly the available amount and quality of the geological information throughout the different project phases

Based on the data from the GeoDocu Model, suitable geological homogeneous areas or units are defined. Geological units may not necessarily have similar geotechnical properties within one unit. A typical example is a geological formation. They are usually defined on a stratigraphic or lithostratigraphic basis and thus based on time markers or common depositional environment or genesis. The final decision about the differentiation and grouping of geological entities into different units and the borders between volumetric bodies is at the discretion of the modeller.

There are aspects that should be clearly defined for differentiation towards the Geotechnical Model. For achieving that, it is strongly recommended that the content of the Geological Model be limited to the lithostratigraphic sequence and the spatial extent of each unit, as well as the types of soils and rocks that

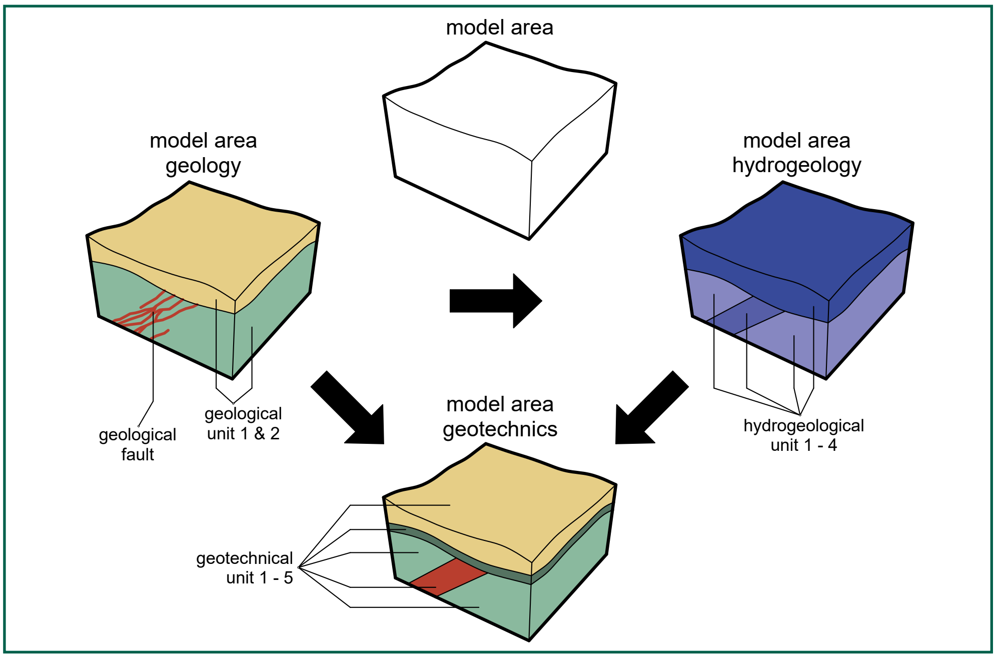


Figure 4-3
Exemplary illustration of different sub-discipline model with potential interaction

form part of the sequence. In addition, structural elements such as faults, contacts between geological units, shear zones, dykes and master joints are also part of the Geological Model.

In the further course of the modelling process, it may turn out that volumetric bodies or entities of the Geological Model are identical to units of the Geotechnical Model, i.e., that a geological homogeneous unit is truly identical to a geotechnical homogeneous unit. The modeller may then at his own discretion decide whether the Geological Model shall be merged directly with the Geotechnical Model (refer also to **Figure 4-3**).

4.3.2 Geotechnical Model

The Geotechnical Model contains and outlines the "geotechnical homogeneous units" that are specifically defined per project by the engineering geologist. The geotechnical units shall be defined in accordance with the relevant standards and recommendations ("homogeneous unit" as per DIN 18300 ff, "Rock Mass Types" as per ÖGG Guidelines etc.). These geotechnical units subdivide the ground specific to clearly defined project requirements and the level of detail required for the current project phase. There can be several Geotechnical Models in one project, each with differently defined geotechnical units and consequently different spatial extent of those. These differing Geotechnical Models are often associated with their purpose, particular requirements, or the project phase (model for structural design, quantities, excavation method, feasibility phase, tender phase, etc.) :

1) Spatial outlining of inferred boundaries between different geotechnical units each having a distinct individual set of clearly defined properties.

   This model clearly defines at which location what kind of material is to be expected and which mechanical properties are to be allocated to it. Mechanical properties, e.g., friction angle and cohesion are clearly bound to different layers or volumes of ground space in this case. The allocated mechanical properties may still be subject to variations in terms of min/max values and a characteristic or design value according to **Chapter 4.8**.

   Approach 1 is only possible if the density of investigation data is high enough and the conditions can be defined with sufficient accuracy. Examples are open-cut tunnels and clearly defined sedimentary strata.

   ➔ Granularity Level GL2 according to **Chapter 4.8**

2) A detailed prediction of the spatial extent of each geotechnical material, i.e., modelling of rock mass quality types, cannot be reliably achieved for deep seated tunnels and in case of complex geological frameworks. A suggested alternative is to summarize or include geotechnical or rock mass quality units that occur jointly along a certain volume or length of underground space and group them together (rock mass quality sections along the alignment). The expected share of each rock mass type within one section can be further detailed in the properties, e.g., by stating percentages share of the rock mass types that are expected within one section. As an example, it is possible to account for typical thickness of any number of faults or intercalations of different materials within a reach by stating that there is x % of the geotechnical unit fault zone included.

   ➔ Granularity Level GL1 according to **Chapter 4.8**

As a summary, it can be concluded that the Geotechnical Model reflects the spatial distribution and extent of geotechnical units. The geotechnical units are understood as volumes or areas where the ground conditions have similar or identical geotechnical properties. **Figure 4-3** outlines the concept of the Geotechnical Model and how it interacts with other sub-discipline models. Moreover, it is shown how it picks up volumetric units and bodies from another sub-discipline model (Geological Model) and uses them as a basis for further detailing and delineating geotechnical units.

4.3.3 Hydrogeological Model

The Hydrogeological Model includes a characterization and classification of the ground with respect to hydrogeologically relevant properties. The temporal variability of the groundwater level represents a challenge in modelling and visualizing groundwater. Hydrogeological modelling often requires complex mathematical calculations, for which numerical FE/FD modelling of the groundwater pressure surface is used for large-scale investigations. For small-scale (detailed) investigations, early project stages and simple hydrogeological systems, an analytical calculation or technical determination can be sufficiently accurate.

For a more detailed discussion of hydrogeological models in the context of underground engineering, please refer to Section 3.4 of the ÖGG guideline "Determination of geological-geotechnical fundamentals for the planning of deep tunnels" **[12]**.

In order to communicate the hydrogeologic information relevant to the project in a model-based manner, it is recommended that geometric modelling of solids is performed in conjunction with the Geotechnical Model (**Chapter 4.3.2** and **Figure 4-3**) and the Geotechnical Synthesis Model according to **Chapter 4.3.4**. Possible hydrogeological volume bodies for the ground model are, for example:

- Volumetric bodies defining hydrogeologic units or areas of similar hydrogeologic properties (see sub-object "Hydrogeological Unit" in **Appendix 1**). Possible contents whose geometric envelope can be modelled in this context are: Rock mass permeability, transmissivity, water temperature, water electrical conductivity, various hydrochemical attributes such as concrete aggressiveness, etc. The sub-object "Hydrogeological Unit" mainly contains the hydrogeological model and bases for calculation, which are used to derive the groundwater levels.
- Volumetric bodies or 3D surfaces that represent groundwater surfaces relevant to construction that are the result of groundwater modelling or assumptions (e.g., various high groundwater levels – HGW). Since these objects are often surfaces without a volume, it must be determined on a project-specific basis whether only the surfaces or, for example, volumes between HGW-X and the lower boundary of the model, or volumes between HGW-X and HGW-Y, etc., are modelled (see sub-object "Groundwater Level" in **Appendix 1**). Different construction states and points in time require different hydrogeological models.

While the above given volume bodies are used to model the hydrogeology that is not directly related to the building, it is recommended that the hydrogeological information directly related to the building be linked to the Geotechnical Synthesis Model (see **Chapter 4.3.4**). The Geotechnical Synthesis Model for hydrogeology may include, for example:

- Prognoses of water ingress (initial and permanent)
- Tunnel sections with expectedly similar water pressure
- Expected aquifer types (fissure and pore water, formation water, groundwater)
- Water chemistry, concrete aggressiveness, temperature etc.

4.3.4 Geotechnical Synthesis Model

The Geotechnical Synthesis Model bridges the important gap between sub-domain models such as the factual data model or interpreted models and the actual underground construction.

In a Geotechnical Synthesis Model, the relevant aspects from the interpreted models of the individual disciplines and the characteristic and reference values derived from them are summarized in the prognosis for the concrete tunnel section and its planned geometry. This model thus contains the information which is described in the ÖGG guidelines as tunnel engineering forecast based on a longitudinal section (project phases up to tendering) and tunnel engineering framework plan (for construction) **[10]**.

The individual modelled sections along the route or tunnel axis correspond to areas of similar thematic properties according to the "tunnel profile bands" in longitudinal section known from traditional planning (**Figure 4-4**). Examples are "rockmass type groups" with similar expected geotechnical behaviour (= "homogeneous areas" according to SIA **[9]**), or thematic subdivisions for logistics planning, environmental constraints, etc.

The content of the geotechnical synthesis model needs to be specified for each project with respect to geological and other boundary conditions. Typical content could be e.g.:

- expected distribution of homogeneous areas (e.g. rock mass types)
- expected orientation of discontinuities, discontinuity spacing
- rock mass behaviour types
- expected ground water ingress
- additional aspects related to geogenic risks like e.g., gas, contaminations, carcinogenic minerals, etc.

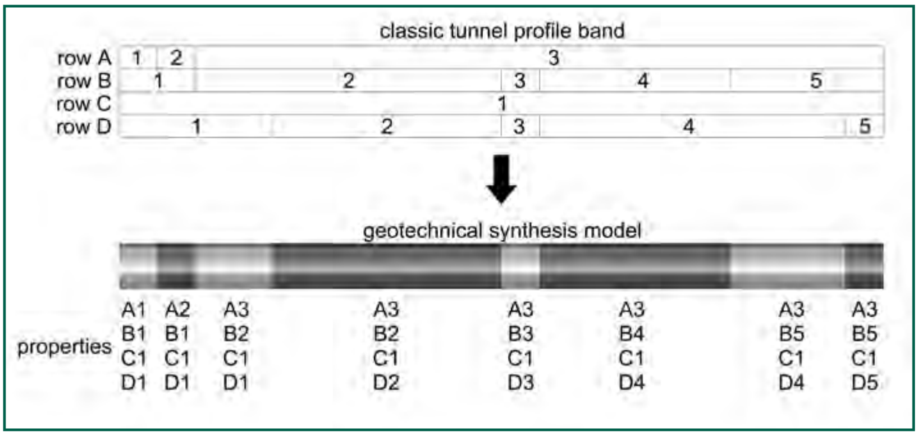


Figure 4-4
Conceptual sketch of how the "classical tunnel profile" can be translated into a "geotechnical synthesis model"

Optimally, the corresponding properties can be partially filled with values by querying the sub-domain models (described above). This enables an efficient adaptation of the tunnel forecast when updating the ground model (progressive exploration) or when adapting the route layout. Thus, the model provides the base for:

- determination of the planned excavation methods
- planned support classes
- planning of measures like exploration ahead of the tunnel face of pre-grouting etc.
- planning of health, safety and environmental measures
- logistics planning

The content of the model shall be agreed between the engineering geologist/modeller, the client and the tunnel designer.

In the course of construction, a large amount of data is collected through the documentation of the encountered ground conditions, which can now be compared with the prognosis model. The characteristics of the geotechnical synthesis model now provide the expected values (or ranges) that can be compared with the documentation in the course of a model-based target/actual comparison for each excavated section.

An ongoing update of the geotechnical synthesis model for the areas of the underground structure that have not yet been excavated can be carried out on the basis of increasing knowledge of the ground and experience gained from tunnelling in order to allow economic optimisation in the prognosis.

A simplified geometry of the tunnel tube can be used as a geometric representation of the geotechnical synthesis model. Depending on the planned applications, the modelled area of the ground can extend beyond the tunnel dimensions.

4.4 Object structure

The object structure presented here should provide a solid basis for all project phases and contain the relevant objects. This structure considers among others the latest conceptual model by IFC Tunnel/buildingSMART International which has been developed simultaneously. Each project needs to decide which information (objects and properties) is necessary and should be included in the ground model. The structure of the ground model is basically divided into two parts:

1) The GeoDocu Model (**Chapter 4.2**) with objects that represent observations, measurements, and documentations (basic data). Examples are borehole data, geotechnical tests, and mappings (including geological tunnel face mappings, carried out during the excavation phase).

2) Objects of the interpreted models (**Chapter 4.3**) based on the GeoDocu Model. They have in common that they classify the natural ground in different ways.

Basically, information can be represented by individual (sub-)objects with a discrete geometry or by properties that are part of parent objects (only semantically).

Example:
The ground water table documented in a borehole could be represented as a property of the parent object “Borehole” (property “groundwater table relative to surface level” – value: “10 (meter below surface level)”) or it could be modelled as an individual sub-object (e.g. “Borehole Water Level”) with a discrete geometry (point, disc, ...).

Depending on the use case each method has their own pros and cons (e.g., higher modelling effort vs. advantages in visualization and a solid base for deriving the interpreted models).

In principle, it is possible to move information between (sub-)objects and properties. Therefore, explicit requirements must be defined for each project and model. This applies to both factual data (e.g., properties and geometrical illustration of borehole data, illustration of test results, ...) and, as well, the interpreted models (see **Chapter 4.8**).

Exemplary question: Is there a need for a comprehensive Geological Model or is it sufficient to include only the project-specific geological units?

The object structure contains objects that organise the model regarding their spatial allocation (object catalogue, level 100 “object”, see **Appendix 1**).

The GeoDocu Model contains:

- Field Outcrop:
  documented area/outcrop derived from a field mapping
- Borehole/Trial Pit:
  complete drilling log/profile, represented e.g., as a cylinder/box
- Tunnel Face Area:
  documented area of the tunnel face derived from a mapping during tunnelling, linked to chainage and/or cycle
- Tunnel Wall Area:
  documented area of the tunnel wall
- Slope Area:
  documented area of the construction pit/slope

These objects represent the space where geological-geotechnical information has been collected (= measurements and observations). As stated above, this information can be transported either by attaching properties to the respective spatial objects or by modelling additional objects (level110 "sub-objects") with their own geometry. Depending on the requirements and needed resolution, the model can also be restricted to the higher-level spatial objects.

Interpreted models:
Handing over the total volume of a sub-discipline model (= 3D boundary of the model) represented by single objects with general properties ("Geology Model Boundary", "Geotechnical Model Boundary", "Hydrogeo Model Boundary" "Geotech Synthesis Model Boundary", Level 100 acc. **Appendix 1**) can be helpful for some uses. This includes information about editors, uncertainties and links to basic data which can be used for checking the models.

Geotechnical units (level 110 acc. **Appendix 1**) can be located on different ways (see **Chapter 4.3.2**).

4.5 Properties catalogue

While preparing this recommendation, around 250 ground-specific properties were identified in a first approach. A sample of these properties, along with the assignment to possible ground-specific objects, is listed in **Appendix 1**. The properties catalogue with all identified properties will be made available following this recommendation via separate property server. The provision via a property server offers the great advantage of a central source of information and allows the retrieval of a data set that is consistent in itself and has been coordinated across all working groups and sub-sections (see **Chapter 5.1**). In addition, property servers usually offer the option of storing the properties in multiple languages in order to use them internationally. The properties identified in the course of this task group are currently only available in German. However, they should also be to be translated into other languages.

The exemplary list in **Appendix 1** is intended to illustrate the basic considerations when introducing and using properties. Each property is specified by several attributes, such as the property name, its data type, a definition, or a proposed unit. The "Unit" attribute can be empty for properties without a unit, but, usually, there is a unit. In most cases, the default units will be given for the property. Furthermore, each property is assigned to one or more property groups. The property group represents the object to which the property belongs to (e.g., borehole, dig, etc.). This way, the property group with all its required properties can be easily assigned to the respective object in the model in order to describe the object during all service phases. If necessary, it is also possible to assign a property directly to a model object. The assignment of a property group to a model object is presented in **Figure 4-5**.

The future properties catalogue should be seen as a proposal for projects in underground construction which apply the BIM working method and which, therefore, require a digital model of the ground. It is structured as specified in DIN EN ISO 23386 **[13]**.

The collection of properties was developed regarding the broadest and most comprehensive range of sections and users possible, but the properties can only represent general use cases. Project and (national) standard-specific attributes in particular cannot be reproduced in their entirety. For these project-specific properties, the DAUB can only give an exemplary recommendation for action (see below). In principle, it is a good idea to indicate the standard to which the used properties refer in order to achieve a common understanding of the information content of the property.

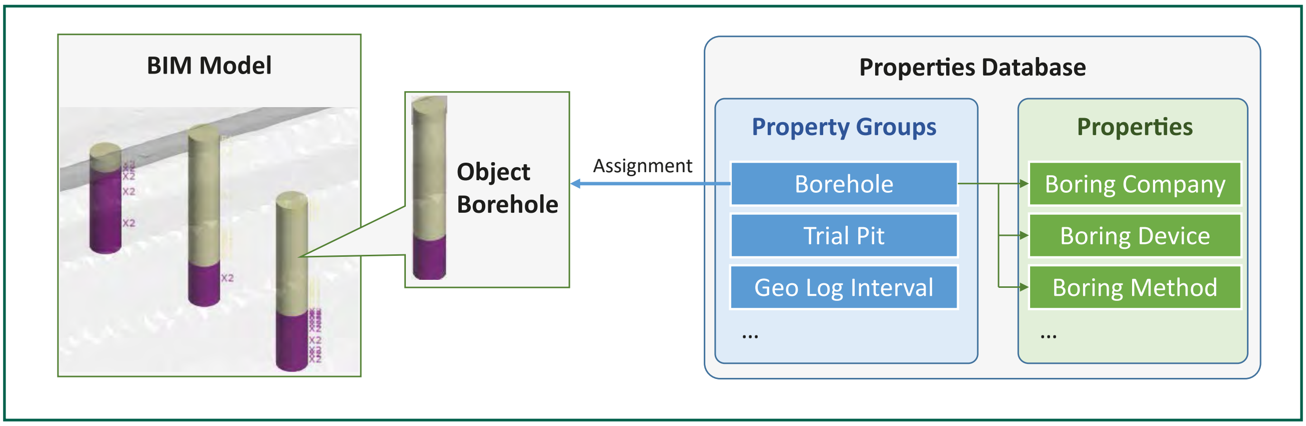


Figure 4-5 *Linking of the property group to its respective model object for the assignment of the required properties where the group and the model object have the same name*

With respect to the model, the properties listed can be divided into three categories, independent properties, properties for the description of (geotechnical) characteristics and properties for the description of project-specific or national characteristics. In the following, the three different property categories and their use will be discussed in detail.

4.5.1 Independent properties

Independent properties are properties that can be attached to their associated objects in a flat structure without a relation to other properties. They only consist of the property itself and are used for the clear description/attribution of the object properties. They stand on their own and the entire information content can be transported within the individual property.

Example:
The property «Boring Company» describes the executing boring company. The property is part of the object «Borehole».
➔ Property name: *Boring Company*;
Value: *Sample Company*

4.5.2 Properties for describing the (geotechnical) parameters in the Geotechnical Model (interpretation)

Parameters that describe the ground numerically are subject to a certain spread due to the inherent heterogeneity of the ground. This must be taken into account according to current regulations, which is why geotechnical reports often contain information on minimum, maximum, mean values, etc., as well as often a “characteristic value“. In order to clearly describe the required spread of geotechnical parameters in the model and to make them digitally evaluable, it makes sense to break down the parameters into individual properties. As a solution that is easy to implement, characteristic values can be provided in multiple forms with the suffix _min, _max, _mean, _char etc. The property “friction angle“ (i.e., internal friction angle of soil/rock [°]) is presented as an example, which can be captured in individual properties as follows:

Friction_Angle (Base word)

➔ Property name: *Friction_Angle_min*	Value: 27.5
➔ Property name: *Friction_Angle_max*	Value: 30.0
➔ Property name: *Friction_Angle_mean*	Value: 28.75
➔ Property name: *Friction_Angle_char*	Value: 28.0

4.5.3 Properties for describing project and standard-specific characteristics

Classifying characteristics, in particular, are often project, standard and country specific. Therefore, only one possible structure for creating classifying characteristics can be shown. The names of the properties (e.g., geotechnical unit), but, in particular, their content, can only be defined within the project.

This primarily affects classifications/homogeneous areas or, in a broader sense, geological-geotechnical summaries. The required properties must be defined project-specifically while creating the geotechnical report and while taking into account the regulations and specifications used. They also have to be documented accordingly in the client information requirements (EIR) and the BIM execution plan (BEP). Furthermore, in the further course of the project, a subsequent adjustment is required, for example to be able to react to changed information content in the ground (e.g., due to additional homogeneous areas), as further described in **Chapter 4.10**.

Examples:
The property “Geotechnical Unit“ describes the name of the rock mass types (by ÖGG Richtlinie **[10]**, **[11]**) or rather the name of the homogeneous area (by DIN 18300ff **[14]**).

Project 1:
Application of homogeneous areas by DIN 18300ff **[14]**
➔ Property name: *Geotechnical Unit*
➔ Possible values: *Homogeneous area B1, B2, X1, etc.*

Project 2:
Application of rock mass types by ÖGG Richtlinie
➔ Property name: *Geotechnical Unit*
➔ Possible values: *Rock mass Type GA1, GA2, GA3, etc.*

4.6 Scope of exploration

The scope of investigation recommended by the applicable technical standards as well as the principle of phase-by-phase ground investigation do not change when applying the BIM method. The consistent use of digital tools to improve visualisation and evaluation of information allows an efficient use of existing geotechnical information (maps, as-built boreholes, etc.; see **Chapter 3.1.1**). The design of ground investigation campaigns and the positioning of exploration points can be carried out in a more specific and efficient manner.

Therefore, the ground model should be established in an early project stage to be used as a communication and analysis tool for subsequent planning phases (**Chapter 1.2** and **Chapter 4**). A comprehensive clarification of all geological structures and uncertainties is not always possible or economically feasible in early project stages. Nevertheless, the model serves to provide a transparent illustration of the information obtained, but also to show the underlying ignorance and vagueness about the ground (**Chapter 4.7**). This provides a high degree of transparency and an equal level of knowledge for all project participants.

4.7 Modelling uncertainty

In the context of (hydro-)geological-geotechnical 3D ground models, it is often anticipated that 3D visualisation will result in "pseudo accuracy". However, this accusation is unsubstantiated because an interpreted 3D ground model is subject to the same fuzziness as an interpreted 2D ground section.

It should be noted that fuzziness in engineering geology has not yet been researched in detail and there is still room for further development. However, the sources of fuzziness listed below, and their significance is strongly project-dependent and therefore dealing with fuzziness should also be project-specific and professional.

Sources of uncertainty in geological forecasts in 2D or 3D are according to **[15]**:

- Resolution, measurement inaccuracy and statistical ranges of variation in baseline data.
- Variation ranges due to the project-dependent choice of rock mass classification or the designation of geotechnical homogeneous areas.
- Geometry and resolution of the model, which do not allow an exact prognosis of small-scale structures, and with a higher degree of detail usually also a more uncertain localisation.
- Fundamental conceptual uncertainty of the interpreted geological model, which was created by process-oriented, expert interpolation between fixed points.

Although the uncertainty of a 3D geological model is no different from conventional geological models, it is still useful to communicate this aspect in the BIM process. The sources of uncertainty mentioned above can be described in this context with properties at least qualitatively and, at best, quantitatively. As a development in the direction of quantifying geological model uncertainty in underground construction, the „R-index" by Bianchi et al. (2009) **[16]** should be mentioned, for example (see also Venturini et al. (2019) **[17]**), which can be attached to a model as a property. Simple methods for visualising uncertainties include, for example, the distance in the model to the nearest trusted source of information (e.g., boreholes, see **Figure 4-6**) or using the edge length from an automatic triangular mesh as a parameter for modelling uncertainty **[18]**.

Voxel models offer numerous possibilities for dealing with uncertainty in this context, which will not be discussed in further detail here.

4.8 Level of detail regarding ground modelling

As stated in **[2]**, the degree of detail of a construction model is defined by the "Level of Detail" (LOD),

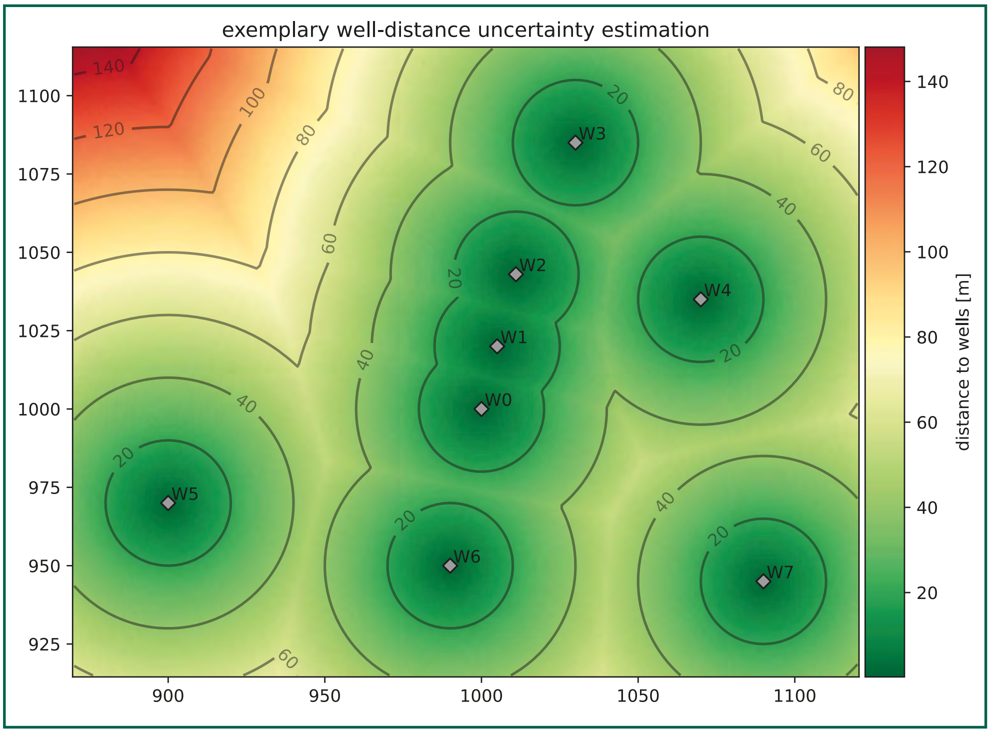


Figure 4-6
Map displaying model uncertainty by the distance to the nearest source of information (here e.g., bore-holes)

which in turn is composed of the "Level of Information" (LOI) and "Level of Geometry" (LOG). While the LOD for all components in underground construction can be defined with reasonable effort due to the exact knowledge of the planned materials and geometries, this concept cannot be implemented for the ground model (cf. **Chapter 1.1** with **Figure 1-1** and **Table 1-1**), as the basic data (GeoDocu) are only shown with a representation of the observed area and the interpretation models are defined by the state of knowledge and requirements from the planned use case. Challenges arise in particular from the inherent fuzziness of a geological model as well as the highly project-specific exploration requirements for a ground model. The standardised definition of the existing LOD concept from building modelling is therefore not applicable for ground models. Instead, use case-specific definitions of geometry and information content can be made according to the so-called LOIN concept (see also Part 2 Information Management **[3]** with DIN EN 17412-1:2021-06 **[19]**).

For the classification of individual levels of detail in connection with the ground model, the use of "**Granularity Levels**" is therefore being proposed in this recommendation. These contain application-specific specifications for the sub-subject models instead of conventional LOD definitions for individual objects.

As an example to illustrate the systematics, a classification is chosen which is set up in the following **Table 4-1**. The table lists the objects of level 100 (green) and sub-objects of level 110 (blue) listed in **Appendix 1** and assigns them possible representations in the individual Granularity Levels. It is divided into two areas:

- **Table 4-1**: The upper part contains granularities for the GeoDocu Model, which can be divided into five Granularity Levels.
- **Table 4-2**: The lower part contains the objects or sub-objects of the interpreted models, for which a detailing comparable to the GeoDocu Models seems impracticable. Instead, a combined definition for detailing is appropriate, which consists of the Granularity Levels GL1 – GL3 and additionally of information on resolution and permissible uncertainty.

The following considerations led to the recommendation of this system.

A project-specific definition of the level of detail for the ground model, taking into account the real issues and available resources (e.g., within the framework of the AIA), is in the interest of the client, who can thus tender for more precise services and, above all, check the quality of the services provided in a comprehensible manner. In addition, well-defined requirements for detailing help the model creator to work more efficiently towards the required digital ground model and to minimise the need for coordination.

Two aspects determine the approaches for defining levels of detail for ground models:

1) Requirements according to selected use cases:
   In the case that detailed information is available, as for example in the case of ground investigation data (drilling documentation including sampling, labour and in-situ measurements), it can be decided which information with which geometric representation should be transferred to the model.
   ➔ Known geometry is simplified and information is filtered (comparable with building models).

2) Level of knowledge:
   Interpreted models represent a prediction of unknown conditions and contain uncertainties (see **Chapter 4.7**). If little information is available, detailed predictions are often not useful and a high-resolution modelling of, e.g., ground layers (geotechnical unit) is only possible with a very high amount of uncertainty.
   ➔ Lack of knowledge limits the geometric resolution (specific problem of ground models)

For objects of the GeoDocu sub-discipline model, the first aspect is decisive:

Based on the presented object catalogue (**Appendix 1**), an approach for detailing can be implemented in which a higher level of detail can be accompanied by more objects and properties. However, individual objects such as a borehole or a tunnel face documentation can also be modelled in more detail (see **Appendix 2**), which is to be defined project-specific in the AIA.

For the interpreted sub-discipline models, the second aspect (level of knowledge) is the limiting factor. The "accuracy" of a model is not only determined by the resolution and the level of detail, but also by the included uncertainty, which varies spatially (see **Chapter 4.7**.

The requirements for the location of the expected conditions depend on the planned structure and can vary in the project area or in the model area. Usually, the highest accuracy is required in the area of the planned cavities and the immediate surroundings and is higher in sections with special construction parts such as crosscuts, shafts and caverns than, e.g., in sections of a TBM tunnel.

A standardised specification of LOGs for interpreted models is therefore not considered expedient (see above), as the requirements are on the one hand related to the complexity of the expected geology and the structures to be constructed, and on the other hand also depend on the respective project phase

Table 4-1 *Exemplary structure of "Granularity Levels" for the sub-discipline model GeoDocu*

Sub-discipline model GeoDocu **Relative allocation of Granularity Levels to „spatial objects“ and „sub-objects“**					
Object-/(Sub-)Object	**Granularity Level**				
	GL1	**GL2**	**GL3**	**GL4**	**GL5**
FieldOutcrop	point	point	surface	volume	Detailed 3D visualisation with specialized software or data (e.g. photogrammetry, histogramms, 3D-scans, well logs, etc.)
Discontinuity Set		point	disc	3D-network	
Borehole	(starting-)point	line	cylinder	measured well deviation log	
Trial Pit	point	line	cuboid		
Geo Log Interval	—	(represented by properties of „Borehole“ and „Trial Pit“)	line	cylinder	
Borehole Construction	—		line	cylinder	
Borehole Test	—		point/line	cylinder	
In Situ Test	—		point/line	cylinder	
Hydraulic Test	—		point/line	cylinder	
Sample	—		point/line	cylinder	
Borehole Water Level	—		point	cylinder	
Ground Temperature Measurement	—		point	cylinder/symbol	
Water Inflow/ Outflow Measurement		(represented by properties of e.g. "Tunnel Face Area")	point	surface	
Gas Concentration Measurement			point	surface	
Ground Temperatur Measurement			point	surface	
Tunnel Face Area	point	surface			
Tunnel Wall Area	line	3D-shape			
Slope Area	line	surface			
Mapped Unit	—	(represented by properties of e.g. "Tunnel Face Area")	surface	surface	

and the planned use cases. Instead, according to these project-specific requirements

- the geometric resolution and
- the maximum permissible uncertainty

for a geotechnical model should be defined.

The geometric resolution can be described, for example, by specifying the edge length for triangular meshes or other object representations used. The maximum permissible uncertainty can be specified by specifying the length of possible deviations from the modelled surface to be taken into account, possibly also depending on the direction. When new additional information is presented, this specification makes it possible to assess the correctness of the model. In order to be able to generate high-resolution models, the required level of knowledge must be created through appropriate exploration measures.

As a result, the ground model for a project area is composed of sub-models, each with a different level of detail. **Figure 4-7** shows an example with a delimitation into the sub-models Portal W, T1, T2, T3 and

Table 4-2 *Exemplary structure of "Granularity Levels" for interpreted models*

Interpreted sub-discipline models Combined statements of Granularity Levels					
Object-/(Sub-)Object	**Granularity Level + additional information**				
	GL1	**GL2**	**GL3**	**Resolution**	**allowed vagueness**
Geological Model Boundary	2D model boundary	volume			
Geology Model Boundary	Bounding volume for groups of geological units with %-distribution	3D-geometry of single geological units		e.g. max. 3m mesh edges	e.g. +/-1 m
Fault	line on map	3D-surface	3D-volume		
Geotechnical Model Boundary	2D model boundary	volume			
Geotechnical Unit	Bounding volume for groups of geotechnical units with %-distribution	3D-geometry of single geotechnical units		e.g. max. 3m mesh edges	e.g. +/-1m
Discrete Discontinuity	Properties in geotechnical unit	3D-geometry			
Geotech Synthesis Model Boundary	line	cylinder	excavated geometry		
GeotechTypical Section	line	cylinder	excavated geometry	schematic/ idealised	e.g. +/- 10m tunnel section
Hydrogeo Model Boundary	2D model boundary	volume			
Hydrogeological Unit	3D-geometry	(geostatistical description of hydraulic properties)		e.g. max. 3m mesh edges	e.g. +/-1m
Groundwater Level	Z=constant	3D-geometry	temporal component		

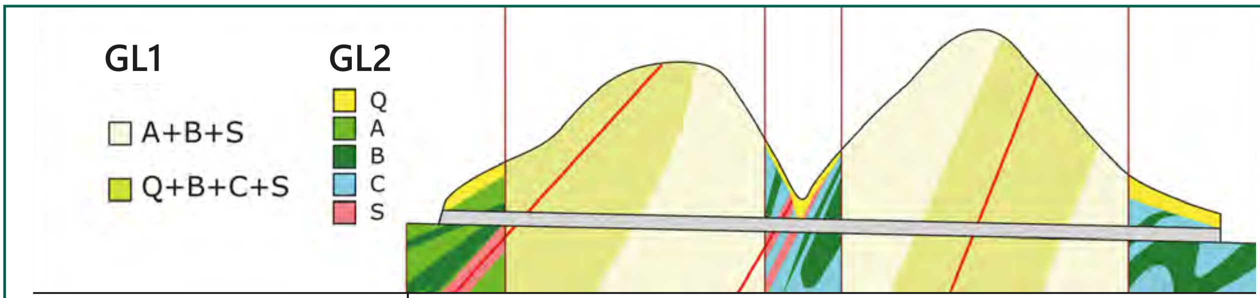
Portal O. Here, the sub-discipline models described in **Chapter 4.3** can be used, whereby especially the two approaches for the geotechnical model (**Chapter 4.3.2**) offer possibilities for dealing with different levels of knowledge, uncertainty and requirements for detailing.

4.9 Requirements for the quality of the ground model

The engineering geologist is responsible for the creation of the ground model in accordance with the country-specific standards and guidelines on the basis of the existing knowledge and the geological, hydrogeological and geotechnical interpretations. He is considered to be the modeller (MOD) according to Part 2 Information Management Appendix 3 **[3]**.

Project-specific requirements regarding information content (properties, level of detail, etc.), model structure, model designation, etc. are defined in the AIA or the BAP. **Appendix 1** to this recommendation contains examples of (sub-)objects and properties for the ground model.

The creation and coordination of the ground model are subject to the coordination and quality assurance processes defined in the project-specific BAP. The requirements for quality assurance are described in more detail in Part 2 Information Management



Geology Model		One single model				
Knowledge / site invest. density		high	low	high	low	high
Geotechnical Model	Model approach *	2	1	2	1	2
	Sub model (name)	Portal W	T1	T2	T3	Portal O
	Resolution	3 m	10 m	3 m	10 m	3 m
	Allowed uncertainty	1 m	5 m	1 m	5 m	1 m

* 1: Enveloping geometry for similar units (materials) with expected %-distribution
2: Explicitely modelled units

Figure 4-7 *Exemplary representation of sub-models with different Granularity Levels: Higher exploration density and better knowledge in portal areas and with low overburden (T2): Detailed modelling of geotechnical units (GL2). Low exploration density with higher overburden: Less detailed modelling (GL1). Specification of resolution and uncertainty as example values!*

Chapter 5 **[3]** for the application of BIM and can be transferred to the ground model accordingly.

4.10 Ground model update requirements

The development and updating of the ground model are iterative processes that extend over various project phases. In a first step, the GeoDocu Model is processed on the basis of the existing data from the exploration and other geological information (maps, historical reports, etc.). In a second step, the interpreted models are created on the basis of the interpretation of the GeoDocu Model (geology model, geotechnical model, hydrogeology model, and geotechnical synthesis model). The completion of the models takes place in relation to the project phases. This means that a consolidated ground model is available at the end of each phase. The updating of the ground model can therefore be carried out for each project phase on the basis of the knowledge gained during the project work. For example, between the preliminary planning and tendering phases, the ground model is updated with the additional exploration campaigns carried out for each phase (GeoDocu Model and interpreted models). The update is thus carried out in each project phase. The updated model can serve as a base for planning (**Figure 4-8**).

It is possible that, between certain phases, no additional information is expected from investigation campaigns or similar (no update of the GeoDocu Model); however, the ground model (interpreted models) should be supplemented with information relevant to the contract with regard to the tender (drilling classes, support classes, material classes, etc.).

It is advisable to freeze the ground model from the tender phase after signing the construction contract until the end of construction as a "contract ground model".

It is also recommended that during the construction phase (see **Figure 4-9**) the GeoDocu Model is continuously updated on the basis of the excavation documentation (e.g. face surveys, water ingress). On this basis, the interpreted models can also be adjusted and thus the target/actual comparison can be continuously updated (basis for invoicing, forecasts of driving sections still to be completed and thus forecasts for construction time and costs at the end of the construction period, etc.).

At the end of the construction phase, all existing data can be documented and archived in a separate model version. For the transition to the operational phase, the information content should be adapted to the needs of the operating organisation and thus a new model version should be used.

The versioning of the respective states of the ground model is done according to the principle of so-called "DataDrops" as described in the DAUB Model Requirements – Part 2 Information Management **[3]**.

If it appears necessary for project-specific reasons that certain states of the ground model must be documented between individual project phases, a corresponding versioning must take place at these times. This may be the case if, for example, the company

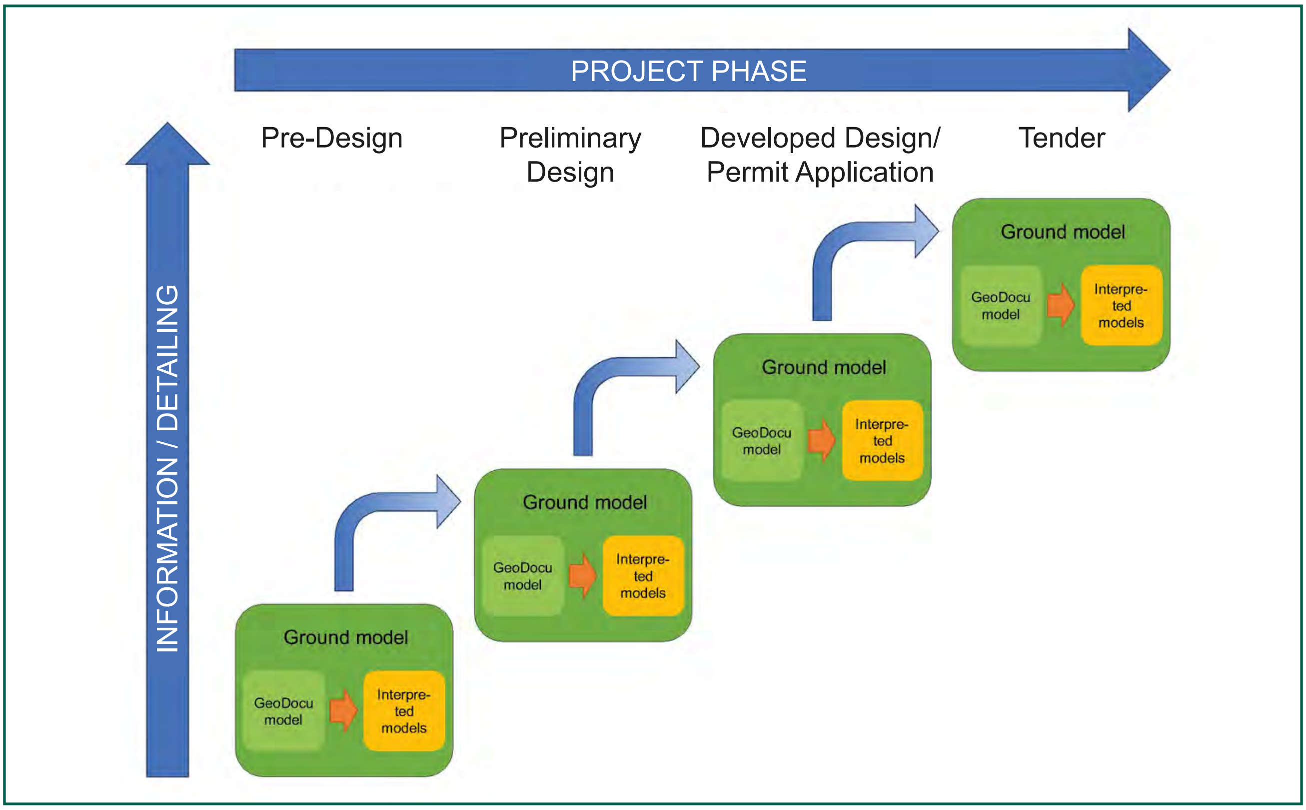


Figure 4-8 *Schematic representation of updating the ground model depending on the project phase (planning phase)*

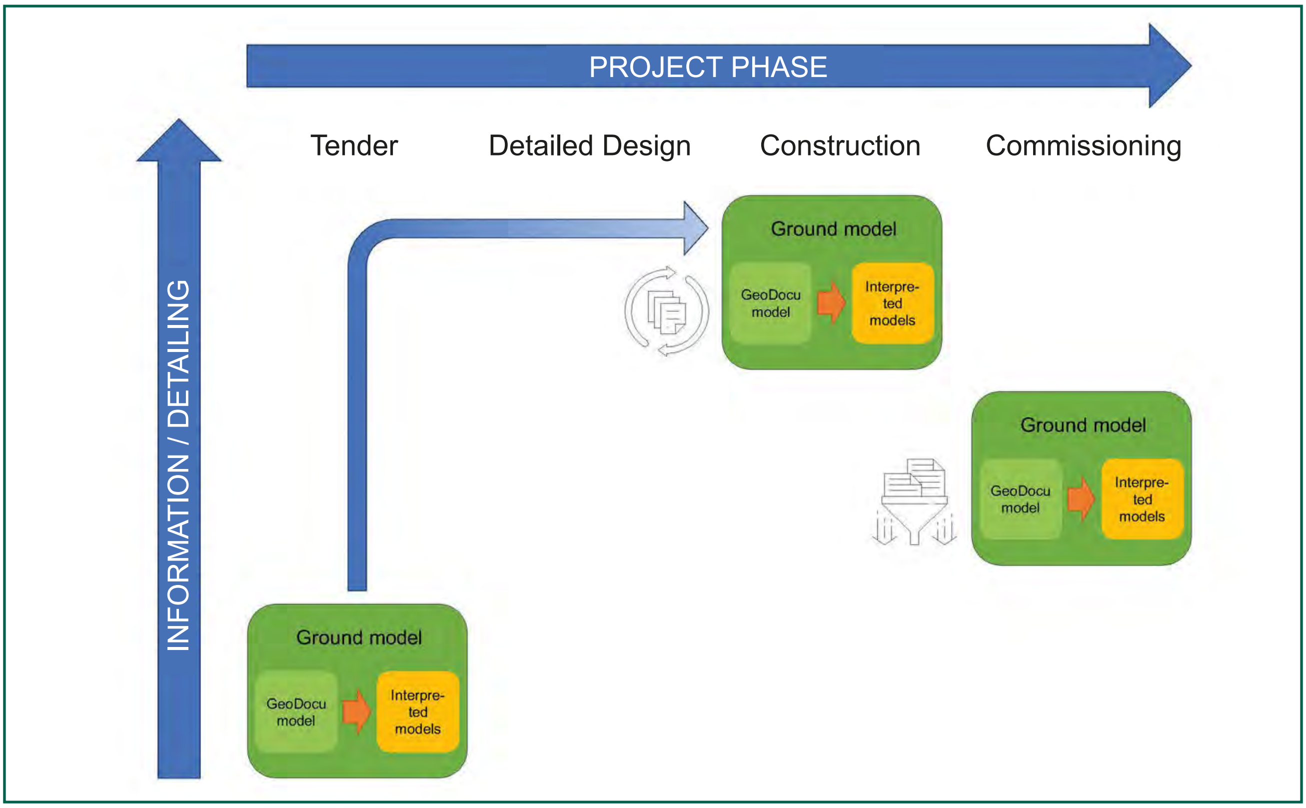


Figure 4-9 *Schematic representation of updating the ground model depending on the project phase (construction phase)*

working on the ground model changes, new use cases are pursued or unplanned information gains from third-party exploration campaigns etc. occur.

4.11 Requirements with respect to data exchange

Ground data are available in many different formats (analogue and digital), as they are generated by different software in the different phases.

First of all, new measurements and existing data ("GeoDocu Model") must be brought together in the working environment of the creator of ground models (including terrain models etc.), where their technical interpretation and the creation of interpreted models take place (cf. also **Chapter 4.3**).

It should be mentioned that the GeoDoc Model that consists of "Facts/Documentation", purely serves as an information model and is not suitable for the creation of a coordination model for building ground/structure.

In order to create a coordination model for ground/building, the sub-discipline models from the "Interpretation" area (cf. **Figure 4-1**), including the parts of the basic layer data relevant for further use cases, are therefore linked with the corresponding sub-models of the building model. Depending on the project phase and the use case, it will have to be decided which of the sub-discipline models will be used for coordination with the building model. The linking itself usually takes place in a suitable coordination software, whereby the files from the ground or building modelling are imported via open file formats. It should be noted that in addition to the correct linking of the geometries and their location (georeferenced, observance of model origin), the selected information (properties) is also transferred to the appropriate place (e.g., property place-holder).

On the one hand, the link can be used to visualise the position of the planned underground workings in the developed and interpreted ground ((hydro)geology or geotechnical model or geotechnical synthesis model). On the other hand, it is also possible, for example, by defining queries using test rules, to support the planning of excavation classes or to check the plausibility of its results. Among other things, it is possible to determine whether the planned support class with a pipe umbrella actually covers the entire section of unconsolidated rock or whether it was set too short or too long. When determining the relevant criterion – transition from unconsolidated to solid rock – it is advisable to include the "uncertainty" described in **Chapter 4.8** (e.g., +/- 10 m) in the tests.

If the coordination software has a BCF function (BIM Collaboration Format), discrepancies that become apparent from the overlay of the domain models can be communicated directly between the domain s of ground and building.

The models are coordinated on the defined data exchange platform ("common data environment", CDE). A more detailed description of the CDE is given in the publication Part 2 on Information Management **[3]**. However, care should be taken not to overload the coordination model and to maintain its clarity. Therefore, "exotic" data or large amounts of data (e.g., those generated by process controlling during construction) should only be linked. Exactly what information is integrated into the coordination model and in what form must be defined in the project's BAP/modelling guideline with the help of the object catalogue in connection with the specifications for detailing.

The BAP/Modelling Guideline should define the data transfer points, i.e., when data should be exchanged. This usually depends on the project phases and the desired level of detail for certain project milestones. The exchange of data or the transfer of information is also referred to as "data drop" (see also **[3]**).

In general, ground information is densified gradually as the project progresses. The GeoDocu Model is continuously updated by incorporating current exploration results and geological excavation documentation. The documentation is ideally carried out using digital methods (face scan, measurement while drilling (MWD) or similar). The quality control by the ground modeller (BIM coordinator), who has to enter the collected data into the database and BIM model, is particularly important.

Due to the fact that data contributions come from many different sources during the planning and implementation of underground structures, special requirements for data interoperability must be observed. The details on this can be found in Appendix 5 of **[3]**.

In connection with the data exchange of ground information, the same questions regarding transparency and collaboration arise as in the general model-based handling of the overall project, which must be clarified on a project-specific basis and defined in the respective AIA or BAP

4.12 Applied Software

When modelling the ground, there are different requirements for software products in comparison to modelling buildings with their clearly defined structures. The requirements are as follows:

- Processing of geometries with heterogeneous levels of detail, grinding intersections or generally complex shapes

- Simple classification (assignment of geometry to objects/classes)
- Efficient mapping of properties (automated where possible)
- Efficient adaptation of the model (GeoDocu and interpretations) to new fundamental data (new outcrops and measured values)
- Revision of the ground model due to planning adaptations (e.g., change of the alignment)

In order to meet all these requirements, BIM-based ground modelling usually requires the knowledge of a whole range of software packages. A project-specific processing cascade (e.g., as part of the BEP) must be defined. It cannot be assumed at the present time or in the foreseeable future that there are individual programs that meet all requirements and that can cover the entire digital ground modelling.

For the modelling of ground-relevant data and geometries, various programs for processing and recording are available. These can be classified by type of data acquisition and functionality:

- **GIS (Geographical Information System):** GIS systems enable the collection, organization, modelling, analysis, and visualization of spatial information. GIS systems have been in use for decades. The GIS-based modelling of geometries and information comes very close to the concepts of BIM. The main difference is the predominant focus on 2D or 2.5D (especially raster data, which, for example, cannot display overhangs and therefore no full 3D information) of GIS systems. Existing GIS systems should be integrated into BIM when modelling the ground.
- **CAD (Computer Aided Design):** CAD programs are applied for computer-aided drawing and the documentation of real and planned objects in building modelling. In principle, the ground conditions (e.g., boreholes and layer boundaries) can also be modelled. Despite parametric modelling tools and links to databases, these programs reach their limits when dealing with large amounts of data and complex geological conditions.
- **Geological 3D-modeling:** These programs are specially designed for analysing, editing, and visualizing extensive spatial and geological data. They rely on different statistical methods for their processing, help with the interpolation and extrapolation of data sets and, in contrast to conventional CAD programs, can deal with particularly complex surfaces.

5 Fields of action for further developments

5.1 Database for property catalogue

The identified property catalogue (see **Chapter 4.5**) is an important tool for the management of digital ground models in underground construction, as it specifies a variety of fundamentally required information needed during the planning, construction and operation phases. By providing the properties in a central manner, those involved in the project are able to integrate the required properties from the same source into the respective model, which supports the interoperability and integration of the individual (sub) domain models. The central provision of the properties is therefore of great importance for the respective projects, so that there should be no individual solutions for individual projects. The resulting high-level server solution enables projects to be easily compared. For example, if you want to compare the thickness of several layers in different projects, the property (e.g., layer thickness) must be named the same in all projects to avoid misinterpretations. This is given with a high-level server solution. Therefore, the aim is to develop a sustainable property server for ground properties, which is constantly maintained and serviced, and which can also be continuously expanded with new properties supervised by a central administration (e.g., properties for recording and quantifying fuzziness, see **Chapter 4.7**).

This central property server is still a work in progress at the time of the publication of this recommendation. How a property server works is described in the publication on information management **[3]**.

A central and uniform solution for the management of properties is also important with respect to the Geological Data Act (GeolDG) in Germany. Here, newly generated geological data must be entered into a central location (e.g., databases of state offices), which in turn must also provide available data for the areas examined. The exchange of data with the help of a central server solution and in a common exchange format makes it easier to feed in new data and to process existing, extracted data.

Similar to the German GeolDG, the legislation in Austria is currently being adapted (e.g., Geodata Infrastructure Act – GeoDIG) and obliges public institutions to pass on geodata that was created on behalf of the public, in accordance with specified standards for data modelling, data download and data visualization. State institutions (e.g., state geological services) currently operate extensive databases for drilling data, which can be accessed digitally and are based on current standards but are not structured in a uniform manner. The Geologische Bundesanstalt (GBA) also operates GIS and database systems that conform to the specifications of INSPIRE ("Infrastructure for Spatial Information in the European Community") and OGC standards (OGC: Open Geospatial Consortium). As part of the restructuring of this institution (GBA becomes GSA), a centre for the "establishment and operation of a central data infrastructure as a service for science, business, public administration and society with automated access..." is to be created (GSAG §4,(3), point 5).

In principle, public clients and operators of large tunnels (e.g., ÖBB, Asfinag, Wiener Linien) intend to develop common, compatible data structures. However, the harmonisation efforts are still at the beginning.

The goal of the GEOL_BIM innovation project, carried out by the Swiss Geological Association, is to integrate geological data or geological models into digital building models. The GEOL_BIM project has developed a manufacturer-independent, system-neutral and open interface between geological and hydrogeological data and digital building models. The interface converts geological input data into IFC format via a web application and thus enables the import of this data into standard BIM environments. 3D models (layer model and voxel model), profile sections, boreholes and voxels are supported as input data. The developed interface is intended to promote and support the digital exchange between the geology project author and the domain planners.

As part of the research project, the compatibility of the Swiss standard SIA 199 "Erfassen des Gebirges im Untertagebau" with digital geology models was also examined. A workflow was developed for the creation of a domain model geology which contains all information in accordance with SIA 199 as an attribute and can be exported to IFC format. This workflow was developed using the 2nd tunnel lining of the Gotthard road tunnel project as an example.

Further information on the GEOL_BIM innovation project can be found in the final report **[20]**.

5.2 Risk allocation of ground

When it comes to project development and execution of underground constructions there is one crucial and intrinsic issue: managing the risk allocation related to the existing ground conditions with the contractual agreements between parties involved such as employer, consultant engineer, experts and contractor.

Among others, the DAUB recommendation "Empfehlung zum konfliktarmen Bauvertrag im Untertagebau" (April 2020) **[21]** specifically promotes a clearly and equitably defined diversification of risks. In this regard, it recommends jointly bearing particular risks.

Ultimately, the contracting parties in the cooperation are responsible for corresponding obligations of checking and notification, so that a joint assessment of the ground situation by the contracting parties involved is productive. Obviously, the use of digital ground models for project development and execution may best match the principle of contractual processing based on partnership. The necessary transparency for equal cooperation and collaboration is achieved through the implementation of 3D models and the associated information management combined with an appropriate involvement of the project shareholders. Thus, the identification of risks – not only from the ground – and the target-oriented decision making of coping with can be done at an early stage and a in a proper way.

6 Outlook

Many different aspects of ground modelling are covered by the DAUB-recommendation on digital design, building and operation of underground structures, with some topics being more in focus than others e.g., the requirements on modelling fuzziness and updating the ground model during construction. This is partly due to limited experiences on selected topics and based on the individual roles of the authors, mainly with a background in tunnel design. With future focus on these topics in scope of new BIM pilot projects and hence, growing experience in these areas, the statements of the DAUB-recommendation should be evaluated and adapted if necessary.

The catalogue of properties is filled with the required attributes for ground modelling in an ongoing process. The current version of the property catalogue covers the majority of the required attributes which will constantly be expanded and adapted. However, project-specific properties should not be added to the catalogue for the sake of clarity and to prevent irritation of users in other projects. Therefore, the processing of the catalogue should be monitored by an assigned committee.

The complexity of creating, managing, and maintaining building ground models leads to the expectation that the various steps will be carried out with diverse software solutions. For a continuous and smooth cooperation of all project participants, it is therefore important that the respective software solutions communicate well with each other, and data exchange is possible. A standardisation of interfaces should therefore be aimed for.

In this outlook, however, future fields of application of ground models in tunnelling and underground construction are also to be highlighted. Rapidly advancing technologies and developments, for example in the field of artificial intelligence (AI) and the Internet of Things (IoT), offer new application possibilities for planning and process optimisation in all planning phases up to real-time process adaptation during the construction phase.

The construction industry is developing site units into "smart systems". These systems are increasingly monitoring data via sensors, with direct and automatic evaluation via edge computing or forwarding them for technical analysis e.g., through finite element applications, initiating reactions or triggering interactions between smart systems. The models created in the planning phase, be it 3D ground or building models, can then be adapted in real time to enable, for example, an immediate and automated update of time requirements, construction costs as well as the CO_2 footprint.

For the reasons mentioned above, the recording of in-situ geology will also become increasingly important to learn from the experience gained for future projects, beyond billing-related motivations. This is increasingly done through machine learning prediction models that use the historical process data as training and test data sets. The ground model can virtually become the database, consisting of georeferenced, structured data, which describe the geotechnical boundary conditions in numerical form.

In addition, building ground models are already being used in the field of virtual or augmented reality. Here, geotechnical boundary conditions and processes concerning the ground can be optimally illustrated to the project participants.

Even if the above-mentioned developments do not directly relate to the building ground or its exploration, the ground model may represent the single source of truth in the future to which all these systems refer. Especially in tunnelling and underground construction, the digital ground model can therefore gain increasing importance and influence. Even if purely digital and 3D model-based planning is currently still a vision, especially with regard to approval planning. This must be the goal to fully exploit the advantages of digital planning in 3D. It is therefore all the more essential to standardise developments in the creation of building ground models in order to enable all project participants to exchange the corresponding data. The present DAUB recommendation aims to make a fundamental contribution here.

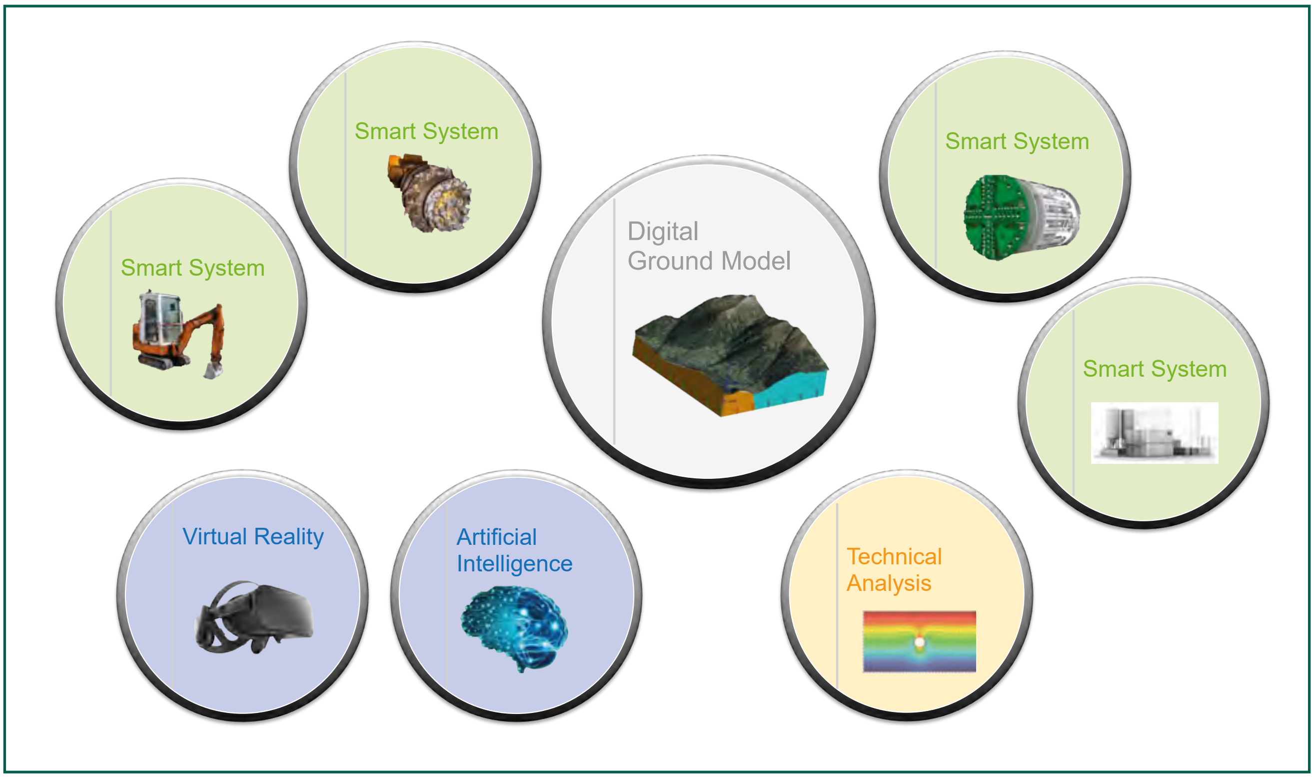


Figure 6-1 *Application of the ground model for planning and process optimisation using advanced technologies such as Artificial Intelligence, Internet of Things, Virtual and Augmented Reality*

7 Glossary

3D		Three-dimensional geometry that can be constructed and displayed by volumetric bodies in the space
As-built		Representation and documentation of the actually executed situation at site
Attribute		Any data relative to the description of a property, group of properties, etc (acc. ISO 23386)
BIM Collaboration Format	BCF	Format for coordinating issues and information on the model irrespective of the software tools used
BIM execution plan	BEP	Document that specifies the general set-up of the BIM application during project execution
Classification		Standardised system covering the allocation/structure (Classification) of elements/information
Client information requirements or **Exchange information requirements**	EIR	Document that specifies the client's information requirements during tender process in order to define the general set-up of the BIM application
Common Data Environment	CDE	Digital platform for jointly data filing and exchange of models and related information
Construction model		Model generated during execution of construction works including all allocatable information
Coordination model		Model composed by different domain and/or sub-models for coordination purposes
Data Drop	DD	Specified point in time at which defined deliverables are handed over, checked and documented
Domain model		Contains discipline-specific information of the specialist designer. Regarding underground works the domain models for tunnelling, lining, drainage or fire protection can be taken as examples.
Engineering geologist		Role of the expert on (hydro-)geology/geotechnics
Existing conditions model		Model displaying the existing conditions for a site
Factual model		see GeoDocu Model
Forecast model		Model displaying the forecast ground conditions to be expected during construction. It describes the status of the interpreted model/geotechnical synthesis model prior to construction.
GeoDocu Model		Model containing all existing factual information from recent and previous exploratory campaigns (see **Chapter 4.2**)
Geology Model		Model of the discipline „geology" reflecting interpretations of the geological ground structure based on the GeoDocu model (see **Chapter 4.3.1**)
georeferenced		Spatial allocation of an object within a system of coordinates
Geotechnical Model		Model of the discipline „geotechnic" reflecting interpretations of the geotechnical ground conditions (see **Chapter 4.3.2**)
Geotechnical synthesis model		Representation of the relevant aspects specified by the interpreted models of individual disciplines (e.g. geology, geotechnics hydrogeology) referring directly to the projected underground structure
Granularity Level	GL	Classification for specifying the level of detail of ground models

Ground model		Model representing the geological/hydrogeological/geotechnical ground conditions
Group of properties		Container enabling the properties to be prearranged or organised. A list of properties as defined in ISO 16739 is a group of properties, but a group of properties is not necessarily a list of properties (acc. ISO 23386)
Hydrogeological Model		Model of the discipline „hydrogeology" reflecting interpretations of the hydrogeological ground conditions (see **Chapter 4.3.3**)
Interpreted Model		Assembled by the interpreted sub-discipline models (Geology/Hydrogeological/Geotechnical/Geotechnical synthesis model, see **Chapter 4.3**)
Level of detail	LOD	Characterisation of geometric and semantic information
Model		Three dimensional model containing physical, geometric and functional properties with related attributes
model based		Processing by means of a digital model
Object		Single element of a model containing information. It can be a structural element, machine or space
object based		Processing by using objects
Object catalogue		Structured compilation of all (sub-)objects needed for modelling in an the appropriate level of detail. See also Model Requirements – Part 1, Object definition, coding and properties
Project phases		Phases referring to development, construction and operation of a project. The phases are separated by appropriate milestones.
Property		Inherent or acquired feature of an item to describe (sub-)objects (acc. DIN EN ISO 23386)
semantic		Meaning expressed by (sequence) of characters/figures
Semantics		Meaning of sequences of characters/figures
Sub-discipline model		Breakdown of the domain model "Ground" into specific disciplines as geology, geotechnic and hydrogeology
Sub-domain model		Possibility to breakdown domain models into different structural parts. Exemplarily, the domain model "underground works" can be divided into the sub-domain model "shaft sinking" and the sub-domain model "tunnel excavation".
Sub-model		Sub-models are representing a part of the overall model. They contain all domain models of their particular sub-structure as portal area, shaft #1, tunnel drive north.
Sub-object		Smallest element used in a model
Uncertainty		Divergence in the domain model „Ground" compared to reality e.g. due to forecast inaccuracy, level of detail or limited computing or filing facilities
Use case	UC	Tasks derived from the BIM goals for implementing the BIM methodology
Voxel model		In this model volumetric objects are segmented into smaller (steady) rectangular volume elements with distinct information

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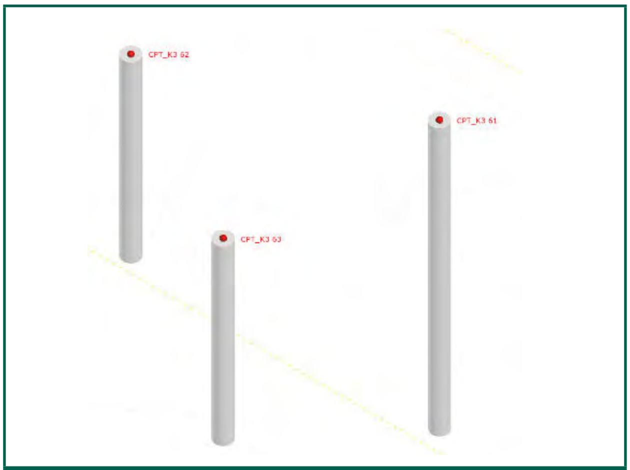
Appendices

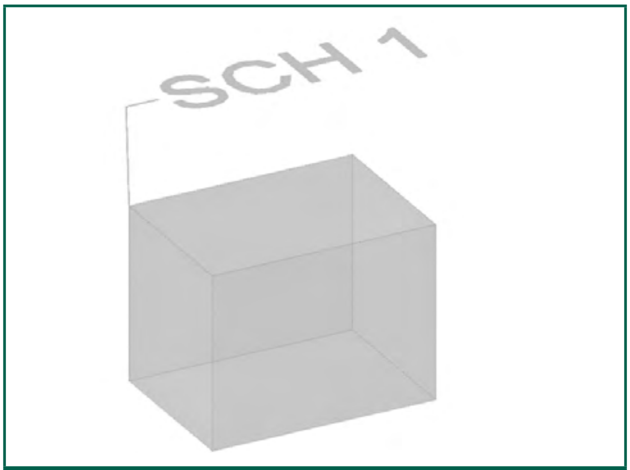
Appendix 1: Object catalogue including selection of features

Appendix 1 is available for download as an Excel file.

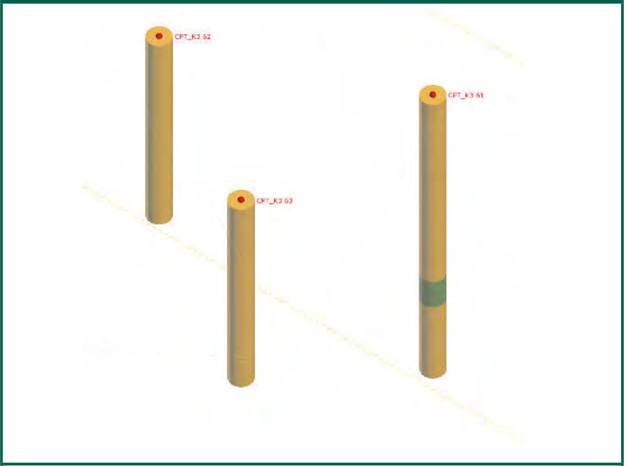
Appendix 2: Examples of visualisations



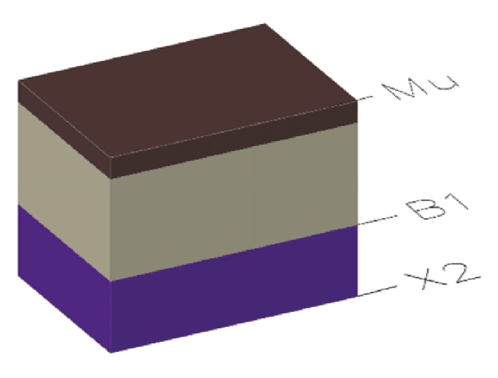
Borehole



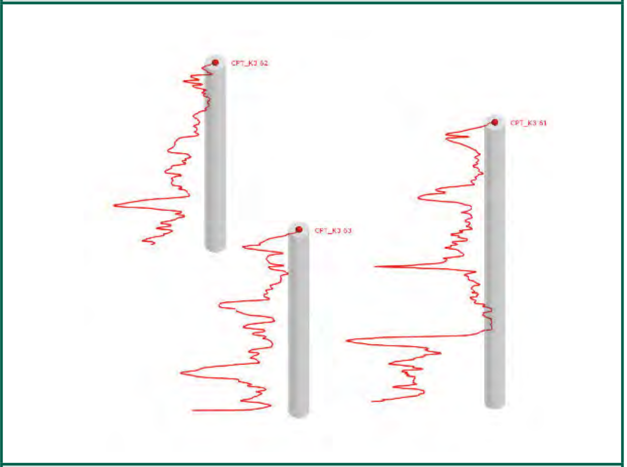
Trial Pit



Geo Log Interval
(here: Example of a borehole interval)



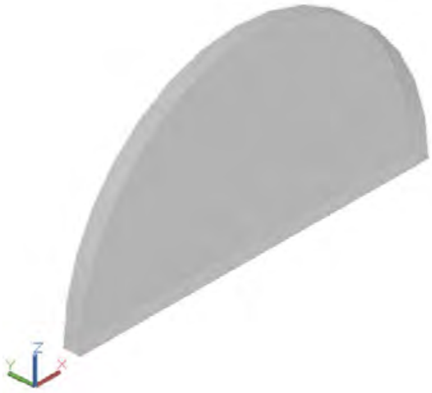
Geo Log Interval
(here: Example of an interval in a trial pit)



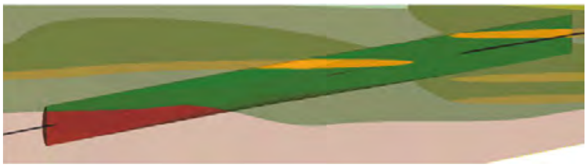
Borehole Test
(here: Example of the CPT cone resistance)

Sample
(here: example representation as a sphere)

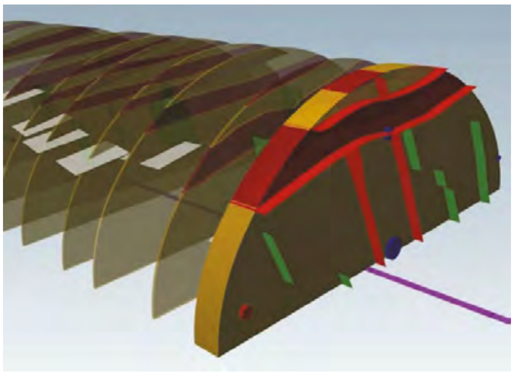
Geotech Synthesis Model Boundary
(here: Example representations as GL1 and GL 2)



Tunnel Face Area
(here: Representation as Granularity Level GL2)

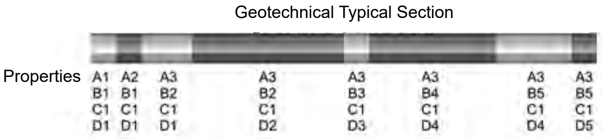


Geotech Synthesis Model Boundary
(here: Visualisation of the geotechnical unit)

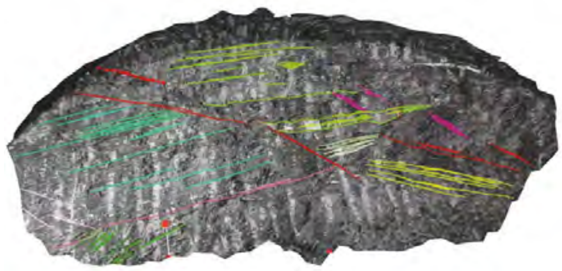


[A2-U1]: Weichenberger (2022), TuGIS

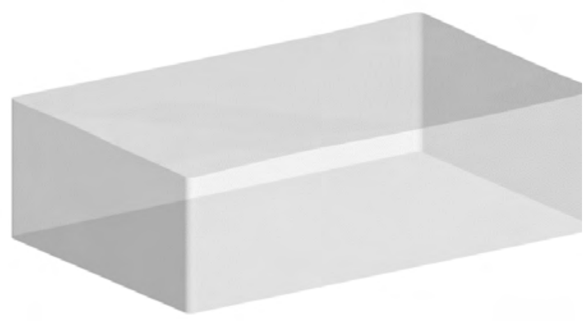
Mapped Unit + Discontinuity Set
(here: Representation as Granularity Level GL4)



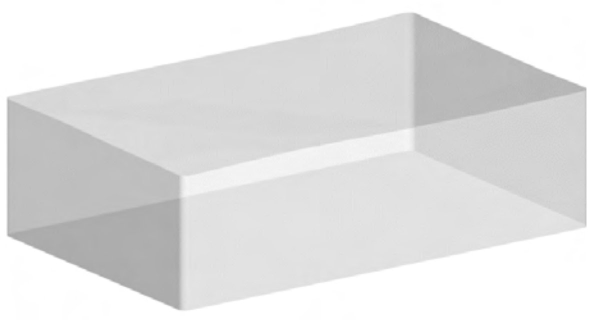
GeotechTypicalSection
(here: Representation of further properties)



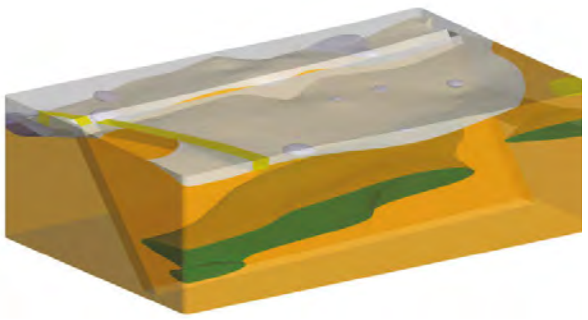
Tunnel Face Area + Discontinuity Set
(here: Representation as Granularity Level GL5)



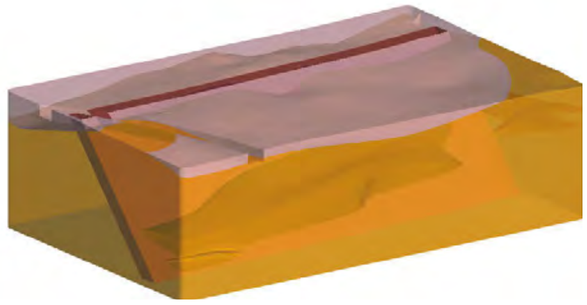
Geology Model Boundary



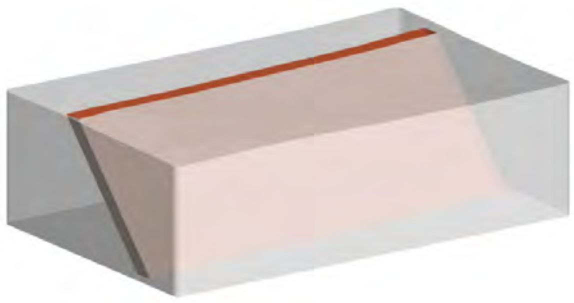
Geotechnical Model Boundary



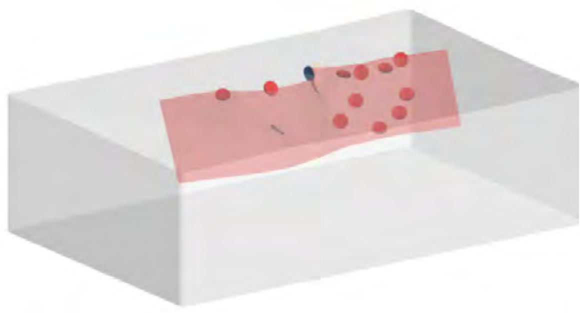
Geological Unit
(here: Visualisation of geological units)



Geotechnical Unit



Fault
(here: Representation of a geological fault)



Discrete Discontinuity + Discontinuity Set