DATA DRIVEN GEOTECHNICAL DESIGN: TOWARD A DIGITAL GEOTECHNICAL BASELINE FOR HARD ROCK MECHANISED TUNNELLING

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ABSTRACT: In hard rock mechanised tunnelling, early planning and design are vital for decisions on alignment and excavation, impacting performance, safety, and costs. However, linking geological characterisation with geotechnical design remains a complex challenge.

Current workflows manage datasets without systematic integration, causing fragmentation, subjective interpretation, and limited traceability. This study proposes a digital, data-driven workflow for geotechnical planning in hard-rock tunnelling that integrates geological, geotechnical, and engineering data within a traceable framework.

Central to this is the concept of digital geotechnical baselines, generated via a semi-automated workflow estimating ground behaviour based on rock parameters.

The methodology relies on structured data management and knowledge exchange among geologists, geotechnical experts, and engineers. Geological models are enriched with geotechnical parameters, forming engineering-ready datasets for analysis and design. Semi-automated routines connect geological attributes with material properties, supporting tunnel analysis and costing.

The platform combines database management, analysis, and visualization tools, consolidating all data and results within a single system developed according to regional standards, including those of D-A-CH region (Germany (D), Austria (A), Switzerland (CH)).

By establishing a direct link between geological input, geotechnical characterisation, and tunnel information modelling (TIM), the platform facilitates the development of adaptive geotechnical design, supporting timely updates and risk-informed evaluations as new data becomes available.

1. INTRODUCTION

Underground space is increasingly used for transport and infrastructure, making reliable geotechnical design an essential part of tunnelling projects. In current practice, geotechnical design largely relies on expert judgement, guideline-based classification systems, and experience from comparable projects. Geological investigations and laboratory test results form the basis for these assessments, while established procedures—such as those developed by the Austrian Society for Geomechanics (OEGG)—link ground conditions to support measures, excavation methods, and construction strategies. These approaches have proven robust and remain vital for both planning and construction phases.

Despite their reliability, the practical implementation of these methods is still characterised by discipline-specific workflows and heterogeneous documentation. Geological interpretations, geotechnical assessments, and engineering design decisions are typically developed in parallel and connected through reports, drawings, and manual data exchange. As a result, the underlying assumptions of geotechnical and tunnel design are often scattered across multiple formats, limiting traceability and making systematic verification or updating difficult when new information becomes available. This limitation becomes increasingly critical as tunnel projects grow in scale and complexity and as geological uncertainty and continuous risk assessment demand high transparency and adaptability in design.

A central cause of this fragmentation is the separation of geological and geotechnical information. Geological models typically focus on lithological and structural ground characterisation, whereas geotechnical data—such as rock mass properties and classification systems—are often assessed separately, leading to a fragmented workflow. Consequently, design assumptions become less traceable, and key design parameters are often determined through manual interpretation rather than through a structured and reproducible process. Updates to geological and geotechnical information, therefore, frequently require repeated manual interpretation, decreasing efficiency and increasing the risk of inconsistencies between datasets, design stages, and construction decisions.

In response to increasing demands for time and cost efficiency, sustainability, and risk management, the integration of digital technologies like Building Information Modelling (BIM) and Tunnel Information Modelling (TIM) is a key trend towards more coordinated execution of large-scale projects (Poisel, A.; Meier, A.; Bach, D. 2023)

The digital ground model is a vital component of the Tunnel Information Model development, encompassing three specialised models for ground, structure, and construction site. Within the scope of TIM, specific requirements for a digital, parameterised ground model must be developed to facilitate the transformation of the infrastructure construction sector, enabling it to fully adopt digital engineering methods and processes (Exenberger, H., Gächter, W., and Flora, M., 2022; Gächter, W. et al., 2021).

For geologists, layer-based modelling approaches have long been established and provide a solid foundation for advancing BIM integration. However, although geological models are widely recognised as 3d geometric representations, adding detailed, parametrised information into them remains fairly uncommon. The challenge in visualisation, modelling, and exchange of geotechnical information stems from the existence of diverse data models, either two-dimensional with selective information or three-dimensional without a database foundation (Exenberger, H., Gächter, W., and Flora, M., 2022) (Exenberger, H., Gächter, W., and Flora, M., 2022 – Poisel, A.; Meier, A.; Bach, D. 2023).

This paper addresses this gap by introducing the geological and geotechnical aspects of the future envisioned *Tunnel Vision* platform. The platform is conceived as an integrative environment in which guideline-based geotechnical decision logic—such as the methods of the Austrian Society for Geomechanics (OEGG)—is explicitly formalised and embedded into the digital model. Geological and geotechnical information is systematically transformed into engineering-ready, rule-based datasets, creating an explicit and reproducible link between ground conditions, ground behaviour, and design-relevant parameters under defined boundary conditions. By combining structured data management, semi-automated data enrichment, and expert validation, the approach enables transparent, traceable, and updateable geotechnical design and provides a consistent digital foundation for design decisions and interdisciplinary collaboration throughout the project lifecycle.

The paper is organised as follows. Section 2 presents the use case for geotechnical design in hard-rock tunnels and describes the methodological framework and baseline concept underlying the proposed approach. Section 3 discusses the results obtained using this methodology, highlights its advantages and limitations, and outlines potential directions for future development. Section 4 summarises the limitations of the proposed workflow. Section 5 concludes the paper and provides an outlook on future prospects.

2. USE CASE: GEOTECHNICAL DESIGN FOR HARD ROCK TUNNELS

2.1 CONCEPTUAL FRAMEWORK

The Guideline for the Geotechnical Design of Underground Structures with TBM Excavation, published by the Austrian Society for Geomechanics, provides a practical and clearly structured framework for TBM tunnel design. It aims to ensure a transparent and traceable design process and to support the optimal adaptation of construction methods and support measures to encountered ground conditions throughout both design and construction phases (Poisel, A.; Meier, A.; Bach, D. 2023).

Rather than reproducing the guideline descriptively, the proposed framework extracts and formalises its implicit decision logic. Links between geotechnical parameters, boundary conditions, and Behaviour Types (BT) are converted into structured, parameterised rules suitable for digital processing. This formalisation clarifies guideline-based design assumptions, makes them traceable, and allows systematic adaptation within a digital environment.

The workflow presented in this paper focuses on steps one to three of the geotechnical design phase, as described in earlier conceptual work on parameterised ground models for tunnelling, as shown in Figure 1 (Exenberger, H., Gächter, W., and Flora, M., 2022).

While earlier similar approaches were limited to two-dimensional applications aimed at accelerating calculations on ground behaviour (Steiner, A., & Schubert, W. 2007), the proposed method extends this concept into a three-dimensional framework suitable for BIM- and TIM-based geotechnical planning. The framework integrates intact rock data, derives rock mass properties, maps ground types, and assigns Behaviour Types, thereby supporting a consistent, transparent digital design workflow adaptable across projects and stakeholders. The resulting homogeneous sections along the alignment serve as the baseline for the further stages of the tunnel design.

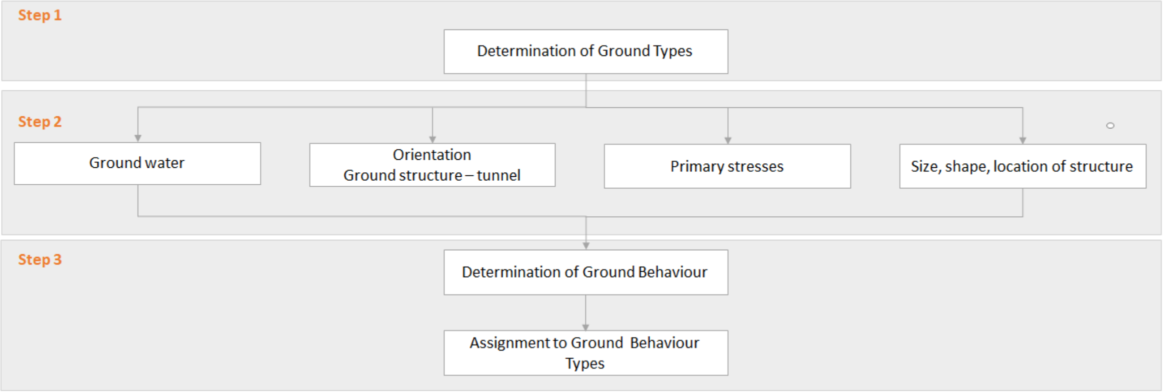


Figure 1. Relevant steps from the schematic geotechnical design procedure

2.2 WORKFLOW OVERVIEW

The proposed framework consists of a sequence of structured steps, illustrated in Figure 2 that transform heterogeneous ground data into homogeneous sections suitable for tunnel design.

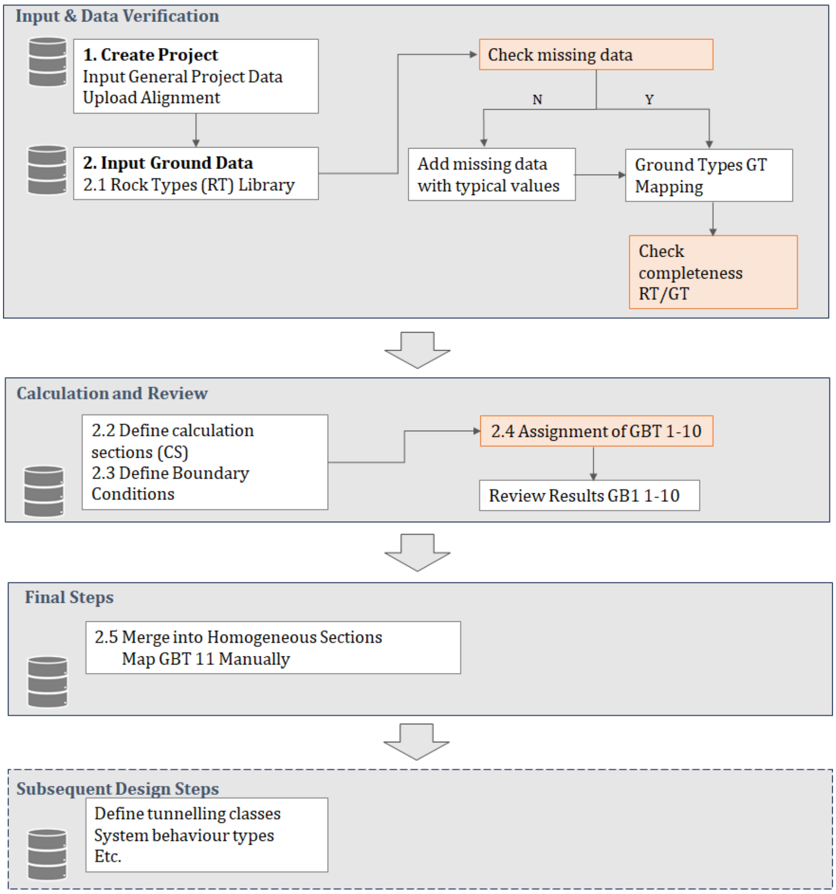


Figure 2. Workflow: Ground Data to Homogeneous Sections

Step 1: Project Creation

The workflow starts with creating a project and establishing a shared database accessible to all stakeholders.

Step 2: Input and evaluation of ground data

Step 2.1: Creating the Rock Type (RT) Library

A Rock Type library is established containing lithology, intact rock properties, Geological Strength Index parameters, discontinuity characteristics, and groundwater conditions. Data completeness and plausibility are automatically checked. Missing parameters may be supplemented using reference values, which are explicitly flagged to preserve transparency. This step guarantees that all subsequent interpretations are based on a consistent and well-documented dataset. Ground Types are then derived along the tunnel alignment by grouping Rock Types with similar mechanical behaviour. This facilitates engineering-relevant simplification while retaining essential geological variability.

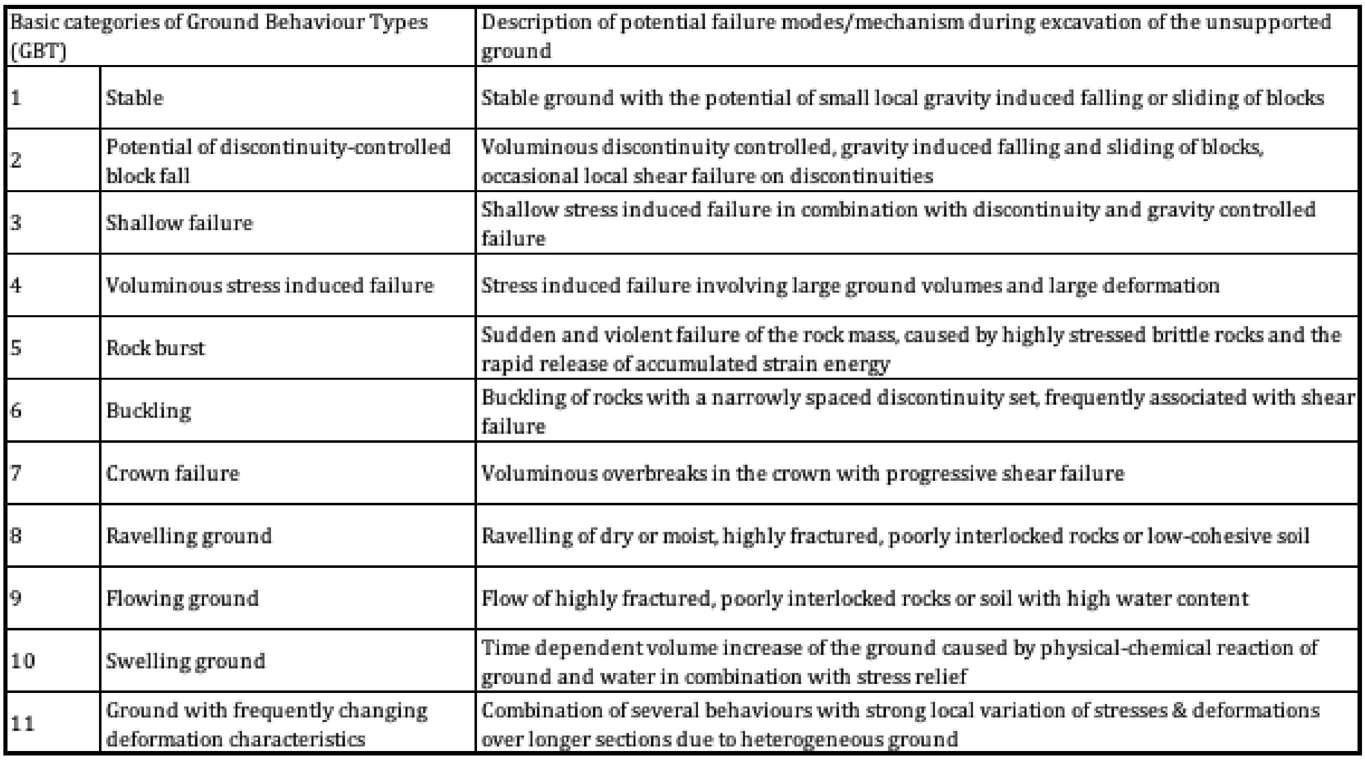
Step 2.2 Definition of Calculation Sections

Calculation sections are defined along the alignment under geotechnical supervision, based on mapped Ground Types and local conditions. Tunnel geometry and overburden parameters are integrated using LandXML data, ensuring spatial consistency and traceability.

Step 2.3 Definition of Ground Behaviour Type Boundary Conditions

Boundary conditions for Ground Behaviour Types (GBT1–GBT10) are defined using adjustable parameter ranges. These boundaries represent formalised design assumptions and can be adapted to project-specific requirements. Subclasses may be introduced to reflect more detailed behavioural distinctions.

Table 1 General categories of Ground Behaviours



Basic categories of Ground Behaviour Types (GBT)		Description of potential failure modes/mechanism during excavation of the unsupported ground
1	Stable	Stable ground with the potential of small local gravity induced falling or sliding of blocks
2	Potential of discontinuity-controlled block fall	Voluminous discontinuity controlled, gravity induced falling and sliding of blocks, occasional local shear failure on discontinuities
3	Shallow failure	Shallow stress induced failure in combination with discontinuity and gravity controlled failure
4	Voluminous stress induced failure	Stress induced failure involving large ground volumes and large deformation
5	Rock burst	Sudden and violent failure of the rock mass, caused by highly stressed brittle rocks and the rapid release of accumulated strain energy
6	Buckling	Buckling of rocks with a narrowly spaced discontinuity set, frequently associated with shear failure
7	Crown failure	Voluminous overbreaks in the crown with progressive shear failure
8	Ravelling ground	Ravelling of dry or moist, highly fractured, poorly interlocked rocks or low-cohesive soil
9	Flowing ground	Flow of highly fractured, poorly interlocked rocks or soil with high water content
10	Swelling ground	Time dependent volume increase of the ground caused by physical-chemical reaction of ground and water in combination with stress relief
11	Ground with frequently changing deformation characteristics	Combination of several behaviours with strong local variation of stresses & deformations over longer sections due to heterogeneous ground

Step 2.4 Assignment of Ground Behaviour Types (GBT)

Based on the defined rules and mapped parameters, Ground Behaviour Types are systematically assigned to each calculation section. The governing parameters and boundary conditions influencing each classification are documented and visualised along the tunnel profile, ensuring visibility and transparency. GBT11 is assigned at a later stage during section merging.

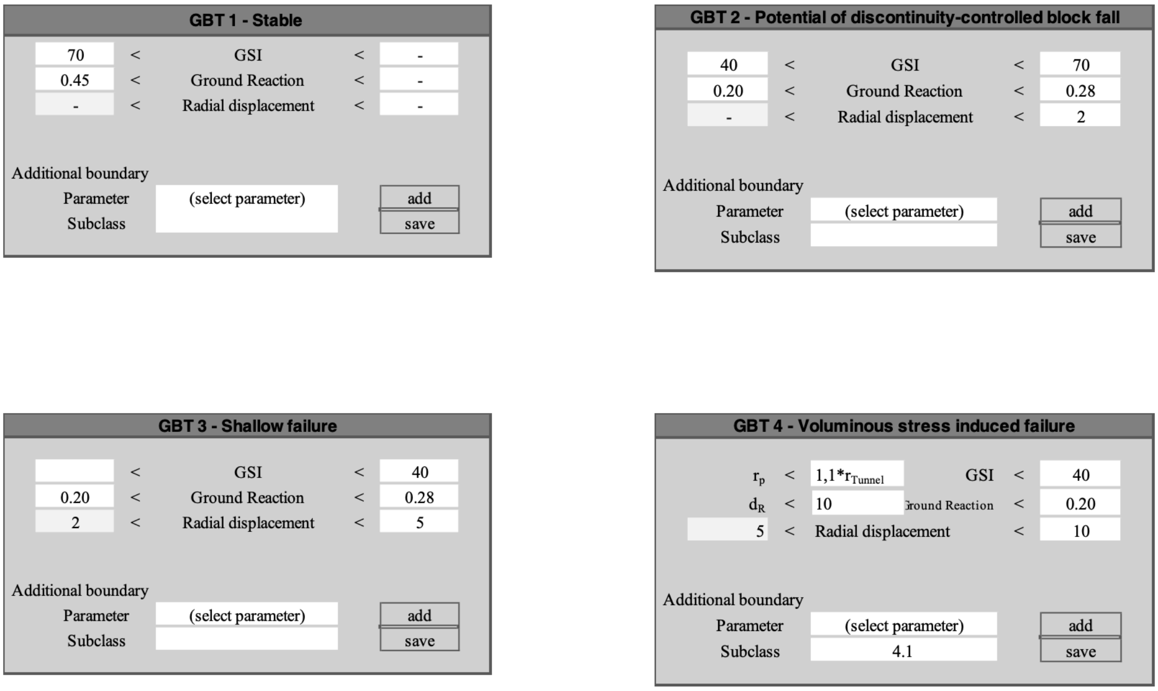
Step 2.5 Merging into Homogeneous Sections

Following expert review, calculation sections with similar characteristics are merged into Homogeneous Sections, forming a consistent basis for subsequent analyses and design steps.

2.3 METHODOLOGY

The proposed workflow was applied and qualitatively validated using several tunnel projects. One representative case study (Project A) is presented in the following section. The case study demonstrates the framework's ability to enforce data completeness, make design assumptions explicit, and support consistent Behaviour Type assignment across the tunnel alignment.

In Project A, 51 Rock Types were grouped into 31 Ground Types, and the alignment was subdivided into 1500 calculation sections. Project-specific boundary conditions were defined; selected examples for GBT1 – GBT4 are shown in Figure 3.



GBT 1 - Stable

70	<	GSI	<	-
0.45	<	Ground Reaction	<	-
-	<	Radial displacement	<	-

Additional boundary
Parameter (select parameter)
Subclass

GBT 2 - Potential of discontinuity-controlled block fall

40	<	GSI	<	70
0.20	<	Ground Reaction	<	0.28
-	<	Radial displacement	<	2

Additional boundary
Parameter (select parameter)
Subclass

GBT 3 - Shallow failure

	<	GSI	<	40
0.20	<	Ground Reaction	<	0.28
2	<	Radial displacement	<	5

Additional boundary
Parameter (select parameter)
Subclass

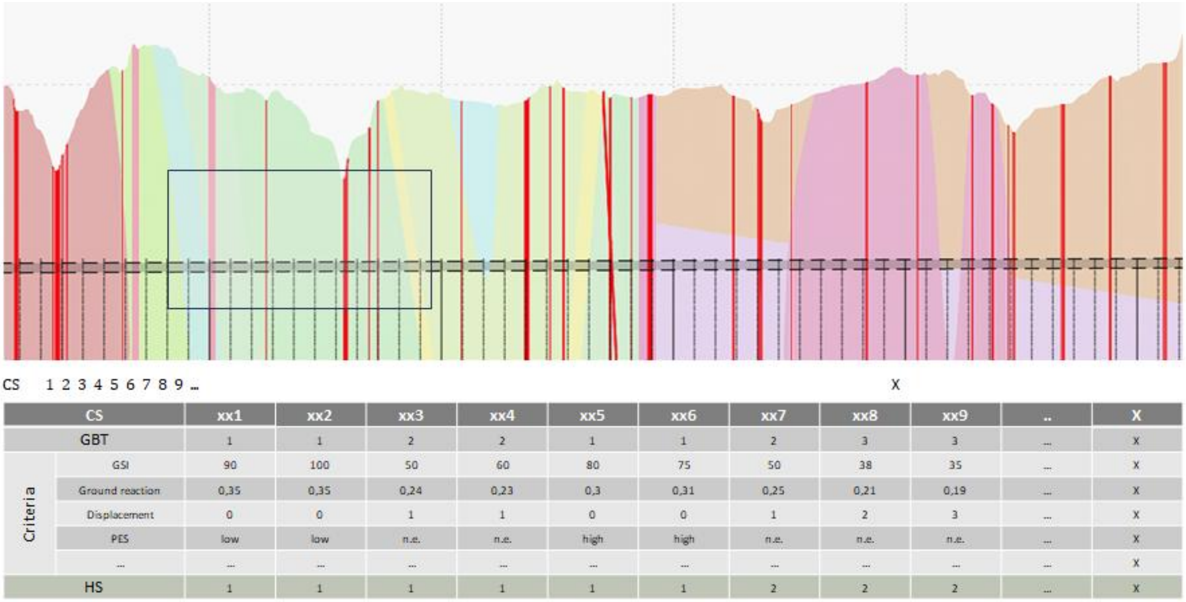
GBT 4 - Voluminous stress induced failure

r_p	<	$1,1*r_{Tunnel}$	GSI	<	40
d_R	<	10	Ground Reaction	<	0.20
5	<	Radial displacement		<	10

Additional boundary
Parameter (select parameter)
Subclass 4.1

Figure 3 Ground Behaviour Boundary Conditions

An example output view is provided in Figure 4.



CS		xx1	xx2	xx3	xx4	xx5	xx6	xx7	xx8	xx9	..	X
GBT		1	1	2	2	1	1	2	3	3	...	X
Criteria	GSI	90	100	50	60	80	75	50	38	35	...	X
	Ground reaction	0,35	0,35	0,24	0,23	0,3	0,31	0,25	0,21	0,19	...	X
	Displacement	0	0	1	1	0	0	1	2	3	...	X
	PES	low	low	n.e.	n.e.	high	high	n.e.	n.e.	n.e.	...	X
	...	...	...	...	...	...	...	...	...	...	...	X
HS		1	1	1	1	1	1	2	2	2	...	X

Figure 4 Output view

3. RESULTS AND DISCUSSION

The application of the proposed workflow to selected case studies demonstrates the feasibility of formalising guideline-based geotechnical design processes within a structured, parameterised digital framework. Beyond technical feasibility, the results highlight the critical role of structure in ensuring transparency, consistency, and reproducibility in decision-making. The platform provides a unified digital environment that integrates geological, geotechnical, and engineering data and supports geotechnical and tunnelling design processes within a clearly defined data and rule hierarchy.

A shared library of Rock Types and Ground Types enables close collaboration between geologists and geotechnical engineers and ensures consistent data usage across disciplines, design stages, and project participants. Geological observations, laboratory results, and structural information are systematically linked to engineering-relevant properties, such as rock mass classifications, ground behaviour types, and derived design parameters. This structured linkage replaces ad-hoc manual interpretation with a clear data chain, making assumptions and derivation steps transparent and verifiable.

Where data are incomplete or uncertain, missing parameters can be defined using standardised or reference values, while integrated completeness and consistency checks ensure that datasets are suitable for subsequent calculations and reduce errors in semi-automated processing. Based on the available input data, the platform supports the semi-automated assignment of Ground Behaviour Types (GBT), thereby standardising the translation of observations into design-relevant outputs while preserving expert oversight.

The evaluated GBTs form the basis for assessing ground–structure interaction and system behaviour, thereby supporting risk identification and management during construction and enabling semi-automated time-related analyses that directly contribute to construction scheduling and cost estimation. Compared to conventional document-based workflows, the structured model allows rapid reassessment of design scenarios when boundary conditions, geological interpretations, or project requirements change.

An integrated dashboard enhances traceability and collective decision-making by documenting data sources, assumptions, parameter choices, and calculation results, thereby strengthening communication among stakeholders and supporting reproducible design procedures. By making the design logic explicit and navigable, the platform supports interdisciplinary communication and reduces ambiguity at interfaces between geology, geotechnics, and construction planning. This transparency is particularly relevant in projects characterised by geological uncertainty and evolving knowledge during excavation.

Conceptually, the methodology follows the DAUB principle of separating sub-models and aligns with the well-established design practices recommended by the Austrian Society for Geotechnics for underground structures.

This structured approach is essential because it clarifies, traces, and reproduces the decision logic in geotechnical design for hard rock tunnels, reducing common issues from manual data transfer, subjective judgments, and loss of information. Without a formal structure, these judgements remain implicit, difficult to communicate, and challenging to update. By facilitating semi-automated data sharing, accommodating various calculation methods, and including statistical analysis techniques, the platform enhances the accuracy of predictive assessments, while still allowing experts to maintain control over interpretation, uncertainty evaluation, and strategic decisions.

Importantly, the primary benefit of the proposed framework is not to replace established design methods, but to formalise and operationalise their underlying decision logic. The structured framework supports expert-driven design by improving transparency and consistency, while responsibility for interpretation and decision-making remains with the engineer.

Expert validation remains integral during boundary condition definition and the aggregation of calculation sections into homogeneous sections, thereby preserving the adaptability required to address project-specific geological uncertainty while ensuring that design decisions remain transparent, consistent, and systematically reviewable.

4. LIMITATIONS

The workflow is currently tailored to hard rock tunnelling and aligned with D-A-CH regional standards, and its reliability depends on the quality and completeness of input data as well as on calibration of parameter-mapping rules. While the approach has proven effective within its intended scope, further validation across a wider range of geological and project conditions is required.

5. OUTLOOK / CONCLUSION

This study demonstrates that guideline-based geotechnical design for hard-rock tunnels can be translated into a structured, parameterised digital workflow that supports integral tunnel planning without replacing expert judgement. By formalising decision logic, data dependencies, and assumptions within a shared digital environment, the proposed framework improves transparency, consistency, and traceability across geological, geotechnical, and engineering domains.

Despite significant advances in digital planning tools, geological and geotechnical aspects of tunnel design remain largely document-based and fragmented. This limitation becomes particularly critical in large-scale projects dominated by geological uncertainty. As subsurface uncertainty cannot be eliminated—especially in deep hard-rock tunnelling—design approaches based on ground behaviour concepts offer a more robust foundation than isolated parameter values. The presented framework addresses this challenge by structuring the integration of geological, geomechanical, and boundary conditions into coherent, reviewable design units.

Building on these results, the envisioned *Tunnel Vision* platform aims to support integral tunnel planning by consistently integrating geological, geotechnical, structural, and construction-related information within a shared, parameterised environment.

Successful implementation of such an approach requires not only suitable digital tools but also close interdisciplinary collaboration among geologists, engineers, contractors, and authorities. By providing a common data and logic framework, *Tunnel Vision* has the potential to improve communication, support consistent decision-making, and enhance the resilience of tunnel design in the presence of uncertainty.

Future research will focus on extending the framework to additional mechanised tunnelling methods and ground conditions, integrating observational data from construction, and validating the approach through comparative studies across multiple projects. In the long term, structured and parameterised geotechnical workflows such as the one presented may form the basis for adaptive design processes that systematically link predicted and observed ground behaviour, contributing to more robust, transparent, and risk-informed underground infrastructure development.

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