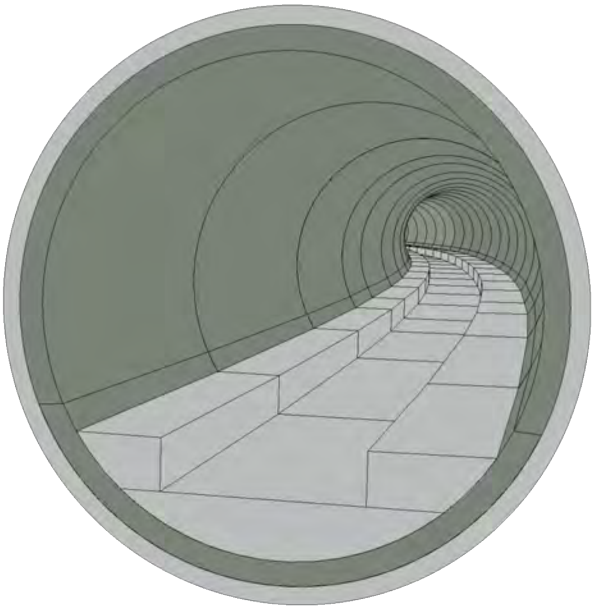

Recommendation Digital Design, Building and Operation of Underground Structures

Model requirements – Part 5

Allowance of tolerances and superelevation

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 5: Allowance of tolerances and superelevation
Supplement to DAUB recommendation BIM in Tunnelling (2022)

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Title picture: Own illustration

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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 digitalization 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 5 of the series of recommendations, deals with the basic handling and consideration of tolerance allowances and superelevation in 3D design.

After an overview of the current initial situation in the three D-A-CH countries, the relevant use cases during modelling are discussed. This is followed by explanations of the requirements for the model and recommendations for implementation. 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 3 and Part 4).

All recommendations published so far are listed as follows for a better overview:

BIM in Tunnelling	**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

In tunnelling, in addition to taking construction tolerances into account, allowance of tolerances/superelevation are also required for the excavation and construction of the support and the tunnel lining to compensate for geologically induced deformations.

In the three D-A-CH countries Germany, Austria and Switzerland, the definition and consideration of deformations, tolerances, superelevation (Überhöhung), and oversizes (Übermaß) are described in various standards and guidelines. In principle, the definitions given are similar. Nevertheless, there are country-specific differences and the terms used in the three countries differ from each other.

The purpose of the design dimensions is to consider any construction tolerances or expected deformations of the structure or the edge of the cavity to ensure that the required geometry is maintained in the final state.

According to existing 2D design processes used in some countries, drawings are created based on a target/design geometry, which are also used for invoicing.

The necessary allowance of tolerances (Vorhaltemaße) and superelevations (Überhöhungen) are indicated in text form on the design documents. Due to the idea of a "single source of truth" with models that are free of contradictions, models are required that contain the geometry to be built, including the allowance of tolerances and superelevation. To avoid a considerable additional effort in modelling, separate models with different dimensions should not have to be created for the different use cases such as cost determination, detailed design and invoicing due to allowance of tolerances (Vorhaltemaß) and superelevation (Überhöhung).

The objective of this recommendation is to create a reasonable and realistic way of dealing with allowance of tolerances and superelevation during 3D design. This results in the following tasks of this working group:

- Identification and definition of situations related to the handling of allowance of tolerances and superelevation
- Clear definition for the consideration of allowance of tolerances and superelevation when creating models

It should be noted, however, that the consideration of allowance of tolerances and superelevation in the modelling can also influence the quantity estimation and thus the cost estimation.

1.2 Scope and target group

With the present recommendation, all project participants in underground construction should be addressed.

The principles presented can be applied in the design of all underground structures. They should already be applied consistently in the preliminary design, but at the latest in the design phase. A consistent application of these approaches should then be maintained and implemented from the approval phase, through the tendering phase, during construction and up to subsequent operation.

1.3 Delimitation

The trades involved in underground construction depend on the type of use and the construction method of the respective project. Very often there are interfaces with civil engineering, foundation engineering, structural engineering, road or track construction and tunnel equipment. To make a clear distinction, this document focuses on the underground structure in the design phase, in the construction phase and in the operational phase.

2 Current situation of existing practice

2.1 Definition of terms

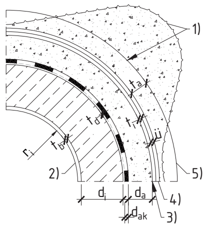
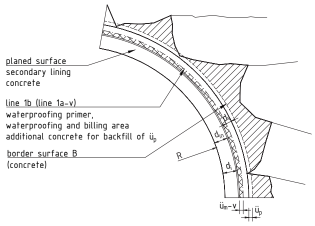
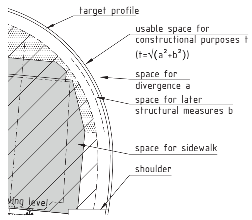
In the three D-A-CH countries, the terms tolerance, superelevation (Überhöhung), oversize (Übermaß), and deformation are sometimes used differently. **Table 2-1** compares the terms used in these countries. In the following chapters, the terms "Allowance of tolerances" and "Superelevation" are used as defined in this Table.

2.2 Clearance profile and Structure gauge

In the following, a distinction is made between the clearance profile and the structure gauge.

The clearance profile is defined using the tunnel and the associated traffic or usable space to be kept free. The approach to defining the required usable space differs for road tunnels (EABT/RVS 09.01.22/SIA 197/2) and railway tunnels (RIL 853/ÖBB RW 10.01.02.01/SIA 197/1).

Table 2-1 *Comparison, terms and definition of terms for this document*

Definition of terms used in this document	Germany (D)	Austria (A)	Switzerland (CH)
			
	see **chapter 2.3.1**	see **chapter 2.3.2**	see **chapter 2.3.3**
Allowance of tolerances	t_b: Construction tolerance of the secondary lining (rise of an arch, formwork tolerance, set-up tolerance)	V_{GZ} + X/2: Allowance of tolerances for tunnel vault + rise of an arch	Total tolerance is composed of: ▪ Deformations of the supporting structure ▪ Manufacturing inaccuracies ▪ Measurement axis deviations (measurement errors)
	t_i: Internal tolerance		
	t_a: External tolerance	$ü_p$: Excessive profile (*Überprofil*) specified by the client during the invitation to tender	
Superelevation	t_d: Deformation tolerance of the primary lining	$ü_m$: Oversize (*Übermaß*) determined by the client during the excavation work	d: Work-related excessive profile (*Überprofil*)
	ü: Superelevation (*Überhöhung*) to compensate for unavoidable deformations		

The structure gauge describes the area within the tunnel cross-section that must always be kept clear and into which the tunnel lining must not penetrate. The structure gauge depends on the clearance profile and takes into account other technical influencing factors. Basically, the structure gauge includes the following usable spaces:

- Usable space for traffic (cf. **Figure 2-1** and **Figure 2-2**)
- Usable space for constructional purposes (cf. **Figure 2-3**)
- If necessary, usable space for ventilation

The basis for determining the required geometry of the tunnel cross-section is thus the structure gauge based on the clearance profile.

2.3 Preliminary design and tender

In the following sections, normative bases for the determination of the cross-section geometry in the design and tendering phase are described for the three D-A-CH countries.

2.3.1 Germany (D)

In Germany, DIN 18312 – "VOB Vergabe- und Vertragsordnung für Bauleistungen – Teil C: Allgemeine Technische Vertragsbedingungen für Bauleistungen (ATV) – Untertagebauarbeiten" (German Construction Contract Procedures – Part C: General Technical Terms of Contract for Construction Work – Underground Construction Work) provides guidance for drawing up the specifications. In addition to the excavation classes, information on the dimensions of the excavation, the structure limits and the tolerances are also defined there (**Figure 2-4**).

There is no uniform regulation for the definition of the design section/target profile and it is therefore handled differently in the tendering phase.

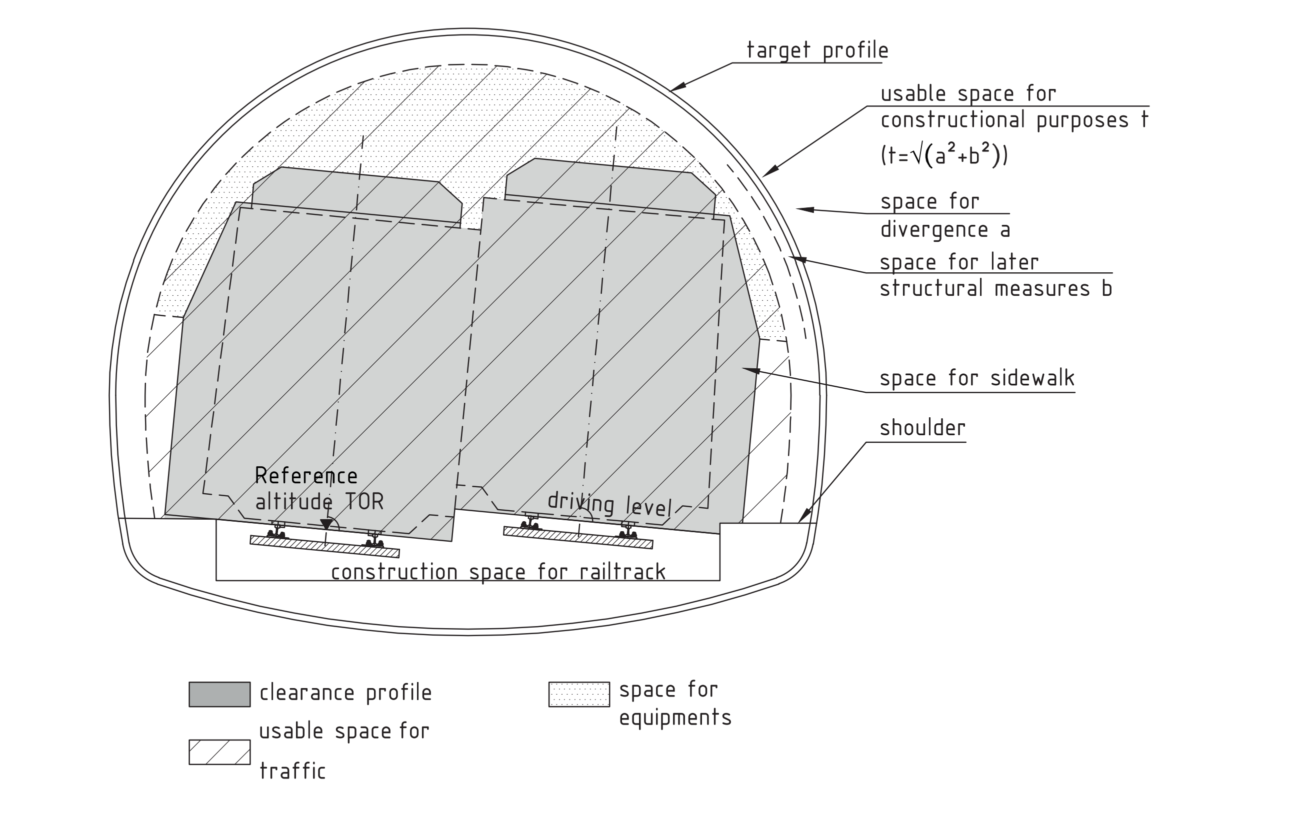


Figure 2-1 *Example of definition of usable space for railway, according to SIA 197:2004, Figure 2* **[7]**

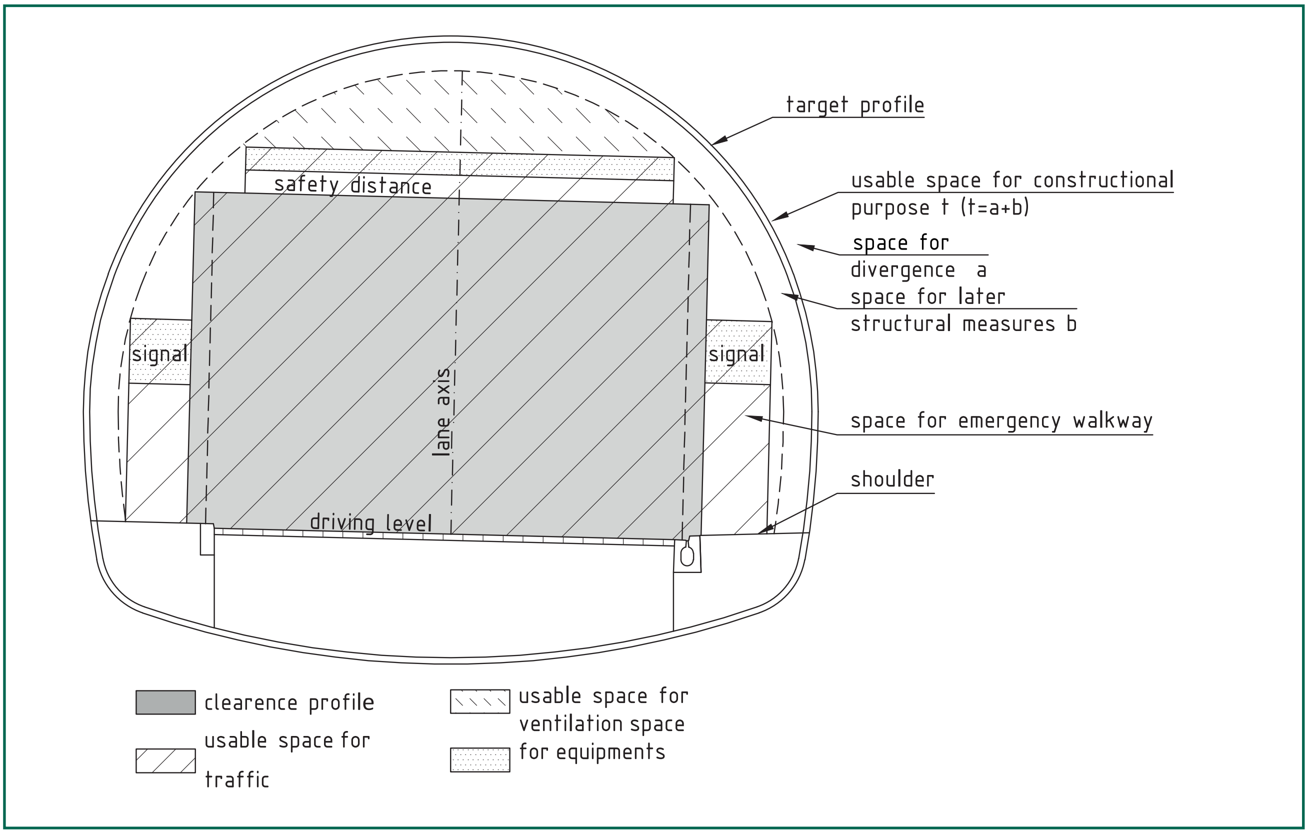


Figure 2-2 *Example of definition of usable space for roads, according to SIA 197:2004, Figure 3* **[7]**

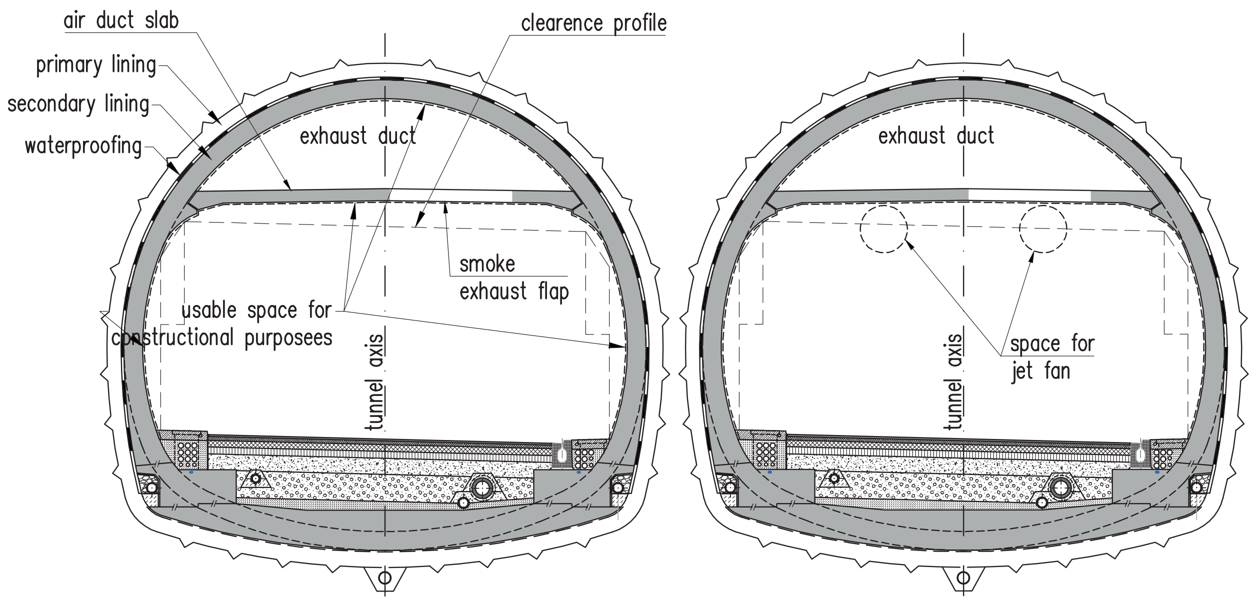
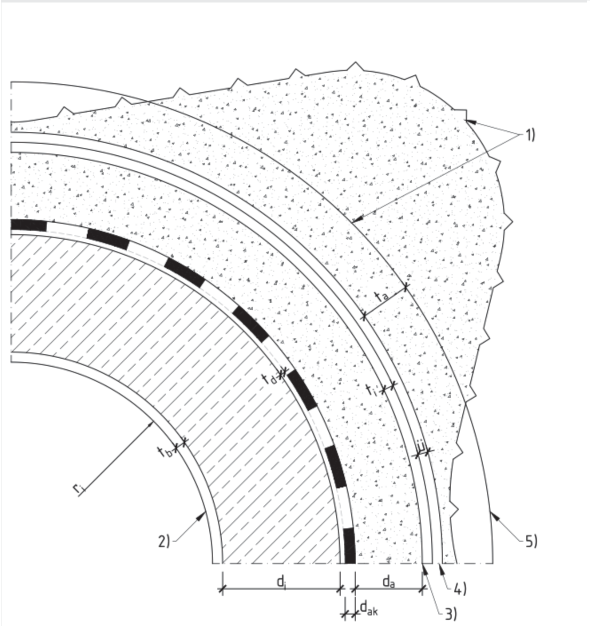


Figure 2-3 *Structural usable space (left) and space for the installation of jet fans (right); Source: Amberg Engineering AG*

For conventional tunnelling, the preliminary design is sometimes prepared without considering the tolerances and superelevation required for construction and production. For the contractor, this results in a deductible for polygonality, construction tolerances and possibly even rock deformations.

With mechanised tunnelling, on the other hand, a reserve dimension for shield drive tolerances and possible ring deformations is usually considered in the preliminary design when determining the drilling or segment diameter. The nominal dimension of the inner diameter thus corresponds to the geometry to be built (segment mould, reinforcement).



Legend:

r_i Planned radius of the inner structure boundary
d_i Planned thickness of the secondary lining
d_{ak} Thickness of anchor heads and sealing
d_a Planned thickness of the primary lining
t_b Construction tolerance of the secondary lining
t_d Deformation tolerance of the primary lining
t_i Internal tolerance
t_a External tolerance
ü Superelevation to compensate for unavoidable deformations in problem zones

$L_{AS} = L_{TW} + t_b + d_i + t_d + d + d_{aka} + t_i + ü$
$L_i = L_{AS} - t_i - ü$
$L_A = L_{AS} + t_a$

1) Boundary lines of the geologically caused, unpredictable, unavoidable additional excavation
2) L_{TW} -line (inner structural boundary line)
3) L_i -line
4) L_{AS} -line (breakout target profile)
5) L_A -line (outer breakout tolerance)

Figure 2-4 *Representation of the lining thicknesses, the tolerances and the additional excavation according to DIN 18312: VOB Vergabe- und Vertragsordnung für Bauleistungen – Part C, Figure 1*

2.3.2 Austria (A)

According to the ÖBV-Richtlinie Innenschalenbeton **[8]** (ÖBV Guideline for Concrete of secondary lining) the determination of the standard profile (**Figure 2-5**) is described in three steps for cyclic tunnelling.

1. Step: Determination of the minimum profile
   The minimum profile describes the structure gauge required for all technical equipment and utility spaces in the tunnel. The minimum profile shall not be undercut throughout the tunnel and shall be shown on the drawings.

2. Step: Determining the theoretical profile (= minimum profile plus rise of an arch)
   The theoretical profile additionally considers the polygonal formation of the secondary lining blocks in curved sections and thus results from the minimum profile enlarged by the maximum rise of an arch.

3. Step: Determination of the standard profile (= theoretical profile plus allowance of tolerances)
   The standard profile results from the theoretical profile considering defined allowance of tolerances.

In addition, the client may also specify a maximum profile that may not be exceeded.

For cyclic or mined tunnelling, the excavation geometry with its oversize/superelevation is specified in ÖNORM B 2203-1 **[9]**. Various oversize/superelevation is to be specified by the client (**Figure 2-6** and **Figure 2-7**).

Any excess dimensions required for technical reasons must be considered by the contractor.

For continuous driving, the drilling diameter is determined according to ÖNORM B 2203-2 **[10]**. All allowance of tolerances shall be determined and presented, which cover the steering accuracy, the surveying inaccuracy of the machine and the tolerances of the support (**Figure 2-8** and **Figure 2-9**).

A distinction is made here between TBM tunnelling with conventional lining, segmental lining without secondary lining and segmental lining with secondary lining.

2.3.3 Switzerland (CH)

The allowance of tolerances in relation to the target size, target shape and target position, as well as the consideration of the curvature, are taken into account in the tunnel cross-section by defining the target profile. This is done in the mining part on the one hand by an additional tolerance space (usable space for construction measures) outside the usable space for traffic, and on the other hand by an increase in the vault concrete cross-section due to the total tolerance. The total tolerance is composed of the tolerances described below.

Tolerances in mining tunnels

Deformations of the supporting structure

After the installation of the excavation support, a rock deformation is to be assumed. This is absorbed by enlarging the excavation cross-section.

Manufacturing inaccuracies

The tolerance towards the inside is taken up by increasing the break-out cross-section. Towards the outside, the break-out cross-section shown by the

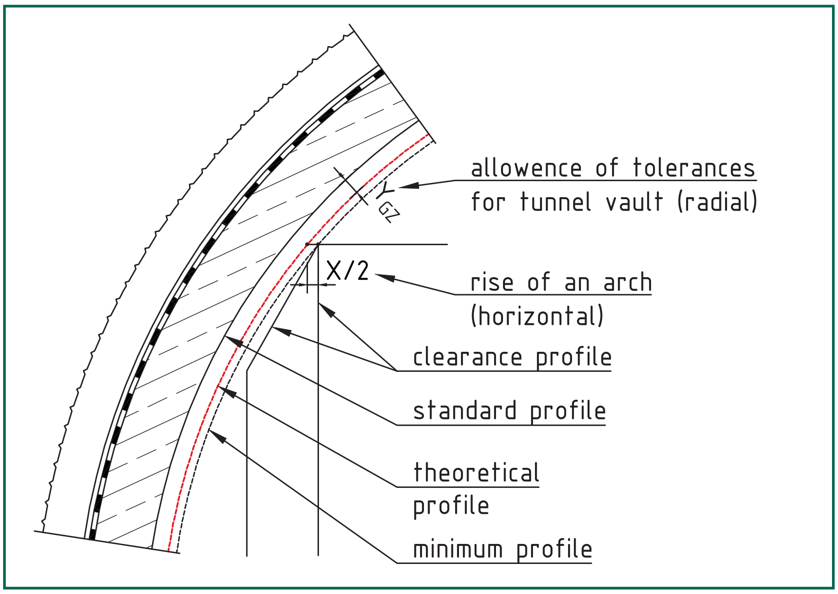


Figure 2-5
*Representation of the minimum profile, the theoretical profile and the standard profile according to **[9]***

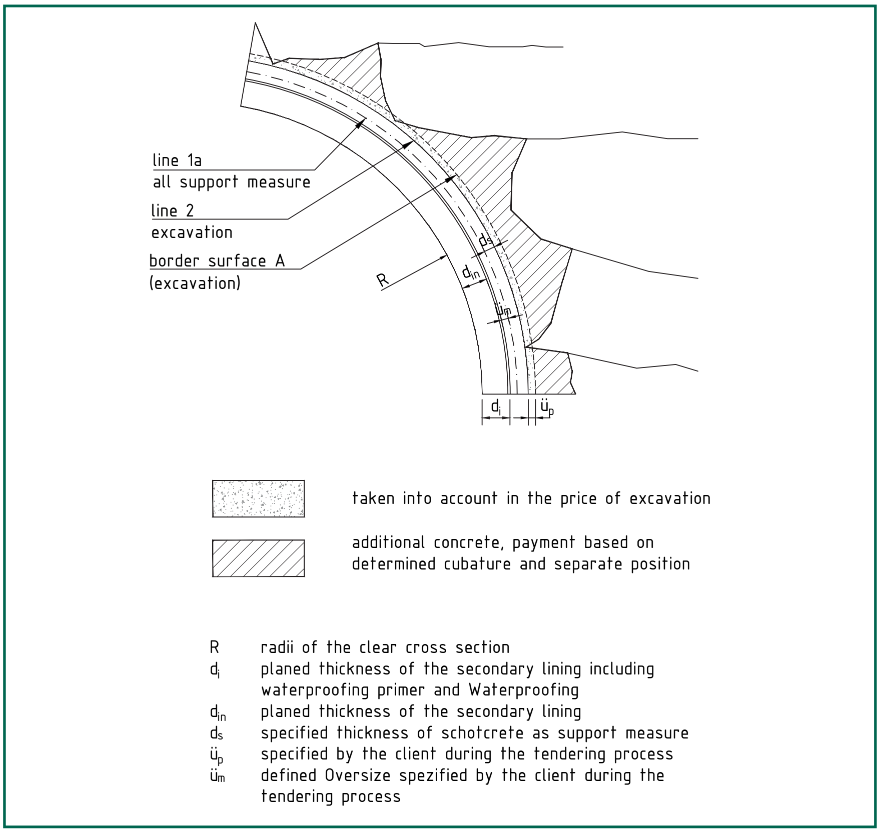


Figure 2-6
Representation of settlement lines; excavation and support – representation before deformation according to Figure 2 ***[9]***

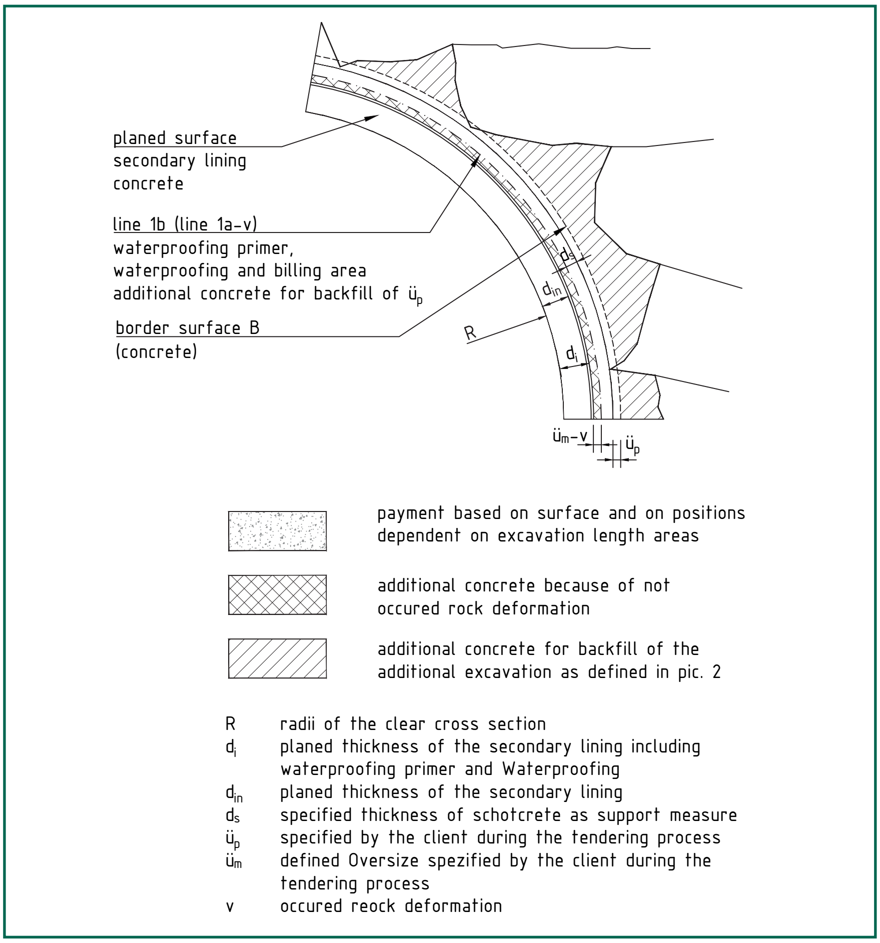
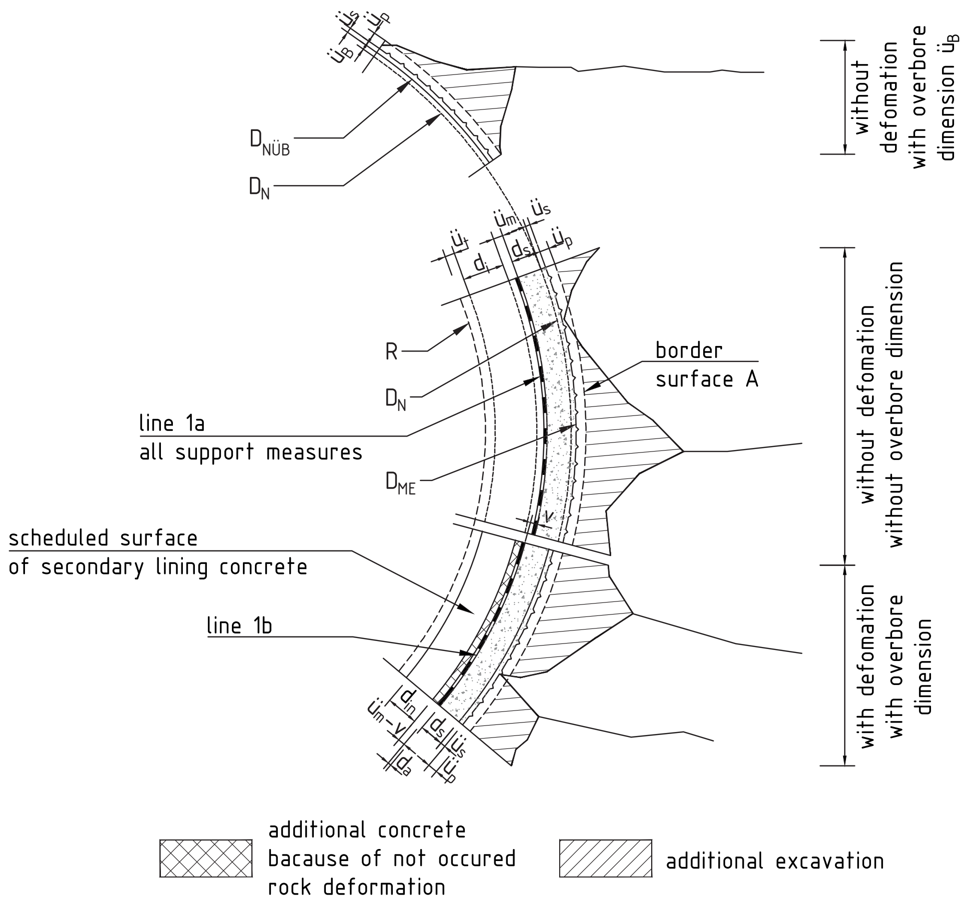


Figure 2-7
Representation of settlement lines; concrete and additional concrete – representation after deformation according to Figure 3 ***[9]***



R radii of the clear cross section

$ü_t$ in the tender defined measure for compensation of TBM drive deviation and formwork tolerances; defined from the client

d_i scheduled thickness of the secondary lining included waterproofing primer and waterproofing ($d_i = d_{in}+d_a$)

d_{in} scheduled thickness of the secondary lining

d_a scheduled thickness of waterproofing primer and waterproofing

v occured rock deformation

d_s defined thickness of the shotcrete as support measure

$ü_s$ over cut from the sphere of the contractor for tool wear, kurve driving etc.; to qoute by the contractor

$ü_p$ by the client in the tender phase specified and from the contractor excessive profile to be taken into account according to his assessment up to the border surface A

$ü_B$ overboreing dimension

$ü_m$ Oversize for the compensation of the expected rock and ring defomrations; in the tender phase to define from the client

D_N nominal boring diameter to qoute by the client; $D_N=2\ (R+ü_t+d_i+ü_m+d_s)$

$D_{NÜB}$ nominal boring diameter with overbore dimension; $D_{NÜB}=D_N + 2_{üB}$

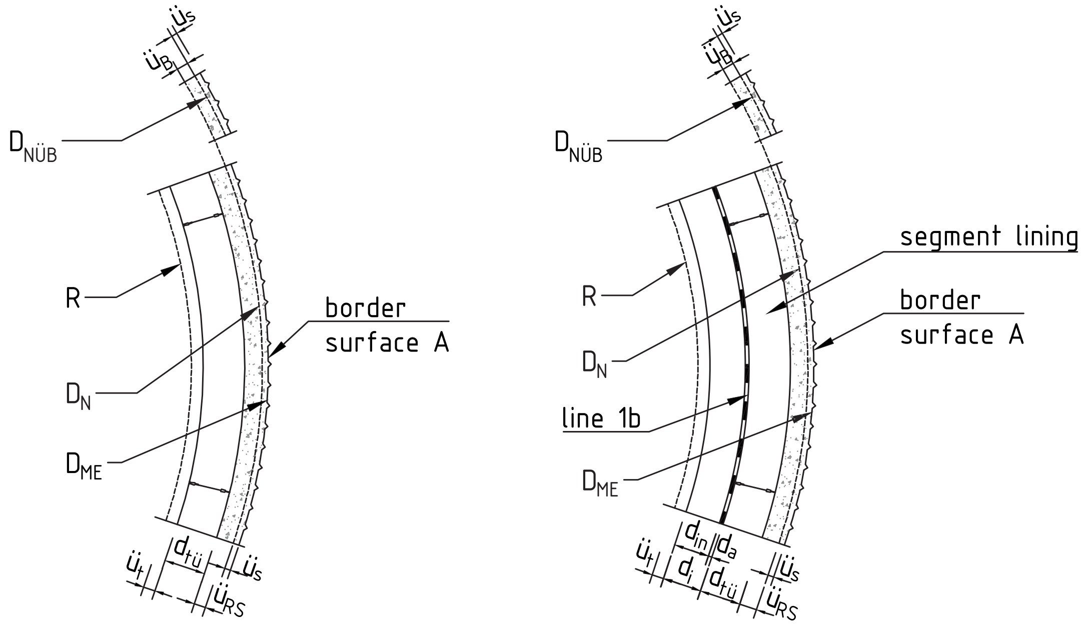
D_E effektive boring diameter (changeable)

D_{ME} max. effektive boring diameter with not reduced cutting tools

A border surface, defined by $D_{ME}+ü_p$

Figure 2-8 *Representation of the bore diameter for TBM driving with conventional support according to Figure 1* ***[10]***

Segment lining without secondary lining | **Segment lining with secondary lining**



Segment lining without secondary lining:

R	radii of the clear cross section
$ü_t$	in the tender defined measure for compensation of TBM drive deviation; defined from the client
$d_{tü}$	thickness of segment lining
$ü_{RS}$	grouting gap
$ü_B$	overbore dimension
$ü_s$	over cut from the sphere of the contractor for tool wear, kurve driving etc.; to qoute by the contractor
D_N	nominal boring diameter to qoute by the client
$D_{NÜB}$	nominal boring diameter with overbore dimension; $D_{NÜB}=D_N + 2_{üB}$
D_E	effektive boring diameter
D_{ME}	max. effektive boring diameter with not reduced cutting tools
A	border surface, is equivalent to D_{ME}

Segment lining with secondary lining:

R	radii of the clear cross section
$ü_t$	in the tender defined measure for compensation of TBM drive deviation; defined from the client
d_i	scheduled thickness of the secondary lining included waterproofing primer and waterproofing ($d_i = d_{in}+d_a$)
d_{in}	scheduled thickness of the secondary lining
d_a	scheduled thickness of waterproofing primer and waterproofing
$d_{tü}$	thickness of segment lining
$ü_{RS}$	grouting gap
$ü_B$	overbore dimension
$ü_s$	over cut from the sphere of the contractor for tool wear, kurve driving etc.; to qoute by the contractor
D_N	nominal boring diameter to qoute by the client
$D_{NÜB}$	nominal boring diameter with overbore dimension; $D_{NÜB}=D_N + 2_{üB}$
D_E	effektive boring diameter
D_{ME}	max. effektive boring diameter with not reduced cutting tools
A	border surface, is equivalent to D_{ME}

Figure 2-9 *Representation of the bore diameter for TBM driving with segmental lining according to Figure 2* ***[10]****. Assumption of common centre of cutting wheel, shield and segment support.*

designer represents the minimum. According to SIA standard 118/198 **[11]** the excess profile d due to working conditions is defined by the contractor (in the offer).

The tolerances in accordance with SIA 198 apply to the production of the break-out protection in Annex I.2 **[12]**. The tolerance for the thickness of the cladding (inner vault) is defined as a function of the statically required vault thickness according to SIA 198 **.**

Axial deviations (measurement errors)

Axial deviations result from the unavoidable, random measurement errors. They consist of the positional inaccuracies of the base network and the tunnel driving network.

The actual deviation of the existing tunnel axis from the target axis can only be determined after breakthrough. The axial deviations in the size of the maximum anticipated breakthrough error are compensated by increasing the excavation cross-section. Thus, the standard profile can be pushed into the correct position after attaching the breakout protection.

Total tolerance

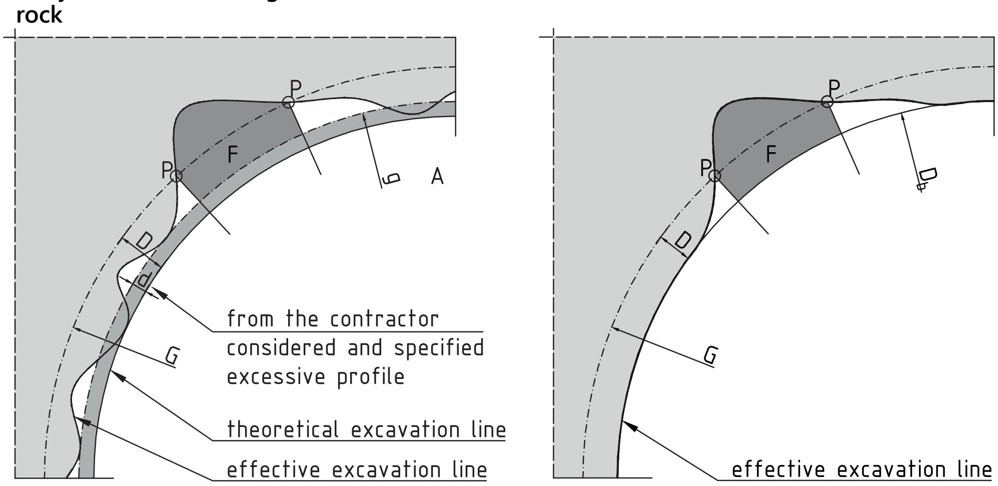
The vectors of deviations from the nominal dimension due to deformations, manufacturing inaccuracies and axial deviations in general do not sum up with their maximum value and same direction in one location. Therefore, the total deviation considered is determined by means of an error propagation law (mean error = root of the squares of the individual errors).

The requirements for the size of the clearance profile and the usable space for traffic are specified by the client in the user agreement and correspond to the specifications in SIA 197 **[7]**. The required accuracy is understood to be the permitted deviation from the target dimension. The deviation is the difference between the actual dimension and the corresponding target dimension. The target position is based on the theoretically calculated axis.

SIA 118/198:2007 **[11]** gives definitions for excess excavation and excess profile (**Figure 2-10**). The calculation of individual values and the specification of minimum values can be found in SIA 118/198 and 197-1.

Limitation of the geological excessive profile in drill & blast tunneling and mechanically assisted tunnelling in rock and loose rock

Limiting the geological excessive profile in TBM tunneling with or without shield



A theoretical excavation surface
D distance between the theoretical excavation line and the border line G
d distance between the theoretical excavation line and the border line g
g up to that line the excessive profile is in the excavation price included
G border line, dependent of D
F surface, for that the geological caused excessive profile will be payed
P intersection of the border line G with the effective excavation line

A theoretical excavation surface
D distance between the theoretical excavation line and the border line G
D_b boring dimaeter with reduced cutting tools
G border line, dependent of D
F surface, for that the geological caused excessive profile will be payed
P intersection of the border line G with the effective excavation line

Figure 2-10
Boundary to geological excessive profile according to Figure 4 and Figure 5 ***[11]***

2.4 Tender Offer/Estimation

The following chapter will explain how allowance of tolerances and superelevation are considered in the pricing in the respective D-A-CH countries.

2.4.1 Germany (D)

In the case of TBM tunnelling, the shield travel tolerances, and the allowance of tolerances for deformations of the lining are usually already included in the specifications in the invitation to tender. The specified inner radius, e.g. of the segment lining, corresponds to the segment geometry built later. Quantity adjustments are not necessary.

Conversely, in case of conventional tunnelling, the target geometry and the tolerances and excesses contained therein are defined differently depending on the client and their tenders. If the design geometry of the tunnel cross-sections is presented in the design or tender documents without considering tolerances and superelevation, the resulting additional quantities are not included in the quantity specifications of the bills of quantities. For pricing purposes, the additional quantities resulting from the tolerances and superelevation required for construction and production reasons must therefore be considered in the calculation. It is up to the bidder to decide how these quantities are to be included in the calculation. As a rule, this is considered with the help of factors when determining the quantity.

If, on the other hand, the tolerances and superelevation are already considered and presented in the design or tender documents when defining the target geometry of the tunnel cross-sections, there will be no additional quantities that have to be included in the pricing by means of corresponding factors.

2.4.2 Austria (A)

For both TBM (continuous) tunnelling and conventional (cyclical) tunnelling, the tender design includes the geometry of the tunnel cross-sections with the oversize/superelevation to be specified by the client.

In the case of cyclic excavation, the specified excessive profile ($ü_p$) is determined with the tender documents. The specified $ü_p$ is to be considered in the excavation positions, within which no separate payment is made for additional excavation. Any additional, geologically determined excessive profile shall be invoiced and remunerated with separate items in the bill of quantities.

In the area of the excavation, the required $ü_m$ is added to the excavation geometry and is thus compensated via the excavation. For rock deformations that have not occurred, there are separate positions for backfilling the remaining $ü_m$.

In the case of continuous excavation, the specification of all advance dimensions, which relate to the control accuracy, the surveying inaccuracy of the machine and the tolerances of the lining, is also carried out with the tender documents, differentiated according to TBM drive with cast in place lining, segmental lining without secondary lining and segmental lining with secondary lining. The allowance of tolerances are to be considered in the excavation positions, within which no separate remuneration is made for additional excavation. The remuneration is analogous to the principles of cyclic tunnelling.

2.4.3 Switzerland (CH)

In both TBM and conventional tunnelling, the tender design includes the geometry of the tunnel cross-sections with the oversize to be specified by the client. These include information on execution errors (from deformations, manufacturing inaccuracies and axis deviations). According to SIA 118/198 **[11]** the excavation is remunerated according to the theoretical extent if no other regulation is made in the work contract. For full or partial excavation, the face area is the free-standing area of the working face after excavation.

The work-related excessive profile "d" according to **Figure 2-10** is included in the unit prices for excavation and removal. The contractor must state this calculated excessive profile in the quotation.

A geologically induced excessive profile is defined as a localised collapse that has not occurred as a result of carelessness on the part of the contractor (e.g., due to overloading or incorrect placement of blasting shots, defective or delayed excavation support, staking errors), as well as the excessive profile in the invert that has to be excavated for geological-geotechnical reasons.

Loading and transport to the intermediate landfill, as well as the measures required to fill the cavity and secure the excavation, are paid for in the case of a geologically induced excessive profile for the entire profile portion F (see **Figure 2-10**). The area F is determined where the collapse extends beyond the boundary line G and counts from the boundary line G. The remaining areas within the boundary line G are included in the excavation prices.

2.5 Detailed design and construction

In this chapter, the handling of allowance of tolerances and superelevation in the respective D-A-CH countries is described in the phases of detailed design and construction.

2.5.1 Germany (D)

For the detailed design, it is mandatory to consider the allowance of tolerances and superelevation required for construction and production. Nevertheless, in accordance with the contractual specifications, only the nominal dimensions are shown on the execution documents for the formwork design and the excavation and support design without superelevation and tolerances. The required tolerances and superelevation are indicated in text or tabular form on the drawings and documents. The nominal geometry serves as the basis for invoicing.

Exceptions are usually the design of formwork (e.g. vault formwork carriages) and the reinforcement as well as the steel arch in the primary lining. In these designs, the tolerances and superelevation required for construction and production must be considered during production so that the required target geometry can be reliably maintained in the final state. This results, for example, in regular differences between the geometry shown in the formwork drawings and the design of the reinforcement or between the shown geometry of the primary lining and the associated steel arch drawings of the support arches. The allowance of tolerances and superelevation dimensions chosen by the contractor are to be specified.

2.5.2 Austria (A)

In the execution phase, the client defines any construction-related allowance of tolerances and normally both the target dimensions without allowance of tolerances and the geometry including the required allowance of tolerances are shown in the execution documents of the formwork drawings. However, invoicing is done according to the target geometry (standard profile).

2.5.3 Switzerland (CH)

In the execution phase, design and invoicing are carried out according to SIA. As the tolerances (total tolerance) and excessive profile are already considered in the design or tender phase according to SIA, there are no changes here.

For the formwork of suspended ceilings, the contractor gives the designer the value of the superelevation from the structural analysis for the formwork to cover the difference from deformation due to dead weight and creep influences (deflection during concreting).

3 BIM use cases for model-based design

Hereafter, those use cases are briefly described, which either directly require the consideration of allowance of tolerances and superelevation or which have an impact on the quantities to be determined and thus on the preparation of the bill of quantities or on the costs. All use cases are described in detail in Part 1 of the series of recommendations **[2]**.

3.1 Design

3.1.1 Design variant investigation

Description
▪ Variant investigations based on models of the existing situation ▪ Geometric conflict analysis, e.g. with underground infrastructure
Goals

▪ Comparison of different design options based on the model for decision-making purposes
▪ Determination of variants for further detailing in the following design phases
▪ Consideration of allowance of tolerances and superelevation, especially if superelevation in the compressive rock is required due to geological boundary conditions.
▪ Ensuring geometric non-conflict by considering allowance of tolerances and superelevation
  - Compliance with the clearance profile and spaces to be kept clear
  - Consideration of polygonal secondary lining to be manufactured
▪ Clash detection by considering allowance of tolerances and superelevation, especially in critical space conditions
▪ Achieve higher accuracy in the model-based determination of quantities by considering allowance of tolerances and superelevation already in early project phases

3.1.2 Structural design

Description
- Transfer of geometry and input parameters from models for structural design of underground structures to increase the effectiveness and support of the structural engineer

Goals
- Consideration of the actual building geometry in the structural systems
- Implementation of the results from design into the models

3.1.3 Coordination of specialist's design

Description
- Merging of sub-discipline models in a coordination model
- Clash detection of the sub-discipline models with other disciplines

Goals
- Risk minimisation through early coordination of all domains
- Minimisation of design and construction conflicts

3.1.4 Production of preliminary design and design approval

Description
- Design and approval drawings are derived in 2D from the structure model

Goals
- Ensuring consistent design documents
- Ensuring design that conforms with standards and quality

3.1.5 Cost estimate and cost calculation

Description
- Model-based and structured determination of quantities

Goals
- Transparent quantity determination
- Achieve higher accuracy in the model-based determination of quantities by considering allowance of tolerances and superelevation
- Improved analysis of project risks
- Increasing cost certainty

3.2 Construction Preparation

3.2.1 Bill of quantities, tendering, award

Description
- Model-based determination of relevant quantities, considering allowance of tolerances and superelevation
- The contract documents shall clearly specify whether and which allowance of tolerances are included in the models
- Use of the models to study the variants and determination of variant-dependant quantities for decision making purposes
- Model based BoQ generation, especially for excavation, primary lining, secondary lining, and reinforcement items of the BoQ

Goals
- Correctness, transparency, and verifiability of the expected quantities
- Achieve higher accuracy in the model-based determination of quantities by considering allowance of tolerances and superelevation

The use case of model-based creation of bill of quantities is dealt with in detail in part 4 of the series of recommendations **[5]**.

3.3 Construction

3.3.1 Preparation of construction drawings

Description

- Construction drawings in 2D are derived from the model of the structure, if necessary

Goals

- Ensuring that the work is carried out in accordance with the standards and quality requirements
- Creation of conflict free, consistent models considering allowance of tolerances and superelevation for drawing generation from the model for:
  - primary lining, support arch and reinforcement
  - secondary lining, reinforcement, and formwork
- Ensuring geometric conflict-free design by considering allowance of tolerances and superelevation
  - Compliance with the clearance profile and spaces to be kept clear
  - Consideration of polygonal secondary lining
- Preparation of construction documents for the previously traditional checking and approval process with checkers , authorities, and client departments

3.3.2 Invoicing of construction works

Description

- Use of the model, updated in a timely manner with the actual excavation classes excavated and any additional and/or shortfall quantities of securing agents, as the basis for invoicing for excavation services, considering the associated time-related costs

Goals

- Increase in accuracy and transparency in the determination of quantities by considering allowance of tolerances and superelevation
- Clear documentation on the model
- Reduction of effort during invoicing

3.3.3 As-built documentation

Description

- Use of the model for an ACTUAL-TARGET comparison
- Linking tunnel scans to the model

Goals

- Achieve higher accuracy and transparency when checking ACTUAL geometry with TARGET geometry by considering allowance of tolerances and superelevation
- Clear documentation on the model

4 Requirements for the model

4.1 Cases for consideration of allowance of tolerances and superelevation

In the following, eight cases are described in which it makes sense to consider allowance of tolerances and superelevation. The terms and definitions commonly used in Germany are used as a basis. For Austria and Switzerland this applies analogously (see **Table 2-1**), although the cases described are already practised in these countries.

In the following tables, the application of the respective case is indicated in key words under “Description”. The “Explanation” describes the application and the boundary conditions in more detail and specifies the resulting requirements. In the row “Modelling proposal”, concrete information is given on the modelling implementation and changes to the previous 2D design are mentioned. In the row “Quantity take-off”, the effects of the modelling implementation on the quantity take-off are clarified.

4.1.1 Case I – Single-shell segment lining – Target geometry (TBM)

Description

- Segments
- Target geometry
- TBM

Explanation

- The target geometry defines the construction target specified by the client and the structure gauge to be maintained for the tunnel lining.
- The target geometry refers to the planned radius of the inner structural boundary, the inner reveal of the segment ring. According to DIN 18312, it is not permissible to fall below this limit towards the inside.
- The specified target geometry or the specified inner diameter of the segment ring already considers the required approach tolerances of the TBM and ring deformations.

Modelling proposal

- The target geometry corresponds to the model geometry.
- All allowance of tolerances is included in the model.
- No changes are necessary compared to the previous design.

Quantity take-off

- The quantities/volumes from the model result in the billing quantities.

4.1.2 Case II – Secondary lining – Target geometry (TBM and conventional tunneling)

Description

- Secondary lining
- Target geometry
- Conventional tunnelling
- TBM

Explanation

- The target geometry defines the construction target specified by the client and the structure gauge to be maintained for the tunnel lining.
- The target geometry refers to the planned radius of the inner structural boundary. According to DIN 18312, it is not permissible to fall below this limit inwards.
- However, the actual production of the blocks is not carried out according to this cross-section geometry, but with an additional superelevation/ widening into account the following:
  - The deformation of the formwork during concreting and of the secondary lining after stripping must be compensated by a superelevation.
  - If tunnel blocks are in a circular or transitional arc, the internal secant between 2 block joints cut into the theoretical target cross section in the middle of the block due to the polygonal design.
- The increase in the radii of the inner structural boundary is referred to in DIN 18312 as t_b = construction tolerance of the secondary lining.

Modelling proposal

- The solid for the secondary lining is designed and modelled for the superelevated/expanded geometry (including superelevation t_b).
- To be able to represent the reference to the target geometry, this is modelled as an inner surface (or as a solid body of the structure gauge). The inner surface of the target geometry (or the volume body of the construction gauge) is created as “sweeping” along the tunnel or route axis. Thus, the target geometry does not follow the polygonal axis of the volume bodies of the secondary lining. This also allows the degree of superelevation or expanding to be recognised at any point in the cross-section.
- See **chapter 4.2** and **chapter 5**.

Quantity take-off

- The volume of the vault concrete is determined for the superelevated/expanded geometry.
- For the reinforcement, this results in the required, increased bending radii and rebar or mesh lengths.

4.1.3 Case III – Secondary lining – Formwork design (TBM and conventional tunnelling)

Description

- Secondary lining – formwork design
- TBM
- Conventional tunnelling

Explanation

- For the design of the formwork geometry, the superelevated cross-section is necessary (for justification see case I).
- The target geometry defines the construction target specified by the client and the structural gauge to be maintained for the tunnel lining.
- The nominal geometry refers to the planned radius of the inner structural boundary. According to DIN 18312, exceeding this limit inwards is not permitted.
- However, the actual production of the blocks is not carried out according to this profile, but for the following reasons with an additional superelevated/expanded dimension:
  - The deformations of the formwork during concreting and of the secondary lining vault after stripping must be compensated by a superelevation.
  - If tunnel blocks are in a circular or transitional arc, the internal secant between 2 block joints cut into the theoretical target cross section in the middle of the block due to the polygonal design.
- The increase in the radii of the inner structural boundary is referred to in DIN 18312 as t_b = construction tolerance of the secondary lining.

Modelling proposal

- The formwork/formwork facing for the secondary lining is designed and modelled for the superelevated/expanded geometry (including superelevation t_b).
- See **chapter 4.2** and **chapter 5**.

Quantity take-off

- This case has no influence on the quantity take-off.

4.1.4 Case IV – Secondary lining – Reinforcement design (TBM and conventional tunnelling)

Description

- Secondary lining – reinforcement design
- TBM
- Conventional tunnelling

Explanation

- The reinforcement shall be designed for the superelevated/expanded cross-section according to case I, as the bending radii and lengths of the reinforcement bars and meshes must be produced according to the formwork carriage geometry.

Modelling proposal

- The reinforcement for the secondary lining is designed and modelled for the superelevated/expanded geometry (including superelevation t_b).
- The segment reinforcement is designed and modelled for the geometry according to case I including all allowances for tolerances.
- See **chapter 4.2** and **chapter 5**.

Quantity take-off

- There are no differences compared to the previous 2D design, as the reinforcement design is already designed including the superelevation.

4.1.5 Case V – Secondary lining – Sealing (TBM and conventional tunnelling)

Description

- Secondary lining – sealing
- TBM
- Conventional tunneling

Explanation

- The waterproofing is located between the primary lining with superelevation but already deformed and the expanded secondary lining.

Modelling proposal

- The waterproofing is designed and modelled on the outer surface of the secondary lining, which is raised by the dimension t_b.
- This means that d_{AK} only represents the thickness of the anchor heads without the waterproofing. The waterproofing inclusive protective fleece is modelled separately.
- See **chapter 4.2** and **chapter 5**.

Quantity take-off

- Compared to the previous design based on the target geometry, the area for sealing will be slightly larger.

4.1.6 Case VI – Tunnel advance – Excavation (conventional tunnelling)

Description

- Tunnel advance – excavation
- Conventional tunnelling

Explanation

- The excavation of tunnel tubes considers the required construction thicknesses for the anchor heads, sealing and protective layers, as well as the manufacturing and deformation tolerances of the primary lining.

Modelling proposal

- The (actual) excavation volume results from the limitation of the outer breakout tolerance (L_A-line), which is composed of the excavation target cross section L_{AS} -line and the outer tolerance t_A
- With reference to the specifications of DIN 18312, the model for the breakout is constructed and modelled offset outwards by the following thickness and tolerance dimensions in relation to the outer line of the model of the secondary lining defined in case II (L_A-line):
  - t_A = outside tolerance
  - d_{AK} = thickness of anchor heads and sealing
  - t_i = internal tolerance
  - t_d = deformation tolerance of the primary lining
  - ü = Elevation to compensate for unavoidable deformations in problem zones
- See **chapter 4.2** and **chapter 5**.

Quantity take-off

- The excavation volumes are determined considering the specified tolerance and construction dimensions.
- The modelled quantities for the excavation become slightly larger compared to the previous 2D design based on the target geometry.

4.1.7 Case VII – Primary lining – Support (conventional tunnelling)

Description

- Primary lining – support
- Conventional tunnelling

Explanation

- The excavation or excavation support of tunnel and gallery tubes, caverns, niches, etc. considers the required construction thicknesses for the anchor heads, sealing and protective layers, as well as the manufacturing and deformation tolerances of the primary lining.

Modelling proposal

- With reference to the specifications of DIN 18312, the model of the primary lining is constructed offset outwards from the outer line of the model of the secondary lining defined in case II by the following thickness and tolerance dimensions:
  - d_{AK} = thickness of anchor heads and sealing
  - t_i = internal tolerance
  - t_d = Deformation tolerance of the primary lining
  - ü = Elevation to compensate for unavoidable deformations in problem zones
- See **chapter 4.2** and **chapter 5**.

Quantity take-off

- The volumes and the quantities of support elements are determined for the position of the primary lining, considering the specified tolerance and construction dimensions.
- The quantities for shotcrete support are slightly larger compared to the previous 2D design based on the target geometry.

4.1.8 Case VIII – Primary lining – Clash detection (conventional tunnelling)

Description

- Primary lining – support
- Conventional tunnelling

Explanation

- If there are increased requirements for the positional accuracy of the model to be planned in relation to these objects for a project due to the presence of building structures and/or underground infrastructure in the ground, the clash detection should include the maximum possible outer contour of all support devices, in particular the anchors and spiles.

Modelling proposal

- Using the model of the primary lining defined in case VII, an outer contour surface is modelled at the distance of all possible structural tolerances, which serves as a reference surface for clash detection.
- See **chapter 4.2** and **chapter 5**.

Quantity take-off

- This case VIII has no influence on the quantity determination.

4.2 Consideration of allowance of tolerances and superelevation

The cases listed in **chapter 4.1** result in requirements for the model or the modelling.

The models should always be created considering the required allowance of tolerances and superelevation. This is unavoidable to obtain a consistent and geometrically coherent design free of contradictions.

The basic principle in creating the model should consider the actual geometry of the steel arches in the primary lining and the reinforcement in the secondary lining as these construction elements are manufactured and installed according to this design. The geometry of the secondary lining and the primary lining is thus inevitably also based on this principle.

Therefore, all possible allowance of tolerances and required superelevation, which are necessary for the construction of the tunnel and the compliance with the required structure gauges, shall be included in the models. The existing standards and guidelines apply to the determination and definition of the allowance of tolerances and superelevation.

Figure 4-1 and **Figure 4-2** illustrate the conflicts and clashes when modelling without considering the allowance of tolerances and superelevation of tunnel shells in curved sections. **Figure 4-2** shows the section in the middle of the block. In yellow colour, the structure gauge of the tunnel to be maintained is shown, which follows the tunnel axis continuously. The polygonal secondary lining is modelled in green. At the outer radius, the secondary lining cuts into the structure gauge at the centre of the block, and at the inner radius, the secondary lining "lifts off" the structure gauge. The primary lining is shown in red, which also follows the tunnel axis continuously. At the inner radius, the primary lining cuts into the secondary lining in the middle of the block and at the outer radius, the primary lining "lifts off" the secondary lining. There are no penetrations in the block joints.

In **Figure 4-3** a model is used to illustrate the implementation and consideration of allowance of tolerances and superelevation in accordance with DIN 18312. In **Figure 4-4** this is based on ÖNORM B 2203-1 and ÖNORM B 2203-2 and the ÖBV guideline for secondary lining concrete.

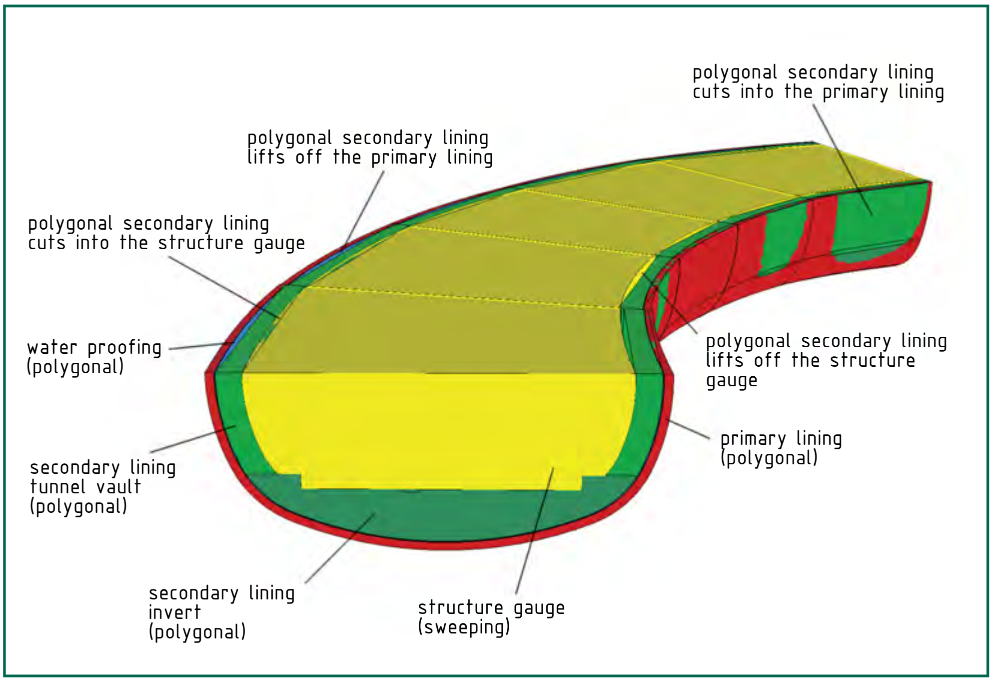


Figure 4-1
Collisions when modelling without allowance for tolerances for tunnels in curved sections

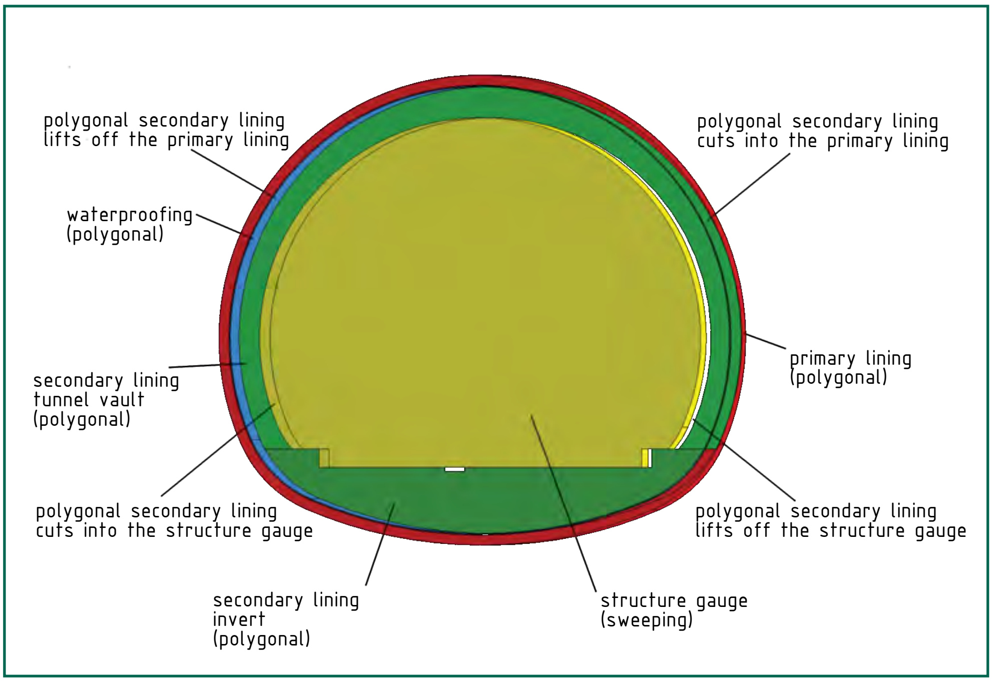
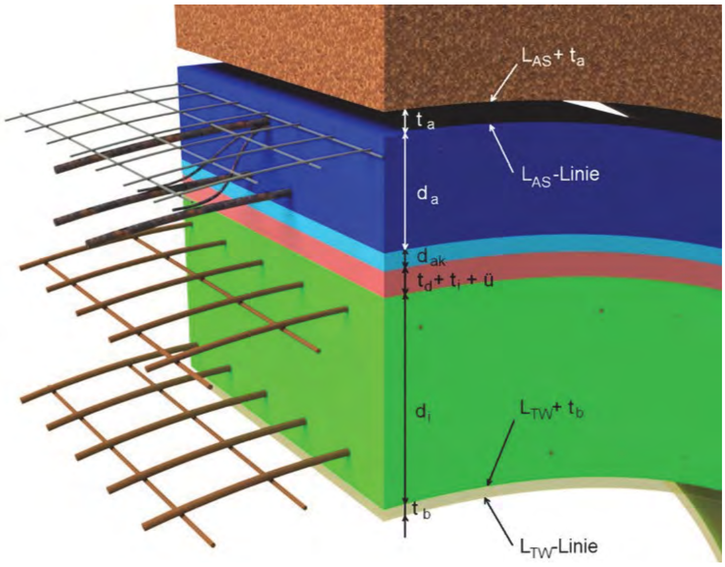


Figure 4-2
Collisions when modelling without allowance for tolerances for tunnels in curved sections, section in the middle of the block

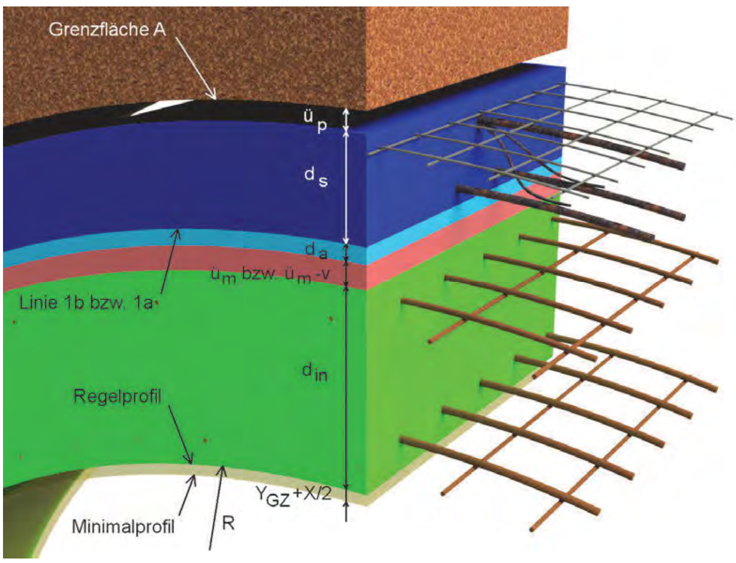


r_i Planned radius of the inner structure boundary
d_i Planned thickness of the secondary lining
d_{ak} Thickness of anchor heads and sealing
d_a Planned thickness of the primary lining
t_b Construction tolerance of the secondary lining
t_d Deformation tolerance of the primary lining
t_i Internal tolerance
t_a External tolerance
ü Superelevation to compensate for unavoidable deformations in problem zones

$L_{AS} = L_{TW} + t_b + d_i + t_d + d + d_{aka} + t_i + ü$
$L_i = L_{AS} - t_i - ü$
$L_A = L_{AS} + t_a$

1) Boundary lines of the geologically caused, unpredictable, unavoidable additional eruption
2) L_{TW} -line (inner structural boundary line)
3) L_i -line
4) L_{AS} -line (breakout target profile)
5) L_A -line (outer breakout tolerance)

Figure 4-3 *Illustration of tolerances and excess heights based on DIN 18312: VOB Vergabe- und Vertragsordnung für Bauleistungen – Teil C (German Construction Contract Procedures – Part C)*



R Radii of the clear cross section
d_{in} Planned thickness of the inner shell
d_s specified thickness of shotcrete as a support measure
v rock deformation that has occurred
$ü_p$ specified by the client during the tendering process
$ü_m$ Excess dimensions specified by the AG during the excavation work
d_a planned thickness of the waterproofing substrate and the waterproofing
y_{GZ} Vault lead dimension (radial)
X/2 rise of an arch (horizontal)

Figure 4-4 *Representation of the dimensions and projections according to ÖNORM B 2203-1 and ÖNORM B 2203-2 and ÖBV guideline for inner shell concrete*

5 Recommendations for modelling

5.1 Determination of the allowance of tolerances and superelevation to be considered

Since the consideration of allowance of tolerances and superelevation have direct impact on the quantities determined from the model, the contract documents shall specify the dimensions considered for allowance of tolerances and superelevation in the models. Accordingly, this must be considered in the bill of quantities and/or in the calculation. It must be clear whether allowance of tolerances and superelevation are included in the model and thus in the initial quantity rates, or whether an additional quantity factor must be included in the calculation (see also Part 4 of the series of recommendations **[5]**)

The allowance of tolerances and superelevation are to be considered in the models. This leads to a more accurate and transparent determination of quantities. Imputed quantity surcharges are therefore no longer necessary for the above-mentioned reserve quantities and excess quantities.

5.2 Determination of the standard profile of the secondary lining

Prior to start of modelling, the standard profile shall be defined. The definition of the standard profile should be done in the following three steps:

1. Step: Determination of the minimum profile
   The minimum profile depends on the use of the tunnel and the resulting requirements. It describes the clearance required for all technical equipment and usable spaces in the tunnel. The minimum profile shall not be under cut in the entire tunnel and shall be represented in the model.

2. Step: Determination of the theoretical profile
   (= minimum profile plus rise of an arch)
   The theoretical profile considers the polygonal design of the secondary lining in curved sections. It results from the minimum profile, which is to be enlarged by the curvature of the minimum alignment radius. This means that a block length or block division must already be defined for the tunnel to determine the maximum curve cut.

3. Step: Determination of the standard profile
   (= theoretical profile plus allowance of tolerances)
   The standard profile is derived from the theoretical profile, considering the defined preliminary dimensions. The allowances consider the tolerances required to construct the secondary lining. They are essential for the production and should be specified as realistically as possible and included in the models. This is the only way to ensure consistent design.

With this procedure, the cases described above in **chapters 4.1.2, 4.1.3, 4.1.4** and **4.1.5** are covered.

5.3 Modelling of structure gauge

The structure gauge of a tunnel structure corresponds to the minimum profile in the cross-section that the tunnel secondary lining shall not under cut. The structure gauge defines the space to be kept free within the tunnel (see **Figure 5-1** left). In this context, structure gauge does not mean the clearance profile of traffic routes such as railways or roads (see **Figure 5-1** right).

The structure gauge and the clearance profile continuously follow the continuous track, road, or tunnel axis. In modelling terms, this corresponds to "sweeping" along the corresponding axis. Both the structure gauge and the clearance profile are to be modelled and checked for clashes for quality control.

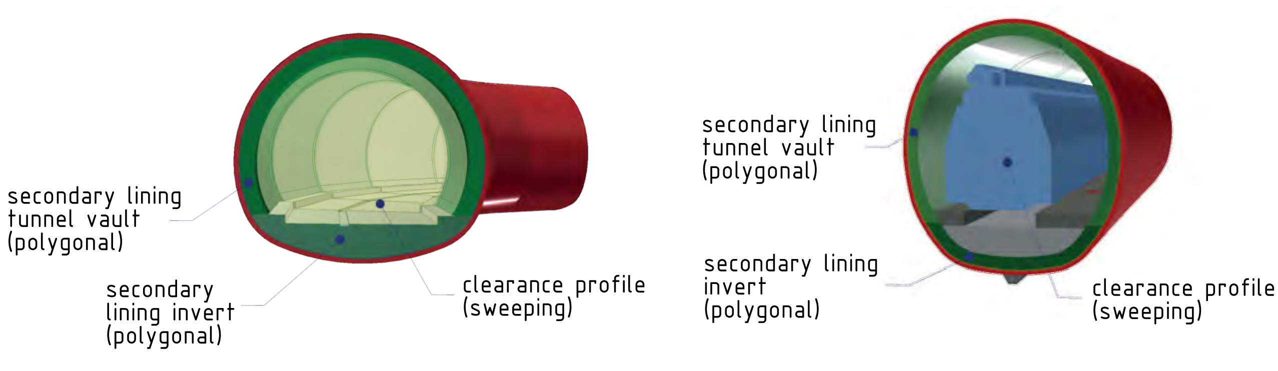


Figure 5-1 *Structure gauge (left, yellow-transparent) and clearance profile (right, blue) as "sweeping" along the tunnel or track axis*

5.4 Modelling secondary lining

The secondary lining is modelled along the polygonal tunnel axis (three-dimensional space curve from gradient and alignment). The block axis usually meets the continuous tunnel axis in the block joints. The secondary lining thus forms a polygonal construction (see **Figure 5-2**), which in curve sections or crests and troughs in the centre of the block shows the greatest deviation (rise of an arch) from the target tunnel axis.

To ensure that the secondary lining does not cut into the structure gauge, the secondary lining shall be modelled considering the corresponding lead dimensions including the rise of an arch. Thus, a clash detecting check between the objects "structure gauge" and "secondary lining" is also possible and can be visualised transparently.

5.5 Determination of the standard profile of the primary lining

Before modelling the primary lining, the standard profile must also be defined for this. The definition of the standard profile of the primary lining is based on the standard profile of the secondary lining. The inner contour of the primary lining is determined by the thickness of the secondary lining, possibly the sealing, the dimension of allowance of tolerances and superelevation. The required dimension of allowance of tolerances is determined by the excavation axis and the primary lining is produced. If the excavation is performed analogous to the secondary lining blockwise, less superelevation is required than if the excavation is performed continuously along the tangential or curvilinear tunnel axis. The superelevation depends essentially on the existing ground conditions and the deformation behaviour. This must therefore be determined accordingly in advance.

This takes into account the cases described above in **chapters 4.1.6, 4.1.7** and **4.1.8**.

5.6 Modelling primary lining

There are two possibilities for modelling the primary lining:

1. The primary lining is modelled along the tangential or curvilinear track of the road or tunnel axis (three-dimensional space curve) or a small-scale polygon with side lengths corresponding to the length of advance (see **Figure 5-3**).

2. The primary lining is modelled along the polygonal tunnel axis defined for the construction of the secondary lining, which usually coincides with the continuous tunnel axis in the block joints (see **Figure 5-4**).

When modelling the primary lining, the required allowance of tolerances and superelevation are considered.

As described above, variant 1 result in larger allowance of tolerances to comply with the minimum thickness of the secondary lining (see **Figure 5-3**).

If the block division and thus the polygonal tunnel axis is already known when driving the tunnel tubes, variant 2 (see **Figure 5-4**) can be used. This allows for lower allowance of tolerances than with variant 1 (see **Figure 5-3**).

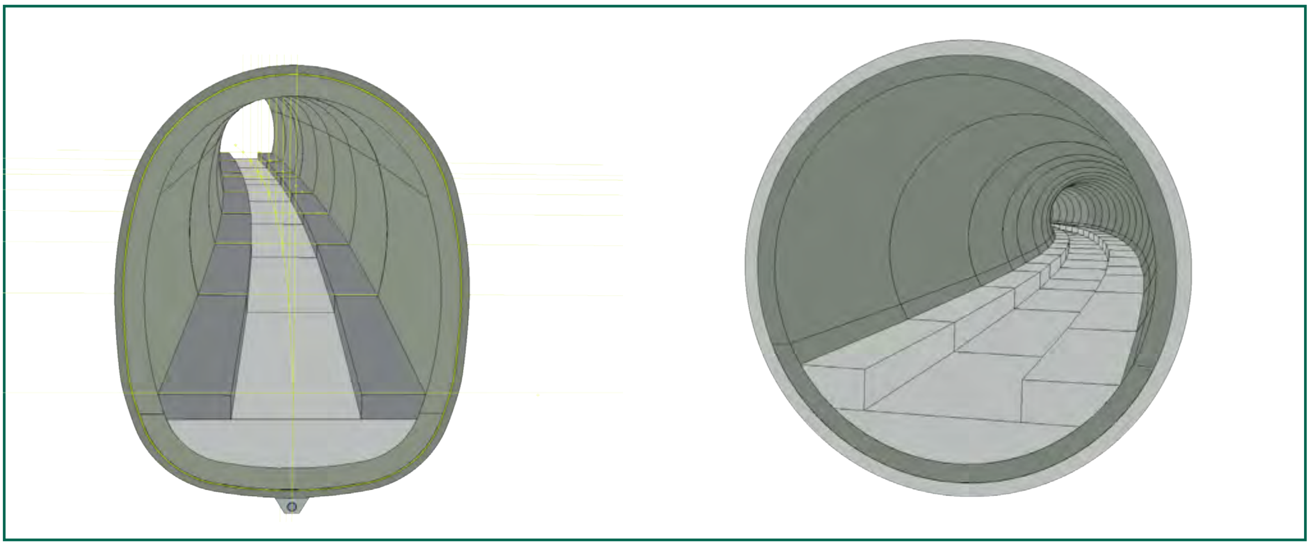


Figure 5-2 *Examples for polygonal secondary lining along the polygonal tunnel axis*

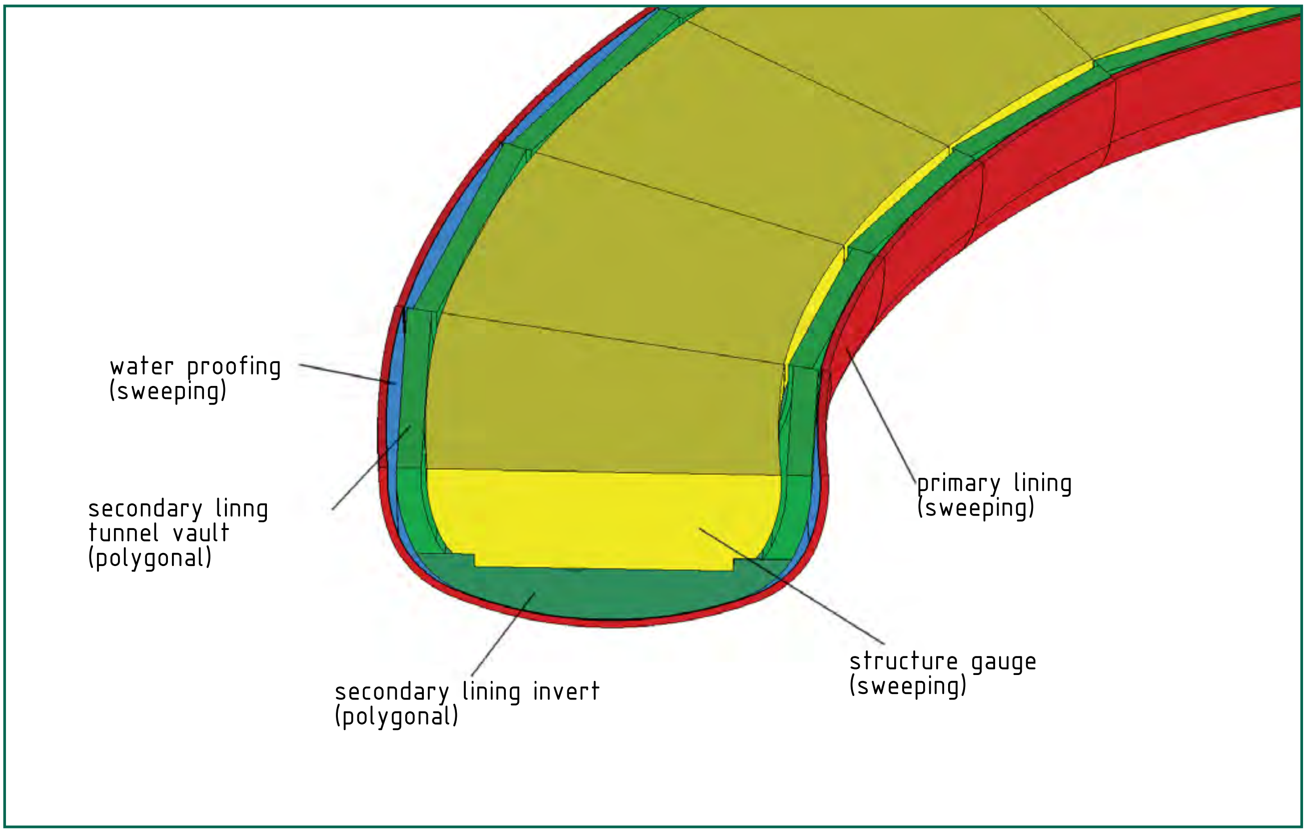


Figure 5-3 *Continuous primary lining along the continuous tunnel axis – variant 1*

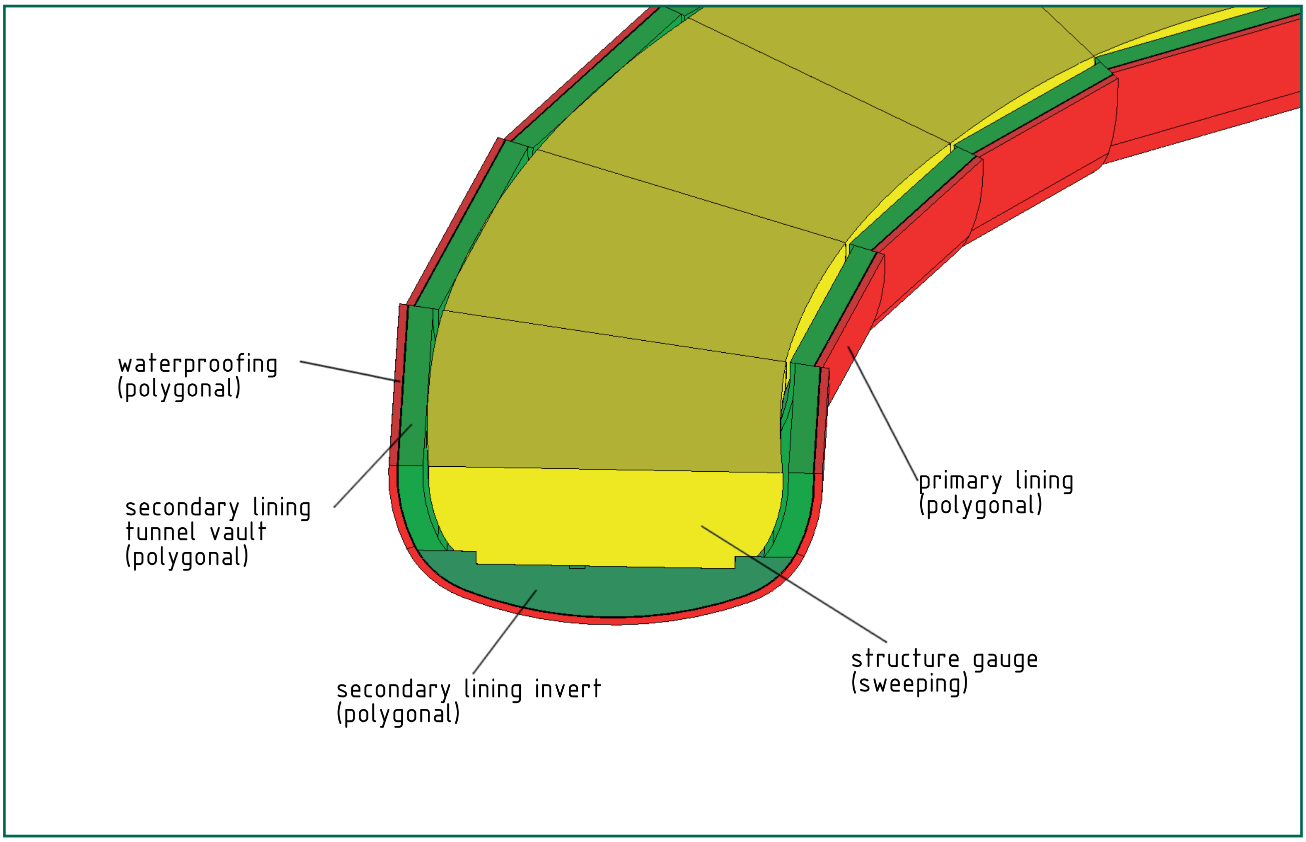


Figure 5-4 *Polygonal primary lining along the polygonal tunnel axis – variant 2*

5.7 Invoicing regulations

If the invoicing regulations in Germany are not adapted to the recommended modelling rules, it will remain necessary in the future that additional models must be created solely for the quantity determination of the billing. These are detached and independent of the models for execution design.

It is obvious that the creation of several different models of the same structure is time-consuming and uneconomical. In addition, the BIM principle of the "single source of truth" is abandoned.

In the D-A-CH countries and here in particular in Germany, the existing regulations, guidelines, and standards (e.g. DIN 18312: VOB Vergabe- und Vertragsordnung für Bauleistungen – Teil C) should therefore be adapted to the possibilities and requirements of a model-based way of working with regard to the invoicing regulations.

For Austria and Switzerland, there is currently no compelling need to adapt the billing rules, as in these countries they already fit the modelling recommendations described above. In the medium term, however, the invoicing rules are to be reviewed in detail and adapted if necessary, so that, on the one hand, model creation and attribution can be implemented as simply as possible here and, on the other hand, the respective quantities of the modelled elements from the models can be used.

6 Outlook

In the construction documentation, the actual built and existing geometries of the tunnel linings result from the measurement of the tunnel linings (tunnel scans). This applies to both the primary and secondary lining. By measuring the tunnel lining, the existing tolerances are thus revealed. With the data obtained in this way, a target/actual comparison can be created.

If point clouds of the inner contour of the tunnel lining are created with the help of tunnel scans, surface models can be generated from them and integrated into the construction models. Differences can thus be easily visualised.

The definition of the conditions for carrying out the tunnel scans should already be done before the execution of the underground construction work to achieve the desired quality and completeness of the results. In addition to the software and hardware boundary conditions for the scans and their transfer to the construction model, the temporal organisation of the execution of the scans must be carefully planned so that the point cloud to be generated is not disturbed by objects or obstacles (e.g. construction equipment, pipes, materials, etc.) from the construction operation.

7 Glossary

Term	Abbreviation	Explanation
3D		Three-dimensional geometry that can be constructed and displayed by volumetric bodies in the space
Bill of quantities	BoQ	As part of the statement of work, a tabular directory of specific tasks, activities and deliverables is included to define the overall service to be provided within a contract
Clearance profile		Defines the space to be kept free for traffic routes, e.g. railway, road, footpaths, etc.
D-A-CH		Acronym for Germany (D), Austria (A) and Switzerland (CH)
Minimum profile		Delimits the clearance that must not be undercut by the secondary lining of a tunnel
Model		Three-dimensional model containing physical, geometric, and functional properties with related attributes
Polygon, polygon course		Distance that is composed of finitely many straight-line segments
Single source of truth		Source of all currently valid information
Space curve		Axis resulting from the superposition of the path axis and gradient axis
Standard profile		Corresponds to the theoretical profile plus an allowance of tolerances
Structure gauge		Defines the space to be kept free within the tunnel cross-section
Target geometry		Geometry to be maintained or cross section to be kept free, corresponds to the minimum profile
Theoretical profile		The minimum profile enlarged by the rise of the arch of a block length
Usable space		Defines the free space in the tunnel cross-section, for a defined purpose
Use case	UC	Tasks derived from the BIM goals for implementing the BIM methodology

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