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Prospects for designing tunnels and other underground structures in the context of the Eurocodes

Support to policies and standards for sustainable construction

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Abstract

The construction ecosystem is of strategic importance to the European Union, as it delivers the buildings and infrastructure needed by the rest of the economy and society while being a key element for the implementation of important EU strategies and initiatives, including the European Green Deal and the EU Climate Adaptation Strategy. Within the construction ecosystem, road and railway tunnels take an important share of the European infrastructure market, playing a central role in securing business continuity and supporting fast connections, especially for emergency services.

Despite tunnels and other underground structures being unique structures, there are no European design standards or harmonised guidelines, and their structural design is based primarily on national standards, knowledge and experience. Thus, there is need for developing common European design standards for tunnels and other underground structures within the established framework of the Structural Eurocodes (EN 1990 – EN 1999), already covering many other types of structures.

The standardisation works can build upon the initial technical assessment of the Eurocodes applicability for the design of underground structures as performed by the JRC Expert Network on the standardisation needs for underground structures in the period 2020-2022. An Ad-Hoc Group on Tunnelling and Underground Structures under CEN/TC250 "Structural Eurocodes" is recommended to be established and prepare a Project Plan with the items to be treated in the various TC250 Sub-Committees.

Foreword

The construction ecosystem is of strategic importance to the European Union (EU), as it delivers the buildings and infrastructures needed by the rest of the economy and society, having a direct impact on the safety of persons and the quality of citizens' life. The construction ecosystem[1] includes activities carried out during the whole lifecycle of buildings and infrastructures, namely the design, construction, maintenance, refurbishment and demolition of buildings and infrastructure. The industrial construction ecosystem employs approximately 24.9 million people in the EU and provides an added value of EUR 1 158 billion (9.6% of the EU total).

The construction ecosystem is a key element for the implementation of the European Single Market and many other important EU strategies and initiatives. Ensuring more sustainable and climate resilient buildings and infrastructures, i.e., adapting the construction ecosystem to the inevitable impacts of the changing climate is one of the central priorities of the European Green Deal (COM(2019) 640)[2]. The European Green Deal aims to achieve climate neutrality for Europe by 2050, and relies on numerous initiatives, noteworthy:

- the **New Circular Economy Action Plan** (COM(2020) 98 final)[3] and the **New Industrial Strategy for Europe** (COM(2020) 102 final)[4] intending to accelerate the transition of the EU industry to a sustainable model based on the principles of circular economy;
- the **Renovation Wave for Europe** (COM(2020) 662 final)[5] addressing the twin challenge of energy efficiency and energy affordability and aiming to double, at least, the annual renovation rates of the building stock (currently around 1%) and launching the **New European Bauhaus** (COM(2021) 573 final)[6] initiative;
- the **review** (COM(2022) 144)[7] of the **Construction Products Regulation** (Regulation (EU) No 305/2011)[8] and the proposal for the revision of the **Energy Performance of Buildings Directive** (COM(2021) 802 final)[9] to ensure that the design of new and renovated buildings is in line, at all stages, with the needs of the circular economy, and lead to increased digitalisation and climate-proofing of the building stock.
- the new **EU Climate Adaptation Strategy** (COM(2021) 82 final)[10] that sets out how the EU can adapt to the unavoidable impacts of climate change and become climate resilient by 2050. The Strategy has four principle objectives: to make adaptation smarter, swifter and more systemic, and step up international action on adaptation to climate change.

Recognizing that the EU's ambitions towards a climate neutral, resilient and circular economy cannot be delivered without leveraging the European standardisation system, the European Commission presented a **new Standardisation Strategy** (COM(2022) 31 final)[11], to enable global leadership of EU standards in promoting values and a resilient, green and digital Single Market. The Strategy spots standards as "*the silent foundation of the EU Single Market and global competitiveness*", since they are "*invisible but a fundamental part of our daily life*". European standards are embedded in the EU policy objectives and play a key role in achieving a climate-neutral, resilient and circular economy.

The EU has already put in place a number of policy and regulatory instruments for the construction sector, including related European Standards (EN). Within this framework, the **Eurocodes** are,

1 https://ec.europa.eu/docsroom/documents/47996
2 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN
3 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN
4 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0102
5 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0662
6 https://europa.eu/new-european-bauhaus/index_en
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8 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32011R0305
9 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802&qid=1641802763889
10 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN
11 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0031

presently, a series of 10 European Standards, EN 1990 to EN 1999, comprising 59 parts and providing common technical rules for the design of buildings and other civil engineering works. They cover in a comprehensive manner the basis of structural design, actions on structures, the design of structures of the principal construction materials such as concrete, steel, composite steel-concrete, timber, masonry and aluminium, and the geotechnical, seismic and structural fire design as well.

The **Commission Recommendation** 2003/887/EC[12] **on the implementation and use of the Eurocodes** for construction works and structural construction products recommends undertaking research to facilitate the integration into the Eurocodes of the latest developments in scientific and technological knowledge.

In this context, the European Commission's Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW) issued in 2012 the **Mandate M/515**[13] to initiate a process of further evolution of the Eurocodes, incorporating improvements to the existing standards and extending their scope. The detailed work programme prepared by the European Standardisation Committee (CEN) Technical Committee (TC) 250 "Structural Eurocodes" (CEN/TC250) as a reply to M/515 ensures that the so-called **Second Generation of the Eurocodes** continues to be the most comprehensive and advanced state-of-the-art codes for structural and geotechnical design in the world. The new suite will remain fully up to date through embracing new methods, new materials, and new regulatory and market requirements.

Within the construction ecosystem, projects involving tunnels and underground spaces in Europe take an important share of the infrastructure market with a continuous demand for constructing such structures. Road and railway tunnels play a central role in securing the business continuity in the modern economy, with thousands of people and tons of goods passing through them every day, as well as supporting fast connections for emergency services providing help in man-made and natural disasters. The design of tunnels and other underground structures has unique characteristics as the surrounding geotechnical environment, i.e., soils and rocks play a part in the tunnel bearing capacity and construction.

Currently, however, there are no European tunnel design standards or harmonised guidelines at European level. Tunnel and underground spaces design in Europe is based primarily on national standards, recommendations, knowledge and experience with the use of industrial/client standards and guidelines developed at national level. Moreover, some parts of the Eurocodes are used for the design of tunnels despite having no specific parts devoted to underground structures design. Further, the standardisation work programme of CEN/TC 250 "Structural Eurocodes" for the Second Generation of the Eurocodes does not include specific activities addressing the design of tunnels and other underground structures.

In view of these facts, in 2017 the Joint Research Centre (JRC) of the European Commission started activities on the assessment of standardisation needs for the design of underground structures with particular focus on tunnels. The initiative was launched in the framework of a series of Administrative Arrangements between JRC and DG GROW on support to policies and standards for sustainable construction.

The activities on standardisation needs for underground structures are supported by an Expert Network on the design of underground structures, convened by the JRC. The objective of the JRC Expert Network is to review the state-of-the-art of technical background and standards available for tunnels and other underground structures, explore the potential benefits from a new European standard or new standards (eventually a Eurocode, a Eurocode Part or a Clause) for their design, assess the feasibility for such new standard(s) and ponder on the initiation strategies.

[12] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32003H0887

[13] https://ec.europa.eu/growth/tls-databases/mandates/index.cfm?fuseaction=search.detail&id=523

The JRC Technical Report "*Standardisation needs for the design of underground structures*"[14] published in 2019 argued that the development of design standards for tunnels and underground structures is necessary and feasible, fostering harmonisation of design rules between countries. It appeared suitable that the concept of new standards or guidelines shall be developed in line with the Eurocodes and shall delineate how to complete and/or restrict their use for the design of tunnels.

The present report discusses the assessment of the applicability of the most relevant parts of the Second Generation of the Eurocodes, when designing tunnels and underground structures. It provides recommendations for possible content for the Eurocodes addressing underground structures, based on expert judgements. A proposal is presented on how to proceed with the development of a new Part or Clause in the Eurocodes to address the design of new tunnels and underground structures.

This document is published as a part of the JRC Report Series "*Support to the implementation, harmonization and further development of the Eurocodes*". It has been developed by the JRC with the support of experts from CEN/TC250 Sub-Committees and having input and consultation with the Expert Network. This JRC Report presents technical material based on expert judgement and extensive discussions, intended to provide views and prospects on the standardisation needs for underground structures covering the most important aspect of their design. As such, it serves as a proposal for further work to achieve European standards for the design of underground structures, in the context of the Eurocodes.

The report is available to download from the "Eurocodes: Building the Future" website (http://eurocodes.jrc.ec.europa.eu).

We hope that this report will provide a sound and helpful basis for discussions related to the design of underground structures, serving future standardisation works.

The editors Adamantia Athanasopoulou, Silvia Dimova, Gunilla Franzen and Adriaan van Seters and the authors have sought to present useful and consistent information in this report. However, users of information contained in this report must satisfy themselves of its suitability for the purpose for which they intend to use it.

Ispra, 2022

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[14] Athanasopoulou, A; Bezuijen, A; Bogusz, W; Bournas, D; Brandtner, M; Breunese, A; Burbaum, U; Dimova, S; Frank, R; Ganz, H; Grunicke, U; Jung, H; Lewandowska, A; Nuijten, G; Pecker, A; Psomas, S; Roessler, K; Sciotti, A; Sousa M.L., Stille, H; Subrin D, Standardisation Needs for the Design of Underground Structures, EUR 29633 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79-99075-5, doi:10.2760/615209, JRC115352, https://data.europa.eu/doi/10.2760/615209.

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The work presented in the report was developed under the coordination of the Safety and Security of Buildings Unit of the Directorate for Space, Security and Migration of the European Commission's Joint Research Centre with the extensive contribution of the JRC Expert Network on the standardisation needs for the design of underground structures. All members of the Expert Network are listed in Annex A to this report.

JRC would like to express appreciation and acknowledgement to all members of Expert Network on the standardisation needs for the design of underground structures for the substantial support to the activities since the establishment of the network. The input and reviews received by the network and the fruitful discussions during the working meetings and various exchanges have been essential for the preparation of the report.

JRC further expresses appreciation for the support and feedback to the German mirroring group on the design of underground structures created by the German Ministry of Transport and Digital Infrastructure in 2019 and to the European Organization for Nuclear Research (CERN) for supporting the activities through participation to the expert network.

The authors would also like to express their deep gratitude and acknowledgement to the Expert Network involved in the co-creation process and brainstorming that contributed to developing the ideas and concepts towards the standardisation needs for the design of underground structures. These ideas and the content presented in the report have been discussed and debated with the Expert Network and the publication of the report would not have been possible without the support by the Expert Network.

The report with the title "Assessment of applicability of EN 1997 for tunnels and other underground structures", enclosed as Annex C to this report was commented by the Expert Network in the period January - February 2022 and the present JRC Technical Report was reviewed by the Expert Network during August 2022. The independent review of the report by expert Roger Frank is greatly appreciated.

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Executive summary

The ideas and concepts discussed in the report were consulted in the period 2020-2022 with the Expert Network on the standardisation needs for the design of underground structures coordinated by the JRC. The report full draft was commented by the Expert Network, prior to its publication during August 2022. The complementary report on the assessment of applicability of EN 1997 for tunnels and other underground structures, enclosed as Annex C to this report, was commented by the Expert Network in the period January-February 2022.

Background and previous work

The construction ecosystem is of strategic importance to the European Union (EU), as it delivers the buildings and infrastructures needed by the rest of the economy and society, having a direct impact on the safety of persons and the quality of citizens' life. Within the construction ecosystem, projects involving tunnels and underground spaces in Europe take an important share of the infrastructure market with a continuous demand for the construction of those structures.

Given the importance of the construction ecosystem, the EU has already put in place a number of policy and regulatory instruments for the construction sector. In addition, European Standards (EN) for the construction sector support these European policies. Within this framework, the Eurocodes are a series of 10 European Standards (EN 1990 - EN 1999) for the structural design of buildings and infrastructure works. The Eurocodes are the product of a long procedure of bringing together and harmonising the different design traditions in the EU Member States, leading to more uniform levels of safety in construction in Europe and allowing for a common technical language. The EN Eurocodes are developed under the guidance and co-ordination of the European Committee for Standardisation (CEN) Technical Committee 250 (CEN/TC250) "Structural Eurocodes".

Currently, however, there are no European tunnelling design standards or harmonised guidelines at European level. Tunnel and underground spaces design in Europe is based primarily on national standards, recommendations, knowledge and experience with the use of industrial/client standards and guidelines developed at national level. Moreover, parts of the Eurocodes are used for the design of tunnels, despite having no specific parts devoted to underground structures design.

In 2012, the European Commission's Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW) issued the Mandate M/515 to initiate a process of further evolution of the Eurocodes (the so-called Second Generation of the Eurocodes), incorporating improvements to the existing standards and extending their scope. The on-going standardisation work programme for the Second Generation Eurocodes does not include specific activities addressing the design of tunnels and other underground structures.

In view of these facts, in 2017 the Joint Research Centre (JRC) of the European Commission started activities on the assessment of standardisation needs for the design of underground structures, with particular focus on tunnels. The first phase of the work was concluded with the recommendation that the development of design standards for tunnels and underground structures is necessary and feasible15. It was concluded that new standards or guidelines for the design of tunnels should be developed in line with the Eurocodes and delineate how to complete and/or restrict their use for tunnels and other underground structures.

[15] Athanasopoulou, A; Bezuijen, A; Bogusz, W; Bournas, D; Brandtner, M; Breunese, A; Burbaum, U; Dimova, S; Frank, R; Ganz, H; Grunicke, U; Jung, H; Lewandowska, A; Nuijten, G; Pecker, A; Psomas, S; Roessler, K; Sciotti, A; Sousa M.L., Stille, H; Subrin D, Standardisation Needs for the Design of Underground Structures, EUR 29633 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79-99075-5, doi:10.2760/615209, JRC115352, https://data.europa.eu/doi/10.2760/615209.

Assessment of the applicability of the Eurocodes for the design of tunnels and other underground structures

In the period 2019-2021, JRC performed the second phase of the work on the standardisation needs for the design of underground structures. The work focused on collecting and reviewing the available sources of guidance for the design of tunnels and underground structures. The aim was to identify which aspects of the design have been of primary interest in the existing documents and to which existing Eurocodes these documents are mostly related with. Moreover, the review of the collected documents served to identify which of these documents could potentially be considered as main sources of reference when preparing a new European standard for the design of tunnels and other underground works.

Then, an assessment was performed on the applicability of the most relevant parts of the Second Generation Eurocodes, when designing tunnels and underground structures. The assessments of applicability of the most relevant Eurocodes were made primarily for the following Eurocode parts: EN 1991 "Eurocode 1: Actions on structures", EN 1992 "Eurocode 2: Design of concrete structures", EN 1997 "Eurocode 7: Geotechnical design" and EN 1998 "Eurocode 8: Design of structures for earthquake resistance".

The assessment of the applicability of EN 1997 has been very detailed as the evaluation was performed on basis of Sub-Clause (Sub-Chapter) level of the Second Generation EN 1997 draft. The objective included the identification of (i) items that were sufficiently covered in the draft, (ii) items that were covered but need clarifications to avoid misunderstanding/misinterpretation and (iii) items that need to be added.

Conclusions on the Eurocodes applicability for the design of underground structures

Tunnels and other underground structures are not explicitly included in the Eurocodes as they are often major structures, which sometimes fall outside the Eurocodes' scope. Their design is partially based on empiricism when assessing ground behaviour type and stability risks or selecting effective supports to minimize the risks or to establish robust design for tunnel construction. Moreover, their design is largely based on ground-structure interaction, deformation behaviour, observational method and other design methods. These methods are less used for other types of structures.

In contrary to other structures, the use of partial factors for tunnel design is sometimes limited. At the same time, Serviceability Limit State (SLS) may be governing over the Ultimate Limit State (ULS) for the design of tunnels and other underground structures, which is different from other structures. The general rules, as stated in EN 1990 "Eurocode: Basis of structural design", can be applied for the design of tunnels and other underground structures as the design of these structures should be able to cope with the safety approach in EN 1990. However, issues are identified (e.g., use of partial factors, ground-structure interaction, Ultimate Limit State, uncertainties in tunnelling, unloading) that should be addressed within EN1990 in order to implement the design of tunnels and underground structures into the Eurocodes suite.

It was concluded that current Second Generation EN 1991 is not intended to be used for tunnels and underground structures. However, there are many items which with some modifications can be used for tunnel design, as weight of constructions, thermal and fire actions, accidental actions (collisions of traffic, explosions), actions during execution (temporary works), and actions from road and rail traffic. Therefore, the code needs updating for tunnelling and underground structures on these aspects.

The current Second Generation drafts of EN 1992 can be applied to tunnels and other underground structures. Specific provisions considered to apply to buildings only are clearly marked as such, either in the heading of the clause or inside the clause text. Specific topics relevant and important for tunnels and other underground structures may not be covered by EN 1992, particularly aspects of sprayed concrete – as indeed may be the case also for other particular types of structures. Due to the advanced state of development of the Second Generation EN 1992, such missing information may in a first instance be added in National Annexes to EN 1992, as so-called Non-Contradictory-Complementary Information (NCCI). Later, Clauses could be added to EN 1992 specifically addressing tunnels and other underground structures.

The performed assessment of EN 1997 concludes that the Second Generation EN 1997 is an appropriate basis which, with additional development, can serve as the common standard for design and verification of tunnel and underground structures design in Europe. It is emphasised, that the design of these structures requires that the designer understands the design principles and is capable to select appropriate design methods in correspondence to given conditions. The designer shall also use experience from projects in similar (ground) conditions. These aspects should be included in the additional Clauses or a new Part of EN 1997 dedicated to tunnels and underground structures.

The current draft of Second Generation EN 1998 addresses specifically underground structures16 as for the determination of action effects. EN 1998-5 includes tunnels of different types (bored, cut and cover, immersed) and other underground structures (i.e., culverts and underground large works such as metro and parking stations, and pipelines). For these structures general requirements for seismic actions are defined referring to the contents of EN 1998-1-1 "General rules and rules for buildings", accounting for the depth and dimensions of the underground structure and the spatial variability of ground motion. The code could be extended in the future by e.g., adding dynamic numerical modelling for high seismic action classes and design of tunnels in potentially active faults.

Recommendations and prospects

The need for developing new standards for the design of tunnels and other underground structures within the framework of the Eurocodes, points to the recommendation for starting the standardisation process with the installation of an Ad-Hoc Group (AHG) on Tunnelling and Underground structures under CEN/TC250 "Structural Eurocodes". Members of this Ad-Hoc Group could be the Chairs of the involved TC250 Sub-Committees together with other experts on tunnelling design.

The objective of the Ad-Hoc Group will be to establish a Project Plan with the items to be treated in the various TC 250 Sub-Committees. Input for this Project Plan will be derived from the JRC Technical Reports on the standardisation needs for the design of underground structures and from TC250 Sub-Committees. The Ad-Hoc Group should also be responsible for the planning of the activities. After the Project Plan is finalised, this should be approved by TC250 and an acceptance for further development should be obtained.

After the finalisation of the Project Plan, the various Sub-Committees would start assembling knowledge and experts for writing the new Eurocodes text, following the rules and procedure established by CEN and CEN/TC250. This could preferably result in direct writing of a standard with intermediate enquiries. However, a Technical Specification is also possible as a prequel for a standard, where rules for design (with possible alternatives) are provided for comments and discussion.

[16] EN 1998 – Part 5: "Geotechnical aspects, Foundations, Retaining and Underground structures" - Clause 11 "Underground structures"

1 Introduction

1.1 Design of underground structures and the Eurocodes

Within the construction ecosystem, projects involving tunnels and underground spaces in Europe take an important share of the infrastructure market with a continuous demand for those structures. Underground structures, and tunnels in particular, are unique structures. Their key design considerations and structural behaviour are different from other structures, such as buildings and bridges. In particular, in tunnels and underground structures, similarly to flexible retaining structures, the surrounding geotechnical environment is a major part of the structure contributing to its loads and geotechnical and structural resistance and hugely affecting the construction process.

Tunnels require a particular design with respect to the specific geotechnical conditions and their interaction with buildings and infrastructure around them, which calls for detailed consideration. In particular, the main bearing element in tunnelling is the surrounding soil and rock and one of the basic aims in tunnelling is to keep these stable or to prevent them to get loose. Changes in the stress-state due to changes in construction stages may lead to those effects. Therefore, tunnelling mostly requires a continuous construction process in excavation/boring and lining that reduces changes in the stress-state situation to a minimum. As a result, an observational design method and construction process is mostly aspired wherever and whenever possible. This is one of the most important difference of tunnels compared to other civil engineering structures (Athanasopoulou et al., 2019).

Despite the unique characteristics of tunnel design, European tunnel design standards or harmonised guidelines are currently not available. Tunnel and underground spaces design in Europe is based primarily on national standards, recommendations, knowledge and experience with the use of industrial/client standards and guidelines developed at national level. Although no specific Eurocode for tunnels has been developed, the existing parts of the Eurocodes (European Standards EN 1990 – EN 1999) can be applied as a general framework.

The Eurocodes are a series of European Standards (EN 1990 – EN 1999) that provide a common approach for the structural design of buildings and other civil engineering works and construction products. The Eurocodes cover the basis of structural design, actions on structures and the design of concrete, steel, composite steel-concrete, timber, masonry and aluminium structures, together with geotechnical, seismic and structural fire design. The first generation of the Eurocodes, published in 2007, covers buildings and some other civil engineering works, e.g., bridges, towers, masts, chimneys, silos, tanks, and pipelines.

Within the present generation of the Eurocodes (published in 2000 to 2007), no parts are devoted to the design of tunnels as their original scope was not to explicitly include all underground structures. Still, the current versions of EN 1990 (Eurocode: Basis of structural design), EN 1991 (Eurocode 1: Actions on structures), EN 1992 (Eurocode 2: Design of concrete structures) and EN 1997 (Eurocode 7: Geotechnical design), or some aspects of them, are presently partially being used for the design of tunnels. This unintended application opens gaps in terms of different interpretation, depending on the particular country and the level of experience of the designers and contractors.

In particular, EN 1997, devoted to the interaction between the structure and the ground (soil and rock), covers excavations needing retaining walls in soils, such as embedded walls or nailed walls, but does not cover any kind of tunnels, whether in soils or rocks (with the exception of cut-and-cover tunnels). It is admitted that the clauses covering geotechnical design in rock are presently too limited altogether. As for the design of tunnels in soils, there are several reasons, mostly historical, that tunnels are not explicitly covered by the Eurocodes. The lack of provisions specific for tunnel design within the Eurocodes can be explained by the fact that the scope in the first generation of the Eurocodes was to cover buildings and some specific civil engineering works including bridges, towers, masts, chimneys, silos, tanks, pipelines, but without parts devoted to the design of tunnels and underground works.

The European Commission's Mandate M/515[17] to the European Standardisation Committee (CEN) initiated a process of further evolution of the Eurocodes, incorporating improvements to the existing standards and extending their scope. The detailed work programme prepared by CEN's Technical Committee (TC) 250 "Structural Eurocodes" (CEN/TC250) as a reply to M/515 ensures that the so-called **Second Generation of the Eurocodes** continues to be the most comprehensive and advanced state-of-the-art codes for structural and geotechnical design in the world. However, the on-going works on the evolution of the Eurocodes do not encompass specifically the design of tunnels and other underground structures.

Considering the current status of standards for the design of tunnels and other underground structures in the EU countries, it becomes apparent that if no local regulations, specifications or guidelines are available, the responsibility of choosing the appropriate reliability level (i.e. by the choice of corresponding partial safety factors, setting up design requirements, and expected quality assurance procedures) falls down to the designers. However, it should not be the designer's responsibility to define safety levels, which should be based on the accepted probabilities of failure and possible consequences of its occurrence. Therefore, the use of current set of the Eurocodes, which were not meant to be used for underground structures' design purposes, does not absolve the designer from this responsibility.

A special issue of concern is linked to the life-cycle of structures. Default partial safety factors presented in the Eurocodes were derived for standard types of structures, which are usually designed for a 50-year serviceability span with an appropriate reliability index corresponding to the 50-year design life. In that regard, tunnels are more closely related to bridges, which are often expected to last for, at least, 100 years[18]. However, numerous railway tunnels throughout Europe have been in service for even longer periods of time.

Lack of the standards might stem from dependency of tunnel design on empiricism, uncertainties and on variability of not only geological conditions but also construction technologies. In this respect, standards could contribute to increasing construction safety by making the tunnelling experience from previous projects available to designers.

Acknowledging the lack of an applicable set of European-wide common design rules for underground structures, and particularly tunnels, has primarily motivated the work and proposal described within the report. No less important, this work is driven by the fact the tunnelling market in Europe is one of the most globalised segments of the construction sector. Contractors are particularly specialised, operating across the EU countries and internationally. Tunnel projects, even though not particularly numerous in each country, are mostly "large projects" in terms of capital cost, form, and potential consequences, often constructed as parts of large infrastructure investments funded by the public sector. Thus, there is need to maintain a high level of technical proficiency in the European tunnelling construction sector and promote the competitiveness of this sector worldwide.

1.2 JRC activities in support of standardisation for underground structures

Since March 2005, the Joint Research Centre (JRC) of the European Commission provides scientific and technical support to Directorate General (DG) for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW) of the European Commission in the frame of Administrative Arrangements on the Eurocodes and support to policies and standards for sustainable construction. In 2017, JRC started activities on the assessment of standardisation needs for the design of underground structures, with particular focus on tunnels driven by the lack of harmonised European guidelines and approaches for the design of underground structures.

[17] M/515 Mandate for amending existing Eurocodes and extending the scope of structural Eurocodes.

[18] However, it is noted that EN 1990 "Basis of design" provides some guidance for structures with design life of 100 years and structures with higher Consequence Class than typical buildings. This is found in EN 1990 Annex B: "Management of Structural Reliability for Construction Works".

The activities on standardisation needs for underground structures are supported by an Expert Network on the design of underground structures, convened by the JRC. The objective of the JRC Expert Network is to review the state-of-the-art of technical background and standards available for underground structures, explore the potential benefits from a new European standard or new standards (eventually a Eurocode or a Eurocode part) for the design of underground structures, assess the feasibility for such new standard(s) and ponder on the initiation strategies. Experts from various disciplines and European countries were invited to the group, following proposals by members of CEN/TC 250 Sub-Committee 7 "Geotechnical design" (CEN/TC250/SC7). The activities of the Expert Network are widely supported by TC250 and its Sub-Committee 7.

The JRC Expert Network held its first meeting on 22-23 May 2017, at the JRC site in Ispra (Italy). The objective of the first meeting was to assess the standardisation needs for design of underground structures and discuss the feasibility for new standard(s). During the discussions at the meeting, it was agreed that the primary focus of the Expert Network will be on tunnels but some other underground structures (e.g., caverns) can also be considered when appropriate. It was agreed that the development of design standards for tunnels and underground structures is certainly feasible (at least for typical configurations) and that it would be advantageous to foster harmonisation of design rules between the EU countries.

The first phase of the work was concluded with the publication of the JRC Technical Report "*Standardisation needs for the design of underground structures*" (Athanasopoulou et al., 2019). It is argued that the development of design standards for tunnels and underground structures is necessary and feasible, fostering harmonisation of design rules between countries. It appeared suitable that the concept of new standards or guidelines for the design of tunnels shall be developed in line with the Eurocodes. It was recommended that such new standards shall delineate how to complete and/or restrict the use of the Eurocodes for tunnels, having in mind their specificity and diversity and without limiting the required flexibility and future innovations. Naturally, it was recommended that any new standards shall be consistent with the new developments in the Second Generation of the Eurocodes, expected to be published after 2026.

The second phase of the work focused first on collecting and reviewing the available sources of guidance for the design of tunnels. The goal was to identify which aspects of the design have been of primary interest in the existing documents and to which existing Eurocodes these documents are related the most. Moreover, the review of the collected documents served to detect which of them could potentially be considered as main sources of reference when preparing a new European standard for the design of tunnels and other underground works.

Then, an assessment was performed on the applicability of the most relevant parts of the Second Generation Eurocodes, when designing tunnels and underground structures. For issues related to geotechnical design, a core group of geotechnical experts with the coordination of JRC had working meetings from September 2021 to March 2022 to assess the application of the Second Generation EN 1997 "Geotechnical Design". The possible content in the Eurocodes addressing underground structures was discussed extensively during the plenary meeting of the expert network in February 2022. This report presents a consolidated proposal on how to proceed with the development of a new Part or Clause in the Eurocodes for tunnelling and underground structures. The proposal is based on expert judgement serving future standardisation work for the design of underground structures, in the context of the Eurocodes.

1.3 Organisation of the report

The work and considerations presented in the report deal with the development and design of new underground structures, whereas the evaluation of existing structures is outside of its scope. The focus of the assessments and proposals is primarily on tunnels, but the considerations in the report, in principle, are also valid for other underground structures.

Moreover, the report makes primary reference to the Second Generation Eurocodes (2G) – i.e. to the latest drafts available at the time the work was performed (2021-2022). In cases where there is a reference to the first generation Eurocodes (the parts published until 2007), this is explicitly mentioned in the text.

Chapter 1 of the report provides an introduction to the topic of standardisation needs for the design of underground structures and explains the framework of the activities coordinated by JRC. **Chapter 2** discusses the need for developing design standards for underground structures, noting the feasibility and potential benefits of developing such standards. The chapter is an overview of the first Technical report published by JRC on the topic.

Chapter 3 discusses the context of the activities within the European policies related to the construction sector. **Chapter 4** follows with an analysis of the existing documents and sources of guidance related to tunnels design, performed with the support of the Expert Network coordinated by the JRC.

Chapter 5 presents the assessment made on the applicability of selected Second Generation Eurocodes, when designing tunnels and underground structures, complemented by recommendations for possible scope and content of a Eurocode text. A proposal for the next steps for the development of the Eurocodes for tunnelling and underground structures is elaborated in **Chapter 6**.

The members of the JRC Expert Network on the standardisation needs for the design of underground structures are listed in **Annex A.**

Annex B presents two brief examples of selected aspects of tunnel design calculations, one example with a tunnel constructed using an Earth Pressure Balance Tunnel Boring Machine (EPB-TBM) shield in soils (Annex B1) and another example of a tunnel that is driven using a conventional method (Annex B2). The goal of the examples is to conduct design calculations following the requirements and recommendations of the Eurocodes in order to identify, in practical terms, any issues related to their application in tunnel design as well as to provide better understanding of their impact

The full assessment of the applicability of the Second Generation EN 1997 (current draft of prEN 1997) for tunnels and other underground structures is available in **Annex C**. The report identifies items that are sufficiently covered in the draft, items that are covered but need clarifications to avoid misunderstanding or misinterpretation and items that need to be added in future Eurocodes.

The ideas and concepts discussed in the report were consulted with the Expert Network in the plenary meetings held in November 2020 and February 2021. The report full draft was commented by the Expert Network, prior to its publication during August 2022. The complementary report with the title "Assessment of applicability of EN 1997 for tunnels and other underground structures", enclosed as Annex C to this report was commented by the Expert Network in the period January-February 2022.

2 Standardisation needs for the design of underground structures

It is highlighted in the previous chapter that due to the absence of bespoke European design standards for underground structures, tunnel design in Europe is currently based primarily on national standards, recommendations, knowledge and experience complemented by adapting relevant parts of the Eurocodes. This chapter discusses the need for developing design standards for underground structures, noting the feasibility and potential benefits of developing such standards. The chapter presents an overview of the first Technical report published by JRC on the topic (Athanasopoulou et al., 2019).

Several issues require attention in the design of underground structures and tunnels in particular. Some of the main issues of tunnel design are the overall approach for safety/reliability of these important (high-consequence) structures with long service life, ground conditions and assumed properties, relevant actions, adequate consideration of ground-structure interaction. In the framework of the Eurocodes, the basis of design is presented in the EN 1990 "Eurocode: Basis of Design" and EN1991 "Eurocode 1: Actions on structures". Once the assumptions are all adequately considered and effects of actions determined, the actual design/dimensioning of structural elements in concrete, steel or other material or the ground itself may usually follow the provisions of the Eurocodes and in particular EN 1992 "Eurocode 2: Design of concrete structures", EN 1993 "Eurocode 3: Design of steel structures", EN 1997 "Eurocode 7: Geotechnical Design" and EN 1998 "Eurocode 8: Seismic Design". Hence, what is currently missing and is primarily necessary in future for tunnel design are specific technical documents and regulations which define the overall approach and concept, including addressing these issues mentioned above before the dimensioning of structural elements may be performed. Secondly, in the case of tunnels, design/dimensioning of the structural elements is strongly interdependent with the ground response.

At the same time, it has been identified a need to address questions related to tunnel design regarding other issues covered by the Eurocodes, such as:

- the design of tunnels in soils and rocks (with reference to the Second Generation EN 1997, which is extended to cover geotechnical design in rock);
- the design of tunnels in soils and rocks in relation to groundwater;
- the design of sprayed concrete lining (with reference to EN 1992);
- the design of steel linings (with reference to EN 1993);
- the design of tunnels in seismic areas (with reference to EN 1998);
- the design of ground reinforcement and pre-reinforcement (e.g., radial bolting, face bolting) and pre-linings (e.g., forepoling, umbrella arch, mechanical pre-cutting), elements already described in Second Generation EN 1997;
- the assessment and retrofitting of existing tunnels (with reference to the related Second Generation Eurocodes currently in preparation);
- the protection of tunnels against fire (with reference to the appropriate parts of the existing Eurocodes).

The initial phase of work by the JRC in the period 2017 to 2019, carried out with the support of the Expert Network on the standardisation needs for the design of underground structures, highlighted that the development of design standards for tunnels and underground structures is considered feasible (at least for typical configurations) and that it would be advantageous to foster harmonisation of design rules between countries. It appears suitable that the concept of new standards or guidelines for the design of tunnels and underground structures will be developed into the framework of the Eurocodes and delineate how to complete and/or restrict their use for tunnels, having in mind their specificity and diversity, without limiting the required flexibility and innovations.

In parallel, it would be beneficial that the concept will be consistent with the new developments in the Second Generation Eurocodes currently under development and expected to be published after 2026. Further, it is evident that there is need to (i) define what is specifically being used for tunnel design from the first generation Eurocodes, (ii) assess what is missing and (iii) identify what should not be used in tunnel design, keeping in mind that the Eurocodes were originally not meant for dealing explicitly with tunnels and other underground structures.

Sufficient literature, case studies and experience is available to prepare the general framework of a standard or guiding document, as well as addressing most common types of underground structures. Currently, existing standards, guidelines and recommendations for tunnels in some European countries, as well as the Eurocodes and international codes, can serve as the basis for the development of the new standards or guidelines. As a new standard for the design of tunnels and underground works can address the needs of various stakeholders, including national authorities and regulatory organisations, industrial organisations, designers, contractors and clients, it would be important to seek synergies with interested groups.

New European standards and/or guidelines for tunnels and underground structures will provide the following main benefits:

- harmonised level of construction safety across Europe and enhanced resilience of tunnels considered as critical infrastructure;
- clear definition of the applicability of the concerned parts of the Eurocodes;
- spread of state-of-the-art practices and innovation to the industry;
- greater transparency in design methods, risk assessment and improved communication between designers, authorities and clients;
- more efficient, easier and quicker design process; common design aids (manuals, handbooks, etc.) and software;
- increased worldwide competitiveness of the European construction industry;
- common language and easier communication between interested parties (designers, authorities, constructors and clients).

The absence of harmonised standards in Europe for the design of tunnels and other underground structures results in the application of several national standards and recommendations with a risk that divergent reliability levels continue to be implemented in the design of these structures, even within the Trans-European Rail and Road Networks[19].

In view of the broad areas defined above and in addition to presented potential benefits of a new standard, potential detriments in its absence can be resumed as follows:

- lack of harmonisation of the design practices in the different countries, which inhibits the market exchange and working as designer and contractor in other European countries; such issues make the cooperation in international projects more difficult and could be a serious obstacle in the case of cross-border tunnels where two (or more) European countries have to design and construct different sections of a common underground infrastructure guaranteeing a common level of safety;
- lack of broadly recognised document(s) that may serve as a reference when evaluating the quality and assumptions of the design;
- lack of clear guidance or/and conflicting guidance to designers when dealing with complex technical issues for the design and safety assessment of underground structures;

[19] More information on the Trans-European Rail and Road Network policy: https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en

- difficulty of getting insurance coverage or excess insurance fees as a result of a perceived increased risk.

It is advisable that new standards and technical documents to be developed for the design of tunnels and underground structures, should especially:

- refer to tunnels safety aspects, both during construction and during operational life;
- draw attention to the tunnel design specificities, which make tunnels somewhat different from other geotechnical structures;
- contain agreed common aspects in Europe for design of tunnels and be a collection of proven design experience verified by practice;
- address specific national requirements and leave enough flexibility to accommodate them;
- not be overly prescriptive so as not to turn the tunnel standard into a barrier for innovation;
- refer to and be consistent with the existing Eurocodes;
- recommend suitable design approaches, including reasonably selected partial safety factors for different design components.

In the next chapter, the context of the activities within the European policies related to the construction sector is presented.

3 Rational and policy context

The original context of the activities on the standardisation needs for the design of underground structures is set within Directive 2004/54/EC[20], Regulation (EU) No 1315/2013[21] and Directive (EU) 2016/797[22], as described in the following.

Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network stipulates that safety in tunnels requires a number of measures relating, amongst other things, to the geometry of the tunnel and its design, safety equipment, including road signs, etc.

Regulation (EU) No 1315/2013 on Union guidelines for the development of the Trans-European transport network sets the long-term strategy for the development of a complete Trans-European transport network (TEN-T) consisting of infrastructure for railways, maritime and air transport, roads, inland waterways and rail-road terminals. The guidelines enable the definition of projects of common European interest to develop new transport infrastructure and upgrade the existing one. Since EU funding is available for these projects, the quality of design and construction shall be backed-up with state-of-the-art standards and guidelines.

Directive (EU) 2016/797 on the interoperability of the rail system within the European Union (recast) has as objective the technical harmonisation to enable the safe circulation of trains. It opens space for mandatory use of European or international standards, specifications or technical documents via reference in the Technical Specifications for Interoperability (TSIs).

More recently, the **reform of the EU's Civil Protection Mechanism with Decision (EU) 2019/420**[23] established RescEU, encompassing a set of resources for the Member States mobilised by the Commission to respond to major disasters. The decision strengthens the prevention and preparedness action as part of the risk management cycle and improves coherence with other EU policies dealing with disaster risk prevention and management.

The construction ecosystem is a key element for the implementation of the **European Single Market** and for many other important EU strategies and initiatives. Ensuring sustainable, safe and affordable transport along with more sustainable and climate resilient buildings and infrastructure are central priorities of the **European Green Deal** (COM(2019) 640)[24].

The EU Green Deal aims to achieve climate neutrality for Europe by 2050 (Figure 1). In relation to transport, the following are noted:

— Focus is placed on a fair and functioning internal market for transport; the missing infrastructure links and the Trans-European Transport Network need to be completed as swiftly as possible.

— There is need for the highest safety standards; this is becoming even more important as traffic increases and security threats become ever more complex.

— The cooperation with key partners needs to be strengthened to enforce existing agreements, open up new market opportunities, promote high safety standards and improve connectivity links, particularly in the European neighbourhood and the Western Balkans.

The **Renovation Wave for Europe** (COM(2020) 662 final)[25] initiated by the European Commission to reach the objectives of climate neutrality for Europe by 2050 set by the European Green Deal

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20 Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network.

21 Regulation (EU) No 1315/2013 of the European Parliament and of the Council of 11 December 2013 on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU..

22 Directive (EU) 2016/797 of the European Parliament and of the Council of 11 May 2016 on the interoperability of the rail system within the European Union.

23 RescEU-Decision (EU) 2019/420 of the European Parliament and of the Council of 13 March 2019

24 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN

25 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0662

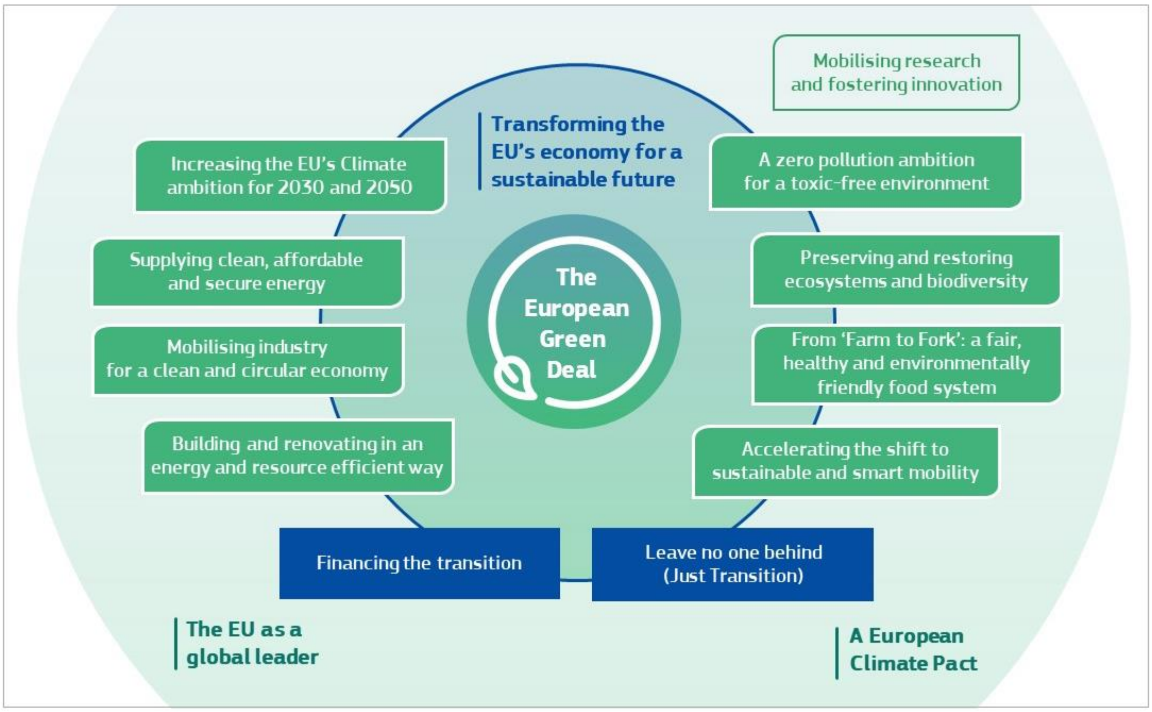
(COM(2019) 640) will massively boost the renovation in the European built environment. The Renovation Wave addresses the twin challenge of energy efficiency and energy affordability, aiming to double, at least, the annual renovation rates of the building stock (currently around 1%).

In support of the European Green Deal and the Renovation Wave, the review (COM(2022) 144)[26] of the Construction Products Regulation (Regulation (EU) No 305/2011)[27] and the proposal for the revision of the Energy Performance of Buildings Directive (COM(2021) 802 final)[28] ensure that the design of new and renovated buildings at all stages is in line with the needs of the circular economy, and lead to increased digitalisation and climate-proofing of the building stock.

Numerous other EU initiatives support the European Green Deal, ensuring more sustainable and climate resilient buildings and infrastructure, including the **New Circular Economy Action Plan** (COM(2020)98 final)[29] and the **New Industrial Strategy for Europe** (COM(2020) 102 final)[30] intending to accelerate the transition of the EU industry to a sustainable model based on the principles of circular economy. Moreover, the **New European Bauhaus** initiative (COM(2021) 573 final)[31] brings a holistic approach to the design of the built environment and any aspect related to safety should not be overlooked.

In addition, the European Commission adopted its new EU strategy on adaptation to climate change COM(2021) 82 final)[32] on 24 February 2021. The new EU Climate Adaptation Strategy sets out how the EU can adapt to the unavoidable impacts of climate change and become climate resilient by 2050. The Strategy has four principle objectives: to make adaptation smarter, swifter and more systemic, and to step up international action on adaptation to climate change.

Figure 1. The European Green Deal.



26 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022PC0144
27 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32011R0305
28 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802&qid=1641802763889
29 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN
30 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0102
31 https://europa.eu/new-european-bauhaus/index_en
32 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN

The **scenarios for a transition pathway for a greener, more digital and resilient construction** (SWD (2021) 419)[33] provide a vision on the needs for faster recovery from the pandemic and increasing the resilience of the construction industrial ecosystem. The construction ecosystem is called to decarbonise its activities and protect them - against the unavoidable impacts of climate change but also from natural and human-made disasters (floods, heatwaves, fires, earthquakes, landslides). Among the priority actions is the enhancement of safety, sustainability and climate resilience in the built environment in the context of the upgrade of the Eurocodes and other relevant building standards.

The **new technical guidance on climate proofing of infrastructure in the period 2021-2027** sets out common principles, requirements and practices to deal with physical climate risks in major infrastructure projects - e.g., funded by the European Regional Development Fund. The guidance rests on two pillars: mitigation and climate neutrality as well as adaptation and climate resilience. The EN Eurocodes are referenced as a tool for climate proofing of infrastructure, strengthening the arguments in favour of developing new European standards for the design of underground structure within their framework.

Further, the recent EU plan for major investment in infrastructure development around the world – the **Global Gateway** (JOIN(2021) 30 final)[34], put focus on physical infrastructure (such as fibre optic cables, clean transport corridors, clean power transmission line) with mobilization of investments of up to €300 billion between 2021 and 2027. The guiding principles point to smart, clean and secure investments in quality infrastructure while connecting goods, people and services around the world in a sustainable way.

Complementary to the EU policies in support of improvements in the construction ecosystem and transport, European standards are fundamental for reaching objectives such as the Green Deal, Digital Strategy and New Industrial Strategy and have indeed played a leading role in creating the EU Single Market. Standards can drive innovation, competitiveness, sustainability and consumer protection, and they are an indispensable tool for raising product safety and environmental performance.

Recognizing that the EU's ambition towards a climate neutral, resilient and circular economy cannot be delivered without leveraging the European standardisation system, the European Commission presented a **new Standardisation Strategy** (COM(2022) 31 final)[35], to enable global leadership of EU standards in promoting values and a resilient, green and digital Single Market. The Strategy spots standards as "*the silent foundation of the EU Single Market and global competitiveness*", since they are "*invisible but a fundamental part of our daily life*". European standards are embedded in the EU policy objectives and have a key role to achieve a climate-neutral, resilient and circular economy.

The Strategy notes that standards are an important instrument to regulate the construction sector, describing five key sets of actions:

- Anticipate, prioritise and address standardisation needs in strategic areas;
- Improve the governance and integrity of the European standardisation system;
- Enhance European leadership in global standards; standards for cybersecurity or the resilience of critical infrastructure carry a strategic dimension;
- Support innovation;
- Enable the next generation of standardisation experts.

The EU has already put in place a number of policy and regulatory instruments for the construction sector, including related European Standards (EN), and the Eurocodes are well placed in this framework, addressing the structural design of buildings and other construction works. The Eurocodes

[33] Scenarios for a transition pathway for a greener, more digital and resilient construction ecosystem - SWD (2021) 419, 14.12.2021

[34] The Global Gateway – JOIN(2021) 30 final, 1.12.2021

[35] The EU Strategy on Standardisation – COM (2022) 31 final, 02.02.2022

are the product of a long procedure of bringing together and harmonising the different design traditions in the EU Member States, leading to more uniform levels of safety in construction in Europe.

The Eurocodes are the recommended means of giving a presumption of conformity with the Basic Requirements of the Construction Products Regulation (CPR) (Regulation (EU) No 305/2011)[36] for construction works and products that bear the CE Marking[37], in particular the Basic Requirement 1 "*Mechanical resistance and stability*" and the Basic Requirement 2 "*Safety in case of fire*". The objective of the CPR is to achieve the proper functioning of the internal market for construction products by establishing harmonised rules on how to express their performance.

Further, the Eurocodes are the preferred reference for technical specifications in public contracts since, according to the **Public Procurement Directive**[38], contracting authorities in the EU must allow the use of the Eurocodes in structural design aspects of tenders. The Eurocodes are the standard technical specification for all public works contracts in the EU and European Free Trade Association (EFTA) Member States. If proposing an alternative design, one must demonstrate that this is technically equivalent to a Eurocode solution.

The **Commission Recommendation 2003/887/EC** on the implementation and use of the Eurocodes for construction works and structural construction products recommends undertaking research to facilitate the integration into the Eurocodes of the latest developments in scientific and technological knowledge. In this context, the European Commission issued to CEN the Mandate M/515 for a detailed work programme to develop the Second Generation of the Structural Eurocodes, which includes amending the existing Eurocodes and extending their scope.

The European Commission's Mandate M/515[39] to CEN initiated a process of further evolution of the Eurocodes, incorporating improvements to the existing standards and extending their scope. The detailed work programme prepared by CEN's Technical Committee (TC) 250 "Structural Eurocodes" (CEN/TC250) as a reply to M/515 ensures that the so-called **Second Generation of the Eurocodes** continue to be the most comprehensive and advanced state-of-the-art codes for structural and geotechnical design in the world. However, the on-going works on the evolution of the Eurocodes do not encompass specifically the design of tunnels and other underground structures.

Some new developments in EN 1997 might accommodate some of the specific aspects of tunnel design – e.g., recently a Project Team within TC 250/Sub-Committee 7 was established, dealing with the compatibility of rock mechanics with the limits states concept. Also, future EN 1998 Part 5 "Foundations, retaining structures and geotechnical aspects" will provide a totally new extensive section on the definition of the seismic actions for underground structures, including pipelines, tunnels and large underground structures like metro stations. Further, future EN 1992-1-1 "General rules and rules for buildings" is intended to provide non-member specific design rules whenever possible. Hence, design provisions in the Second Generation EN 1992-1-1 could most likely be used for tunnels to dimension structural concrete members in most cases (assuming action effects are adequately known).

In the period that the activity presented in this report was performed, the Second Generation Eurocodes Parts were in various stages of preparation and drafting. It is expected that the last Second Generation Eurocode Parts will be made available to the National Standards Bodies by March 2026 and by March 2028 all national standards conflicting with any Second Generation Eurocode Parts will have to be withdrawn[40].

[36] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32011R0305

[37] Information on CE Marking: https://single-market-economy.ec.europa.eu/sectors/construction/construction-products-regulation-cpr/declaration-performance-and-ce-marking_en

[38] Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on public procurement and repealing Directive 2004/18/EC.

[39] M/515 Mandate for amending existing Eurocodes and extending the scope of structural Eurocodes.

[40] The timeline for the development and publication of the Second Generation Eurocodes: https://eurocodes.jrc.ec.europa.eu/2nd-generation-evolution/timeline-eurocodes-second-generation

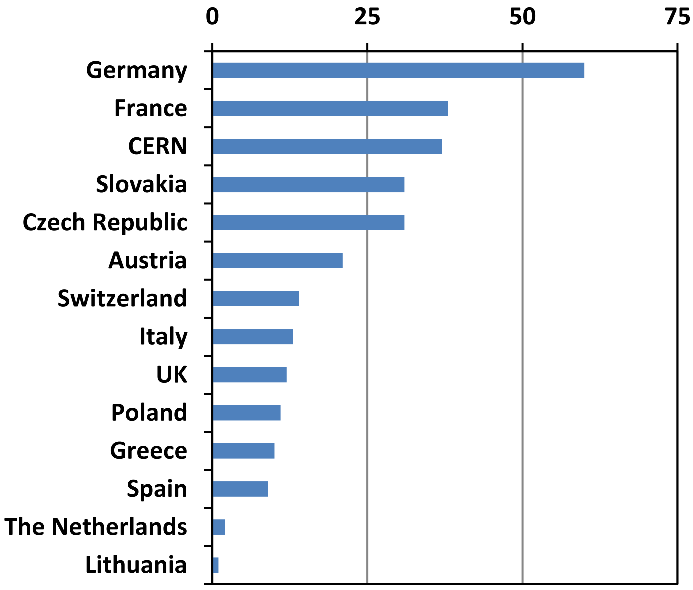
4 Existing sources of guidance for the design of underground structures

As a starting step in the assessment of the standardisation needs for the design of underground structures, a search for existing documents and sources of guidance related to tunnel design was performed with the support of the JRC Expert Network and other associated experts from the EU Member States. The collected documents, the assessment and the statistics presented below is not representing all documents existing in the EU/EFTA Member States as it was not based on an official enquiry but rather on informal exchange of information and knowledge on such documents between the experts in the network. Moreover, the scope was not to compile an exhaustive list of guiding documents or perform a state-of-the-art review but to understand, in broad terms, the extent of available knowledge present in the existing sources of guidance related to tunnel design.

The collected documents were assessed with the goal to identify which aspects of the design have been of primary interest in the existing documents. Also, it was evaluated to which existing Eurocodes these documents are mostly related to, and which of the documents could potentially be considered as main sources of reference when preparing a new European standard for the design of tunnels and other underground works.

A summary of the collected documents was compiled. Figure 2 presents the overview of countries from which the submissions originated. It is noted that documents addressing specifically the design of underground research infrastructures[41] at the European Organization for Nuclear Research (CERN) are mentioned in the figure separately with the label "CERN" due to their particular scope. In total, 293 potential sources of guidance were identified (excluding duplicate entries).

Figure 2. Number of references provided by representatives of each country.

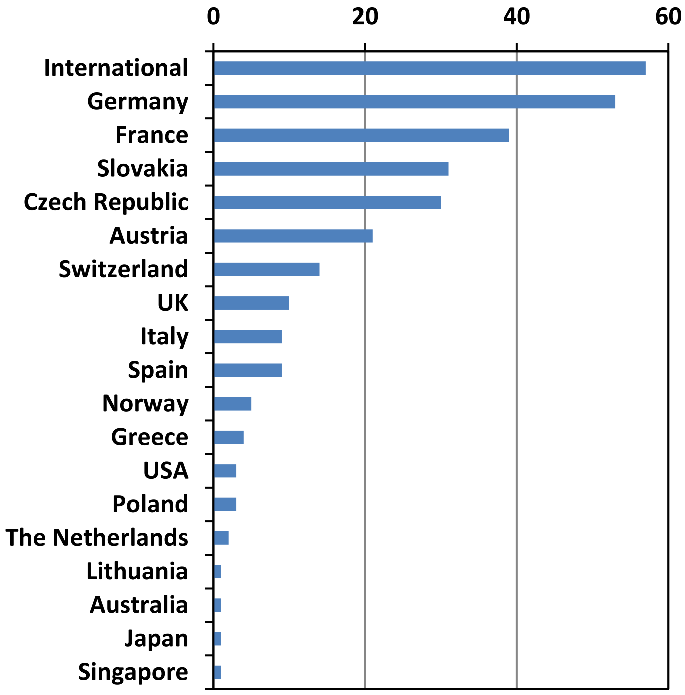


It should be emphasized that the compiled summary is not an exhaustive list containing all available documents related to tunnel design that exist worldwide. Obviously, there are more references available in non-European countries as well as a vast number of scientific literature on the subject of tunnels; however, those documents are not widely used in practice in Europe and they usually show very limited or even no relation to the European standards. Some of the exceptions are the documents originating from Singapore (LTE 2019), Australia (ATS 2020) and international guidelines (e.g. ITA-AITES 2019), where Eurocodes are mentioned or directly referenced.

[41] For example, the Large Hadron Collider (LHC) - a particle accelerator constructed on the CERN site (https://eurocodes.jrc.ec.europa.eu/news/new-underground-infrastructures-and-surface-buildings-cern-designed-eurocodes)

Most of the considered documents have been provided by experts from the countries with strong tunnelling history and traditions; some of the guidelines originating from those countries, despite their national character, are often used internationally. The summary of the origin of the documents or their intended country of use is presented in Figure 3.

Figure 3. Number of references in terms of their origin or intended country of use.



The type of documents that were provided ranged from the level of European regulations, through national standards and guidelines, down to specific scientific papers. Regarding the purpose of their implementation in standardisation, the level of maturity of the ideas and the content presented in those documents vary significantly, and therefore it will require further critical assessment at future stages of the works. At the current stage, it can be assessed that the significant part of guidance used in the design seems to originate from (see **Error! Not a valid bookmark self-reference.**):

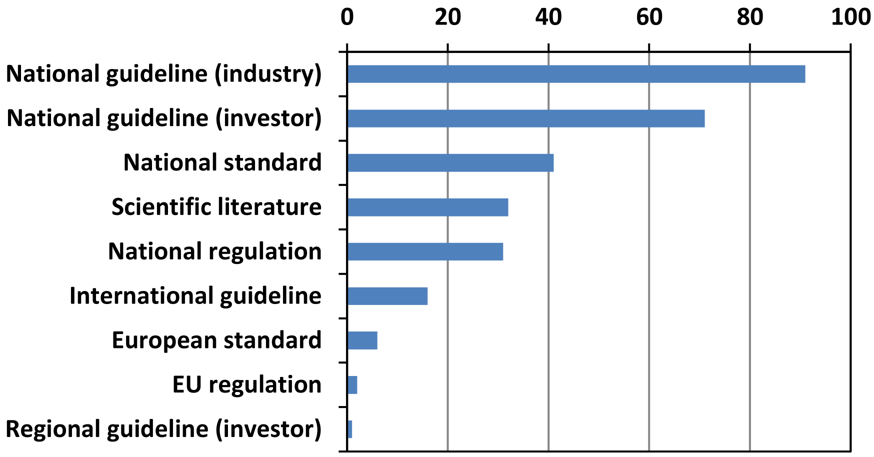
— Guidelines and specifications provided by the owners– e.g., road or railway authorities, who are often the future operators of the tunnels responsible for their maintenance over the entire life-cycle of these structures.

— Industrial guidelines and standards – which were mostly developed by national or international learned societies (e.g., ITA-AITES, AFTES, BTS, DAUB, ICE, etc.)[42] with participation of representatives of various stakeholders (e.g. designers, contractors, investors) in order to promote the best practices and specify requirements, where there were none presented in the higher level documents (e.g. Eurocodes).

— National regulations and standards – their content can vary from specific technical aspects to general aspects of design, risk management, contracting, and operations; similarly, to the guidelines, they often supplement additional tunnel-specific requirements unavailable in European standards.

[42] ITA-AITES: International Tunnelling and Underground Space Association; AFTES: Association Française des Tunnels et de l'Espace Souterrain; BTS: The British Tunnelling Society; DAUB: Deutscher Ausschuss für Unterirdisches Bauen; ICE: Institution of Civil Engineerings.

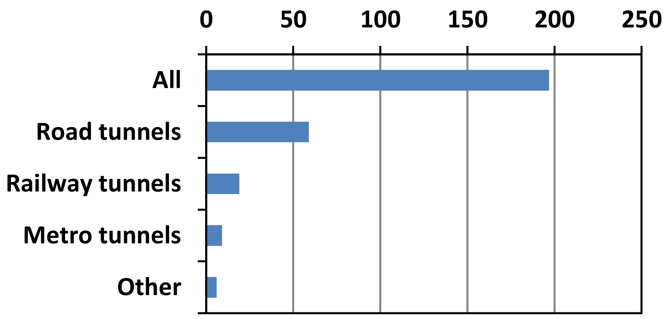
Figure 4. Number of references in terms of their type.



Some national guidelines (e.g. AFTES 2002, BTS 2004, BSI 2016, DAUB 2013 & 2016) are internationally accepted documents, especially, in countries lacking their own established national guidance for tunnel design. The reasons for such wide acceptance usually are their high quality and merit (i.e., the state-of-the-art guidance), as well as good track record of implementation in countries of origin (i.e., validation by experience). Similarly, international guidelines (published primarily by ITA-AITES, e.g., ITA-AITES 2019) are also widely accepted and recognised as primary sources of reference for designers in regard to aspects not sufficiently addressed in the Eurocodes. Such guidelines prepared by learned societies, both national and international, are especially valuable as they present the current state-of-the-art by synthesising the knowledge from scientific literature and practical experiences intro specific design recommendations.

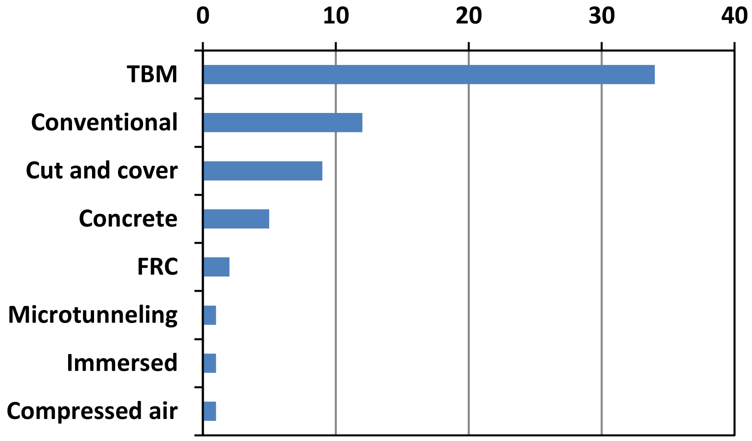
The vast majority of the considered existing sources of guidance are not related to any particular, intended function of the tunnel (see Figure 5); most of these documents are applicable to tunnels irrespective of their envisioned use. In some cases, the provided guidance is intended for tunnels of specific function, e.g., roads, railways, metro lines; however, this is the case mostly when the document was developed by the owner interested in this particular functionality; in general, the function of a tunnel does not seem to be explicitly related to the aspects relevant to the structural and geotechnical design perspective.

Figure 5. Number of documents based on the function of the tunnel covered by the documents.



Many of the reported guiding documents are also not related to any specific construction method. However, there are several documents (Figure 6) that are focused on specific tunnelling techniques or structural characteristics and the design aspects associated with them. The most common occurrences are related to tunnels constructed using Tunnel Boring Machines (TBMs) with segmental concrete lining, as well as those related to sprayed concrete lining (SCL) when the sequential excavation method is used. This is not surprising as those techniques, developed significantly over last few decades, are most commonly used in practice, nowadays. Therefore, future standardisation efforts should be focused on them. On the other hand, there is not much guidance provided for other tunnel types, e.g., microtunnelling and immersed tunnels, which suggest that they potentially can be left out outside the scope of the initial standardisation considerations.

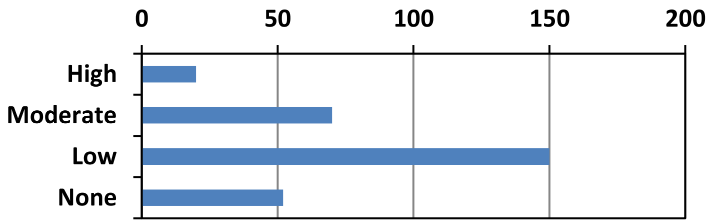
Figure 6. Number of documents based on the tunnel construction method (unspecified cases excluded).



Available guiding documents cover wide range of design, execution, and maintenance aspects related to tunnels. Many reported documents do not focus on structural or geotechnical design, but other aspects like planning, operation of tunnels, ventilation, lighting, etc. Although all these stages and design aspects are important for the final function of the structure, not all of them are relevant in the context of structural and geotechnical design, which is the primary focus of the Eurocodes. Based on the initial review of the provided references, a qualitative assessment was made to identify potentially the most relevant documents in the context of the structural and geotechnical design within the Eurocodes concept (Figure 7). This limits the need of in-depth review of all available documents, necessary later at the stage of standard development, to a relatively low number of highly relevant sources.

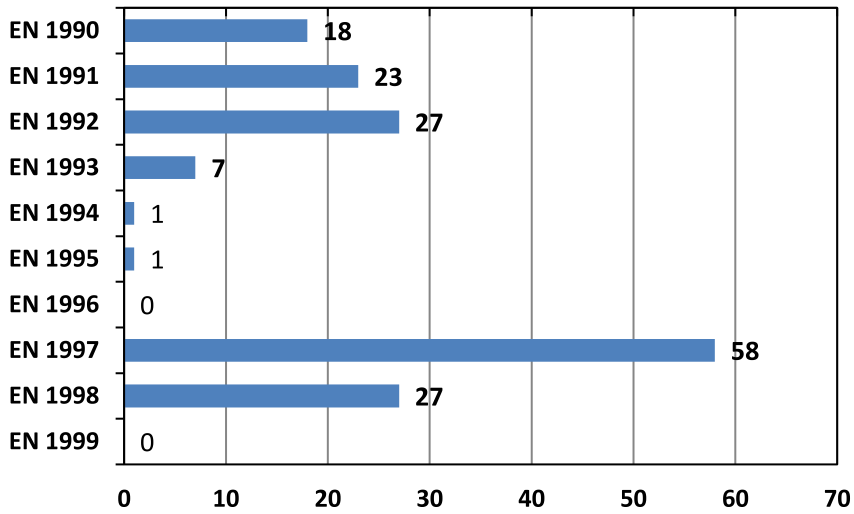
The documents identified as the most relevant are primarily the recent guidelines and standards, which are already summarizing and synthesizing the available knowledge and current state of the art design requirements. They are often already presenting the information in the context of the existing standardisation framework of the Eurocodes.

Figure 7. Potential relevance of collected guiding documents in the context of structural and geotechnical design.



Finally, the main part of the conducted initial summary of the existing sources of guidance was to assess to which Eurocodes they are the most related to and to identify where insufficient guidance or potential conflicts might exist in comparison with the current European standards. Interestingly, relevance of only some Eurocode parts has been highlighted based on the review of the existing guideline documents (see Figure 8); those are: EN 1990, EN 1991, EN 1992, EN 1997, EN 1998, and to some extent also EN 1993. Although practically no conflicts of the assessed documents with the Eurocodes have been reported, some adjustments to the approaches presented in the standards were introduced in some documents; especially, where no relation to the tunnelling-specific design aspects is present in the Eurocodes (e.g., lack of calculation models dedicated to tunnelling related aspects).

Figure 8. Number of references to specific Eurocodes in the considered sources of guidance.



Based on the compiled database of existing sources of guidance and its initial analysis, following conclusions can be stated:

— International and national guidelines and standards are the most relevant sources of guidance and should be considered as primary sources of reference in standardisation efforts – they are already presenting current state-of-the-are requirements related to structural and geotechnical design of tunnels, as well as they synthesise the available knowledge from scientific and technical literature.

— Standardisation efforts should primarily focus on tunnels executed using TBMs with segmental concrete lining as well as on the conventional methods with sequential excavation – except cut-and-cover execution, which design is already covered by the current Eurocodes; those are the most common techniques used in practice.

— Only certain Eurocode parts seem to be of primary interest for tunnel design (i.e. EN 1990, EN 1991, EN 1992, EN 1997, EN 1998) – those parts should be the focus of future standardisation activities related to tunnel design, at least in the first phase of the standardisation works and those parts might need supplementation with additional information and requirements.

— No significant conflicts with existing Eurocodes were identified so far. In most cases, existing sources of guidance tend to supplement additional information to the existing Eurocodes design framework in order to make the design of tunnels code-compliant with the basic principles of the Eurocodes.

5 Assessment of selected Second Generation Eurocode Parts for the design of tunnels and other underground structures

5.1 Introduction

This chapter presents an assessment of the applicability of the Second Generation Eurocodes, when designing tunnels and underground structures. In the development of the Second Generation Eurocodes, tunnels and underground structures were not included, with the exception of EN1998 "Eurocode 8: Design of structures for earthquake resistance" - Part 5 "Geotechnical aspects, Foundations, Retaining and Underground structures".

The reason for the temporary exclusion was that tunnels and underground structures are often major structures, which fall outside the Eurocodes scope of application. Their design is partially based on empiricism when assessing ground behaviour type, and stability risks, or selecting effective supports. Furthermore, the design is based on ground-structure interaction, deformation behaviour, observational method and other design methods. These methods are less used for other structures and therefore not extensively covered in the Eurocodes so far. Furthermore, in contrary to other structures, the use of partial factors for tunnel design is sometimes limited. However, it is felt that the general Basis of Design rules, as stated in EN 1990 "Eurocodes: Basis of structural design", can be applied for the design of tunnels and other underground structures as the design of these structures should be able to cope with the safety approach in EN 1990. Nevertheless, several issues should be addressed within EN 1990 in order to implement tunnelling design into the Eurocodes suite. Such issues are noted in Chapter 5.2.

In 2021, a core group of geotechnical and structural engineers started the work on evaluating the applicability of the Second Generation EN 1997 "Eurocode 7: Geotechnical Design" on tunnelling and underground structures design. The work was performed in the framework of the Expert Network on standardisation needs for the design of underground structures and coordinated by the JRC. Before performing the assessment, the core group made an evaluation of the most involved parts of the Eurocodes and also indicated where most of the adaptations would be necessary based on expert judgment. The limitation of the scope to those Eurocodes (**Table 1**) was also a result of the assessment of the existing sources of guidance.

Other Eurocodes were not considered in this phase of the work due to their limited relevance for the design of new tunnels and other underground structures. It is recognised that some of the other Eurocodes may be relevant for less common design problems and existing tunnels, but the intention of this evaluation is to assess general applicability and compatibility of the Eurocodes with the current state-of-the-art.

During 2021 and 2022 assessments of applicability of the Eurocodes were made for the following parts: EN 1991 (Section 5.3 below), EN 1992 (Section 5.4 below), EN 1997 (Section 5.5 below) and EN 1998 (Section 5.6 below). A core group of geotechnical experts has evaluated EN 1997 in detail, with respect to tunnelling on basis of Sub-Clause (Sub-Chapter) level. These findings are given in Annex C of this report. A summary of this Annex is provided in Section 5.5.

Table 1. Summary of selected Eurocodes Parts assessed related to tunnelling and other underground structures design.

Eurocode	Topic
EN 1990 – Basis of structural and geotechnical design	Tunnel design should be able to cope with the safety approach in EN 1990, adaption of points of discussion as noted in Section 5.2
EN 1991 – Actions on structures	Special actions should be determined for tunnels
EN 1992 – Design of concrete structures	Special concrete applications for tunnelling: shotcrete, grout
EN 1993 – Design of steel structures	No specific issues for steel are expected, EN 1993 would also be valid for underground structures and tunnels.
EN 1997 – Geotechnical design	Large adaptions in design methods, observational method, interaction of structure with the ground, stiffness considerations for the Serviceability Limit State (SLS), stability risks (Ultimate Limit State, ULS)
EN 1998 Design of structures for earthquake resistance	Important for tunnels, already a Clause in EN 1998 Part 5

5.2 EN 1990 "Eurocode: Basis of structural design" applicability in tunnel design

It is noted that at the time the selected Eurocodes Parts were assessed related to tunnelling and other underground structures design, the Second Generation EN 1990 draft was not finalised and changes were to be expected. Thus, a detailed assessment of the Second Generation EN 1990 was not performed by the JRC Expert Network. However, the applicability of EN 1990 and its safety concept was discussed and debated among the experts. It is noted that the Second Generation EN 1990 is expected to have the title "Basis of structural and geotechnical design". The major points of discussion are noted below:

1. Use of partial factors

EN 1990 states in its scope: "*Design and verification in this document are based primarily on the partial factor method*". There are limitations for using the partial factor method as described in EN 1990 for designing tunnels and underground structures. A problem is the variation of the ground conditions along the tunnel alignment. The ground conditions may not be described in advance in sufficient detail to be used for verification of the design. The design must therefore be verified by applying the observational method. In EN 1990 Clause 1.1 "Scope of EN 1990" this has been recognized and added in Clause 1.1(4) Note 1: "*Alternative methods are given in the other Eurocodes for specific application*". This has to be specified further for tunnelling design.

2. Ground-structure interaction: evaluation of effect of actions

Design of tunnels and underground openings is a ground-structure interaction problem. The equation as described in EN 1990 Clause 8.3.1 "Verification of ultimate limit states (ULS)" is based on the prerequisite that load and resistance are independent and can be physically separated. This is not the case for ground-structure interaction problems. In EN 1990 Clause 3.1.3.4 "Effect of action" internal forces (quantities) are given as examples and shall accordingly in Clause 8.3.2.3 be multiplied with a partial factor. This may give situations that violate the principle of mechanics and should be elaborated further for tunnelling.

3. Ultimate Limit States: failure of structure or ground

It is stated in EN 1990:5.3 (3) that "*the following ultimate limit states shall be verified, as relevant: - failure of the structure or the ground, or any part of them including supports and foundation* …". This formulation is not consistent with the general basis for designing of ground-structure interaction problems. To optimise this type of geotechnical structures it is normal to accept yielding of ground, structure elements or part of them without jeopardizing the safety. The formulation set up in EN 1990 may give conservative and expensive tunnelling structures.

4. Uncertainties in tunnelling, especially for rock

The structural material, for rock tunnels, is the rock itself. The rock has both aleatoric and epistemic uncertainty. The current draft for EN 1997 Part 1 "General rules" has, in some extend, indirectly addressed this issue by allowing for the Observational Method. However, now it shall be addressed directly, calling the uncertainties by name and classify them.

In underground engineering / tunnelling in rock a 95% certainty level will never be achieved, even when performing very many tests on ground. EN 1990 requires a 95% certainty level for the structural materials.

The philosophy of the Eurocodes is based on man-made materials and designing them having sufficient strength by using design resistance values in reference to design loads and actions. In underground engineering, the strength is not achieved from steel or concrete, but is dependent on the strength of the existing material. Tunnelling depends on the strength of the ground with the help of additional steel and concrete. This is opposite to the approach of EN 1990.

5 In tunnelling: unloading instead of loading

In tunnelling, generally unloading of the ground takes place due to the excavation. This implies redistribution of existing in situ stresses, which cannot be addressed as an action, like in EN 1990 and EN 1991.These issues should be addressed within EN 1990 in order to implement tunnelling into the Eurocodes suite.

The implementation could, for instance, be achieved by adding an Addendum to EN 1990, consisting of a new Annex A.7 on Tunnels and Underground structures.

5.3 EN 1991 "Eurocode 1: Actions on Structures"

5.3.1 General

In the following extracts, various parts from the introduction or/and the scope of EN 1991 "Eurocode 1: Actions on structures" which are associated with the design of tunnels and other underground structures are presented and briefly commented.

Because of the advanced status of development of the Second Generation EN 1991, the following information is based on the drafts of the Second Generation EN 1991.

5.3.2. Introduction to EN 1991 (all parts)

All parts of EN 1991 specify actions for the structural and geotechnical design of buildings, bridges and other civil engineering works, or parts thereof, including temporary structures, in conjunction with EN 1990 and the other Eurocodes. EN 1991 does not cover the specific requirements of actions for seismic design. Provisions related to such requirements are given in EN 1998, which complement and are consistent with EN 1991.

EN 1991 is also applicable to existing structures for structural assessment, strengthening or repair and change of use. Also, EN 1991 is applicable for the design of structures where materials or actions outside the scope of the other Eurocodes are involved.

It can be concluded that no literal exclusion of tunnels and underground structures is noted in EN1991, even in case of actions outside the scope of the Eurocodes, but that additional or amended provisions are needed.

5.3.3 EN 1991-1-1 "General actions – Densities of material, self-weight of construction works and imposed loads on buildings"

In EN 1991-1-1 rules are given on the following aspects related to actions, which are relevant to the structural design of buildings and civil engineering works including some geotechnical aspects:

- specific weight of construction materials and stored materials;
- self-weight of construction works; and
- imposed loads for buildings.

It can be concluded that no literal exclusion of tunnels and underground structures is noted in EN 1991-1-1, as far as self-weight is concerned.

5.3.4 EN 1991-1-2 "General actions – Actions on structures exposed to fire"

EN 1991-1-2 describes the thermal and mechanical actions for the structural design of buildings and civil engineering works exposed to fire, including safety requirements and design procedures. It is intended to be used in conjunction with the fire design parts of EN 1992 to EN 1996 and EN 1999 which give rules for designing structures for fire resistance. The thermal actions are either nominal or physically based. More data and models for physically based thermal actions are given in annexes.

EN 1991-1-2 does not cover the assessment of the damage of a structure after a fire. Also, supplementary requirements are not covered, for example:

- the possible installation and maintenance of sprinkler systems,
- conditions on occupancy of building or fire compartment, and
- the use of approved insulation and coating materials, including their maintenance.

It can be concluded, that although reference is made to "civil engineering works" and no literal exclusion of tunnels and underground structures is cited, the document is axed on buildings. Eventually some parts of it could be used for underground structures following necessary adaptations. It is certain, for example, that nominal fire curves or other design fire curves to be used for tunnels are different from the respective one for buildings, as well as fire scenarios.

5.3.5 EN 1991-1-5 "Thermal actions"

EN 1991-1-5 gives design guidance for thermal actions arising from climatic and operational conditions on buildings and civil engineering structures.

Principles and rules are given for calculating thermal actions on buildings, bridges and other structures including their structural members. Principles needed for cladding and other attachments of buildings are also provided.

It can be concluded that, although there is no literal exclusion of tunnels and underground structures, the document is axed on buildings and bridges. There is only a reference: "*Temperatures* T_{out} *for* *underground parts of buildings*" in Table 7.1 (a Nationally Determined Parameter[43]), which concerns ambient temperature for the basements of buildings in summer and winter.

EN 1991-1-5 has no direct provisions for thermal actions in tunnels, though at least basic provisions are required. More specific provisions would likely be in the National Annexes or require tunnel specific project dependent definition.

5.3.6 EN 1991-1-6 "Actions during execution"

EN 1991-1-6 provides guidance and general rules on the determination of actions relevant for the design during the execution of buildings and other civil engineering works, including geotechnical structures.

The actions for design during execution include those that only arise from execution activities and act during execution, termed construction actions, and other that are present during the service life of the completed structure (for example self-weight, wind, etc.) but which can act differently and/or have different values during execution.

EN 1991-1-6 also provides guidance and general rules for the determination of actions for the design of auxiliary structures and equipment used during execution, as well as for the determination of actions that usually act on auxiliary elements used during execution.

It can be concluded, that although there is a general reference to geotechnical structures, with no literal exclusion of tunnels and underground structures, the document is axed on buildings and bridges (and relevant retaining/geotechnical structures).

The construction actions mentioned in Tables 5.1 (classification) and 6.2 (characteristic values) are not very pertinent for/oriented to tunnelling. But some other actions present during construction and classified in Table 5.2 of the document (e.g., self-weight, imposed loads, thermal, shrinkage and aging, traffic, water, geotechnical, prestressing, pre-deformation, (seismic)) could be of relevance, generally for transient design situations.

The actions during execution often are of high importance for tunnel design as the loads are very specific to tunnelling and play an important role in providing the required resistance of the structures.

Technical material on actions associated with the execution of tunnels with TBMs is available in some guideline documents (see Chapter 4), which may be used as a basis for the drafting a new standard.

5.3.7 EN 1991-1-7 "Accidental actions"

EN 1991-1-7 describes principles and application rules for the assessment of accidental actions on buildings and other civil engineering works. The following actions are included: impact forces from vehicles, rail traffic, ships and helicopters; actions due to internal explosions and combustible gases and dust, actions for tying systems and key members.

According to EN 1991-7 Clause 6.3, structures shall be designed to resist progressive collapse resulting from an internal explosion.

Guidance on dealing with the specific types of explosions is given in Annex D -12 "Gas and vapour/air explosions in rooms and closed sewage basins, road and rail tunnels and energy ducts and dust explosions in rooms, vessels, bunkers and energy ducts".

It can be concluded that although there is a general reference to buildings and civil engineering works, with no literal exclusion of tunnels and underground structures, the document does address impact from traffic and explosions in tunnels.

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[43] The Eurocodes provide for National Choices full sets of recommended values, classes, symbols and alternative methods to be used as Nationally Determined Parameters (NDPs).

5.3.8 EN 1991-2 "Actions from traffic loading"

EN 1991-2 gives design guidance and actions due to road and railway traffic on bridges **and civil engineering works**. The load models and values given in this document are also applicable for the design of geotechnical structures (retaining walls and embankments, sections 6.9 and 8.10) subject to road or rail traffic actions. This document also provides applicability conditions for specific load models.

It can be concluded that although there is no literal reference to tunnels or underground works, the document is also applicable for geotechnical structures, such as retaining structures and earthworks (e.g., embankments). Normally road or rail traffic loads are not present during the procedure of excavation but after the finishing of the works, and they are generally applied on the earth works bearing the road or the rail tracks (and possibly transferred to the underlying tunnel structure). Typically, the load models LM1 and the LM71, respectively, could be considered as formulated for geotechnical structures (e.g. embankments behind a bridge) in clauses 6.9 and 8.10 of the document, respectively.

5.3.9 Conclusions on applicability of EN 1991 (all parts) to tunnels and other underground structures

Generally, it can be concluded that EN 1991 is not intended to be used for tunnels and underground structures. However, there are many items mentioned which can basically be used but should be adapted for tunnel design as for example weight of constructions, thermal and fire actions, accidental actions (collisions of traffic, explosions), actions during execution (temporary works), and actions from road and rail traffic.

The code needs updating for tunnelling on these aspects. Aspects related to tunnelling-specific actions, including those in execution (e.g. loads on the lining due to TBM advancement), can be found in some guidance documents (see Chapter 4), which may be used as a basis for the new standard.

5.4 EN 1992 "Eurocode 2: Design of concrete structures"

5.4.1 General

The objective of this section is to provide background material and information on the potential use of EN 1992 "Eurocode 2: Design of concrete structures" for the design of tunnels and other underground structures, including:

- main conclusion of assessment of the applicability of current draft of Eurocode.
- any identified limitation of the Eurocode in relation to tunnels and underground structures.
- specific topics that need to be further developed and added.

Because of the advanced status of development of the Second Generation EN 1992, the following information is based on the drafts of the Second Generation EN 1992, i.e. prEN 1992-1-1:2021 "Design of concrete structures" – Part 1-1: General rules – Rules for buildings, bridges and civil engineering structures, prEN 1992-1-2:2021 "Design of concrete structures" – Part 1-2: General rules - Structural fire design, and current EN 1992-4:2018 "Design of concrete structures" – Part 4: Design of fastenings for use in concrete.

5.4.2 Introduction to EN 1992 (all parts)

EN 1992 applies to the design of buildings, bridges and civil engineering structures in plain, reinforced and prestressed concrete. It complies with the principles and requirements for the safety and serviceability of structures; the basis of their design and verification are given in the Second Generation EN 1990 "Eurocode: Basis of structural and geotechnical design".

EN 1992 is only concerned with the requirements for resistance, serviceability, durability and fire resistance of concrete structures. Other requirements, e.g., concerning thermal or sound insulation, are not considered. EN 1992 is applicable to new and to existing concrete structures.

EN 1992 does not cover seismic design of concrete structures. Provisions for seismic design of concrete structures are given in EN 1998 (all parts).

Hence, although not directly mentioned, tunnels and other underground structures are within the scope of EN 1992 (all parts).

5.4.3 prEN 1992-1-1 "General rules, rules for buildings, bridges and civil engineering structures"

EN 1992-1-1 applies to the design of buildings, bridges and civil engineering structures in plain, reinforced and prestressed concrete made with normal weight, lightweight and heavyweight aggregates, including temporary structures, under temperature conditions between −40 °C and +100 °C generally.

EN 1992-1-1 does not cover:

- Particular aspects of special types of civil engineering works (such as dams, pressure vessels);
- Structures made with no-fines concrete, aerated or cellular concrete, lightweight aggregate concrete with open structure components;
- Structural parts made of concrete with a smallest value of the upper sieve aggregate size D_{lower} <8 mm, unless otherwise stated in the code.

Clause 4 – Basis of design: EN 1992-1-1 uses limit state design in conjunction with the partial factor method in accordance with prEN 1990, and actions in accordance with prEN 1991 (all parts) and prEN 1997 (all parts), and combination of actions in accordance with prEN 1990.

Partial factors for materials and concrete-specific actions are given in this Clause which are based on a reliability index β = 3,8. However, procedures to adapt the partial factors for other values of β are given in Annex A.

Specifically mentioned are effects resulting from restrained, imposed deformations, ground-structure interaction and effect of water or gas pressure. However, no specific rules are given on the specific analysis methods to consider ground-structure interaction.

Design assisted by testing in accordance with EN 1990 is covered by EN 1992-1-1, and could be applied to specific applications such as sprayed concrete.

Clause 5 – Materials: This clause gives the properties of concrete, reinforcing steel, prestressing steel and prestressing systems required for design to the Eurocode. Supplementary information on less frequently used materials is given in Annex JA for structures with Embedded FRP reinforcement, Annex L for Steel fibre reinforced concrete structures, Annex M for Lightweight aggregate concrete structures, Annex N for recycled aggregate concrete structures, and Annex Q for structures with Stainless reinforcing steel.

EN 1992-1-1 covers normal-weight concrete strengths of 12 MPa up to 100 MPa, and reinforcing steel grades of 400 – 700 MPa yield strength, i.e., probably covering the full range of material strengths used in tunnels and other underground structures.

Sprayed concrete (shotcrete) is not specifically mentioned but considered just one form of placing of concrete. Hence, it is considered to be covered for design respecting the lowest limit value of the upper sieve aggregate size D_{lower} noted above. However, as shown by Psomas (2022), certain particularities and consequences of placing sprayed concrete may not be fully covered by EN 1992-1-1 (shadowing and hence, more unfavourable bond conditions than the "poor bond conditions" assumed in Clause 11 "Detailing of reinforcement and post-tensioning tendons").

Clause 6 – Durability: Exposure conditions given in Clause 6 are considered to cover applications of tunnels and other underground structures but may be amended if needed.

As a new feature, a performance-based approach with exposure resistance classes has been introduced in EN 1992-1-1. This approach permits testing and classifying special and new concrete mixes to determine the resistance to CO_2 and chloride ingress and hence, the durability of these mixes. Design models are used to evaluate the durability performance as a function of time. While EN 1992-1-1 gives concrete covers for exposures up to 100 years, these models may be used to extrapolate to even longer design service life, if needed. Resistance to chemical attack still follows the current approach given in EN 206 "Concrete - Specification, performance, production and conformity".

Clause 7 – Structural analysis: EN 1992-1-1 covers current conventional methods of analysis commonly used for buildings, bridges and civil engineering structures (linear elastic analysis without or with redistribution, plastic analysis). The provisions for non-linear analysis have been updated and amended. Annex F gives provisions for the safety format when performing non-linear finite elements analysis at Ultimate Limit State, using either the partial factor method, the global factor method or a full probabilistic method.

Hence, it is believed that the general basis for analysis methods used in design of tunnels and other underground structures are provided. Specific amendments may, however, be needed, in particular for consideration of ground-structure interaction.

Clause 8 – Ultimate Limit States (ULS): The models given in Clause 8 to determine the capacity of concrete members for bending without and with normal force, shear without and with shear reinforcement, torsion and punching, and combined actions are independent of the type of member and hence, considered applicable to tunnels and other underground structures. Provisions for confined concrete have been amended which may be useful for some members in tunnel and other underground structures. The clause on strut-and-tie models has been significantly updated and amended. Also, the clause on partially loaded areas has been amended which should assist design of tunnel linings and other similar members subject to high local actions.

Clause 9 – Serviceability Limit States (SLS): The provisions of the current EN 1992-1-1 have been updated. Provisions for crack control of thick members have been amended which may be relevant for tunnels. Annex D provides supplementary information for the evaluation of early age and long-term cracking due to restraints considering effects such as heat of hydration in thick members. Annex H gives guidance on design of concrete structures for water-tightness.

Clause 10 – Fatigue: Clause 10 gives simple rules for fatigue verification. In Annex E refined methods using damage equivalent stresses and Palmgren-Miner rule are provided. These provisions have little changed compared with current EN 1992 and may be less relevant in general to tunnels.

Clause 11 – Detailing of reinforcement and post-tensioning tendons: The content of this clause has significantly changed compared to current EN 1992. A new bond model for reinforcing steel has been introduced which permits a more realistic determination of anchorage and lap lengths of reinforcement as a function of concrete strength, bar diameter and cover. Provisions have been significantly amended for minimum mandrel diameter, and different partly new types of anchorage (headed bars, U-loops, post-installed bars, etc.). Also, the topic of deviation forces due to curved tensile and compressive chords, relevant for tunnel linings, is now covered in Clause 11.7.

Clause 12 – Detailing of members and particular rules: The provisions have been updated and made consistent with the design models used for Ultimate Limit State (ULS). However, these provisions are not specific to tunnels and may need to be amended based on national practice and experience.

Clause 13 – Additional rules for precast elements and structures: No significant changes have been introduced for precast structures. In fact, although not specifically said, this clause is providing primarily detailing rules for building structures. However, design provisions given in earlier clauses are fully applicable to precast members and may be applied also to precast members for tunnel linings and other members in underground structures.

Clause 14 – Plain and lightly reinforced concrete structures: The limited number of provisions are addressing mainly building applications. However, other plain concrete members may be designed using strut-and-tie models given in Clause 8. The provisions in Clause 14 may be considered by some overly conservative for certain types of plain concrete members common in tunnel construction.

Annex A – Adjustment of partial factors for materials: This annex provides information on how partial factors for materials may be adjusted depending on the specified reliability level, and considering specific conditions of execution and quality control. Hence, partial factors given in Clause 4, valid for $\beta = 3,8$, may be adapted for other reliability indices as may be specified in countries for tunnel or underground structures.

Annex B – Time dependent behaviour of materials: This annex provides detailed information regarding strength development of concrete at early age as well as shrinkage and creep of concrete. While no specific maximum design service life is given for the validity of shrinkage and creep provisions, it is believed that the provisions are applicable also to extended design service life of tunnels above 100 years.

Annex C – Requirements to materials: This annex serves as an interface to product standards and shall ensure that materials are specified such that the properties assumed in design models will in fact be provided for construction.

Annex G – Design of membrane-, shell- and slab elements: This annex provides detailed rules for the ULS and for crack control at SLS of membrane-, shell- and slab elements under combined out-of-plane and in-plane effects of actions.

Annex I – Assessment of existing structures: This is new scope in EN 1992 and provides amendments to the design models developed for new members and given in Clauses 5 - 14 for application in existing structures. The amendments permit a more detailed verification such as to avoid expensive strengthening measures where possible.

Annex J – Strengthening of existing concrete structures with CFRP: This is new scope covering the use of carbon fibre reinforced plastics applied externally to concrete for strengthening of members.

Annex Q – Stainless reinforcing steel: This is new scope covering the use of stainless reinforcing steel in concrete structures with design provisions and for durability.

5.4.4 prEN 1992-1-2 "General rules - Structural fire design"

EN 1992-1-2 applies to the design of concrete buildings within the scope of EN 1992-1-1 and requires to fulfil loadbearing, separating, integrity and insulation functions. It deals with the accidental situation of fire exposure and is intended to be used in conjunction with EN 1992-1-1 and EN 1991-1-2. Hence, application of EN 1992-1-2 to tunnels may require some significant adaptations, particularly related to the required reliability level.

Clause 4 – Basis of design: EN 1992-1-2 covers fire design of buildings based on standard fire exposure, hydrocarbon fire exposure and physically based fire exposure. Thermal and mechanical actions are taken from EN 1991-1-2. The partial factors for materials are commonly assumed to be 1,0 unless modified in the National Annex. The following design methods may be used: Tabulated design data for specific types of members, simplified design methods for specific types of members, and advanced design methods for analysis of members, parts of structures or the entire structure. Alternatively, to design by calculation, fire design may be based on fire tests or on fire tests in combination with calculations. Consideration of higher reliability levels (higher reliability indices) for tunnels is possible by modifying the partial factors based on Annex A of EN 1992-1-1 and using these together with either simplified design methods or primarily with advanced design methods.

Clause 5 – Materials: Thermal and mechanical properties of concrete, reinforcing and prestressing steels are given.

Clause 6 - Tabulated design data: Tabulated design data is given for typical members in buildings, i.e., columns, walls, tensile members, beams and slabs. Design values given as tabulated data is assumed to be as or more conservative than design using simplified or advanced methods. The minimum dimensions given in the tables apply to buildings with the respective reliability level. Modifications are necessary to allow for tabulated design for tunnels, e.g., related to different fire curves.

Clause 7 – Simplified design methods: Simplified design methods may be used to determine a temperature field in a section, a temperature in a part of it or a loadbearing capacity of a section or member. The method may be applied for verification of action effects of bending, bending with axial force, shear and torsion. Provisions for the determination of member capacity need to be adapted for consideration of higher reliability levels (and different fire curves) applicable to tunnels.

Clause 8 – Advanced design methods: Advanced design methods shall be based on fundamental physical behaviour, employing local equilibrium equations which are satisfied at every point in the structure. They may be used in association with any thermal action, provided material properties are known for the relevant temperature history. A validation of the accuracy of the method should be made on the basis of relevant test results. Provisions for the determination of member capacity need to be adapted for consideration of higher reliability levels applicable to tunnels.

Clause 9 – Detailing: Detailing rules of EN 1992-1-1 are assumed to be complied with. EN 1992-1-2 gives few additional detailing rules.

Clause 10 – Rules for spalling: This clause gives specific rules to prevent severe, explosive spalling. It is not self-evident that spalling design rules and mitigation measures for buildings also conservatively apply to tunnels. Modifications are appropriate.

Annexes: Complementary information for steel fibre reinforced concrete structures, recycled aggregates concrete structures and light-weight aggregate concrete structures is given in Annexes to EN 1992-1-2. In addition, extensive tabulated data is given for verification of buckling of columns under fire conditions. It is not self-evident that the information also conservatively applies to tunnels. Modifications are appropriate.

5.4.5 EN 1992-4 "Part 4: Design of fastenings for use in concrete"

EN 1992-4 provides design methods for fastenings (connection of structural elements and non-structural elements to structural components) which are used to transmit actions to the concrete. It is valid for applications which fall into the scope of EN 1992 (all parts).

EN 1992-4 covers also fastenings subjected to fatigue actions, seismic actions and fire actions. It is intended to transfer seismic design provisions to the Second Generation EN 1998.

5.4.6 Conclusions on applicability of EN 1992 (all parts) to tunnels and other underground structures

Current Second Generation drafts EN 1992 (all parts) are considered to apply to tunnels and other underground structures. Specific provisions considered to apply to buildings only are clearly marked as such either in the heading of the clause or inside the clause text.

Specific topics relevant and important for tunnels and other underground structures may not be covered by EN 1992 (all parts) – as indeed may be the case also for other particular types of structures. Due to the advanced state of development of Second Generation EN 1992 (all parts) amendments of the drafts are no longer feasible at this time. However, such missing information may in a first instance be added in National Annexes to EN 1992 (all parts) as so-called Non-Contradictory-Complementary Information (NCCI).

The EN 1992-1-2 needs modifications and additions on a range of clauses and annex material, to allow its use for tunnel design.

Some additional aspects of sprayed concrete which may need to be considered and potentially included in a future amendment to EN 1992 (all parts) have been pointed out by Psomas (2022): (i) design-assisted by testing (trials and special testing); (ii) determination of deformation induced limit states design validation; (iii) provision for interface performance (between primary and secondary lining) including understanding the behaviour of spray-on membranes; (iv) inclusion of high performance cement composites.

It is suggested that tunnel designers now perform trial calculations and test the content of the Second Generation EN 1992 (all parts) in design of tunnels and other underground structures. Feedback on what works well, what may need clarification, what should not be applied to tunnels or missing provisions should be identified and brought to the attention of CEN/TC 250/SC 2. Based on such feedback, a discussion could be held and decisions taken on the best way forward to cover the topics considered sufficiently general and frequent in practice.

5.5 EN 1997 "Eurocode 7: Geotechnical design"

5.5.1 Introduction

A tunnel is mainly a geotechnical structure which is loaded and supported by the ground. Ground-structure interaction, therefore, is of utmost importance. Consequently, within in the framework of JRC Expert Network on underground structures, it was decided to assess the applicability of the draft version of Second Generation version of EN 1997 "Eurocode 7: Geotechnical Design" to tunnels and underground structures. The objective included identification of:

- items that were sufficiently covered in the draft,
- items that were covered but need clarifications to avoid misunderstanding/misinterpretation, and
- items that need to be added.

The assessment is summarised in a report with the title "Assessment of applicability of EN 1997 for tunnels and other underground structures", dated April 2022, enclosed as Annex C to this report.

5.5.2 Method of assessment

The structure and subheadings of Clause 7 of prEN1997-3 (Retaining structures, draft dated April 2021) were used for the assessment. The analogy between tunnels and flexible retaining structures is justified by the fact that behaviour of both types of geotechnical structures is highly dependent on soil-structure interaction. Furthermore, in both cases, various construction techniques can be used, which must be designed in a standardised way.

The content under each sub-heading in prEN 1997-3, Clause 7 was analysed, and the primary questions were answered, as follows:

- Are tunnels and underground structures sufficiently covered by the content of the subheading? Or not covered?
- Are there recommendations or requirements in the text that are not applicable for tunnels or underground structures?
- Or is there a formulation that might result in misinterpretations with respects to tunnels and underground structures?

In the evaluation, parts of EN 1990 "Eurocode: Basis of design" were also considered.

The assessment included tunnels and other underground structures, both in soil and rock. The scope was limited to cover the most common execution techniques such as conventional methods (sequential excavation methods including: drill and blast, Mechanical excavator or road header) and tunnelling machines with focus on TBM.

Tunnels and underground structures differ from other geotechnical structures. The most important differences/specificities were listed below:

- Tunnels have limited access for ground investigation, for construction, and also during operation.
- Methods of excavation, and primary support are significant part of tunnel design.
- Tunnel design must consider excavation methods, and sequences of excavation to maximize preservation of ground strength.
- Design must consider that the ground can be a load, and a support at the same time.
- Tunnel design differentiates between temporary primary support, and final support.
- Significant portion of tunnel design relies on experience.
- Tunnel design often relies on the Observational Method.

These specificities were considered in the assessment of applicability of the codes.

5.5.3 Applicability

The Second Generation of EN 1997 is developed with the aim to include soil and rock on equal bases. EN 1997-1 "General Rules" and EN 1997-2 "Ground Properties" have therefore been updated and reworded to be applicable also to rock. Also, EN 1997-3 "Geotechnical Structures", was updated to accommodate rock engineering, in particular for slopes, spread foundations, ground reinforcing elements and groundwater control (including grouting).

The conclusion is that the Second Generation of EN 1997 can be used for tunnels and other underground structures as the common basis shared with the other geotechnical structures. However, as noted in Table 2 that summarises the main findings of the assessment of the applicability, there is a need for clarifications and additional material.

5.5.4 Limitations

During the assessment of the applicability limitations of the draft version Second Generation were identified. These limitations need to be handled if the code will be extended to also include tunnels and other underground structures.

The principles of partial factors applicability for tunnels and underground structures have been questioned. Further analyses and development are needed to give recommendations on whether other methods for verification should be utilized. The Second Generation EN 1997 gives the following alternatives for verification of limit states: 1) calculation using the partial factor method or other reliability-based methods; 2) prescriptive rules; 3) testing and 4) Observational Method. For tunnels and underground structures, the Observational Method and other reliability-based methods in many cases will be the main alternative for verification.

For the design of an underground structure, actions, effect-of-actions, overburden pressure, arching effects, initial stress state are some of the items that need to be considered as part of the system. The understanding of the interaction between the ground support, the ground mass and the groundwater is fundamental. The general principles both in EN 1990 and EN 1997 need to be clarified to avoid misinterpretation that could lead to either unsafe and/or uneconomical design.

Table 2. Conclusion on applicability of use of prEN 1997 and prEN 1990 for tunnels and underground structures

Subheading	**Conclusion**[44]	**Comment**
x.1 Scope and x.2 Basis of design	Clarification	General principles applicable. Need to add specific considerations and clarifications for some items.
x.3 Material	Covered	Covered by prEN 1997-1 and prEN 1997-2
x.4 Groundwater	Covered	Covered by prEN 1997-1 and prEN 1997-3, Clause 12
x.5 Geotechnical analysis	Clarification	Covered by prEN 1997, however need to add specific items such as calculation models, guidance in relation to deep tunnels, etc.
x.6 ULS	Not covered	The general principles are established but specific recommendations are needed to be added on handling of arching, passive resistance, ring-stability, shear stresses. Recommendations on verification cases and partial factors.
x.7 SLS	Clarification	Covered by prEN 1997. Need to add specific considerations in relation to impact within the zone of influence due to the tunnel.
x.8 Execution	Covered	Covered by prEN 1997-1, Clause 10.
x.9 Testing	Clarification	General principles covered by prEN 1997 but need to add specific considerations.
x.10 Reporting	Covered	Covered by prEN 1997-1, 12 and prEN 1997-2, 13

The failure modes (mechanisms) that need to be covered by the design depend on the support system, ground, the interaction between the ground and support system, the execution sequence, and the execution technique. They may be grouped as failure modes related to the ground, related to the supporting system, and related to the temporary situation. For many failure modes, appropriate models for their analysis may be necessary. In addition to the general principles given in EN 1997 in relation to the identification and addressing of failure modes, additional guidance is needed to fully cover the large variety of failure modes for tunnels; some modes are not known until decision regarding the construction technique is made.

There are differences between structural and geotechnical design that highlight certain aspect of the Eurocode to be further developed to ensure it is applicable to tunnels and other underground structures. The properties of the dominant building material (the ground) are only anticipated in contrast to the known properties of concrete and steel. As the design and execution process is progressing, the aim for the geotechnical engineer is to increase the knowledge of the site, to limit the uncertainty in presumed bases for design and selected solutions, in contrast to the possibility for the structural engineer to select appropriate material and solutions.

For structural design calculation, appropriate design models are used that have been verified for the different design situations. For geotechnical design, each design situation is unique, hence it is essential that any calculation is followed by engineering judgement of the relevance of the result. The structural design gives a final specification for execution that is the basis for building the structure. For geotechnical structures, and especially for tunnels and underground structures, the execution is the first time when the real ground conditions are revealed. Therefore, it is essential to include measures in the execution specification that should be utilized to adapt the design to the encountered ground conditions at the site (Van Seters and Franzén, 2021). To handle these differences EN 1997 includes items and measures to ensure geotechnical reliability, such as: assembling the ground model, the

[44] Alternatives: Covered (sufficient), Clarification (covered but clarification needed), Not covered

Geotechnical Design Model and the Observational Method. All these items are also essential for design and verification of tunnels and underground structures.

5.5.5 Topics that need further elaboration

The assessment identified topics that need to be further elaborated to be sufficiently covered by the Eurocode.

Amongst the topics, the following can be highlighted:

- Partial factor – safety aspects.
- Definition of consequence class and/or geotechnical complexity class for tunnels and underground structures.
- Failure modes – need of additional items.
- Serviceability Limit State – verification with focus on displacement and impact within the zone of influence.
- Ground model and the specific application for underground structures.
- Design and verification of deep tunnels.
- Use of Observational Method.

5.5.6 Conclusions

Among other geotechnical structures, the design of tunnels and underground structures seems more like an art, (Sczechy, 1970), which requires that the designer to poses even deeper understanding of the design principles, with capability to select appropriate design methods in correspondence to given, often very complex, conditions. That requires experience, ability to predict failure modes (behaviour type), understanding of uncertainties inherent to tunnelling and knowledge of weakness and strengths of the design methods. Although it is recognised that a standard cannot substitute for those qualifications, it can add great value to the design process.

Currently, EN 1997 does not include all the elements required to perform tunnel design only on its basis. However, it also does not include elements that would prohibit the designer to apply basic principles included in EN 1997-1 when designing underground structures. The performed assessment of EN 1997 (which is reported in detail in Annex C to this report) concludes that the Second Generation EN 1997 is an appropriate basis which, with additional development, can serve as the common standard for design and verification of tunnels and underground structures in Europe.

5.6 EN 1998 "Eurocode 8: Design of structures for earthquake resistance"

5.6.1 Introduction

The objective of this section is to assess the applicability of EN 1998 "Eurocode 8: Design of structures for earthquake resistance" for the design of tunnels and other underground structures. This assessment was carried out firstly by identifying the main items that are involved in the seismic design of tunnels and underground structures and then analysing:

- items that are sufficiently covered in the draft
- items that are covered but need clarification to avoid misunderstanding/misinterpretation
- items that need to be covered.

5.6.2 Introduction to EN 1998 (all parts)

The existing Eurocode EN 1998: 2004 “Design of structures for earthquake resistance” and the draft of the Second Generation EN 1998 (prEN 1998-1-1, February 2020:2021, prEN 1998-5: 2021 April 2020) were analysed. The main findings are summarized in **Table 3**.

The main items considered are the following:

- seismic action definition,
- seismic geotechnical characterization,
- seismic site response analysis,
- method of analysis,
- fault crossing, unstable slopes, liquefaction.

The existing Eurocode EN 1998 does not refer to tunnels and underground structures and only some aspects of the general requirements and definition of seismic action can be derived and considered applicable also for tunnels.

Instead, the current draft of the Second Generation EN 1998 addresses specifically underground structures in Part 5 - Clause 11, as for the determination of action effects, not covering the design verification which was not in the Mandate M/515.

In the Second Generation EN 1998-5, the definition "underground structures" includes tunnels of different types (bored, cut and cover, immersed) and other underground structures (i.e. culverts and underground large works such as metro and parking stations, and pipelines).

For these structures general requirements for seismic actions are defined referring to the contents of EN 1998-1-1, accounting for the depth and dimensions of the underground structure and the spatial variability of ground motion.

Annex G (informative) “Simplified evaluation of peak ground parameters for seismic design of underground structures” provides simplified expressions to define ground motion parameters in the absence of site-specific response analyses. Variability of ground motion, particularly relevant for long underground structures, should be considered following EN 1998-1 (Clause 5.2.3.2).

As for the methods of analysis a distinction is made for the shallow tunnels, culverts, cut and cover structures, for which the seismic action may be expressed in terms of pressure distributions in the transverse direction according to the relevant clauses of 10.3, while for deep tunnels and deep large underground structures ground deformations in both transverse and longitudinal direction are preferred.

Structural models with springs of suitable stiffness simulating soil compliance can also be adopted according to clauses 8.3 for rather shallow structures.

Response time-history analyses in 2D or 3D conditions should be used for moderate and high seismic action classes following clauses 11.2.2(4).

Annex H (informative) “Simplified analytical expressions for the seismic design of tunnels” provides closed form analytical solutions for the evaluation of seismic-induced ground deformations in the transverse and longitudinal directions and guidance for the calculation of the internal forces in circular and rectangular shape tunnels accounting for soil-structure interaction and for two different behaviours of the ground-lining interface (i.e. full-slip and no-slip conditions).

Annex I (informative) “Impedance functions for underground structures” summarizes the calculation of impedance functions in the transverse and longitudinal directions for structural models using springs to account for soil compliance.

A specific focus is on the interaction of underground structures with potentially active faults, precarious slopes and potentially liquefiable soils. In these situations, the effect of seismic action due to permanent ground deformation should be expressed in terms of displacements.

The prediction of the permanent ground displacement for landslide and liquefaction hazard may be estimated according to clauses 7.2.2.3 and 7.3.5(6) or other properly validated approach, while for fault dislocation empirical relationships may be used (Clause 7.1.2). The spatial distribution and attenuation of the maximum fault displacement along the tunnel axis may be estimated empirically or numerically using 2D or 3D analyses. Similar approaches should be applied in case of excessive permanent displacements caused by landslides and liquefaction.

5.6.3 Conclusions on applicability of EN 1998 to tunnels and other underground structures and proposals for further development

Dynamic numerical modelling is still a not-standard approach in the design practice and its application should not be prescribed for low seismic action classes. However, for high seismic action classes, numerical 2D or 3D approaches should be used in which the soil-segmented tunnel interaction is adequately modelled.

Similarly, the use of numerical models for the analysis of complex soil-structure interaction problems, i.e., tunnels in liquefiable soils or active slopes, should not be invoked. However, crossings of active faults often cannot be avoided for extended structures like tunnels, pipelines, bridges.

References should be added to the proposed analytical solutions and simplified expressions, in the bibliography or in the background document.

Table 3. Conclusion on applicability of Second Generation EN 1998 for tunnels and underground structures

Item	Covered for tunnelling	Reference to prEN 1998 Part 5	Comments
Underground structures in seismic conditions	Yes	11 Underground structures	Clause 11 is dedicated to underground structures: i) bored, cut and cover, immersed tunnels; ii) underground large spaces (11.4); iii) culverts (11.5). Annex G: Simplified evaluation of peak ground parameters for seismic design of underground structures Annex H: Simplified analytical expressions for the seismic design of tunnels Annex I: impedance functions for underground structures
A: General requirements / Performance requirements	Yes	11.1 General	Seismic performances are described through Limit states (LS) defined in prEN 1998-1-1:2021, 4.3(1), EN 1998-3:2022, 4.1 and the associated seismic actions. Underground structures shall be designed against: - ground shaking - permanent ground deformations due to seismic fault crossing, seismically induced landslides and liquefaction induced phenomena
B: Seismic Action	Yes	11.2 Seismic actions	- Ground shaking: estimated according to prEN1998-1-1:2021, 5.2.2 (see also Annex A), taking into account the depth and dimensions of the underground structure. - Permanent ground displacement parameters: see 7.1.2 (active faults), 7.2 (unstable slopes), 7.3 (potentially liquefiable soils), 7.4 (settlements). Spatial variability of the ground motion and the associated phenomena to be considered if the underground structure is spatially extended (prEN1998-1-1:2021, 5.2.3.2).
C: Seismic Geotechnical characterization	No	6.1 Ground Investigations	No specific indications for underground structures

Table 3 (continues(

Item	Covered for tunnelling	Reference to prEN 1998 Part 5	Comments
D: Seismic Site Response Analysis	Yes	7.5 Site-specific response analysis 11.2 Seismic actions	Ground motion parameters should be evaluated at the surface, as well as at various depth of the embedded structure including the depth at the base of the underground structure: a ground-specific response analysis may be carried out. Site-specific ground response analysis along the total length of the structure should be carried out for moderate and high seismic action classes. For low seismic action classes and in the absence of site specific ground response analysis ground motion parameters may be calculated from PGAe (prEN 1998-1-1:2021, 5.2.2.4, using simplified expressions (see Annex G).
E: Fault crossings, seismically induced landslides, liquefaction	Yes	11.2.1 Seismic actions - General requirements 11.2.3 Seismic actions - Permanent ground displacement parameters 11.3.3 Permanent ground deformation	General requirements for seismic actions (11.2.1, 11.2.3) are defined in the presence of potentially active faults, precarious slopes, potentially liquefiable soils , according to definitions in prEN 1998-5:2021, 7.1.2, 7.2, 7.3. The hazards related to active faults, landslides, liquefaction are described and general provisions for underground structures are defined in 11.3.3.

Table 3 (continues(

Item	Covered for tunnelling	Reference to prEN 1998 Part 5	Comments
F: Methods of analysis	Yes	11.3 Methods of analysis 11.4.1 Seismic loading for large underground spaces Annex H , Annex I	Ground shaking: transient effects may be expressed applying a) or b) a) forces in the transverse direction (shallow tunnels, cut-and-cover structures): see 11.3.2.1 and 10.3. b) ground deformations in both transverse and longitudinal directions (deep tunnels and deep large space structures): see 11.3.2.2. Simplified equivalent static analysis are nevertheless tolerated as per 11.4.1(3) - closed form analytical solutions - Annex H may be used - advanced numerical methods (preferable for high seismic action classes) Annex H contents agree with ITA/AITES Guidelines "Seismic design of underground structures" (2000). Soil-structure interaction effects: see Annex H and Annex I. Permanent ground deformations: the effect should be expressed in terms of displacement. Estimation of the amplitude of ground deformation for landslide and liquefaction hazard according to 7.2.2.3 and 7.3.5(6) and empirical relationship for fault dislocation. Acceptable limits are given in the relevant standards covering the design of the structures under consideration. For high seismic action classes numerical 2D or 3D approaches should be used in which soil-segmented tunnel interaction is modelled. For large underground structures a more complex approach is required, except for rather shallow structures with depth not exceeding 10-15 m (11.4.1); 11.4.1(2) simply forbids the use of static and dynamic earth pressures but does not impose response history analyses; Simplified equivalent static analysis are tolerated as per 11.4.1(3)

6 Recommendations for future standardisation works

6.1 Introduction

In the previous chapters of this report the need and justification for European standardisation of tunnel and underground structure design have been described, together with recommendations for possible content of Eurocode text.

Chapter 6 follows with a proposal for the next steps for the development of the Eurocodes for tunnelling and underground structures. This proposal focuses on the development of standards for new structures. Standards for the evaluation of existing structures are, in principle, outside of the scope of this report, despite related comments found in Chapter 5.

The EN Eurocodes are developed under the guidance and co-ordination of CEN Technical Committee 250 (CEN/TC250) "Structural Eurocodes". CEN/TC250 has the overall responsibility for all CEN work on structural design codes. Also, it is the responsibility of CEN/TC250 and its Sub-Committees (SCs), under the CEN rules, to maintain the EN Eurocodes within their remit. Thus, it is assumed that these next steps will be taken on by CEN/TC250 "Structural Eurocodes". Regarding the timing of these steps, this process would be outside the present process of establishing the Second Generation of Eurocodes, which is already at the final stages of its preparation.

In the opinion of experts that performed the analysis of the Eurocodes applicability for the design of tunnels and other underground structures, this process should start with the installation of an Ad Hoc Group "Tunnelling/Underground structures" under CEN/TC250. Members of this Ad Hoc Group should be the Chairs of the involved Sub-committees, together with tunnelling experts. In the Ad Hoc Group, the coordination of the various items in the various Eurocodes will be performed.

Furthermore, Task Groups would be set up in the various Sub-Committees of TC250. These Task Groups consist of experts, who provide ideas and information for the content of the new Eurocode parts. For the writing of the code text, Project Teams should be formed, comparable with the Project Teams in the Second Generation Eurocodes writing process. The Ad Hoc Group will establish a Project Plan with the items to be treated in the various Sub-Committees. Input for this Project Plan will be derived from the present report and from the Task Groups of the Sub-Committees, where expert groups will be formed. The Ad Hoc Group should also be responsible for the planning of the activities. After the Project Plan is finalised, this should be approved by TC250 and a go-ahead for further development should be obtained.

After finalisation of the Project Plan, the various Sub-Committees would continue assembling knowledge for writing Eurocode text by a Project Team. This could result in direct writing of a standard with intermediate enquiries. However, a Technical Specification as a prequel for a standard, where rules for design (with possible alternatives) are provided for comments and discussion is also possible.

At the last stage, the final writing of new Clauses of the existing Standards or new Parts of Eurocodes is foreseen.

In the following, the separate items are treated in more detail: Ad Hoc Group and Project Plan (6.2), First phase of drafting Technical Specifications (6.3) and Second phase of drafting Eurocode text (6.4). Naturally, the activities in a later stage depend on the first stages and can only be specified in less detail.

6.2 Ad-hoc Group Tunnelling and Underground Structures

In designing Tunnels and Underground Structures, many disciplines are present. The main stakeholders in the Eurocodes organisation were mentioned in this JRC Report and are listed in Table 4. Other stakeholders may be TC250/ Sub-Committee 3 (Design of Steel Structures) and TC250/ Working Group 6 (Robustness). The main activities are probably in TC250/ Sub-Committee 7 (Geotechnical Design).

The Ad Hoc Group should consist of the seven Chairs/Convenor of the TC250 stakeholders of the parties from **Error! Reference source not found.**, together with three tunnelling experts representing different tunnelling design practices. This ensures commitment from the various parties. At the same time, Task Groups of experts should be set up in the Sub-Committees to study the topics and come with ideas for the Project Plan. In these Task Groups all experts are invited to contribute. In Chapter 5 of this report, already a preliminary inventory was made of topics to be covered in Eurocodes.

Table 4. Main TC250 Stakeholders in issues related to design of tunnels and underground structures

TC250 SC/HG[45]	Name	Tasks
TC250	Structural Design	Overall management
SC10	Basis of Design	Reliability, Design Situations, Observational method – Tunnel design to be connected to EN 1990 and vice versa.
SC1	Actions	Specific actions for tunnelling: accidental loads, traffic loads, loads during construction, fire
SC2	Concrete design	Specific requirements for concrete linings and shotcrete, sprayed concrete
SC7	Geotechnical Design	Actions from the ground (water) on the tunnel, calculation models for stability of the tunnel section (walls/ring/arching), face stability, ULS- and SLS-verification, design related to execution, assessment of tunnelling induced ground deformations and their impact on adjacent structures
SC8	Seismic design	Already a Clause exists in EN 1998-5, input required
HG Fire	Fire	Important aspect in tunnel design, maybe should be covered in other codes

The task of the Ad Hoc Group is envisaged as:

- Establish the types of tunnels and underground structures to be covered in the Eurocodes.
- Topics for the Eurocodes must be proposed by the stakeholders. The Ad Hoc Group should decide which items will be covered in the Eurocodes and by which Sub-Committee.
- Setting up a Project Plan for the development of new Eurocode text, including a planning.
- Guard the progress of the drafting development in the Sub-Committees, coordination of the interfaces between the Sub-Committees.
- Representation of and communication on the work on tunnelling and underground Structures to the European Commission relevant stakeholders, the European Standardisation Committee (CEN), the National Standards Bodies and the tunnelling community in Europe.

The Project Plan should at least contain the following topics:

- Reasons for standardisation of the design of tunnels and underground structures.

[45] SC: Sub-Committee, HG: Horizontal Group

— Mentioning the support from experts, industry, public organisations in the EU.
— Refer to the existing knowledge (based on the relevant JRC Technical Reports).
— Connection to Second Generation Eurocodes.
— Types of structures to be covered.
— Overview of the topics of standardisation, to be detailed by the Sub-Committees.
— Products of the standardisation process: Technical Specification(s) (if required) and new Eurocodes Clauses or new Eurocode Parts.
— Phasing of the project.
— Detailed planning.
— Communication.

6.3 First phase of drafting

When the Project Plan is developed, the Sub-Committees will have a task of drafting the Eurocode text.

The experts in the Task Groups of the Sub-Committees will study these topics resulting in recommendations for new text. A Project Team consisting of experts in the Sub-Committee will then write the draft text proposals for an EN Standard (or a Technical Specification).

Depending on the content, the text written by the Project Team will be reviewed in an Informal Enquiry within the Sub-Committee. Thereupon the comments will be implemented by the Project Team. Thereafter a second Informal Enquiry will be organised with subsequent implementation of the comments.

6.4 Second phase of drafting

After incorporating the comments from the last informal enquiry, and after approval by the Sub-Committee and Ad Hoc Group, the draft is sent for Formal Enquiry. Thereafter the comments received via the National Standards Bodies are dealt with in the Subcommittee and the draft is sent for Formal Vote.

References

AFTES 2002, *The convergence-confinement method*, GT7R6A1, France.

Athanasopoulou, A; Bezuijen, A; Bogusz, W; Bournas, D; Brandtner, M; Breunese, A; Burbaum, U; Dimova, S; Frank, R; Ganz, H; Grunicke, U; Jung, H; Lewandowska, A; Nuijten, G; Pecker, A; Psomas, S; Roessler, K; Sciotti, A; Sousa M.L., Stille, H; Subrin D, *Standardisation Needs for the Design of Underground Structures*, EUR 29633 EN, Publications Office of the European Union, Luxembourg, 2019, doi:10.2760/615209.

Australian Tunnelling Society (ATS) 2020, *Tunnel Design Guideline*.

British Standard Institution (BSI) 2016, *Tunnel design - Design of concrete segmental tunnel linings - Code of practice*, PAS 8810.

British Tunnelling Society (BTS) 2004, *Tunnel Lining Design Guide*.

DAUB 2013, *Recommendations for the design, production and installation of segmental rings*, Germany.

DAUB 2016, *Recommendations for the calculation of face support pressure*, Germany.

ITA-AITES 2019, *Guidelines for the Design of Segmental Tunnel Linings*, WG2 Report.

Land Transport Authority (LTA) 2019, *Civil Design Criteria for Road and Rail Transit Systems*, E/GD/09/106/A2, Singapore.

Psomas, S., 2022, *Sprayed Concrete Linings: Existing knowledge, design guidance and needs for standardisation (ref. prEN 1992-1-1)*, Presentation at the 5th meeting of the Expert Network on the standardisation needs for the design of underground structures, online, 8 February 2022.

Van Seters, A. and Franzén, G., 2021, *Eurocode 7 – a toolbox for geotechnical engineering*, Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering, Sydney.

Sczechy, K., 1970, *The art of tunnelling.*

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Annexes

Annex A. The JRC Expert Network on the standardisation needs for the design of Underground Structures

The activities on standardisation needs for underground structures are supported by an Expert Network, convened by the JRC, on the design of underground structures. The objective of the JRC Expert Group is to review the state-of-the-art of technical background and standards available for underground structures, explore the potential benefits from a new European standard or new standards (eventually a Eurocode or a Eurocode part) for the design of underground structures, assess the feasibility for such new standard(s) and ponder on the initiation strategies.

The members of the expert network in the period 2019-2022 are listed below in alphabetical order:

- ANDREINI Marco, European Organization for Nuclear Research (CERN), Switzerland
- ATHANASOPOULOU Adamantia, Joint Research Centre of the European Commission, Ispra, Italy
- BEZUIJEN Adam, Universiteit Ghent (Ghent University)/ Deltares, Belgium / Netherlands
- BILÉ SERRA João, National Laboratory for Civil Engineering (LNEC) Geotechnics Department, President of the Portuguese Commission on Tunnelling and Underground Space, Portugal
- BOGUSZ Witold, Jacobs Engineering Group, Tunnelling and Ground Engineering (formerly at the Building Research Institute - ITB), Poland
- BOLDINI Daniela, Sapienza University of Rome, Italy
- BOTH Kees, Etex, President Society of Fire Protection Engineers (SFPE) Europe, ISO TC92 WG15 Tunnels, Netherlands
- BRANDTNER Markus, IGT Geotechnik und Tunnelbau ZT-GmbH, Austria
- BURBAUM Ulrich, University of Applied Sciences Darmstadt, Department of Civil Engineering, Germany
- DECKER Harry, Dutch Public Work Department (RWS), Department Tunnels, Large Projects and Maintenance, Netherlands
- DIMOVA Silvia, Joint Research Centre of the European Commission, Ispra, Italy
- DYNGELAND Torbjorn, Joint Research Centre of the European Commission, Ispra, Italy
- FERRARI Alessandro, B+S AG, Swiss Society of Engineers and Architects, Member of the Commission for Tunnel Standards, Switzerland
- FRANZEN Gunilla, Vice-Chair CEN/TC 250 SC7, GeoVerkstan, Sweden
- FRANK Roger, Immediate Past President of the International Society for Soil Mechanics and Geotechnical Engineering; Honorary Professor École Nationale des Ponts et Chaussées, France
- GALERA Jose Miguel, UPM - Subterra Ingenieria, Spain
- GANZ Hans Rudolf, CEN/TC 250 SC2 Chairman; Ganz Consulting, Switzerland
- GRUNICKE Urs, UHG Consult Ziviltechniker, Austria
- JUNG Hyuk-il, Ove Arup and Partners, United Kingdom
- LAMAS Luís, National Laboratory for Civil Engineering (LNEC) Modelling and Rock mechanics Unit, Secretary General International Society for Rock Mechanics and Rock Engineering (ISRM), Portugal

- LEUCKER Roland, Research Association for Tunnels and Transportation Facilities, STUVA e. V., Germany
- LEWANDOWSKA Anna, Faculty of Civil Engineering, Warsaw University of Technology (WUT), Poland
- MALAKATAS Nikolaos (Nick), CEN/TC 250/SC 1 Chairman (former Director in the Greek Ministry of Infrastructure &Transports), Greece
- NUIJTEN Guido, AFRY, Tunnels and Underground Spaces, Finland
- PECKER Alain, AP Consultant, Professeur Ecole des Ponts Paris Tech, CEN/TC 250 SC8 PT4 Leader, France
- PINTO Artur, Joint Research Centre of the European Commission, Ispra, Italy
- PSOMAS Sotiris, COWI UK Limited, United Kingdom
- RAMIREZ RODRIGUEZ Pedro, TYPSA, Spain
- ROESSLER Karel, Metrostav a.s., Czechia
- SCIOTTI, Alessandra Italferr, Ferrovie dello Stato Italiane, Italy
- van SETERS Adriaan, Chairman CEN/TC 250 SC7, Fugro, The Netherlands
- SOUSA Maria Luisa, Joint Research Centre of the European Commission, Ispra, Italy
- STILLE P. Håkan, Professor Emeritus in Soil and Rock Mechanics, KTH Royal Institute of Technology, Sweden
- SUBRIN Didier, CETU, Centre d'Etudes des Tunnels (Centre for Tunnel Studies), Ministère de la Transition Ecologique et Solidaire, France
- THEWES Markus, Ruhr University Bochum, Germany
- TSIONIS Georgios, Joint Research Centre of the European Commission, Ispra, Italy

Annex B. Worked examples

Annex B1. Worked example – A tunnel constructed in soils using a Earth Pressure Balance Tunnel Boring Machine (EPB-TBM) shield in soils

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B1.1 Introduction

The purpose of this example is to present in brief the design of a tunnel constructed using an Earth Pressure Balance Tunnel Boring Machine (EPB-TBM) shield in soils. The tunnel lining is composed of precast concrete segments installed inside the shield, while the stability of the soil at the face is maintained by the application of specified pressure in the working chamber.

The main goal of this example is to conduct design calculations following the requirements and recommendations of the Eurocodes in order to help identify any issues related to their application in tunnel design as well as to provide better understanding of their impact. Therefore, the example should not be seen as the only way in which various parts of the analysis can be conducted, as in practice designers can use different approaches and calculation models. The aim here is to identify the key areas in which the future code should provide specific requirements or recommendations, and where decisions should be fully left to the discretion of the designer.

The design presented in the example is based on the current version of the EN 1997 [1] standard to identify any missing elements relevant for design of tunnels constructed using TBM shields, which aspects currently require external guidance to actually accomplish the design. The design assumptions and the main key design parameters are based on real case study of a metro line in the area where prior, well documented experience of tunnelling with similar TBM shields in similar ground conditions exists, resulting in high reliability of parameters chosen on the empirical basis.

The presented example does not cover all the aspects that usually are considered as a part of design process, especially, when those aspects are rather general and addressed in similar way for other geotechnical structures. For example, the selection of representative values of parameters is beyond the scope of this example; specific values of geotechnical parameters were assumed in the analysis. Furthermore, in practice, design of tunnels usually includes analysis of a number of design situations occurring along the planned route, where key design parameters (e.g., ground conditions, tunnel depth, distance between twin tunnels, structures and loads at the surface and underground) will vary along the line. Usually, the analysis will be conducted for a number of characteristic cross-sections, which are considered as representative for some lengths of the tunnel; this example is focused on a single design situation at one of such sections.

As the use of advanced numerical methods (e.g., finite element method) is already a common approach to design of tunnels, at least when complex soil-structure interaction is expected, this method is used for design based on calculations. Due to a significant influence of stress- and strain-dependence of soil stiffness, a non-linear constitutive model is assumed for the analysis. As commonly used in design, nowadays, the use of Hardening Soil with small strain stiffness (HSs) constitutive model is assumed.

Commentary to B1.1:

a) Presented approach is generally applicable not only to EPB-TBM, but also to Slurry TBM shields; however, it requires different choice of some parameters based on empirical experiences.

b) At the detailed design stages, analyses of stresses and deformations for tunnelling in soft grounds (all soils and weak rocks) are often based on advanced numerical methods; nowadays; Eurocode 7 guidance for tunnels should cover that approach. However, at conceptual and preliminary design stages, simpler closed-form analytical solutions, empirical methods, or simplified numerical ones (e.g. bedded beam model), are still commonly in use, e.g. Muir-Wood and Curtis [2] or Duddeck and Erdmann [3] methods. As a number of such methods (i.e. calculation models) exist, they are generally not used in this example, but the new code should accommodate their application. Furthermore, it should be also highlighted that supposedly simpler analytical and semi-empirical models might be very useful for initial assessments, as comparison with numerical results (i.e., checking), and as a method of obtaining quick but rough estimates of the results.

c) Although HSs model is one of the possible choices for underground structures, the use of non-linear constitutive models for soils is practically obligatory to obtain reliable results, especially in terms of predicted deformations – that points to a potential need for including a recommendation clause on their application. However, taking into account the number of available advanced constitutive models and potential new developments in the future, guidance in the new code should remain generalized in that regard.

d) It needs to be emphasized that tunnel design is a very broad term; it can be related to the envisioned function of the tunnel and the installations related to perform this function. However, in the context of standardisation, this term is mostly related to the structural and geotechnical design of the structure.

B1.2 Description of the example and the main assumptions

B1.2.1 Basic information about the designed tunnel

The design example is focused on a metro line planned as two single-track shallow tunnels constructed in soils using Earth Pressure Balance Tunnel Boring Machines (EPB-TBM), with the tunnel lining composed of precast concrete segmental lining.

Summary of the tunnel characteristics (design parameters constant over the entire tunnel):

External diameter of the tunnel lining:	6.00 m
Internal diameter of the tunnel lining:	5.40 m
Assumed TBM excavation diameter:	6.30 m
Thickness of the tunnel lining:	0.30 m
Concrete class of the lining:	C40/50

The stiffness of the lining, both in bending (EJ) and compression (EA), was assumed to be equal to theoretical stiffness of a homogeneous lining, without consideration of bending stiffness reduction due to joints present between individual segments. Detailed design aspects such as segmentation of the lining rings are considered to be beyond the scope of this example.

Commentary to B1.2.1:

a) Internal diameter of the tunnel is dependent on the functional requirements. Usually, it is a main constrain imposed on geotechnical and structural designers.

b) Excavation diameter is dependent on the TBM specification and it is not always accurately known at the preliminary design stage. In general, tunnel design at the detail design stages usually requires a close cooperation with the contractor who will be responsible for execution of the works. Some of the detailed design choices may be dependent on the preferences of the contractor and constrains related to the execution process, e.g. exact type, shape and size of segments of the lining, taper of the rings, spacing of joints, characteristic of the TBM, etc. However, those design choices are usually related to aspects that are beyond the scope of the Eurocodes, anyway.

c) When using numerical methods, tunnel lining is often modeled using curved beam/plate elements. This raises two issues:

- The elements in numerical model are in fact located in the middle of modeled elements of segmental lining. Therefore, the diameter of the tunnel in the model is assumed to be 5.70 m, which results in further implications described later in B.1.2.4.

- Segmental lining is characterising by reduced bending stiffness at the connections between the segments. The lining can be modeled with constant stiffness (EJ), equal to those expected from uniform lining without joints. Usually, this is a conservative assumption as it should result in higher bending moments. Alternatively, modern numerical methods and software allow for explicit implementation of hinges with reduced stiffness to account for segmental tunnel lining joints. Decisions regarding this aspect of design are best left to the discretion of the designer or for specification in national documents. Some guidance on this subject can be found in state-of-the-art summaries (e.g. [4]).

B1.2.2 Description of the considered design situation

A single design situation is considered, in which twin tunnels are located in a primarily non-greenfield area. At this area, both tunnels are designed under an existing, local street, located parallel to the planned tunnel alignment, while some buildings exist over the left side tunnel, with occasional greenfield areas between them. The cross-section presenting the primary considered design situation, representative for that area, is presented in Figure B1.1.

Summary of dominant tunnelling conditions (design parameters representative for a given location):

Depth of the tunnel axis: 17.8 m b.g.l.

Distance between tunnels (axis-to-axis): 13.6 m

Ground conditions: Mixed soils (sands overlaying stiff clays)

Tunnelling situation: Non-greenfield (existing building and a road)

Details of the existing structure and the relative position in relation to the planned tunnels are given in the figure below.

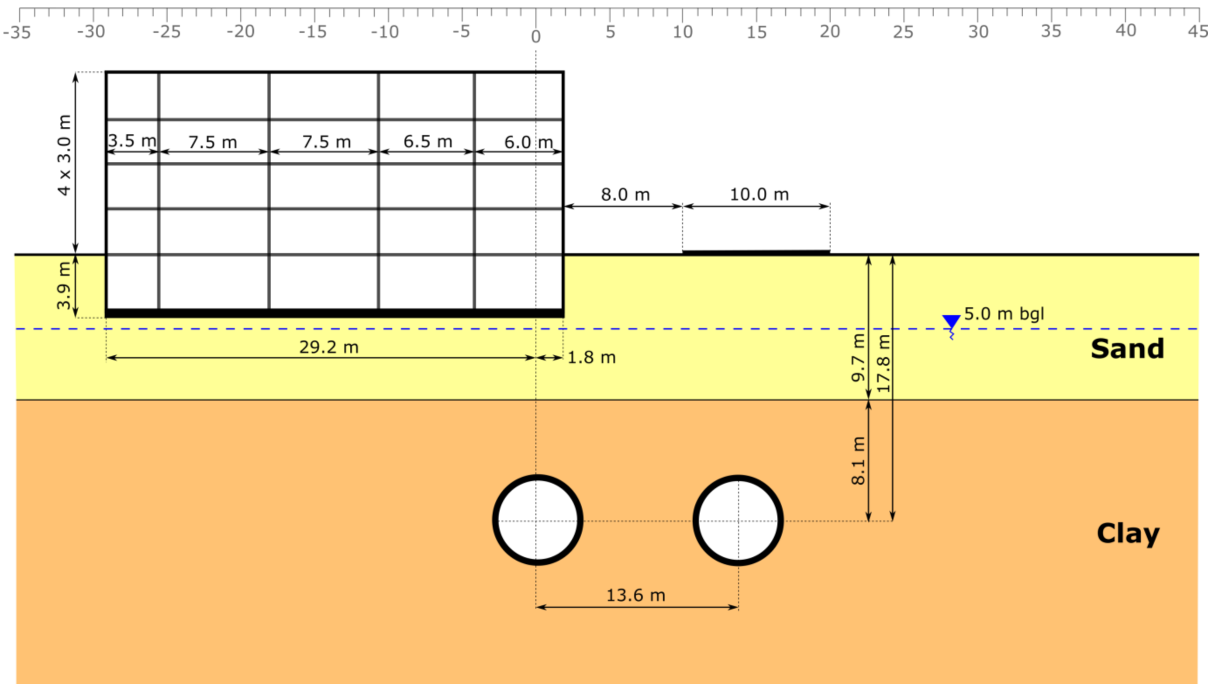

Figure B1.1 Geometry of the considered design example.

Commentary to B1.2.2:

a) Along a given section of a tunnel, a number of representative cross-sections might be selected. Usually, they will include the most unfavorable loading conditions and complex design situations (e.g. large asymmetric load above the tunnel) for structural design of the lining. When design is conducted in stages, relatively large number of cross sections might be analyzed with simpler calculation models (e.g., analytical close-form solutions), followed by more advanced assessment (e.g. FEM) at few selected ones.

b) For design under greenfield conditions (i.e., in undeveloped area), the designer might assume a theoretical excavation on the side of the tunnel with subsequent loading from a new building in order to account for potential change in loading conditions occurring in the future. This might be a requirement of a local authority in order to avoid detailed analysis for new investments located along existing tunnels in the future and a way of increasing the robustness of the tunnel to change in loading conditions. In general, this is a reasonable approach and might be considered as potential recommendation in the code.

c) Even when using numerical methods like FEM, adjacent structures might be considered with their characterization at various levels of detail. In most cases, three approaches can be used:

1) building is not considered at all;

2) building is considered as a distributed load at its foundation level;

3) building is considered accounting for its loading and stiffness characteristic (approach used in the example).

The situation is even more complex when adjacent structures are supported on deep foundations.

d) Depth of the tunnel will often depend on the presence of underground obstacles along the tunnel alignment as well as the geotechnical conditions, with preference for tunnelling taking place in relatively homogeneous conditions at the face. The choice of the depth is usually made at initial design stages, prior to the detailed structural and geotechnical design.

e) It might be necessary to specify relevant design situation / critical load combinations.

B1.2.3 Geotechnical conditions at the site

At the location of the cross-section, where a given design situation is considered, mixed ground conditions are present, with various quaternary soils present in the expected zone of influence of the tunnels. Despite documenting a number of distinctive ground layers at the site, for the geotechnical design model, two primary layers were distinguished for a considered design situation:

Sands – composed primarily of medium dense, fine and medium sands (FSi, MSi)

Clays – glacial tills composed primarily of stiff sandy clays and silts (saCl, saSi).

The approximate 9.7 m thick layer of sands is overlaying the layer of clays reaching down to the depth of expected zone of influence of the tunnels. The boundary separating both layers is relatively constant over the area for which the cross-section is considered as representative. The groundwater level is located at the depth of 5.0 m below ground level, with its seasonal variations expected in a range of ±0.5 m from that mean value. A hydrostatic distribution of pore water pressures with depth is assumed.

Due to the origin of the clay (glacial till), initial risk assessment predicted a medium risk of cobbles and boulders being present in this layer. In their presence, a risk of unplanned stoppages or potential over-excavation was considered as probable. In such case, design should consider a potential scenario of higher than expected ground volume loss associated with the tunnelling process.

Parameters characterizing the soil properties of the defined layers, for the selected constitutive model (HSs), were selected based on a number of field and laboratory tests while considering prior experience of underground constructions in the area and the application of this model to their analysis. The values of the parameters used as representative in this case are presented in Table B.1.1.

Table B1.1 Parameters characterizing the soils.

Parameter	Units	Soil layers	
		Sand	Clay
φ'	⁰	35	30
Ψ'	⁰	5	0
c'	kPa	1	5
γ	kN/m^3	19.5	20.0
e_0	-	0.70	0.50
E_{50}^{ref}	MPa	30	25
E_{oed}^{ref}	MPa	30	25
E_{ur}^{ref}	MPa	90	75
E_0^{ref}	MPa	450	375
m	-	0.50	0.70
σ_{ref}	kPa	100	200
K_0	-	0.40	0.80

Commentary to B1.2.3:

a) Although the choice of representative values of parameters characterizing the ground is a part of the design process, specified to some extent in the code, it should be left to the discretion of the designer, especially in the cases where model-specific parameters are implemented for non-linear constitutive models.

b) In the case of shield tunnelling, some additional aspects of ground characterization are important (compared to other geotechnical structures), e.g. risk of obstacles occurring along the tunnel, presence of boulders, etc. It is a good practice to implement a risk management approach to design, and document potential issues in a geotechnical risk register that might be developed over all the phases of the project.

c) Coefficient of earth pressure K_0 in the case of other geotechnical structures is often not investigated in sufficient detail; however, in tunnelling, it plays a significant role as it impacts the distribution of bending moments in the lining. The more it deviates from 1.0, the larger the bending moment induced in the lining will be. In some cases, sensitivity analysis might be advised to try the influence of this coefficient on results obtained in design.

B1.2.4 Expected geotechnical actions resulting from tunnelling process

The tunnelling process and the aggregated effects of construction, leading to the post-construction pressure distribution acting on the lining, were simulated in 2D FEM analysis using volume loss method [5]. The volume loss (V_L) parameters were based on prior local experience of EPB-TBM tunnelling in comparable soil conditions [6]. As the full face of the TBM at the considered section is located in glacial till soils, values for those soils were chosen. The representative values for design purposes were chosen on a statistical basis, given as:

Expected (median) value: $V_{L,50\%} = 0.40\%$ (0.50%)

Possible (95% confidence) value: $V_{L,95\%} = 1.00\%$ (1.20%)

The volume loss can also be an input parameter, and can be determined in correspondence to the ground condition, lining stiffness, and tunnelling technology. Volume loss method is valid only for specific conditions.

The presented values were derived based on a large database of regionally observed tunnelling-induced ground deformations, assuming the excavation diameter of 6.30 m. The values given in parentheses are the values representative for FEM analysis, adjusted to account for the difference between the excavation and the model diameter.

Commentary to B1.2.4:

a) When using numerical methods for tunnel lining design purposes, calculations can be done in few ways:

- A simple approach is to assume a beam-type element representing a tunnel lining on a series of springs while subjected to actions resulting from ground and water pressures (i.e., bedded beam model). This kind of approach is convenient and easy to use, but it is appropriate for conceptual and preliminary design stages of the project.

- The current state-of-the-art approach in most cases is to implement 2D numerical models in which tunnelling processes, and all the 3D effect associated with it, are still modeled in a simplified way. There are few strategies to do it, but the two most common types include: a volume loss method (i.e., prescribed volumetric strain) and convergence-confinement method (i.e. prescribed unloading prior to lining installation). In both cases, the design could be based on empirical parameters, thus implicitly accounting for prior experience, or on other simplified methods. Note that in convergence-confinement method, the relaxation factor can be estimated also on non-empirical basis from the longitudinal displacement profile.

- More advanced 3D calculations can be done for design purposes, but still are not very common due to time necessary to develop the model, perform the calculations and review the results. In time, with improvements to available commercial software and increasing automation of design, this type of analysis might become more popular. It is sometime used for complex 3D problems, e.g., cross-passages between tunnels.

It might be necessary to specify acceptable methods of analysis. It is not certain now if only advanced numerical methods (e.g. FEM) should be considered, or simpler bedded beam models should be allowed as well for estimating effects of actions for lining design.

b) In this example a volume loss method was chosen as quite common approach for simulating the tunnel construction using TBMs. In most cases, the design volume loss parameter usually is derived on empirical basis, based on prior experience and real scale observations. In the context of design according to Eurocode 7, it seems makes sense to treat the overall volume loss as a geotechnical action, which aggregates the important effects the tunnelling process has on the surrounding ground; that also includes the impact on redistribution of stresses in the ground, affecting the loads imposed finally on the tunnel lining.

c) When considering the use of empirically derived volume loss parameters, it is necessary to consider the conditions under which they were derived, as well as the conditions under which they will be applied. That can include aspects like:

- Characteristic of the project in terms of the type of TBM shield in use, its diameter, ground conditions, etc.;

- Geometrical approximations used in the implemented software (e.g., difference between real excavation and tunnel diameters versus the diameter of the tunnel in the model);

- The way in which the volume loss is introduced in the model.

Regarding the latter, the overall volume loss parameter can be sometimes introduced as imposed strain, often at a single calculation stage, which can be followed by other stages where redistribution of stresses and loading on the lining will occur; this can result in additional deformations around the modeled tunnel. In addition, dilative behaviour (i.e., soil volume change with strain) may result in surface volume loss being different than the tunnel volume loss. In most practical applications, those discrepancies can be safely ignored. However, designers should be aware of those possibilities and be very familiar with the software they are using. When very detailed assessment is required, model calibrations and sensitivity studies should be conducted as part of the design analysis.

d) The choice of volume loss parameters is rarely done on a fully rational (statistical) basis. As it has a dominant influence on the design, it might be necessary to provide a rational guidance for selection of this parameter, in similar way to selection of other design parameters (distinguishing: representative, characteristic, and nominal values). The question arises, what percentile of the statistical distribution should be used in actual design (e.g., 50% for SLS and 95% for ULS, or other values).

e) As the value of volume loss is significantly affected by the particular aspects of the local ground conditions and technology in use, when insufficient data is available for selection of the value on the probabilistic basis, it could be chosen as a nominal (cautious estimate) value. However, in general, unless otherwise specified by relevant authority, the value should be agreed upon by the relevant parties involved in the project.

B1.2.5 Characteristic of adjacent structures

Directly above the designed tunnels, a building and a road are located. The building is a typical residential structure with four levels above the ground and one below. The structural elements are primarily composed of cast-in-place concrete (C30/37), with thickness of:

Walls: 24 cm

Slabs: 24 cm

Foundation slab: 70 cm

The weight of the main structural elements, modeled in a simplified manner as continuous plate elements (neglecting the openings), was directly introduced in the model. Additional load of 6 kN/m^2 per building level was used to account for the weight of partition walls and other loads associated with the use of the structure. A characteristic value of load under the foundation is on average at approx. 100 kN/m^2.

The load due to existing local road was assumed to be 10 kPa.

Commentary to B1.2.5:

a) For existing, adjacent buildings, the available information about their structural characteristic and loads imposed on the ground is often very general. Therefore, it cannot be expected that the representation of such structures and the exact load values will be modeled with very high accuracy. It is also often impractical to perform detailed evaluation of loads for each building, unless benefits of such detailed analysis justify the effort. For practical applications, simplified representation is often sufficient. Especially, as even in the case of shallow underground structures (i.e., those with soil cover of 1-5D), geotechnical actions due to soil and water pressures will be usually dominant.

b) When designing geotechnical structures adjacent to existing buildings, engineers often implement simplified ways of assessing the expected loads imposed by them through the ground. Such approaches are often simple, rule-of-thumb estimations, but were sufficiently validated in practice. For example, Austrian recommendations [7] suggested assuming the loading from adjacent building as a sum of 15 kN/m^2 per each floor and 30 kN/m^2 for the basement. In Polish practice, depending on the type and the use of a building, assumption of 10÷15 kN/m^2 per floor or 2.5÷3.0 kN/m^2 per one meter of height of the building proved over the years to be a sufficient approximation. Assuming that sufficient ground cover exists over a tunnel (e.g., > 1.5D), the designer should have a permission to undertake such simplified approach.

B1.3 Soil-structure analysis results

Calculations were conducted for two specified values of the volume loss V_L. The extent of the zone of influence was assessed based on displacement prediction obtained for $V_{L,50\%}$ (Fig. B1.2). Results regarding characteristic values of effects of actions in the lining for structural design purposes are presented in Fig. B1.3-B1.5. Results in terms of characteristic values of actions for the lining design due to $V_{L,95\%}$ are presented in Fig. B1.6-B1.8. Summary of the results is presented in Table B1.2.

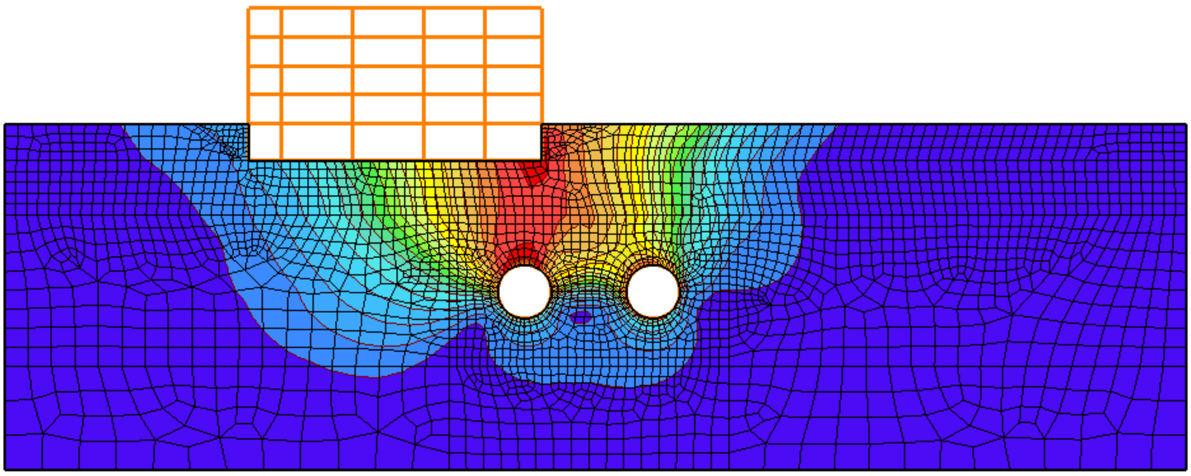

Figure B1.2 Ground displacement map (extent of the zone of influence) for $V_{L,50\%}$ = 0.50%.

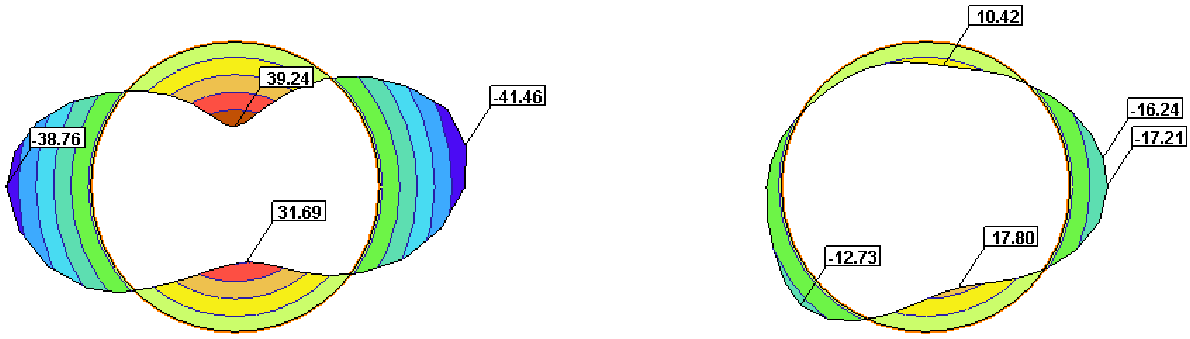

Figure B1.3 Bending moments M [kNm/m] at $V_{L,50\%}$ = 0.50% for both tunnels.

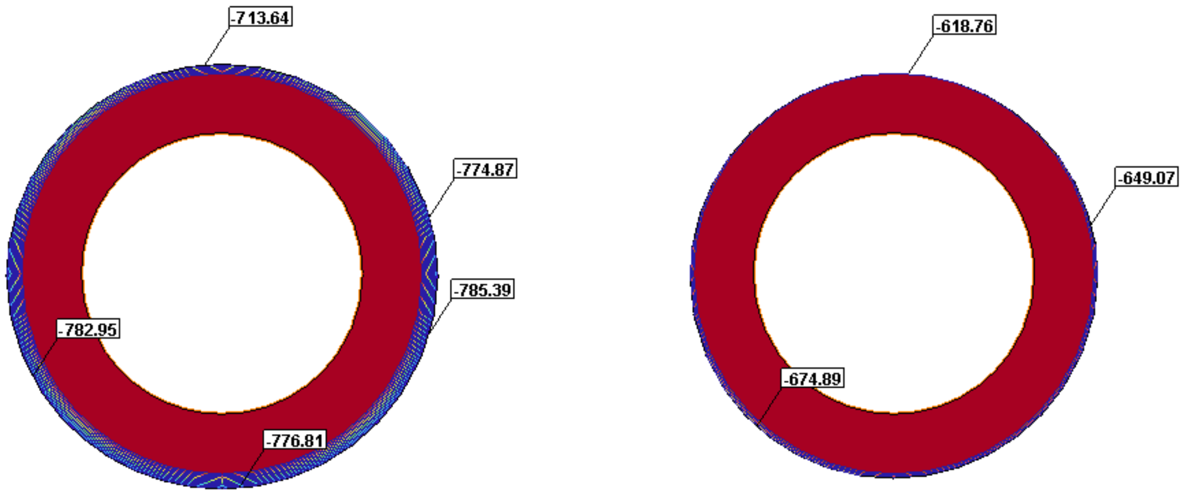

Figure B1.4 Normal force N [kN/m] at $V_{L,50\%}$ = 0.50% for both tunnels.

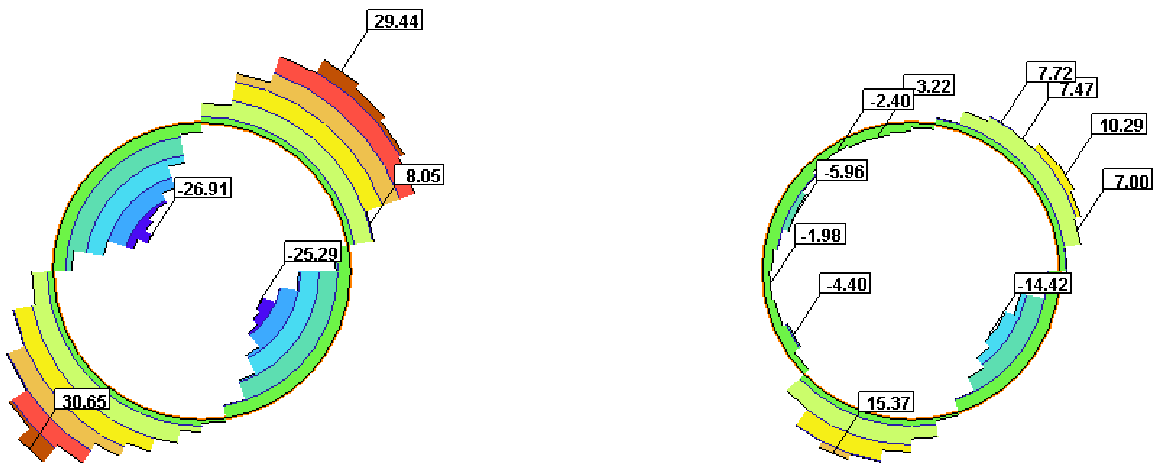

Figure B1.5 Shear force Q [kN/m] at $V_{L,50\%}$ = 0.50% for both tunnels.

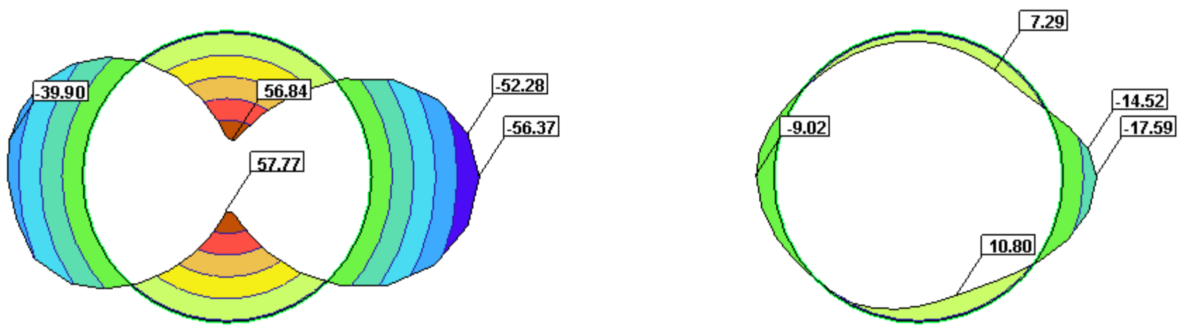

Figure B1.6 Bending moments M [kNm/m] at $V_{L,95\%}$ = 1.20% for both tunnels.

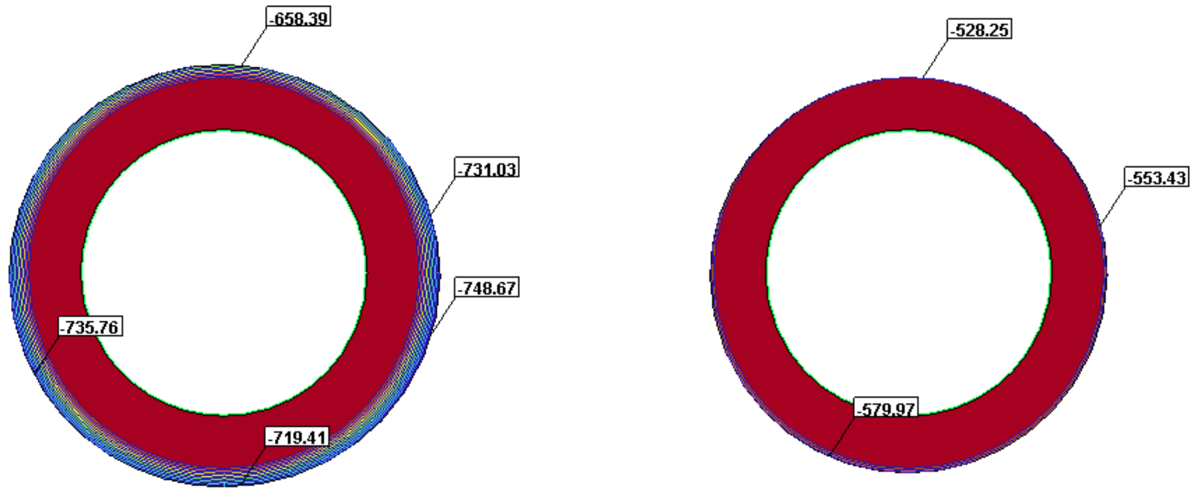

Figure B1.7 Normal force N [kN/m] at $V_{L,95\%}$ = 1.20% for both tunnels.

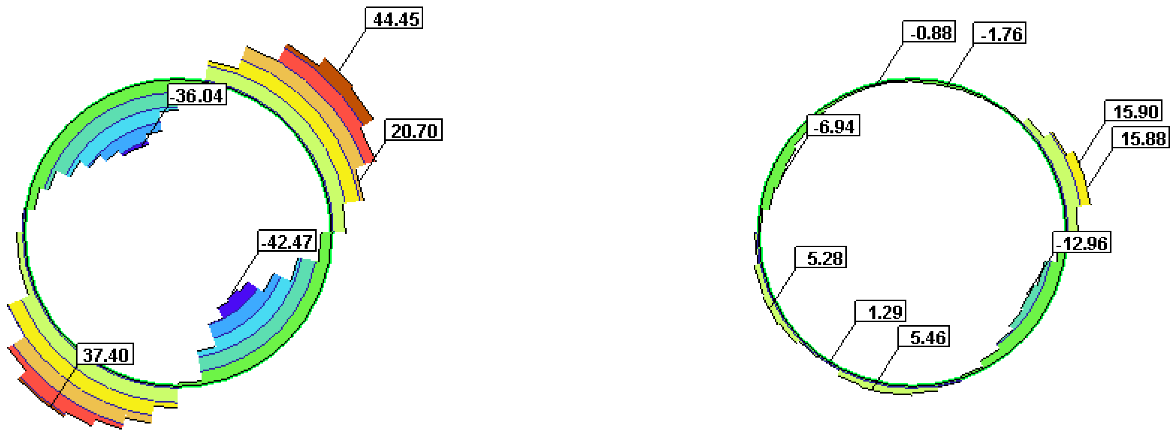

Figure B1.8 Shear force Q [kN/m] at $V_{L,95\%}$ = 1.20% for both tunnels.

Obtained values of effects of actions in the lining are considered as characteristic (representative, unfactored) values. Design values can be obtained by multiplying the effects of actions by appropriate partial factor of safety. In most cases, depending on the considered design verification, this will be favorable or unfavorable partial factor for permanent actions $\gamma_{G,fav}$ = 1.00 or $\gamma_{G,unfav}$ = 1.35.

Table B1.2 Summary of the effects of actions in the tunnel lining.

Volume loss	Effects of action per 1 m of tunnel (absolute values)	Values for the Left tunnel		Values for the Right tunnel	
		Representative	Design (unfavorable)	Representative	Design (unfavorable)
$V_{L,50\%}$ = 0.50%	M_{max} [kNm/m]	41.46	55.97	17.80	24.03
	N_{max} [kN/m]	785.39	1060.28	674.89	911.10
	Q_{max} [kN/m]	30.65	41.38	15.37	20.75
$V_{L,95\%}$ = 1.20%	M_{max} [kNm/m]	57.77	77.99	17.59	23.75
	N_{max} [kN/m]	748.67	1010.70	579.97	782.96
	Q_{max} [kN/m]	44.45	60.01	15.90	21.47

Commentary to B1.3:

a) In the case of structural design of lining, application of Material Factoring Approaches (current DA1C2 or DA3) in the geotechnical part of the analysis usually will not provide any reasonable results, since the problem is dominated by soil-structure interaction. When numerical methods are implemented, Effect Factoring Approach (current DA2*, future VC4) will be the most reasonable choice. In this case, design values of effects of action in the lining are obtained by multiplying the characteristic (representative) value by the partial factor.

b) In the context of application of advanced numerical methods like FEM for tunnel design, it is reasonable and practical to assume that the design values of the effects of actions can be obtained based on the partial factors for permanent actions only, as long as the actions themselves are assessed with sufficient conservatism and when permanent part of the load acting on the tunnel lining is clearly dominant as well as transferred through the ground (with ground cover to diameter ration C/D > 1.0). In such situation, uncertainties associated with the ground parameters and stress redistribution will be far more significant than underlying uncertainties in the variable loads.

This approach, neglecting additional consideration of intermediary partial factor equal to $\gamma_{Q,unfav}/\gamma_{G,unfav}$ = 1.11 on the actions themselves, allows for taking advantage of using numerical methods and considering the serviceability and ultimate limit states in one calculation for each design situation. However, the applicability of partial factors in tunnel design should still be given some consideration at the stage of code development.

c) The value of assumed representative volume loss parameter V_L has a significant impact on the resulting effects of actions; however, it might not always be certain that a higher value of volume loss will yield more conservative effects of actions in the lining. Furthermore, the uncertainty in this parameter cannot be compensated solely by the application of the partial factor and therefore a rational basis for selecting the values of such design parameters is necessary.

d) The presented example considers effects of actions of geotechnical origin (i.e., ground stresses, groundwater pressures, surcharge loads transferred through the ground). In practice, more loads affecting the segmental lining elements during their lifecycle might have to be considered in addition, in separate analysis, i.e.:

- **i.** imposed deformations - e.g., due to adjacent excavations;
- **ii.** loads transferred through deep foundations from other structures (often highly uncertain);
- **iii.** grouting pressure – i.e., due to tail gap backfilling;
- **iv.** internal loads and pressures – e.g., ventilation system, water pressures, self-weight of internal structures and elements, internal traffic loads (during construction as well as the use of the tunnel);
- **v.** seismic actions – both transversal and longitudinal,
- **vi.** thermal actions - e.g., due to fire;
- **vii.** impact actions (accidental situations).

e) Design of structural elements should be conducted for sections where critical design cases were identified. Those sections usually include cases of maximum normal stresses (N), maximum moments (M), maximum shear forces (Q), or maximum deformations. Sometimes, combinations of those effects of actions might be critical. The critical section may be identified based on preliminary analysis conducted with the use of simplified methods (e.g., analytical model) and later subjected to more detailed analysis using numerical methods. However, often just a few types of lining, usually differentiated only by the amount of required reinforcement, will be specified in the design. Too excessive optimization of the lining is often avoided; one of the reasons for that is related to the complications with the prefabrication process.

B1.4 Verification of relevant limit states

Commentary to B1.4:

For TBM tunnelling process and a segmental tunnel lining, there are few commonly addressed issues and limit states that have to be considered as part of structural and geotechnical design; at least following issues should be addressed in design:

- Face stability during excavation (pressurized or not) and sometimes potential blow-out (pressurized only) – this can be considered as ULS, but depending on the type of problem and considered mechanism it can be either GEO, UPL or a matter of pressure equilibrium.

- Grouting pressure – it is not explicitly assessed as a limit state; the choice of the pressure is more of a prescriptive measure to prevent the excessive impact of the tunnelling process on the ground displacement; however, impact of the pressure on the lining itself might be considered explicitly in ULS – STR analysis.

- Impact on adjacent assets (SLS/ULS) – this is often considered using a type of performance-based designed, where the impact is assessed by assigning specific expected Damage Category (due to expected impact of tunnelling) to the existing building.

- Segmental tunnel lining crack width limitation (SLS) – the analysis is conducted as for typical reinforced concrete structures, with limitation sufficient to ensure water tightness of the tunnel.

- Water tightness (SLS) – it is often addressed implicitly by designing appropriate gaskets, which will perform their expected function under the expected conditions, considering the water pressure, normal force in the lining, as well as execution tolerances.

B1.4.1 Stability during excavation (ULS – GEO / SLS)

Stability of the excavation front at the face of a pressurized TBM is ensured by prescribing a range of pressures, for each location, that should be maintained during the execution. Due to possible interbeddings of cohesionless soils in the cohesive stratum in which tunnelling will take place, design muck pressure will need to counterbalance the horizontal effective stresses (σ'_h) and water pressures (p_w) at the face (Fig. B1.9). The design muck pressure (p_{muck}) was estimated on the basis of limiting the disturbance to the surrounding ground (SLS).

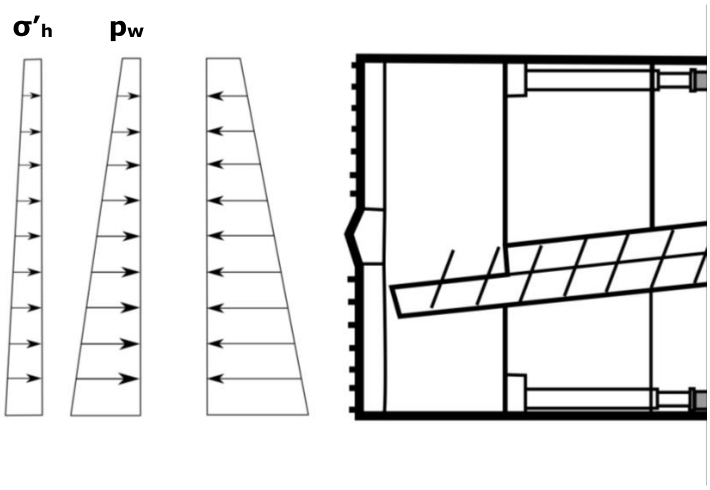

Figure B1.9 Pressures considered in Earth Pressure Balance TBM.

For the initial assessment, the face pressure at the axis was estimated on the assumption of:

Effective horizontal stresses at the axis level (active pressure): σ'h = 87 kPa

Water pressure at the tunnel axis level: pw = 128 kPa

Expected variation of the pressure: Δp = ± 5% kPa

After applying an additional factor of safety of 1.1, the design range of values for muck pressure that should be maintained is:

$$p_{muck,axis} = 1.1 \cdot (\sigma'_h + p_w) \pm \Delta p = 225 \div 250kPa$$

As this is only an initial estimate based on ground properties of the soil in which tunnelling will take place, based on the observations during the construction, the pressure range can be adjusted.

Grouting pressure that will take place behind the shield is specified at 110% of the design face pressure and therefore is prescribed at 260 kPa.

The probability of occurrence of blow-out pressure in EPB-TBM tunnelling in stiff cohesive soils is considered as negligible and therefore not verified explicitly here.

Commentary to B1.4.3:

a) In the case of face-supported TBM tunnelling the stability during excavation considered as ULS is ensured by providing appropriate face support pressure. The prescribed operational pressure range should be higher than minimum (p_{min}) required for maintaining stability and avoiding excessive deformations, and it should be lower than maximum (p_{max}) that would result in significant uplift of the ground (i.e., blow out). In practice, the specified pressure will be also selected on the basis of limiting the ground disturbance around the tunnel and therefore limiting the impact of adjacent structures (SLS).

Furthermore, too high pressure can lead to excessive wear of cutting tools, resulting in a need for more frequent maintenance, which can be conducted at prescribed locations (e.g., at stations after breakthrough or inside jet-grouting blocks). In case of necessary interventions outside of the prescribed areas, the risks to the surrounding are often higher than benefits of working at very high pressures.

b) Specification of face pressure in a design usually is made by defining an operational range of allowable pressure values (min/max). This is important as the actual face pressure might be associated with some relatively high variations, especially at stoppages (e.g., during ring segments installation) or instances of ground layer changes.

Prescribed pressures are more of a first estimate than strict requirement. In practice, the influence of the pressure on the tunnelling process and surrounding ground should be observed at the beginning of TBM drive (preferably under greenfield conditions). Actual pressure used during the drive is adjusted based on those and continuous observations during tunnelling. Because of that, this aspect of design has a strong relation to the observational method.

c) There are various methods that can be used for verification of face stability and the choice of face pressures; some of the available approaches were presented in German recommendations [8]. However, depending on the tunnelling method and ground conditions, the methods that can be applied can range from the simplest analytical approaches like the one presented here, specific limit equilibrium methods (e.g. [9],[10]), and stability ratio approach [11], to the use of advanced numerical methods like FEM and 3D calculations.

Support pressure estimates, obtained based on some of the methods, are often supplemented by additional factors of safety that might be considered as tunnelling-related only. It should be considered what values of partial factors should be prescribed.

d) At the detailed design stage, it might be convenient to estimate the prescribed pressure value at the level at which it is actually measured during the progress of the TBM for ease of comparison between design value and actual measurements.

B1.4.2 Design of the tunnel lining (ULS - STR)

For the sake of simplicity of the example, the design is based on effects of actions predicted in the segments of the lining resulting from the soils-structure interaction after their installation. In practice, the effect of actions resulting from other stages should be included as well. Those stages can involve but are not limited to prefabrication, storage, transportation, advancement of the shield during execution (i.e. TBM ram loads imposed on installed segments).

Based on the obtained effects of actions, design of the segmental lining can be conducted based on EN 1992 standard. This part of design is not presented in this design as it is considered that no significant inconsistencies would be revealed. In practice, structural design of the lining can follow the existing standard. The main difference between segmental tunnel lining design and other typical concrete structures lies in design and verification of joints (concrete-to-concrete type) as significant tensile stresses can occur at their locations when ram forces are applied during construction and between individual longitudinal joints after ring provide support for the overlying ground.

Commentary to B1.4.2

a) Compared to other typical concrete structures, design of joints (concrete-to-concrete) is a subject that might require additional attention in the design standard. Existing guidance related to design of joints can be found in available national and industrial guidelines [12]-[16].

b) The relevant stages and design situations to be considered in structural design of segments used in the lining can be found in specialized guidelines as well [12]-[16]. Most of those documents provide references to relevant structural design codes (e.g., Eurocode 2 for design of concrete structures) and design prepared according to them can be considered as code-compliant. Guidance offered in those documents usually focuses on aspects that are insufficiently covered in the codes in the context of tunnel design.

c) In addition to ultimate limit states, structural part of design should also consider verifications of other relevant criteria such as: stress limitation in concrete and steel, crack width limitation, etc.

B1.4.3 Uplift of the underground structure (ULS - UPL)

As the tunnel will be located at relatively shallow depth and under the groundwater level, verification of potential failure by uplift has been conducted according to schematic in Fig. B1.10. The design value of destabilizing vertical actions ($G_{dst,d}$) on the tunnel are associated with buoyancy forces and are equal to 283 kN/m. The values of stabilizing vertical actions ($G_{stb,d}$) were considered due to self-weight of the tunnel (134 kN/m) and the soil overburden (1197 kN/m), resulting in design total value of 1198 kN/m. The condition of UPL limit state is fulfilled without considering the additional resistance of the soil (conservative approach).

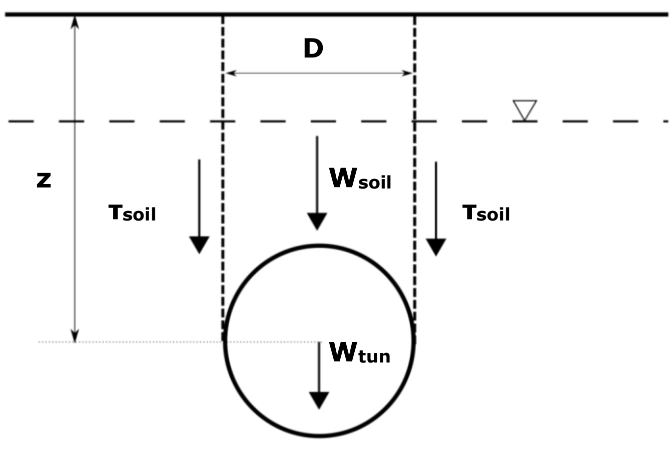

Figure B1.10 Schematic for uplift limit state verification of a tunnel (based on [16]).

Commentary to B1.4.3:

a) The verification of the limit state due to uplift is basically the same as for any other structure embedded in the ground. Current guidance of EN 1997 is considered as sufficient.

b) In the case of deeper tunnels in soft soils, a local loss of stability of the ground around the tunnel might need to be verified. Guideline [16] presents a calculation model for such verification.

B1.4.4 Impact on adjacent structure and ground displacement (SLS/ULS)

The impact on adjacent existing structures and ground displacements was evaluated in two stages. Firstly, the prediction was based on semi-empirical model assuming ground surface deformation profile represented by an inverse Gaussian curve [17], which is presented with additional information that can be derived out of it in Fig. B1.11. In this case, assessment was conducted under the assumption of greenfield conditions and the trough width parameter K was assumed equal to 0.35 for sands and 0.45 for glacial tills, as the average parameters for those types of soils [6]. Results in terms of settlement distributions are presented for the case of normal ($V_{L50\%}$) and potential excessive volume loss ($V_{L95\%}$), in Fig. B1.12 and Fig. B1.13, respectively.

Further analysis was conducted with the use of numerical modeling. Only selected results are presented here. Figures B1.14 and B1.15 are presenting settlement distribution profiles due to single and twin tunnel construction for normal volume loss ($V_{L50\%}$) at greenfield conditions. A comparison between results obtained with semi-empirical and numerical approaches is presented in Figure B1.16. As often observed in such comparisons, the results from numerical analysis show a wider but shallower settlement trough compared to approximation with a Gaussian curve when greenfield conditions are considered. Figures B1.17 and B1.18 present the results for non-greenfield conditions, with the building explicitly included in the model.

Due to location of the building above the designed tunnel, to assess the potential impact of low-probability case of excessive deformations, Figures B1.19 and B1.20 present deformation profiles when higher volume loss was assumed ($V_{L95\%}$) for one and both tunnels, respectively. For additional assessment, Figures B1.21 and B1.22 present distribution of horizontal strains for the same case.

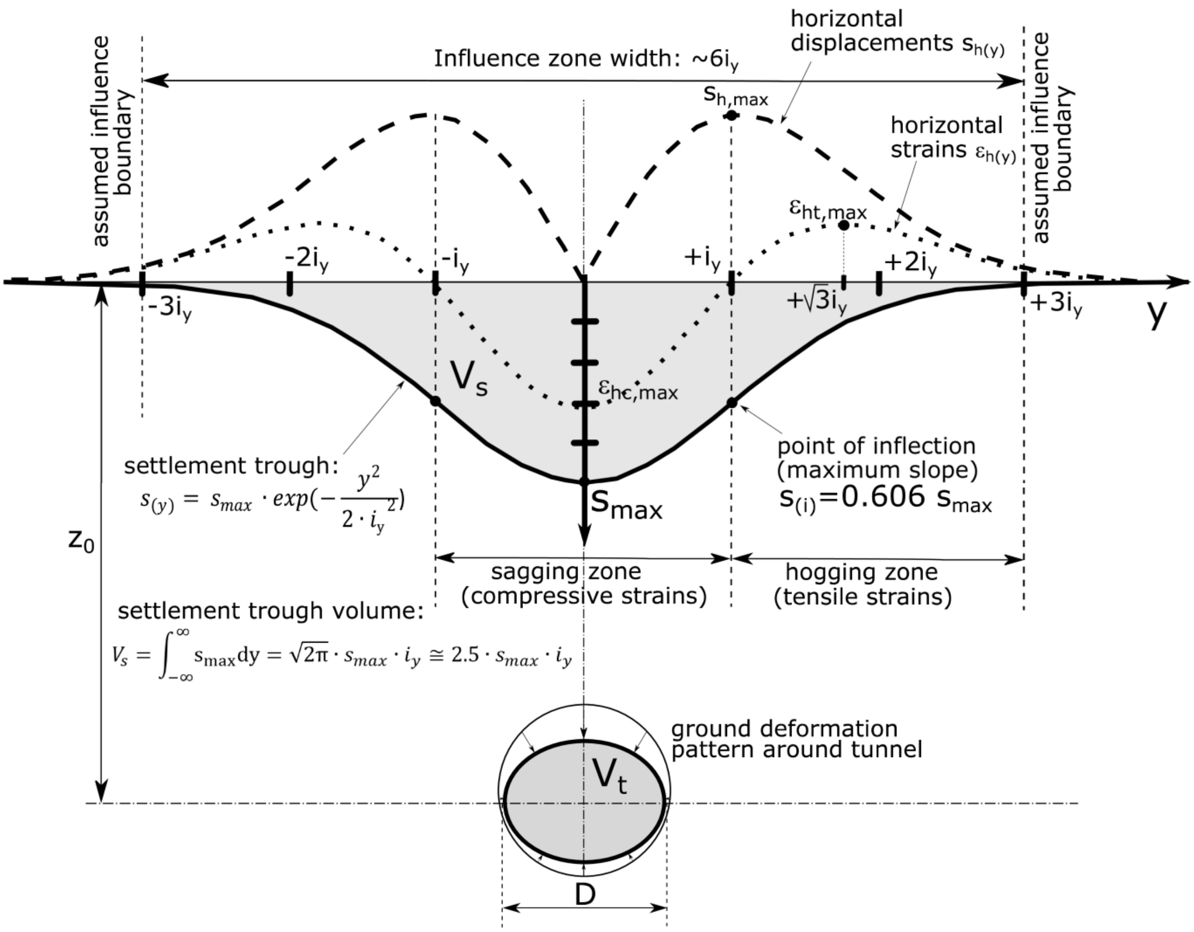

Figure B1.11 Semi-empirical approach for estimating tunnelling-induced ground deformations (based on model by [17], figure after [6]).

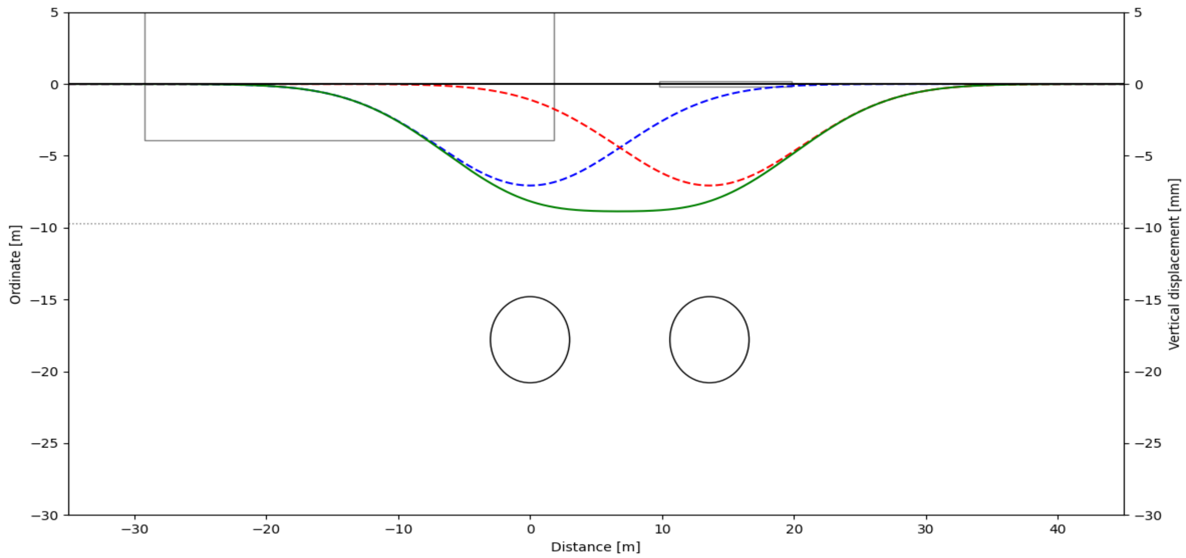

Figure B1.12 Predicted ground settlement profile based on semi-empirical approach under greenfield conditions for $V_{L,50\%}$.

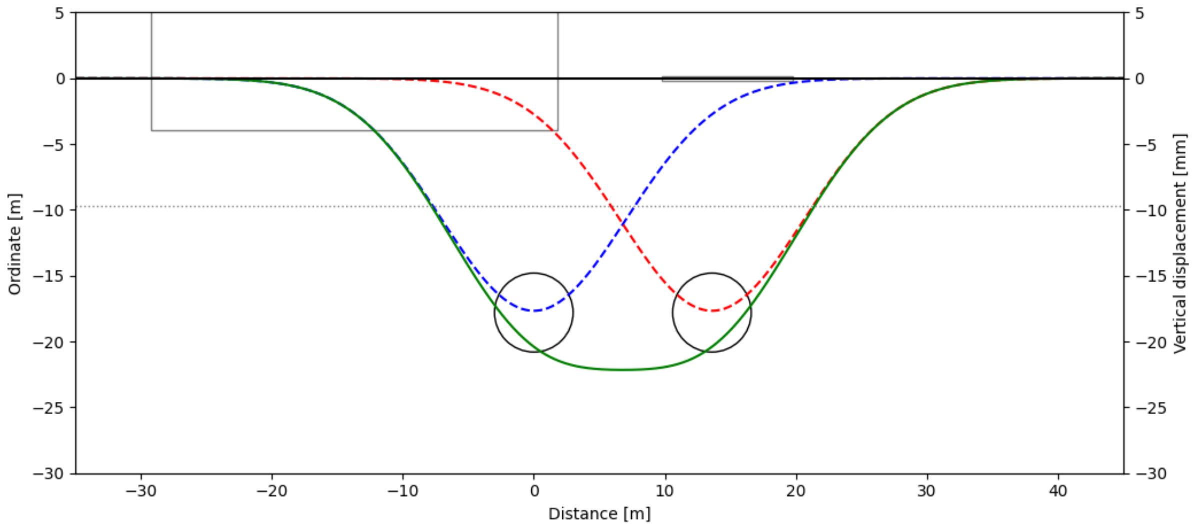

Figure B1.13 Predicted ground settlement profile based on semi-empirical approach under greenfield conditions for $V_{L,95\%}$.

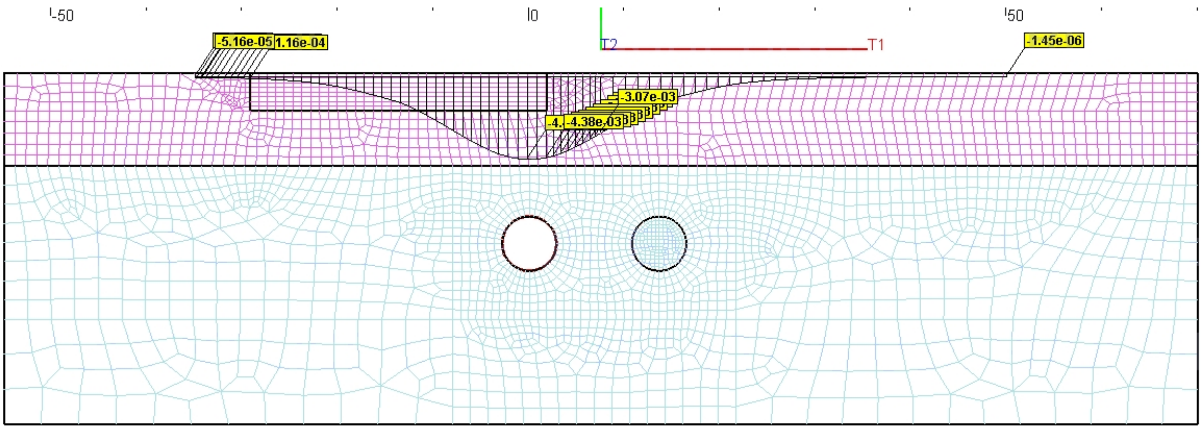

Figure B1.14 Predicted ground settlement profile based on FEM analysis under greenfield conditions for assumed $V_{L,50\%}$. - first tunnel.

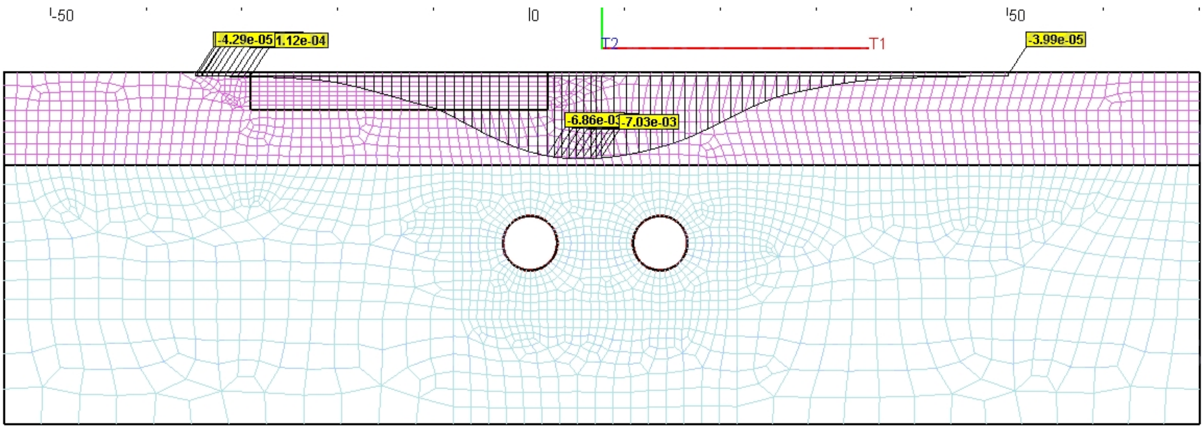

Figure B1.15 Predicted ground settlement profile based on FEM analysis under greenfield conditions for assumed $V_{L,50\%}$. – twin tunnels.

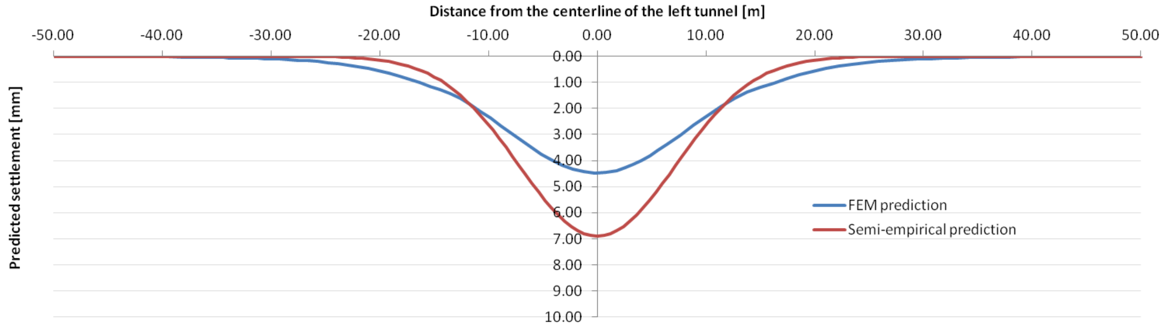

Figure B1.16 Comparison of ground settlement profiles obtained based on semi-empirical approach and FEM analysis under greenfield conditions for $V_{L,50\%}$.

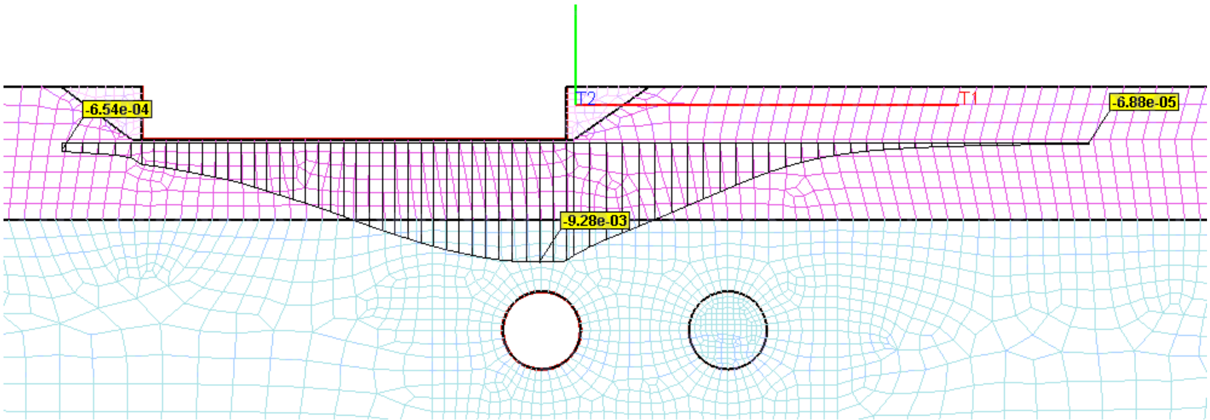

Figure B1.17 Predicted ground settlement profile based on FEM analysis under non-greenfield conditions for assumed $V_{L,50\%}$. - first tunnel.

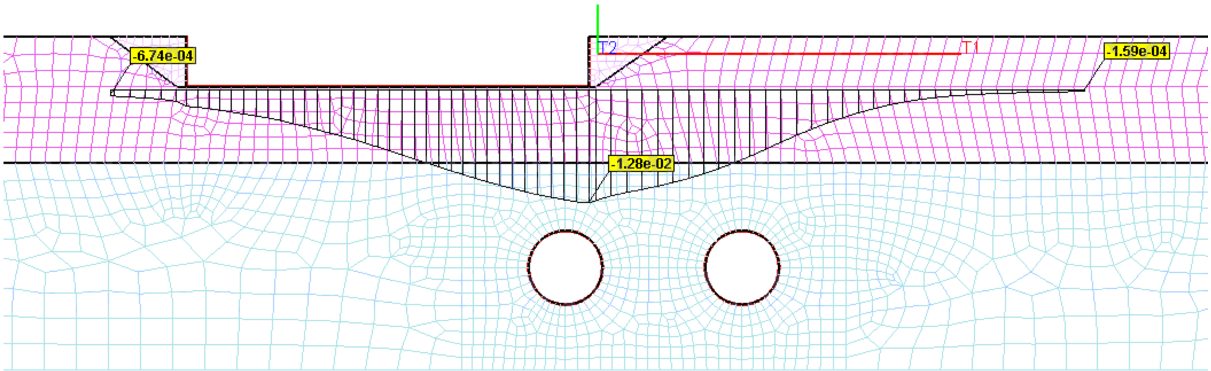

Figure B1.18 Predicted ground settlement profile based on FEM analysis under non-greenfield conditions for assumed $V_{L,50\%}$. - both tunnels.

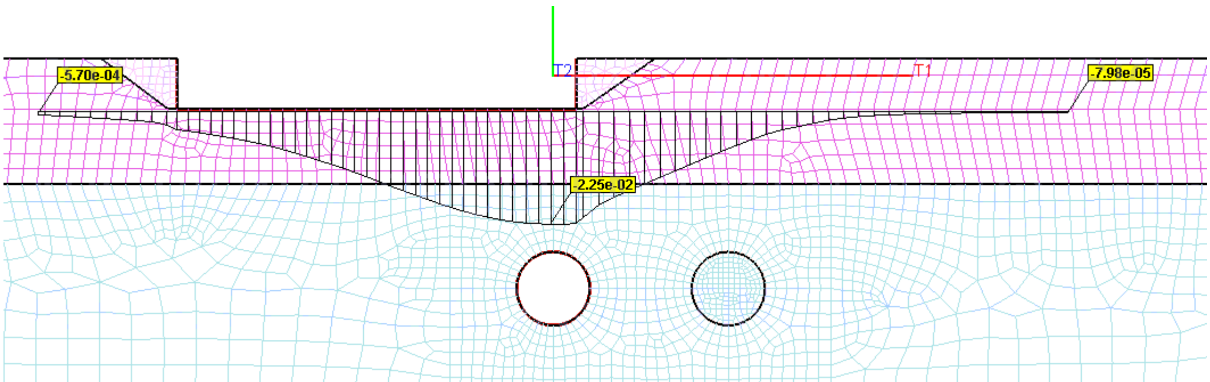

Figure B1.19 Predicted ground settlement profile based on FEM analysis under non-greenfield conditions for assumed $V_{L,95\%}$. - first tunnel.

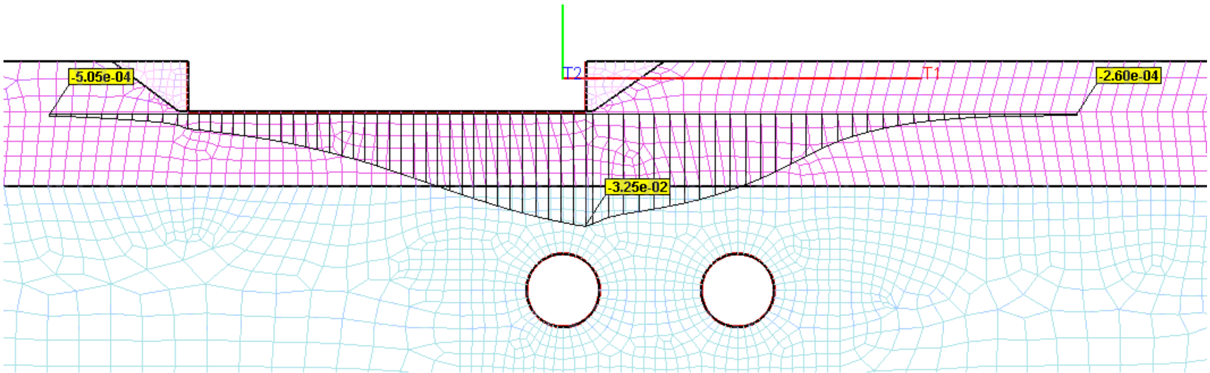

Figure B1.20 Predicted ground settlement profile based on FEM analysis under non-greenfield conditions for assumed $V_{L,95\%}$. – both tunnels.

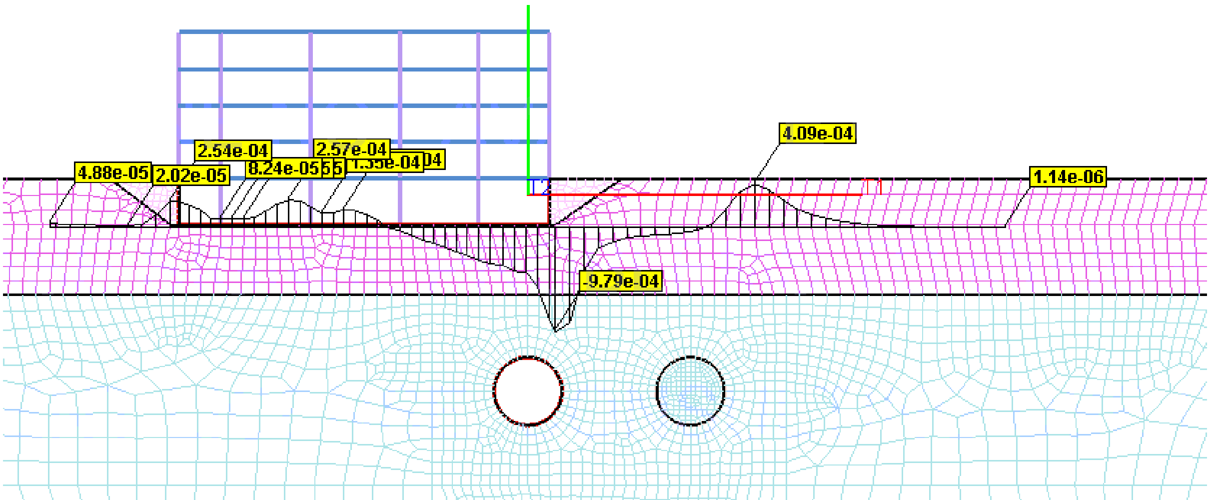

Figure B1.21 Predicted horizontal strain distribution profile based on FEM analysis under non-greenfield conditions for assumed $V_{L,95\%}$. – first tunnels.

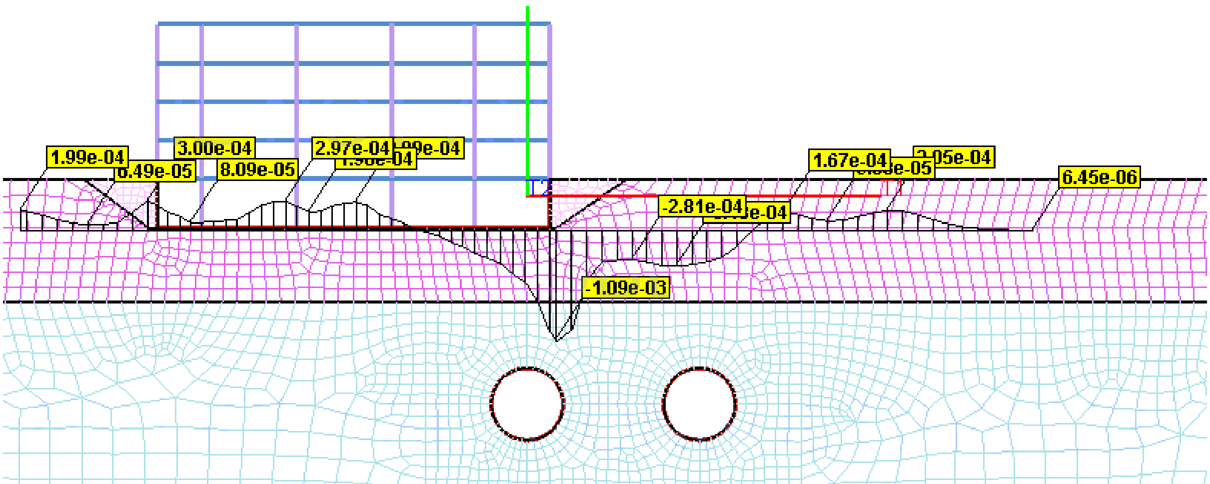

Figure B1.22 Predicted horizontal strain distribution profile based on FEM analysis under non-greenfield conditions for assumed $V_{L,95\%}$. – both tunnels.

Assessment of the impact of tunnelling on existing building can be conducted on a performance based design basis, predicting the category of damage (CD) resulting from imposed deformations [18]. The assumed relation between the different deformations types and categories of damage used in this case is presented in Table B1.3.

Based on initial assessment using semi-empirical model, negligible damage (CD0) was expected ($V_{L,50\%}$), as maximum settlement of the building was predicted as 9 mm, with possibility of reaching CD1/2 in case of higher volume losses ($V_{L,95\%}$), as the maximum settlements could reach 22 mm.

Further, more accurate assessment was possible based on FEM analysis. With explicit consideration of the adjacent structure with its load and stiffness in the model, maximum predicted settlement at the foundation level was estimated at 13 mm for normal volume loss, and at 33 mm in case of its excessive value (CD1/2). Horizontal stresses were evaluated for the possible case of excessive volume loss, reaching under the building a value of approx. 0.030%. Based on those results and considering type of the structure (i.e. reinforced concrete), the building is expected to reach Category of Damage CD1. Only potential superficial damage of aesthetical nature is expected to occur, with no impact on the function or the stability of the structure. On this basis, no remediation measures are required; only standard monitoring and inspections during the construction is planned.

Table B1.3 Example of categories of damage relation to deformations (after [6])

Limit state	Type of damage	Category of damage	Degree of severity	Qualitative risk assessment	Max settlement [mm]	Max slope	Aprox. crack width	Max tensile strain ε_{ht}
-	None	CD 0	Negligible	Damage unlikely	< 10	< 1/500	No or hairline cracking < 0.1 mm	≤ 0.050%
SLS1	Architectural (Aesthetical)	CD 1	Very slight	Superficial damage without structural significance	10 ÷ 50	1/500 ÷ 1/200	First cracks 0.1 - 1 mm	0.050% – 0.075%
		CD 2	Slight				1 - 5 mm	0.075% – 0.150%
SLS2	Functional (Non-subjective serviceability)	CD 3	Moderate	Superficial damage, possible structural damage	50 ÷ 75	1/200 ÷ 1/100	5 – 15 mm (or at least 3 cracks)	0.150% – 0.300%
		CD 4	Severe	Expected structural damage	> 75	1/100 ÷ 1/50	15 – 25 mm (or depending on their number)	> 0.300%
ULS	Structural (Stability)	CD 5	Very severe			> 1/50	> 25 mm (or depending on their number)	

Commentary to B1.4.4:

a) In practice, the deformations imposed on the ground and adjacent structures due to TBM tunnelling will be strongly related to aspects like ground conditions and their variability, TBM shape and overcut, face and grouting pressures and their variations. Deformations induced by tunnelling on the existing buildings will depend on the characteristics of those structures and their current technical condition. Assessing the impact of tunnelling on existing assets cannot be fully standardized, as it requires case-specific evaluations and significant expertise.

b) In the case of two or more tunnels constructed at close spacing (less than 5 i_y), an overlap of settlement troughs will often occur and the impact assessment should be conducted for the case of a single tunnel and twin tunnels to identify in which case the imposed deformations will be the most onerous for the structure.

When conducting the initial analysis using semi-empirical approach, it is common to assume the impact of both tunnels as superposition of the settlements caused by individual tunnels. However, it should be noted that this assumption is a major simplification as it is common to observe asymmetric settlement profiles due to twin tunnel construction. The reasons for that are, for example: general variability of the volume loss during execution, disturbance of the ground caused by the execution of the first tunnel leading to stiffness reduction of the ground, influence of the existing structures, etc. Although it is quite common to observe larger settlements for the second tunnel, when the ground is already disturbed, experience gained during the first tunnel drive allows for more precise control of the second TBM and the lower volume loss.

The decision regarding the order in which the twin tunnels shall be constructed and with what delay between them should be a part of the design process. In general, construction timeline should be designed in a way, which allows for observation of deformations due to construction of individual tunnels as well as for the use of experience gained during the first drive when controlling the second TBM. There is a strong interrelation between design and execution of tunnels.

c) Comparison of tunnelling-induced ground displacements between semi-empirical and numerical methods will often result in some noticeable differences. The semi-empirical model tends to be more conservative in terms of deformations imposed on the adjacent structures by resulting in narrower settlement troughs (i.e. with steeper slopes, larger differential displacements and horizontal strains) than those obtained from FEM, even with assumption of non-linear soil behavior for the latter. However, it does not necessarily mean that FEM approach should be considered as definitely better, as in many cases it might be inferior to the well-established semi-empirical models unless detail calibration and sensitivity analyses of the numerical models are performed. It is the designer's responsibility to select a calculation model that is the most appropriate for the problem at hand, considering the complexity of soil-structure interaction as well as the number of uncertain parameters that are involved. When a designer has limited confidence in one model, it is a good practice to apply a second one for comparison purposes. If significant discrepancies that would affect design decisions are observed, either they should be investigated in more detail or simply more onerous results can be used as a basis for design, depending on the potential consequences and risk level.

In the considered example, trough width parameter K back-analyzed from settlement profile predicted by FEM under greenfield conditions for larger volume loss (1.2%) was 0.55, compared to weighted average of K = 0.40 assumed in semi-empirical analysis, based on prior observations.

d) It is reasonable to perform impact assessment in stages. At early stages of the project (e.g., conceptual and preliminary design), it is common to implement semi-empirical models to get first estimates of expected Categories of Damage for existing structures. This allows narrowing down the focus of further investigation and analysis on the buildings that are most at risk. At detailed design stage it is common to implement numerical methods. Expected complexity of soil-structure interaction should also affect the choice of the model used in the prediction.

e) Criteria used for existing buildings in impact assessment, conversely to requirements for new structures, are best defined on a performance basis and related to Categories of Damage. It is also convenient to divide criteria for serviceability into aesthetical and functional damage. In many cases, it is more reasonable to allow for some level of damage in the existing structures rather than trying to prevent it at all cost. In general, predicting CD1/2 is considered as acceptable case. Under certain conditions, CD3 can be allowed without additional measures as well. However, in all those cases, stakeholder involvement is important, but such aspects should be beyond the scope of the code.

f) Different deformation criteria can be used in the analysis. The assessment can be based on separate criteria or their combinations. Even if the analysis is performed on the basis of more advance criteria (e.g., lateral strain), it is beneficial to consider other associated deformation types (e.g. settlement), as in practice often they will be used as performance indicators to assess the actual behavior of the structure during the construction.

B1.5 Conclusions

The example presented the brief overview of some aspects of design of a tunnel with a segmental lining constructed with the use of TBM. It should be highlighted that the presented example does not reflect the only way in which the analysis of presented design situation could be conducted; in practice, there are multiple ways and proposal of different approaches and calculation models that can be used. Specific requirements, recommendations and permissions to be implemented in the potential future standard should reflect a consensus of a wider group and they should be based on further discussions at the next stages of standardisation works; this example primarily aims to point out the issues where more consideration is necessary. Moreover, the example does not cover the structural verification of the lining (as well as important design stages such as during the TBM erection) as the shortcoming of the current EN 1992 have been discussed in the Chapter 5 of the report.

The main conclusion is that there are no significant conflicts between Eurocodes and tunnel design. What is missing in the current European standards is guidance related to tunnelling-specific aspects. However, national and industrial codes of practice and guidelines (e.g. [12]-[16] and others) provide a very good source of guidance for design aspects that are insufficiently covered in the Eurocodes. As those documents do not present one commonly accepted approach and sometime provide just a summary of some design practices, standardisation efforts should be focused on first identifying which aspects need to be covered in the new code, and then on reaching the widest consensus on common approaches.

B1.6 Inconsistencies and proposals for improvement

a) Eurocode requirements not compatible with tunnel design:

- No significant incompatibilities have been identified so far.

b) Eurocode requirements unclear or problematic for tunnel design – what should be addressed in the code:

- Consideration of design approaches (verification cases) with appropriate factoring approaches and values of partial factors.

c) Expected requirements not sufficiently covered in the code – what should be addressed in the code:

- Design situations and load cases that should be considered in design.

d) Expected recommendations not sufficiently covered in the code – what could be addressed in the code or alternatively supplemented in national documents:

- The need for use of advanced constitutive models for numerical methods (partially covered in the Second Generation EN 1997).

- Inclusion of potential future excavations as potential scenario to consider in design (similarity to unexpected excavation for retaining structures).

- Use of parameters such as volume loss – it is not certain how they should be considered and how their values should be selected.

- Guidance on assessing the impact of construction on adjacent existing structures.

e) Items that should be included in the code as National Determined Parameters only (subject for national choice):

- Calculation models should be included in the annex to the code – allowing for a national choice and modification.

- Values of additional tunnelling-specific partial factors that might be needed.

B1.7 References to Annex B1

[1] EN 1997-1 Eurocode 7: Geotechnical Design – part 1: General rules.

[2] Muir Wood A.M., The circular tunnel in elastic ground, Géotechnique Vol. 25(1): 115-127, 1975 (+ discussion by Curtis D.J.).

[3] Duddeck H., Erdmann J., On structural design models for tunnels in soft soil, Underground Space Vol. 9, 1985.

[4] Gruebl F., Segmental Ring Design – New Challenges with High Tunnel Diameters, Muir Wood Lecture, 2012.
[5] Potts D.M., Zdravković L., Finite Element Analysis in Geotechnical Engineering: Volume two – Application, 2001.
[6] Bogusz W., Prediction of tunnelling-induced ground movements, Building Research Institute, 2021.
[7] RVS 09.01.42 Tunnel structures in soft soil under built-up areas, 2013 (in German).
[8] DAUB 2016, Recommendations for the calculation of face support pressure, Germany.
[9] Anagnostou G., Kovári K., The face stability of slurry-shield-driven tunnels, Tunnelling and Underground Space Technology 9(2): 165–174, 1994.
[10] Jancsecz S., Steiner W., Face support for a large mix-shield in heterogeneous ground conditions, Tunnelling '94, 1994.
[11] Broms B., Bennermark H., Stability of clay in vertical openings, Journal of the Geotechnical Engineering Division, ASCE 1967; 193: pp. 71–94, 1967.
[12] DAUB 2013, Recommendations for the design, production and installation of segmental rings, Germany.
[13] British Standard Institution (BSI) 2016, Tunnel design - Design of concrete segmental tunnel linigs - Code of practice, PAS 8810.
[14] ITA-AITES 2019, Guidelines for the Design of Segmental Tunnel Linings, WG2 Report.
[15] Australian Tunnelling Society (ATS) 2020, Tunnel Design Guideline.
[16] Land Transport Authority (LTA) 2019, Civil Design Criteria for Road and Rail Transit Systems, E/GD/09/106/A2, Singapore.
[17] Peck R.B., Deep Excavations and Tunnelling in Soft Ground - State of the art report, Proc. of the 7th Int. Conf. on Soil Mech. and Found. Eng., 1969.
[18] Burland J.B., Assessment of risk of damage to buildings due to tunnelling and excavation. In Proc. 1st Int. Conf. Earthquake Geotech. Eng. Tokyo, 1995.

Annex B2. Worked example - SCL tunnel constructed with conventional excavation method in soils

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B2.1 Introduction

This example deals with the design of a tunnel that is driven using a conventional method. A conventional tunnelling method is characterized by a sequence of excavation rounds where the equilibrium of the cavity is achieved by the application of a sprayed concrete layer after excavation. As a temporary measure, the face is supported by a shotcrete layer that is removed with the next excavation step.

The objective of this example is to perform design calculations according to the current Eurocodes. All questions concerning the application of standards are clarified, since tunnel design is not covered by the Eurocodes. The design is based on EN 1992 for concrete design **Error! Reference source not found.** and EN 1997 for geotechnical design [2]. The design parameters and associated assumptions were taken from a real case study of a metro in an urban area, but not all aspects of the design were considered. This would be far beyond of the examples scope.

For tunnels with low overburden numerical methods are commonly applied to the design of permanent tunnel linings and temporary support measures. The anticipated in-situ stresses in the ground and the ground-structure interaction play a significant role. The calculation of the internal forces for the design of the sprayed concrete lining heavily depends on the nonlinear behavior of the soil and the modelling of the lining. Therefore, the deployment of advanced constitutive models for soil and sprayed concrete are indispensable. For the nonlinear behavior the HSs model is applied while for the sprayed concrete a further refinement can be achieved by considering the time-dependency of the concrete strength and stiffness. This allows more realistic simulation of the transfer of load from the ground to the young, sprayed concrete at the face. If necessary, effects due to creep, shrinkage and constraints from the hydration process can be taken into account as well.

Commentary to B2.1:

a) Some parameters like the factor for pre-relaxation of the ground are based on empirical experiences or in specific cases need to be calculated.

b) Analysis of stresses and deformations typically in soft and weak grounds in tunnelling is mostly based on numerical methods, nowadays – EN 1997 guidance for tunnels should focus on that.

c) Although HSs model is one of the possible choices, for underground structures, the use of non-linear constitutive models for soils is practically obligatory to obtain reliable results, especially in terms of predicted deformations – that points to a potential need for including a recommendation clause on their application. However, taking into account the number of available advanced constitutive models and potential new developments in the future, guidance in the new code should remain generalized in that regard.

d) Within the context of EN 1997, tunnels are essentially retaining structures. In principle this means limit states for structural capacity (STR) and in the ground (GEO) should be verified.

However, a difficulty is presented by the fact that the surrounding ground is both an action and a resistance. Distinguishing between these two in tunnelling is not generally possible and, therefore, the design approach DA2* is considered.

B2.2 Description of the example and the main assumptions

B2.2.1 Basic information about the designed tunnel

In this case study, a typical layout for a metro station with two single-track platform tunnels and a concourse tunnel in between is analyzed in a 2D-Finite Element model. Since the station is in a clayey silt layer below the water table, two pilot tunnels with a steel fibre reinforced sprayed concrete lining are driven in the uppermost part of the station to ensure dewatering of the tunnelling area. The pilot tunnels are dismantled during the excavation of the platform tunnels.

Summary of the tunnel characteristics (design parameters are constant over the entire tunnel):

Average external diameter of the pilot tunnels:	4.80 m
Average external diameter of the platform tunnels:	10.00 m
Average external diameter of the concourse tunnel:	9.00 m
Thickness of the pilot tunnel lining:	0.15 m
Thickness of the primary lining:	0.35 m
Concrete grade of the lining:	C20/25

The stiffness of the lining is nonlinear both in time and in strength development.

Commentary to B2.2.1:

a) The inner diameter of the tunnel depends on the functional requirements. As a rule, this is one of the main requirements for the geotechnical and structural designers.

b) For this reason, compliance with the minimum dimensions including specified tolerance is a limiting parameter for serviceability. This must be considered when choosing the excavation diameter.

c) The predicted deformations due to the excavation must be considered accordingly.

c) When using FEM analysis, tunnel lining is modeled in 2D using beam elements. The elements in numerical model are in fact located in the neutral axis of the lining. Therefore, the diameter of the tunnel in the model is less than the outer diameter.

B2.2.2 Description of the considered design situation

Since the soil layers do not vary in height and the station has an extension of more than 100 m, the analysis of a 2D model is sufficient for a preliminary design. For the representative loads generated from buildings and roads above the station, representative loads should be applied.

The analyzed cross-section presenting the considered design situation is shown in Figure B2.1.

Summary of tunnelling conditions (design parameters representative for the given location):

Depth of the tunnel axis:	28 m below ground
Distance between tunnels (axis-to-axis):	32 m and 26 m respectively
Ground conditions:	Mixed soils (gravel and overlaying clayey silt)
Tunnelling situation:	Urban area (existing buildings and roads)

Details of the existing structures and their relative position to the planned tunnels are given in the figure below.

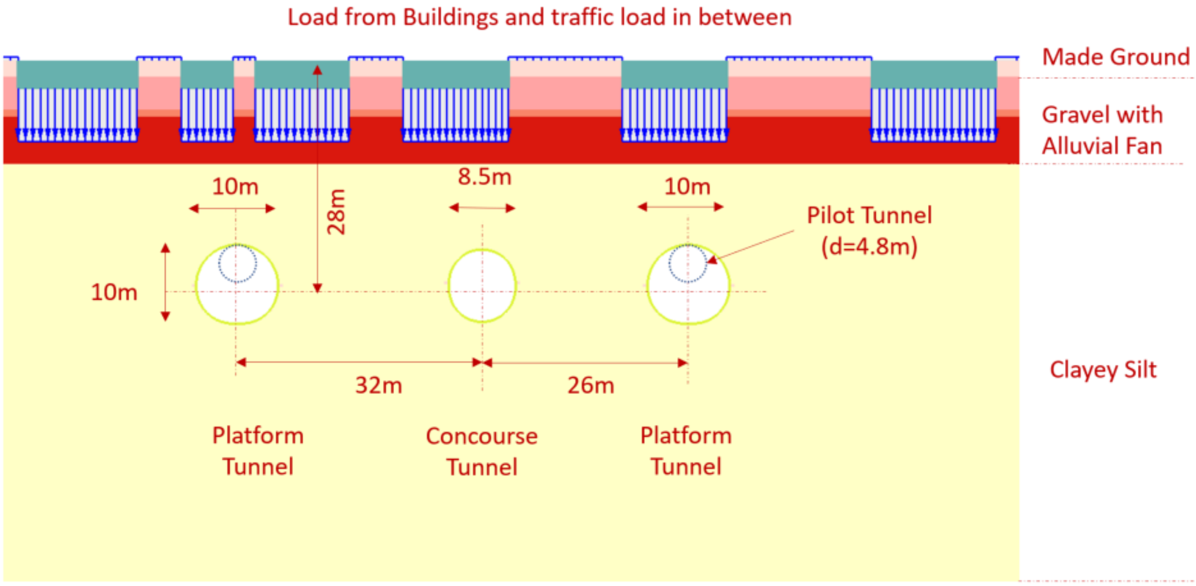

Figure B2.1 Design situation

Commentary to B2.2.2:

a) Along a given section of a tunnel, few representative cross-sections might be selected. Usually they will include the most unfavorable loading conditions (e.g. large asymmetric load above the tunnel) for structural design of the lining. For assessment of the impact of tunnelling on adjacent structures, this might be supplemented by the use of semi-empirical models.

b) For design in greenfield conditions (i.e., in an undeveloped area), the designer might assume a theoretical excavation on the side of the tunnel with subsequent loading from new buildings in order to account for potential change in loading conditions occurring in the future. This assumption should be made in accordance with the urban development plan. – potential change in loading conditions occurring in the future. This might be a requirement of a local authority in order to avoid detailed analysis for new investments located along existing tunnels in the future and a way of increasing the robustness of the tunnel to change in loading conditions. In general, this is a reasonable approach and might be considered as potential recommendation in the code.

c) Even when using numerical methods like FEM, adjacent structures might be considered with their characterization at various levels of details. In most cases, three approaches can be used: 1) building is not considered at all; 2) building is considered as a distributed load at its foundation level; 3) building is considered accounting for its loading and stiffness characteristic. The situation is even more complicated when adjacent structures are supported on deep foundations.

d) Depth of the tunnel will often depend on the presence of underground obstacles along the tunnel alignment as well as the geotechnical conditions, with preference to tunnelling taking place in relatively homogeneous conditions at the face. The choice of depth is usually made at initial design stages, prior to detailed structural and geotechnical design.

e) It might be necessary to specify relevant design situation / critical load combinations.

f) If excavation is below the water table, the effect of pore water pressure on the material law should be considered (dissipation / consolidation).

B2.2.3 Geotechnical conditions at the site

For the present cross-section mixed ground conditions with various quaternary and tertiary soils are considered. The following layers were distinguished for this design situation:

Made ground consisting out of a gravel like material
Gravel with an alluvial fan in between
Clayey silt (Miocene)

The parameters used to characterize the soil properties were selected based on several field and laboratory tests. Previous experience with underground structures in the area and in areas with similar conditions was also incorporated into the parameter selection. The values of the parameters used as representative in this case are presented in Table B2.1.

Table B2.1 Parameters characterizing the soils.

Parameter	Units	Soil layers			
		Made Ground	Alluvial fan	Gravel	Clayey Silt
φ′	°	25	27.5	35	22.5
ψ′	°	0	1	3	0
c′	kPa	0	10	1	30
γ	kN/m³	20	20	20	20
e_0	-		0.49	0.36	0.59
E	MPa	10	-	-	-
E_{50}^{ref}	MPa	-	15	40	14
E_{oed}^{ref}	MPa	-	15	40	14
E_{ur}^{ref}	MPa	-	45	121	42
E_0^{ref}	MPa	-	180	482	168
m	-	-	0.6	0.6	0.99
σ_{ref}	kPa	-	100	100	100
K_0	-	0.58	0.54	0.50	0.75

Commentary to A2.2.3:

a) Although the choice of representative values of parameters characterizing the ground is a part of the design process, specified to some extent in the code, it probably should be left to the discretion of the designer, especially in the cases where model-specific parameters are implemented for non-linear constitutive models.

b) Parameters may deviate from laboratory tests due to experience from similar projects

B2.2.4 Constitutive law for the Sprayed Concrete

Layered beam elements are used for the lining. In the software a user-specific material model was implemented that considers the stress-strain relationship according to Eurocode 2 and the development of strength with time according to the degree of hydration. Since the hydration degree is normalized to concrete strength at infinity the strength development must be adjusted for a 28-days strength according to EC2. For the shotcrete mixture to be applied in this project the strength curve must be calibrated to a hydration degree of 0.72 at 28 days (see figure below).

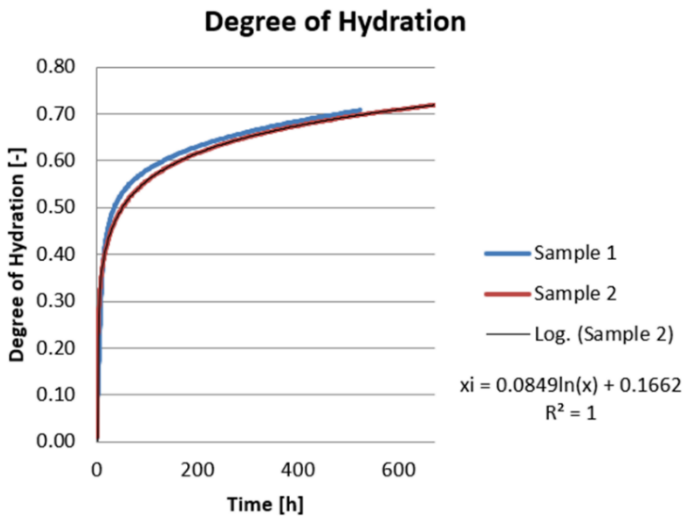

Figure B2.2 Development of hydration degree with time.

As a result, the stress-strain curve is also dependent on time. For each time instance, a different stress-strain relationship must be considered (see figure below).

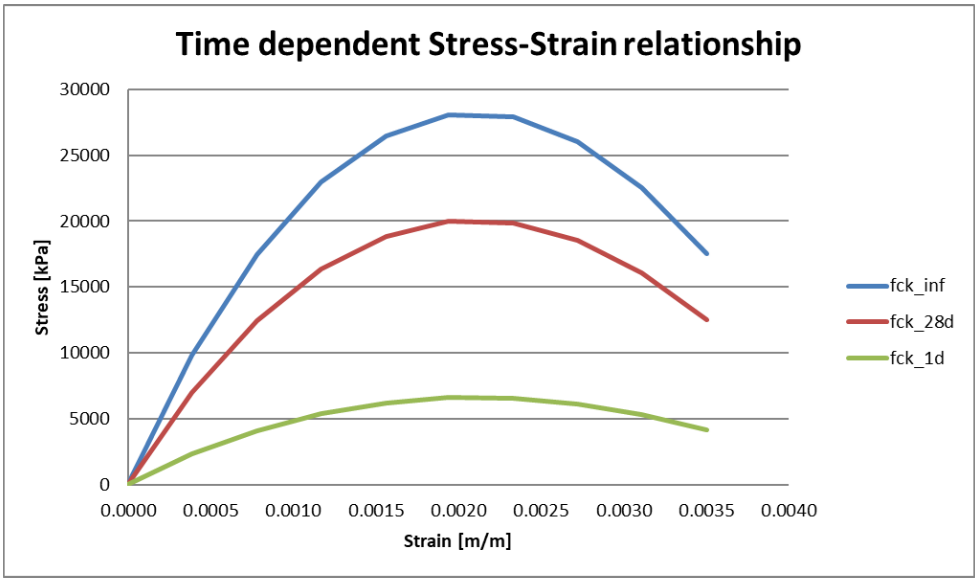

Figure B2.3 Development of stress-strain curve with time.

In addition, a power law for creep considers the time-dependent behavior of concrete under load. The parameters for the creep law were calibrated using a laboratory test with variable load levels (see figure below).

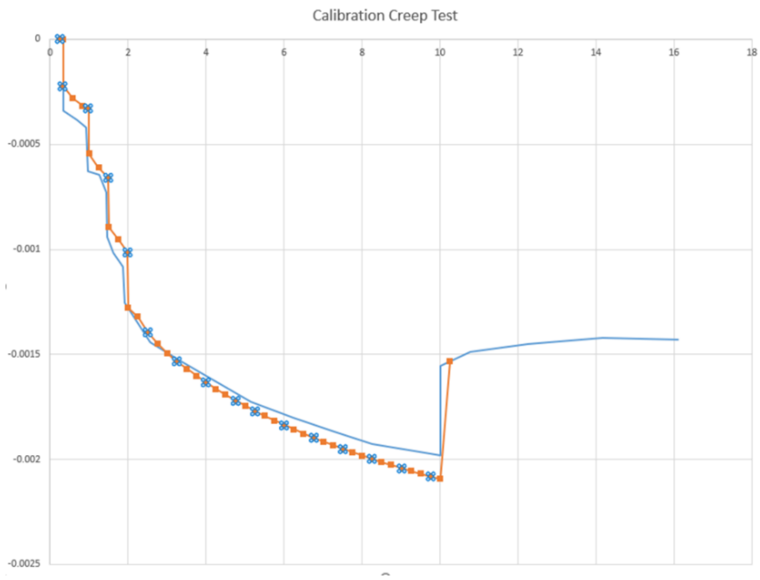

Figure B2.4 Calibration of creep parameters using a laboratory test.

Due to the absence of a standard for fibre reinforced concrete the Annex L of prEN 1992-1-1 (D7) was chosen as a basis.

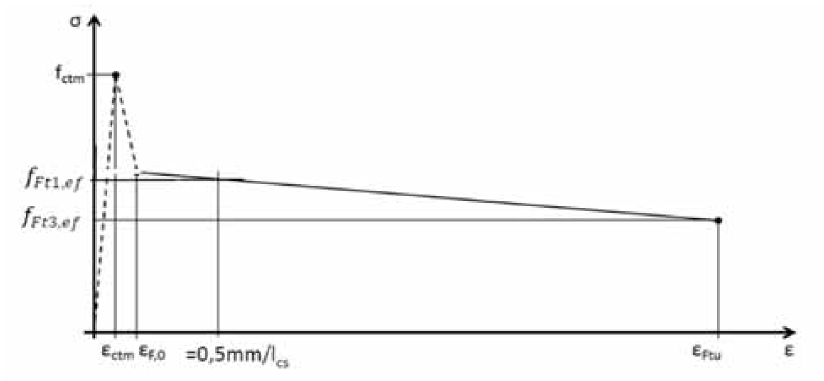

Figure B2.4 Constitutive law of SFRC for structural analysis

Commentary to B2.2.4:

a) The study in [4] showed that modelling of the sprayed concrete in combination with the different design approaches plays an essential role in the assessment of the load-bearing capacity.

b) The choice of a suitable material model for the sprayed concrete plays a role that goes far beyond the influence of different design approaches and partial safety factors.

c) Dependency of stress-strain curve in prEN 1992-1-1 (D7) on x for fibre reinforced concrete: Both stresses and strains on the curve depend on lcs, kappaG, etc., which ultimately depend on depth of concrete in compression (x). The curve is therefore only defined for a given strain distribution, so a user doing calculations by hand would have to solve equations iteratively. For the depicted MN diagram this is not a problem, as x is the variable used to calculate the locus of the capacity, so everything can be defined as a function of x. Could this however be simplified, as it is suspected the dependence on x is quite weak for most of these parameters? DAfStb does not have this for strains, for example. RILEM avoids it for stresses as well.

B2.2.5 Expected geotechnical actions resulting from tunnelling process

During the construction of a tunnel, excavation causes stress redistributions in the ground. These determine to a large extent the loading of the lining. When using 2D models, care must be taken to ensure that the time steps selected for the simulation of the spatial stress redistributions (so-called pre-relaxation phases) correspond to the real excavation process. For modeling the spatial evolution of displacements in the longitudinal direction as a function of the excavation process, a suitable pre-relaxation function must be considered. In an excavation step, the finite elements of the related region are removed and replaced by equivalent nodal forces. As excavation progresses, these forces are gradually reduced as a function of the subsequent steps.

The figure below shows the process described above.

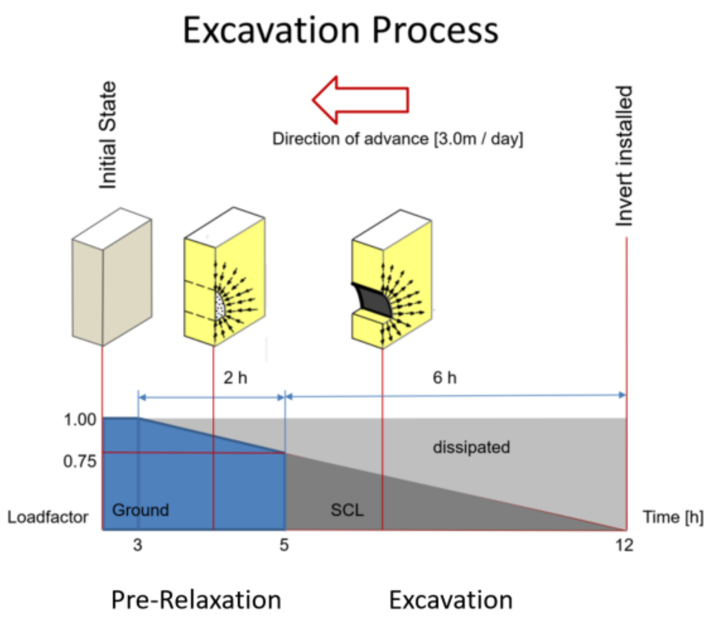

Figure B2.5 Pre-relaxation function to simulate development of deformation in a 2D-Model

Commentary to A2.2.5:

a) The current state-of-the-art approach in most cases is to implement at least 2D numerical models in which tunnelling processes, and all the 3D effects associated with it, are modeled in a simplified way. More advanced 3D calculations are done for design purposes and become more and more state-state-of-the-art.

It might be necessary to specify acceptable methods of analysis. Because of the numerous load case combinations for the design of the secondary lining, bedded beam models should be allowed.

b) In regard to the 2D modeling of tunnel excavation problems, it is often necessary to delay the activation of the lining to account for 3D unloading effect which depends on the distance between the excavation face and the installation of the lining (support takes only a part of total unbalanced forces). Such an effect can be simulated in 2D using unloading functions which are associated with a set of "excavated domain equivalent" forces. In standard finite element software these forces are calculated automatically by the program when the excavation takes place. The procedure exactly equilibrates the domain, replacing the excavated part by forces. These forces are then gradually reduced, initially until the lining is installed, and then typically to 0 value where full unloading has occurred.

B2.2.6 Characteristic of adjacent structures

The metro station is below the typical development for urban areas, such as residential and office buildings, streets, and tramways. Buildings usually have five to six floors above ground and a basement. According to an Austrian guideline [3] in this example the building load is assumed to be 15 kN/m² for each floor and 30 kN/m² for the basement. The loads act on the level of the foundation, and the building itself is simulated by a weightless box with a representative stiffness. A load of 10 kN/m² in the remaining area considers the traffic.

Commentary to B2.2.6:

a) For existing, adjacent buildings, the information about their structural characteristic and loads imposed on the ground is often very general. Therefore, it cannot be expected that the representation of such structure and the exact loads will be modeled with very high accuracy. For practical applications, simplified representation is often sufficient. Especially, as even in the case of shallow underground structures (i.e. those with soil cover of 1-5D), geotechnical actions due to soil and water pressures will be usually dominant.

B2.3 Soil-structure analysis results

In the following figures some typical results are presented.

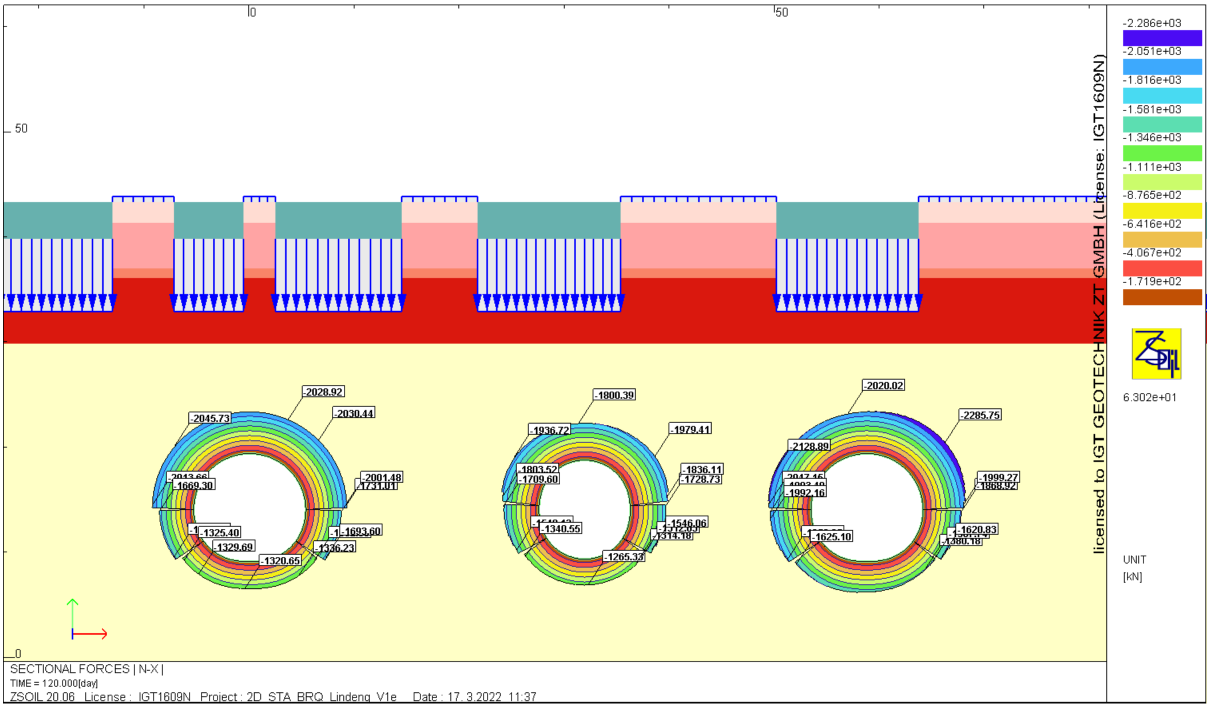

Figure B2.6 Axial Force [kN/m] in the primary lining at end of construction.

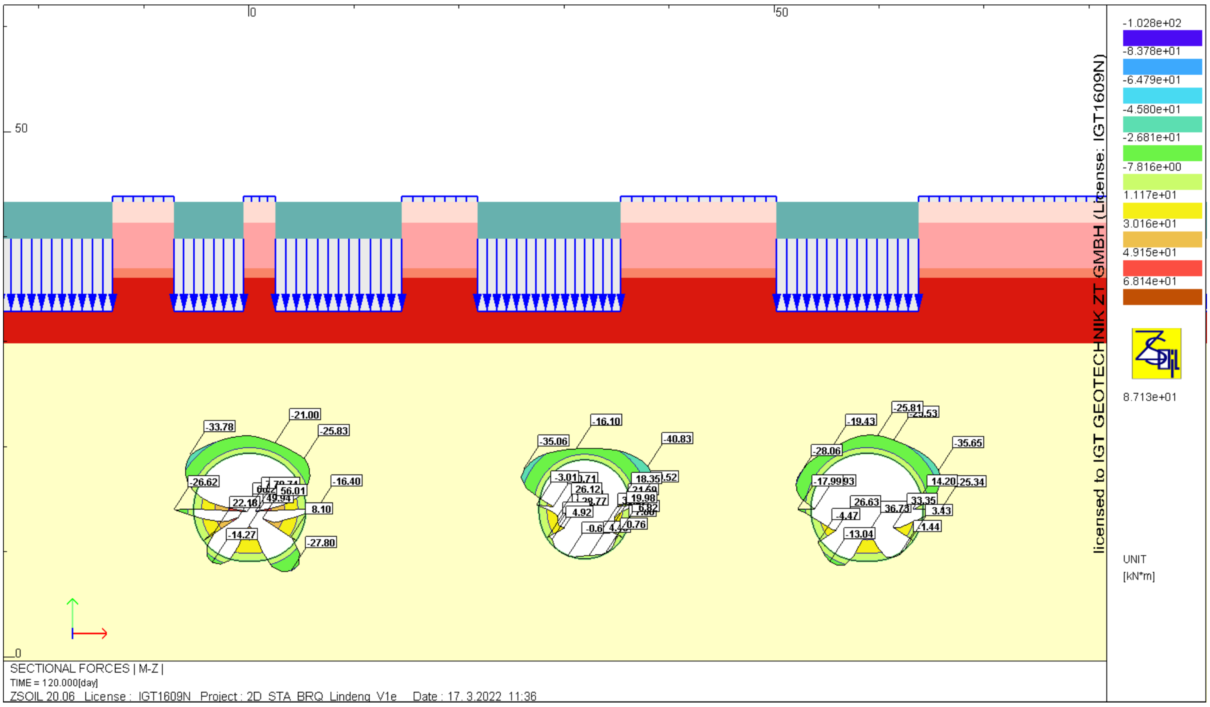

Figure B2.7 Moments [kNm/m] in the primary lining at end of construction.

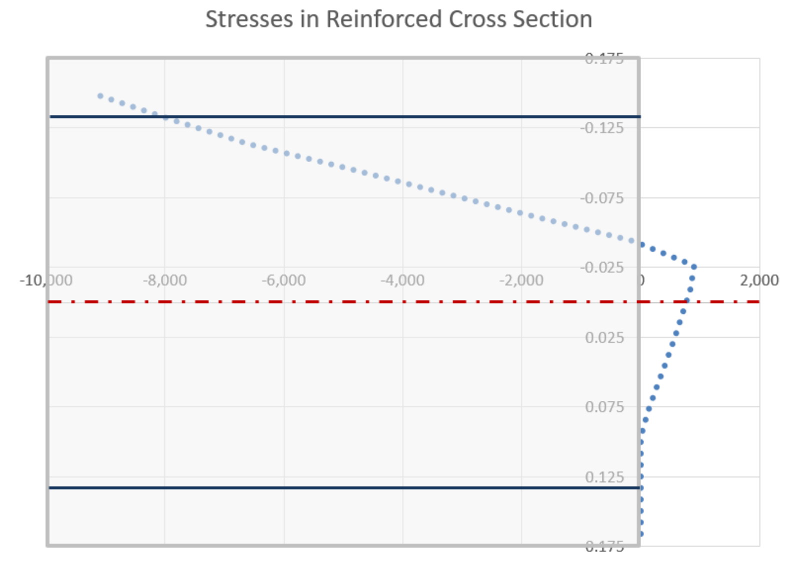

Figure B1.8 Stress distribution in a typical design section of the primary lining (d=0.35m).

B2.4.2 Design of the tunnel lining (ULS - STR)

The design of the concrete lining was conducted according EN 1992-1-1 for wire mesh reinforced concrete applying a partial safety factor of γ=1.5 for concrete strength and γ_M=1.15 for reinforcement. The effects of actions were factorized by γ_E=1.35 according to design approach DA2*. The check of ultimate limit state for the fibre reinforced concrete was conducted according to prEN 1992-1-1 (D7) Annex L.

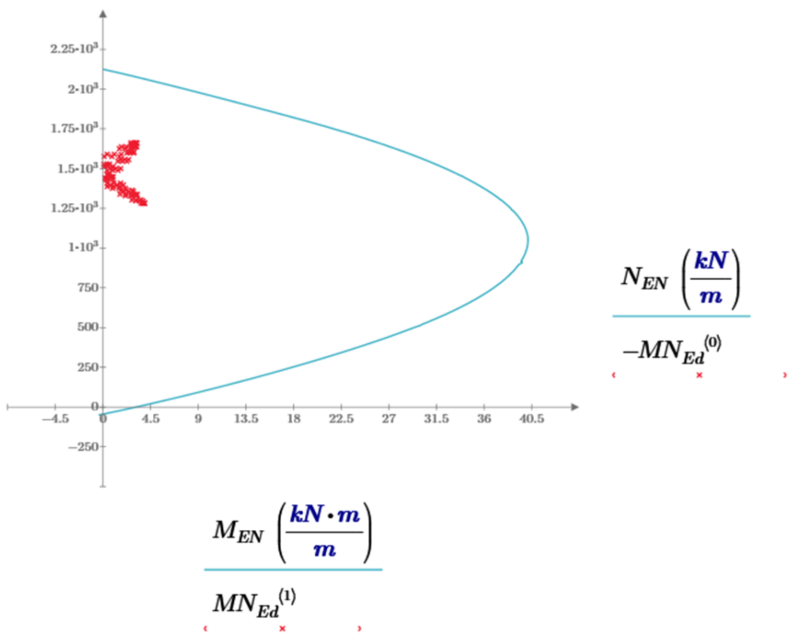

Figure B1.9 M-N Envelope for the fibre reinforced concrete lining in the pilot tunnel

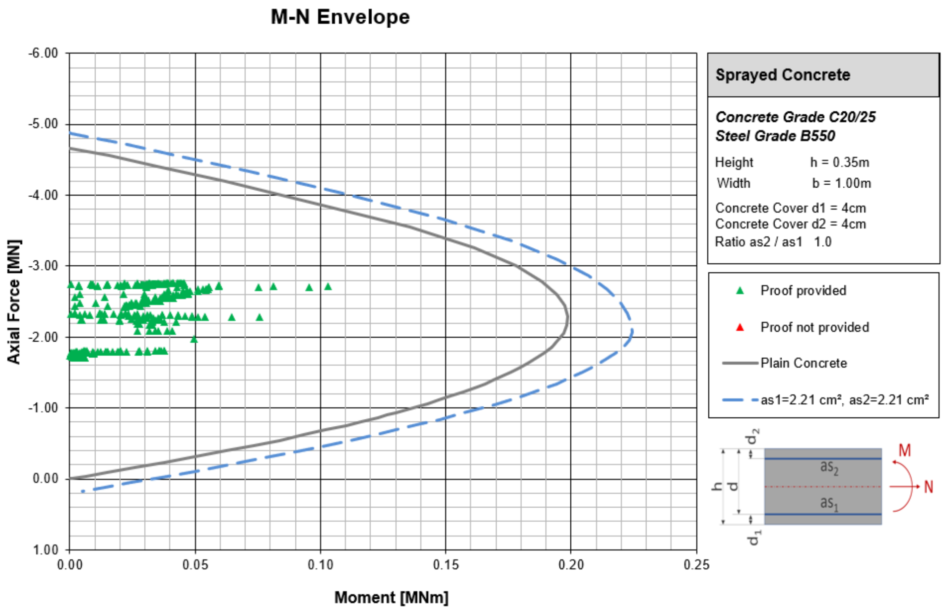

Figure B1.10 M-N Envelope for the wire mesh reinforced concrete lining in the primary lining

Commentary to B1.3:

a) Design values of effects of action in the lining are obtained by multiplying the characteristic (representative) value by factor of γ_G = 1.35. This approach is identical to the DC4 combination when applying Effect Factoring Approach in the new version of the code. In addition, the factor γ_F depending on the consequence class must be considered.

B1.4.1 Face stability during excavation (ULS - GEO)

There are several design approaches with a wide range of results. For a preliminary study, a simple check according to [5] is sufficient. The author has had good experience with this approach, which is based on detailed numerical analyses, in drained as well as undrained conditions.

B2.4.3 Uplift of the underground structure (ULS - UPL)

Since the tunnel region is dewatered by pilot tunnels during construction phase, uplift is not an issue.

Commentary to B1.4.3:

a) Any additional failure modes should be considered? E.g., local loss of stability due to heave in soft soils?

b) In case of staggered excavation, e.g., top heading, bench and invert, the factor for pre-relaxation has to be chosen differently. The dissipation of the excavation forces normal to the stress-free excavation surface must be adapted to the time and position of ring closure. Depending on the excavation schema, different failure mechanisms can occur, which can be avoided by appropriate construction measures (elephant foundation of the footing of top heading, temporary invert etc.). The consideration of different shotcrete age at different excavation phases can also play a significant role.

B2.4.4 Impact on adjacent structure and ground displacement (SLS/ULS)

A building assessment was conducted in the project area and serviceability limits were established by a maximum tilt angle. The tilt angle should not exceed a slope of 1:500. The maximum slope of the settlement trough was determined to be 1:1071 (see figure below).

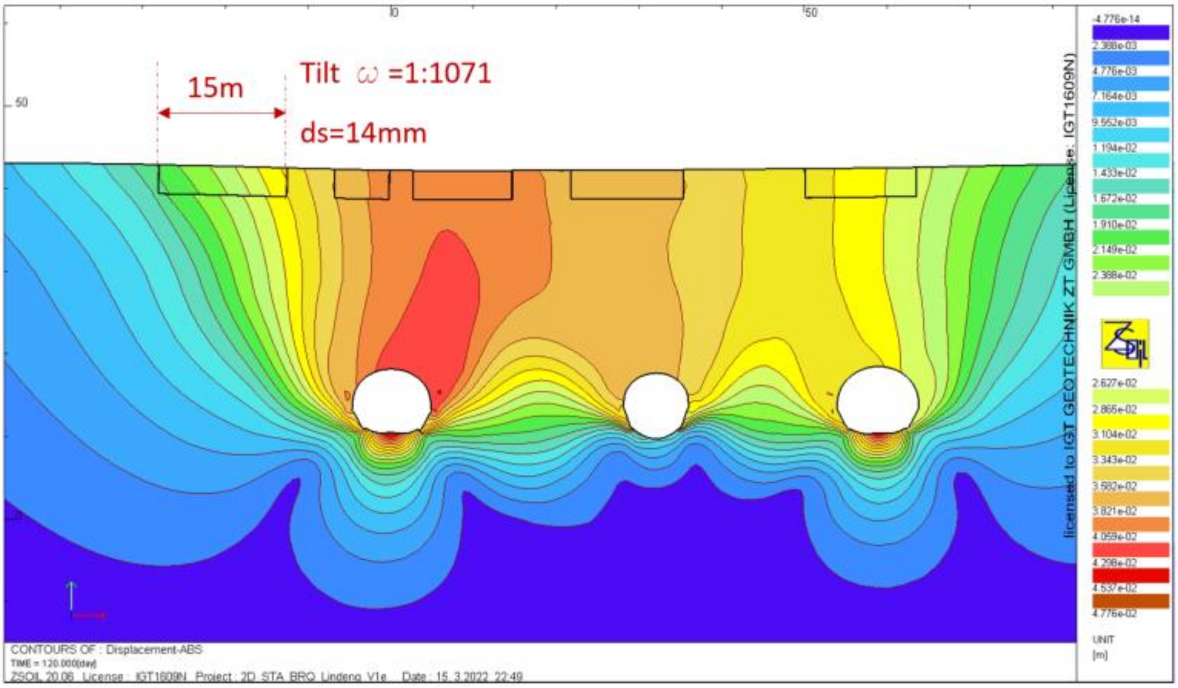

Figure B1.11 Vertical displacement with maximum tilt of buildings above the tunnel

B2.5 Conclusions

The example shows a possible design strategy for a tunnel built in shotcrete and excavated using conventional methods. It should be noted that the standards with national regulations and national recommendations provide alternative ways for the design. Requirements and recommendations for potential future standards should satisfy the needs of the broadest possible technical community. An important finding in carrying out the working example is that there are no insurmountable conflicts between the Eurocodes and tunnel design.

Nevertheless, many tunnel-specific aspects are missing in the current European standards, which have been defined in various national recommendations. Since very different approaches have been established in tunnel design for historical reasons and various verification procedures are not accepted in all countries, it is likely to be very difficult to define such procedures. Therefore, a first approach should be to define design processes and subsequently try to find and define common design principles (see **Error! Reference source not found.**)

B2.6 Inconsistencies and proposals for improvement

Clauses not compatible with tunnel design:

- No significant incompatibilities were identified so far.

Clauses unclear or problematic for tunnel design:

- Consideration of design approaches (verification cases) with appropriate factoring approaches and values of partial factors. The intention in the draft of the Second Generation EN 1997 to make the calculation of all combinations for the verification cases mandatory cannot be implemented in tunnel construction due to the complexity and size of the models.

Expected requirements not sufficiently covered in the code:

- No urgent needs identified.

Expected recommendations not sufficiently covered in the code:

- No urgent needs identified.

Items that should be included in the code as NDPs:

- Values of additional tunnelling-specific partial factors that might be needed.

- Calculation approaches for face stability should be defined in the national annexes

B2.7 References to Annexes B2

[1] EN 1992-1-1 Eurocode 2: Design of concrete structures - Part 1-2: Design of concrete structures – Part 1-1: General rules for buildings

[2] EN 1997-1 Eurocode 7: Geotechnical Design – part 1: General rules.

[3] RVS 09.01.42 (2011)., Tunnel structures in soft soil under built-up areas (German only)

[4] M. Brandtner, M. Hofmann, A. Paternesi, E. Saurer, H. F. Schweiger und H. Walter, Design strategies for sprayed concrete linings, Geomechanics and Tunnelling, Vol. 11, Nr. 5, 2018

[5] P. A. Vermeer, N. Ruse and T. Marcher, Tunnel Heading Stability in Drained Ground, FELSBAU 20 (2002) NO. 6

[6] Austrian Society for Geomechanics, Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation, Österreichische Gesellschaft für Geomechanik

Annex C. Report on the assessment of applicability of EN 1997 for tunnels and other underground structures

Version 0.8, dated April 2022

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