European
Commission

JRC TECHNICAL REPORTS

Standardisation needs for the design of underground structures

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2019

Joint
Research
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EUR xxxxx xx

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JRC Science Hub
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EUR xxxxx xx

Print	ISBN xxx-xx-xx-xxxxx-x	ISSN xxxx-xxxx	doi:xx.xxxxx/xxxxxx
PDF	ISBN xxx-xx-xx-xxxxx-x	ISSN xxxx-xxxx	doi:xx.xxxxx/xxxxxx

Luxembourg: Publications Office of the European Union, 2019

How to cite this report: 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; Stille, H; Subrin D, *Standardisation Needs for the Design of Underground Structures*, EUR xxxxx EN, Publications Office of the European Union, Luxembourg, 2019, ISBN xxx-xx-xx-xxxxxx-x, doi:xx.xxxx/xxxxxx, JRCxxxxxx

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Foreword

The construction sector is of strategic importance to the European Union (EU), as it delivers the buildings and infrastructure needed by the rest of the economy and society. It contributes to about 9% of the EU's Gross Domestic Product (GDP) and more than 50% of the fixed capital formation. It is the largest single economic activity and it is the biggest industrial employer in Europe.

Tunnel projects in Europe form a large portion of the infrastructure market and there is continuous demand for tunnels. Road and railway tunnels play a central role in the modern economy, with thousands of people and tons of goods passing through them every day. Failure of such critical links may lead to significant disruption of large parts of the European transportation system.

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

The activities on standardisation needs for underground structures are supported by an Expert Group, 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.

Experts were invited to the group, following proposals by Andrew Bond, Chairman of CEN/TC250 Sub-Committee 7 'Geotechnical design' and Roger Frank, Immediate Past President of the International Society for Soils Mechanics and Geotechnical Engineering (ISSMGE) in the period 2013-2017 and former Chairman of CEN/TC250 Sub-Committee 7 'Geotechnical design'. The activities of the JRC Expert Group were also supported by Hans Ganz, Chairman of CEN/TC250 Sub-Committee 2 'Design of concrete structures'.

The Expert Group convened by the JRC consists of the following members (listed alphabetically):

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8. Silvia Dimova, Joint Research Centre of the European Commission, Ispra, Italy
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23. Markus Thewes, Institute for Tunnelling and Construction Management, Germany

The JRC Expert Group on design of underground structures 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 Group will be on tunnels** but some other underground structures 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 harmonization 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 consistence with the Eurocodes and should delineate how to complete and/or restrict their use for tunnels without limiting the required flexibility, having in mind the specificity and diversity of tunnel design. In parallel, it appeared beneficial that the concept shall be consistent with the new developments in the second generation of the Eurocodes expected to be published after 2020.

After the first meeting of the Expert Group in May 2017, the present document on the needs for new standard(s) regarding the design of underground structures was prepared by the JRC, based on the discussions during the meeting and the technical contributions prepared by the experts. The document has been reviewed by the JRC Expert Group, experts from the Directorate-General Mobility and Transport (DG MOVE) and the European Union Agency for Railways (ERA). The draft document was further discussed and finalised in the second meeting of the Expert Group in May 2018 in Ispra (Italy).

Acknowledgements

The work in this report is a deliverable within the framework of a series of Administrative Arrangements between DG GROW and DG JRC on support to policies and standards for sustainable construction.

This report was prepared by the Safety and Security of Buildings Unit of the Directorate for Space, Security and Migration of the Joint Research Centre of the European Commission with the contribution of the JRC Expert Group as listed in the Foreword of this report, in consultation with the Directorate-General Mobility and Transport (DG MOVE) and the European Union Agency for Railways (ERA).

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Abstract

Tunnel projects in Europe form a large portion of the infrastructure market, and there is continuous demand for the construction of new tunnels. Underground structures and particularly **tunnels are unique structures**. Their key design considerations and structural behaviour are different from other structures, such as buildings and bridges, as the main bearing element in tunnels is the surrounding soils and rocks.

Despite the unique characteristics of tunnel design, there are **no currently available European tunnel design standards** or harmonized guidelines at European level. Thus tunnel design in Europe is being carried out based on the national knowledge and experience with the use of industrial/client standards and guidelines, as well as with parts of the EN Eurocodes (EN 1990 – EN 1999). The EN Eurocodes are a set of European Standards (Européenne Normes - EN) which provide common rules for the design of buildings and other construction works to check their strength, stability and fire resistance. However, the scope of the first generation of the EN Eurocodes covers buildings and some other civil engineering works, e.g. bridges, towers, masts, chimneys, silos, tanks, pipelines. There are no parts devoted to the design of tunnels, as the Eurocodes do not include explicitly all underground structures.

In view of the above fact and the strategic importance of the construction industry in the European market, the Joint Research Centre (JRC) of the European Commission started in 2017 **activities on assessment of standardisation needs for the design of underground structures**. The initiative was launched in the framework of the series of Administrative Arrangements between DG JRC and Directorate-General (DG) for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW) of the European Commission on support to policies and standards for sustainable construction. The activities on standardisation needs for underground structures are supported by an **Expert Group on the design of underground structures** convened by the JRC.

The JRC Expert Group on design of underground structures held its first meeting on 22-23 May 2017 at the JRC site in Ispra (Italy). Subsequent to the first meeting of the Expert Group, the present document on the needs for new standard(s) regarding the design of underground structures was prepared by the JRC, based on the discussions during the meetings in May 2017 and May 2018, and the technical notes prepared by the experts.

The document delineates 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 harmonization of design rules between countries**. It appears suitable that the concept of new standards or guidelines for the design of tunnels shall be developed in line with the EN Eurocodes and delineate how to complete and/or restrict their use for tunnels without limiting the required flexibility, having in mind the specificity and diversity of tunnel design. In parallel, it would be beneficial that the concept will be consistent with the new developments in the second generation of the Eurocodes currently under development and expected to be published soon after 2020. Further, it is evident that there is need to (i) define what is specifically being used for tunnel design from the current 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 with tunnels.

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 next steps, it is considered important for the Expert Group to brief CEN/Technical Committee 250 "Structural Eurocodes" (CEN/TC250) on its views on the standardisation

needs for the design of tunnels. Thus, the Expert Group intends to prepare brief material for CEN/TC250 with list of issues: (i) covered in the Eurocodes and used for tunnelling; (ii) not covered in the Eurocodes but can be included in the future; and (iii) covered in the Eurocodes, but should not to be used in their present state for tunnelling. In addition, the Expert Group foresees to compile a list of existing documents and sources of guidance related to the design of tunnels in international, European and national level. In the next two to three years (2018-2020), the goal is to prepare a report on the use of standards and guidance for the design of tunnels in Europe, presenting the issues not covered by the EN Eurocodes, consolidating sources for guidance and discussing the JRC Expert Group views on further standardization needs for tunnels and some other underground structures, when appropriate.

1 Introduction

Underground structures and particularly tunnels are unique structures. Their key design considerations and structural behaviour are different from other structures, such as buildings and bridges, as the surrounding geotechnical environment is part of the tunnel bearing capacity and construction. Tunnels require a very particular design with respect to the specific geotechnical conditions and their interaction with the buildings and infrastructure around them requires detailed consideration. The mean bearing element in tunnelling is the surrounding soils and rocks and one of the main 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 thestress-state to a minimum. As a result, a 24/7 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.

However, due to the absence of bespoke European design standards for the underground structures, tunnel design in Europe is currently being carried out by adapting some of the EN Eurocodes or by using national guidelines and recommendations. The EN Eurocodes, i.e. the series of 10 European Standards EN 1990 – EN 1999, provide a common approach for the design of buildings and other civil engineering works and construction products. However, the EN Eurocodes have no parts devoted to the design of tunnels as their original scope was not to include explicitly all underground structures. The lack of an applicable set of European-wide common design rules for underground structures, and particularly tunnels, has primarily motivated the proposal described within the report. No less important, this proposal is driven by the fact the tunnelling market in Europe is one of the most globalized segments of the construction sector. Contractors are very specialized, 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, and form, in most cases, part of large infrastructure investments usually publicly funded. Thus, there is need to maintain a high level of technical proficiency in the European tunnelling construction and promote the competitiveness of this sector worldwide.

1.1 Rational and policy context

The policy context of this proposal is set within the Directive (EU) 2016/797[1], Regulation (EU) No 1315/2013[2] and Directive 2004/54/EC[3], as described in the following.

Directive (EU) 2016/797 on the interoperability of the rail system within the European Union (recast) has as objective the technical harmonization 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). It stipulates, "*TSIs may make an explicit, clearly identified reference to European or international standards or specifications or technical documents published by the Agency where this is strictly necessary in order to achieve the objectives of this Directive. In such a case, these standards or specifications (or their relevant parts) or technical documents shall be regarded as annexes to the TSI concerned and shall become mandatory from the moment the TSI is applicable. In the absence of such standards or specifications or technical documents, and pending their*

[1] 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.

[2] 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.

[3] 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.

development, reference may be made to other clearly identified normative documents that are easily accessible and in the public domain."

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. They cover the technical standards and define priorities for the development of the TEN-T. 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 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.

1.2 The EN Eurocodes and tunnel design

The scope of the first generation of the EN Eurocodes (EN 1990 – EN 1999) covers buildings and some other civil engineering works, e.g. bridges, towers, masts, chimneys, silos, tanks and pipelines. There are no parts devoted to the design of tunnels, as the programme of the Eurocodes does not include explicitly all underground structures. The works on the so-called "second generation of the Eurocodes", as mandated by the European Commission[4], do not also encompass the design of tunnels.

However, it is very important to note that the current versions of EN 1990 ("Basis of structural design"), EN 1992 ("Design of concrete structures") and EN 1997 ("Geotechnical design"), or some aspects of them, are presently partially being used for the design of tunnels. This use opens gaps in terms of different interpretation, depending on the particular country and the level of experience of the designers and contractors. Acknowledging this fact calls for the need to elaborate documents explicitly developed for tunnel design, in order to fulfil the obvious gaps left open by the Eurocodes (not originally meant for dealing with tunnels) and to counteract the misuse of them in some aspects of tunnel design.

In particular, EN 1997 "Geotechnical design" (Eurocode 7), 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. It is admitted that the clauses covering geotechnical design for 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. Two of the most important are the following: the first relates to the initial scope of the Eurocodes as described above, where as the second one is that EN 1997 (Eurocode 7) covers, in principle design for Geotechnical Category 2 and not Geotechnical Category 3[5]. All tunnels, except tunnels in hard, non-fractured rock and not subjected to special water tightness or other requirements, were classified as Geotechnical Category 3 in EN 1997 "Geotechnical design" - Part 1: General rules.

In the period before the introduction of the Eurocodes, the global factor of safety concept and former geotechnical standards were widely applied in tunnelling. The situation

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

[5] According to EN 1997, **Geotechnical Category 1** includes small and relatively simple structures for which is it possible to ensure that the fundamental requirements will be satisfied based on experience and qualitative geotechnical investigation with negligible risk For this category simplified procedures may be applied. **Geotechnical Category 2** includes conventional types of structure and foundation with no exceptional risk or difficult soil or loading conditions. **Geotechnical Category 3** includes structures or parts of structures, which fall outside the limits of categories 1 and 2, for example: unusual structures, structures involving difficult soil, structures in highly seismic areas.

changed fundamentally with the introduction of the Eurocodes and the associated concept of partial safety factors in design. Although the application of the Eurocodes to tunnelling was never really planned and it is not clearly regulated as already noted the consideration of EN 1997 concept and rules is demanded sometimes by the client. Since actions and resistance cannot be distinguished clearly in tunnelling, problems arise when checking the ultimate limit state, especially in cases where nonlinear material models are deployed and the strength of the material is reached in certain regions. This often occurs in tunnelling and does not necessarily lead to collapse. This situation is not a consequence of the Eurocodes concept, but it is more an issue of plasticity in general. Yielding limit and concept of safety factors should be applied with caution.

Overall, considering the current status of standards for design of tunnels in 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) falls down to the designers. However, it should not be their 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 tunnelling purposes, does not absolve the designer from this responsibility. This issue is of even more concern in regard to the life-cycle of the structure. 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[6]. In that regard, tunnels are more closely related to bridges, which are often expected to last for at least 100 years. As the example of London Underground shows, some tunnels are in service for even longer periods of time. Although it is sometimes postulated that adjusting for longer life-cycle of the structure might require an increase in partial safety factors, in order to achieve sufficient reliability level for longer reference period, care has to be taken to avoid excessive conservatism and limit unnecessary expenses (Spyridis, 2014).

More precisely, some of the main issues of tunnel design are the overall approach for safety/reliability of these important structures with long service life, ground conditions and assumed properties, relevant actions, adequate consideration of ground-structure interaction. Once these are all adequately considered and effects of actions determined, the actual design/dimensioning of structural elements in concrete or steel or other material may usually follow the provisions of the Eurocodes and in particular EN 1992 “Design of concrete structures” and EN 1997 “Geotechnical Design”. Hence, what is currently missing and primarily needed in future for tunnel design are documents / regulations which define the overall approach / concept including addressing these issues mentioned above before dimensioning of structural elements may be performed.

At the same time, there is a need to address questions related to tunnel design with regard to other issues covered by the Eurocodes, such as:

- the design of tunnels in soils and rocks (with reference to the future EN 1997, which should be extended to cover geotechnical design in rocks);
- 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 masonry linings (with reference to EN 1996);
- 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. fore polling, umbrella arch, mechanical pre-cutting);

[6] However, it is noted that EN 1990 provides some guidance in Annex B for structures with design life of 100 years and structures with higher Consequence Class than typical buildings.

- the assessment and retrofitting of existing tunnels (with reference to the related Eurocodes currently in preparation);
- the protection of tunnels against fire (with reference to the appropriate parts of the existing Eurocodes).

As regards the second generation of the Eurocodes, it is foreseen that the revised EN 1997 will contain a part devoted to geotechnical constructions, such as slopes, spread foundations, pile foundations, retaining structures, etc. Rock mechanics will be dealt with to a certain extent (phase 3 of the Eurocodes second generation work). CEN/TC250 Sub-Committee 7 (SC7) experts have the task of ensuring the compatibility of rock mechanics with the limits states concept. Anyhow, the present programme for the revision of EN 1997 does not intend, for the time being, to deal with tunnelling either in soils or in rocks.

Evidently, the specificities of tunnels will have to be taken on board and the differences with the design for other structures will need to be explicitly addressed. Thus, the design of tunnels could be the scope of a completely separate set of documents consistent with the Eurocodes, i.e. European tunnelling design guidelines where guidance is given on how to apply the Eurocodes in tunnelling and rules are provided where the specific requirements exceed the Eurocodes. Alternatively, a number of Annexes to the existing Eurocodes may cover the specific design /dimensioning issues of tunnels not currently covered by structural Eurocodes. The decision will depend, of course, on the nature and extent of the clauses drafted for all the aforementioned issues. It is also clear that designers are expecting to find in these documents a set of clauses, recommendations or guidelines defining the correct approaches for the design of tunnels and thus stating which are the inappropriate ones.

2 Interested parties

A new standard for the design of tunnels can address the needs of various stakeholders, including national authorities and regulatory organisations, industrial organisations, designers, contractors and clients.

This section identifies interested parties for standardisation in the design of underground structures, focusing on regulatory and standardization organisations and industrial organisations.

2.1 European regulatory and standardisation organisations

- CEN Technical Committee 250 'Structural Eurocodes' (CEN/TC250): CEN/TC250 and in particular Sub-Committee 7 (SC 7) is aware of the JRC initiative to prepare a document addressing the standardisation needs for the design of underground structures. CEN TC250 has been briefed on the Expert Group set up by the JRC and the preparation of the justification document on standardisation needs for tunnel design as its first activity. JRC has been regularly updating TC250 and the Coordination Group (TC250 CG) on the progress of the activities. The fact that a past Chairman of TC250/SC7 and the current Chairman of TC250/SC2 are members of the Expert Group strengthens the link with TC250.
- European Organisation for Technical Approvals (EOTA): EOTA works in close co-operation with the European Commission, the EU Member and EFTA States, the European Standardisation Organisations, and other stakeholders in research and construction such as European Contractors' Associations, Manufacturing Associations, Technical Associations, and European Research Associations. It also deals with other matters concerning the availability and the use of construction products and the facilitation of innovation in construction. Thus, activities for standardisation in the design of tunnels are of interest to EOTA and in line with its mission.
- European Union Agency for Railways (ERA): ERA contributes, on technical matters, to the implementation of the European Union legislation aiming at improving the competitive position of the railway sector by enhancing the level of interoperability of rail systems, developing a common approach to safety on the European railway system and contributing to creating a Single European Railway Area without frontiers guaranteeing a high level of safety. ERA is aware of the activities on standardisation needs for underground structures, with focus on tunnelling, and the agency is regularly updated on the progress of the tasks.

2.2 European organisations, national standardization bodies, regulatory authorities, companies and organizations

- European Construction Technology Platform (ECPT): it is possible that the proposals in this document might be of interest to the ECPT. in view of the fact that one of its committees focuses on infrastructure and mobility. The committee assesses the need to comprehensively tackle the challenges infrastructures are facing and thus the design of tunnels based on harmonized European standards is in line with the committee's scope.
- Association of the European Rail Infrastructure Managers (EIM): EIM represents the common interests of the European Rail Infrastructure Managers and is dedicated to improve railway infrastructure management and the services provided.
- National Standardization Bodies like Association Française de Normalisation (AFNOR), the British Standards Institution (BSI), Standard Norge, the Swedish Standards Institute, Icelandic Geotechnical Society, etc.

- National Regulatory Authorities like the Ministry of Ecological and Solidarity Transition in France, the Finnish Transport Administration Liikennevirasto, the Norwegian Road Administrations Statens Vegvesen and Nye Veier, the Norwegian Railway administration BaneNOR, etc.
- In Sweden, the Swedish Transport Agency, the Swedish Transport Administration and the Swedish National Board of housing, building and planning, public transport administration in various cities and regions like Stockholm metro's SLL: Stockholms Läns Landsting.
- In Italy, the Italian Railway Network Company (RFI), Società Italiana Gallerie (SIG), Associazione Geotecnica Italiana (AGI).
- In France, public clients as: Société nationale des chemins de fer français (SNCF Réseau), Société du Grand Paris (SGP), Tunnel Euralpin Lyon Turin (TELT), Agence nationale pour la gestion des déchets radioactifs (ANDRA), etc.
- Privately owned-public funded organisations in the U.K., such as National Grid, Network Rail, Transport for London, High Speed 2, Water Companies etc.; also the British Tunnelling Society, U.K.,
- Various Engineering offices and contractors in the EU and third countries.

2.3 Potentially interested international parties

- International Organization for Standardisation (ISO): the works on standardisation for the design of underground works are of interest to ISO/TC 182 'Geotechnics'[7] and may be of interest to ISO/TC 98 'Bases for design of structures'[8].
- International Society for Soils Mechanics and Geotechnical Engineering (ISSMGE)[9]: there is a strong link with the society through the Immediate Past President (2013-2017) and members of TC204 'Underground Construction in Soft Soil' (TC204 Chair and three TC Nominated members are members of the JRC Expert Group on design of Underground Structures).
- International Tunnelling and Underground Space Association (ITA – AITES)[10]: the activities of the expert group are related to several Working Groups (WGs), namely WG2 Research, WG14 Mechanized Tunnelling and WG19 Conventional Tunnelling; additionally ITAtech Committee and ITACosuf Committee and all the national tunnelling associations affiliated to ITA are potentially interested in the standardisation activities for tunnels.
- International Society for Rock Mechanics and Rock Engineering (ISRM)[11]: there is potential link of the expert group activities with the Commission on Subsea Tunnels and the Commission on Evolution of EN 1997 and all the national rock mechanics associations affiliated to ISRM.
- International Federation for Structural Concrete (*fib*)[12]: fib's mission is related to advancing in an international level the technical, economic, aesthetic and environmental performance of concrete construction. As structural concrete plays a primary role in the realisation of tunnel structures, the activities of the expert group are related to the work of Commission 1 (COM1): Concrete Structures and in particular TG1.4 Tunnels.

[7] https://www.iso.org/committee/54054.html
[8] https://www.iso.org/committee/50930.html
[9] https://www.issmge.org/
[10] https://www.ita-aites.org/
[11] https://www.isrm.net/
[12] https://www.fib-international.org/

— World Road Association (PIARC)[13]: PIARC has recommended taking into account the objectives of Directive 2008/96/EC on road infrastructure safety management, in the context of road tunnels, when implementing Directive 2004/54/EC on minimum safety requirements for tunnels in the trans-European road network. Further, the PIARC Committee on Road Tunnels publishes the "Manual of Road Tunnels" which presents various topics related to the operation of road tunnels and thus will be interested in the document discussing the standardisation needs for underground structures.

— Foundation for education and training on tunnelling and underground space use (ITACET Foundation)[14]: ITACET Foundation activities focus on education and training in tunnelling and underground space use.

— International Road Federation (IRF)[15]: IRF's mission encompasses the assistance to countries in progressing towards better, safer and smarter road systems and forming a global network for information exchange and business development. As tunnels are an important part of road systems, standardisation needs for their design is of interest to IRF.

— International Union of Railways (UIC)[16]: UIC, is an international professional association representing the railway sector and promoting rail transport.

Further, the International Tunnelling Insurance Group (ITIG) produced in 2006 the document entitled 'A Code of Practice for Risk Management of Tunnel Works' (ITIG, 2006) to reflect the concern of the Insurance industry of risk management in tunnel design and construction. It is based on the equivalent British document first published in 2003 (BTS, 2003). This is another area where lack of coherent approach can lead to an increased risk profile. Thus, the ITIG will be interested in the activities of the JRC Expert Group and the present document.

[13] https://www.piarc.org/en/
[14] https://www.itacet.org/
[15] https://www.irf.global/
[16] https://uic.org/

3 Timeliness

This section discusses the market situation for underground structure, related future trends and the potential for future development. Following, a short review on the current status of standards for the design of tunnels is presented.

3.1 Market situation and further trends

Underground construction will persist strongly in the future years, both in Trans-European Transport Networks (TEN-T) and in urban areas, which are expected to grow in the coming decades. Utilizing underground space for other purpose than transportation is also forecasted to increase like storage of different kinds, tunnels for irrigation, water supply, sewage and sewage treatment.

The increased activity in underground works affects existing neighbouring infrastructure both underground and on the surface, and is expected to increase the level of difficulty that designers will be encountering. Tunnelling projects, due to their unique nature, can be considered as large geographically distributed systems (O'Rourke, 2010), which puts them at a different scale from most building and civil engineering works. In comparison with other construction activities, a limited number of highly specialized tunnelling contractors are present on the European market. Their activities are not often limited to a single country and they are providing their services across Europe or even worldwide.

Furthermore, the developments in the infrastructure sector, often receiving considerable funding by the EU, are expected to continue. This includes investments in new roads, metro, and railway tunnels, as well as the refurbishment of existing ones to extend their lifetime. The scale of new investments varies as well, from relatively small and standard projects (e.g. II metro line in Warsaw, Poland), to bold undertakings pushing the boundaries of civil engineering (e.g. Grand Paris Express in France and the Stockholm City Line), which may give birth to new ideas and require innovation.

As explained above, the tunnelling market is characterized by a small number of clients and contractors (*Bilateral Oligopoly*). For example, in **Germany** there are about 10-15 contractors in total that are providing tunnel construction works, for a limited number of clients including:

- the Federal Republic (road tunnels and railway tunnels via Deutsche Bahn Group);
- 16 Federal States (road tunnels, metro tunnels);
- cities and communities (road tunnels, metro tunnels, large sewers or large pipes);
- energy suppliers (caverns, large pipes).

These clients have planned 127 projects of tunnels with a total length of 212 km over the next 20–30 years in Germany. The cost range of one meter tunnel is €20,000 to €30,000 for non-adverse geotechnical conditions and infrastructure/buildings around which are not very sensitive to interactions with the tunnel. In adverse geotechnical conditions and/or presence of sensitive buildings/infrastructure around, the costs can rise by factors of 2 to 4 to the above quoted costs. Having in mind these costs, the investment for the planned tunnels is expected be of the order of €4.24 bn as lower estimate.

Similarly to Germany, perspectives in underground structures construction industry in **France** are very promising, including three mega-projects that may well illustrate the increasing national market within the next few decades:

- Grand-Paris-Express project: 160 km of tunnels and 70 metro stations are expected to be completed before 2030 with a particularly active phase until 2024 by the owner Société du Grand Paris (SGP);
- Lyon-Turin railway line directed by Tunnel-Euralpin-Lyon-Turin (TELT): more than 160 km of galleries are planned to be constructed under the Alps with a peak of the activity between 2022 and 2025;

— Nuclear waste underground disposal CIGEO project of ANDRA (French national radioactive waste management agency) - a roughly estimated length of 150 km of tunnels at 500 m depth with particular trends related to radioactive materials are expected to be constructed within the next 100 years or so.

As a reference, there have been a total of 20 large-diameter Tunnel Boring Machines (TBM) underworks in France within the past 15 years, mainly for metro or railway lines and road tunnels, whereas up to 20 TBM per year are expected to be in action just for the Grand-Paris-Express project within the next 10 years. Furthermore, the total sales revenue of the underground works is basically in the order of €1bn per year in France. It is expected to reach more than €4 bn per year only for that specific project as well.

In the **United Kingdom**, there are many tunnelling projects to be mentioned: High Speed 2 – Phase 1: 40 km of Twin Bored Rail Tunnels (£50 bn); Crossrail 2 (London): 35 km Rail tunnels (£29 bn); Thames Tideway (£4.2 bn, under Construction 35 km and 23 shafts in the biggest Hydraulic projects in the UK); Highways England £6 bn programme including Stonehenge and Lower Thames Crossing (15.7mID) Tunnels; National Grid (Power Tunnels), including a programme of more than 40 km of new tunnels; Transport for London (TfL) Underground Stations programme upgrades will exceed £1bn per year for the next 5 years; New nuclear facilities programme involves tunnels and underground structures (£20 bn).

In **Finland** also private companies, banks and insurance companies facilitate tunnel projects for their own needs. Additionally Wastewater Treatment plants, drinking water facilities, municipalities, real estate companies, nuclear authorities and respective companies are having tunnels and are requesting the construction of new tunnels. Nuclear waste underground disposal is already under construction in Finland (ONKALO in Olkiluoto, Eurajoki). Such projects have even more demands and constraints from a nuclear safety point of view, which makes tunnel engineering even more special for these facilities.

Finland and **Estonia** are planning to be connected by a railway tunnel as part of the European Rail infrastructure network with length of over 100 km, and this will be the longest railway tunnel in the world (note: the longest tunnel in Finland is the Päijänne drinking water tunnel for the city of Helsinki, length 129 km).

Norwegian road and railway administrations have over 100 km of tunnels in the pipeline for the coming years. One of them is a 26 km long highway tunnel E39 under the sea. Another interesting example is tunnel for ships from one sea fjord to another fjord.

In **Poland,** the number of clients is limited to three main investors:

— Highways and Road Administration (Generalna Dyrekcja Dróg Krajowych I Autostrad) - road tunnels;

— Railway Administration (Polskie Linie Kolejowe) – railway tunnels;

— Cities (Warsaw, Wroclaw, Cracow) – metro tunnels, tramway tunnels, sewers and large pipelines.

The contractors (also in number of 10-15 like in Germany) and tenders participants are coming from Europe (mainly from Italy, Germany and France) cooperating with Polish sisters companies. The value of Polish market in terms of tunnels and other underground works is about €3,6 m (15 000 000 PLN). Current tunnelling activities in Poland are focused on road and metro tunnels. Tenders for railway tunnels are in progress. Cut and cover and TBM methods are in use. Because of the geographical and geological context, only 20% of tunnels are constructed using the conventional "New Austrian Tunnelling Method" (NATM method).

Practically, identical is the situation in the rest of the EU countries, where although the tunnelling market encompasses relatively small number of "market participants" and projects, the financial investments are high. Overall, considering the forecasts regarding the development of the traffic, it is very clear that the increase of new transportation facilities, but also the required increase in the efficiency of the existing ones are of major importance.

Additionally, tunnels are becoming preferred to overpasses for transport systems, when the protection of landscape and residents are being taken into account, a fact that underlines the importance of developing technologies for this kind of infrastructure as an important component for citizen’s safety. Therefore, the tunnelling market will be a growing market, for which the future trends will be dominated by the requirements for:

— increase of transportation facilities;

— increase of the efficiency of existing transportation facilities;

— emission protection;

— health, safety and well-being aspects.

In parallel with building new tunnels, the issue of assessment and retrofitting of the existing ones which are very old (> 60 years), is becoming progressively of major importance. New guidelines or standards will allow to better address the tunnel’s lifecycle and will directly address the safety of aged tunnels. In addition to retrofitting of aged tunnels, the upgrade and extension of existing tunnels has been an issue these last years: addition of cross passages or second tubes for safety reasons usually comes with a direct involvement with the geotechnical and structural regime around the existing tunnels.

Based on the above considerations, the timeliness and urgency of having standards for design of underground structures is becoming apparent. It is further reinforced when considering the possibilities that such standards could provide opportunity to many European companies to respond to the calls for tenders all around Europe. From this particular point of view, the expected civil works are a positive argument, or rather an opportunity, for the need of well-structured and common/harmonized guidelines on tunnelling designin Europe.

3.2 Potential for future development

The unique nature of tunnels, in comparison to other types of structures, results, among other factors, from their ground-structure interaction characteristic. Regarding the life-cycle of the structure, most tunnels should probably be designed in a similar way to bridges, namely with longer serviceability period in mind, often 100 years or more, as well as higher standards related to quality control, design verification and site supervision.

In view of the increasing number of existing tunnels, management of existing ageing tunnels and maintenance of their structural reliability will gain importance. Infrastructure budget allocation already shows a significant relative shift from new tunnels to upgrading, extension and refurbishment of existing tunnels. This trend will increase even further with the growing number of existing tunnels and underground systems in operation.

Urban development and upgrade will result in the fact that green field projects in urban areas are the exception rather than the rule and there will be increasing demand for available underground space in the European cities. In parallel, the influence of constructing new tunnels entails the need of properly assessing and mitigating the effects of tunnelling on existing structures both under and above the ground.

Upcoming innovations in construction techniques and new materials will improve cost-effectiveness and safety and challenge clients, designers and contractors to adopt them in future projects – even if they are not covered by existing standards.

Developments in tunnel design and execution are inhibited not only by technical issues that a new standard could help to overcome to some extent, but also by issues associated with contractual matters. Two of the major fields for future development within the tunnelling construction market comprise:

— construction of new tunnels related to new transportation, water supply, wastewater treatment or energy facilities;

— upgrade and strengthening of existing tunnels.

The developments in the field of new tunnels are mostly technical ones, such as

— tunnel excavation and lining construction techniques;

— high performance fibre reinforced composites / polymer concrete;

— Smart (real-time) Monitoring & Non-Destructive Testing;

— waterproofing & sealing against high water pressure;

— fire protection of the tunnel structure and evacuation facilities;

— long- term serviceability, e.g. durability assessment and modelling.

Because of the increasing potential for market opportunities in the field of underground structures in various EU countries (e.g. France, Germany, Sweden) discussed in section 3.1, new skills and knowledge need to be acquired in various emerging areas by stakeholders involved in tunnel design and construction as follows:

— Skills development: to assess, what type of training is needed for stakeholders involved in underground works (i.e. engineers, skilled workers, drillers, TBM pilots, etc.) especially regarding geotechnical and structural design;

— Knowledge representation and management systems: what level of importance has to be given to investigation surveys and required instrumentation;

— Underground heritage management: assess how to ensure the adequate level of structural safety in construction works both in the short and long term.

Stakeholders' responsibilities as defined within national legislative and regulatory documents and within the tenders should also be an essential concern. The application of Eurocodes to the design of underground structures, or the development of specific EU standards or guidelines shared at the European level, could be clearly a positive element. However, the standards for design of underground structures must be based on the particular circumstances connected to design of underground openings. General rules developed for structural design using materials with selected properties (like concrete and steel) cannot be directly applied for designing of rock and soil material with properties defined by the geotechnical investigations. Thus, the Eurocodes safety factors concept has to be used with caution since the geotechnical parameters are very important for assessment of the potential failure mechanisms. Relying only on the safety factors without thorough understanding of the geotechnical conditions will lead to possible inappropriate justifications.

3.3 Current status of standards for design of tunnels – Eurocodes and international and national standards

3.3.1 The Eurocodes and international standards

The Eurocodes that are mostly used in tunnel design are EN 1992 "Design of concrete structures" and EN 1997 "Geotechnical Design". In the present state, EN 1990 "Basis of structural Design" is also used in tunnel design practice. The EN 1990 aspects of design assisted by testing described in EN 1990 are also used in tunnel design.

The current **EN 1997 "Geotechnical design"** standard includes mainly 'soil' ground condition. In underground structure design however, the ground condition differentiates the construction/excavation method of the ground, and also the type of the ground support both for the temporary and permanent condition – e.g. rocky ground condition may require blasting and rock bolt. EN 1997 does not cover such ground conditions. Moreover, another key element for tunnel design, namely the ground-structure interaction for underground structures is not covered by EN 1997, except for structures excavated from surface (embedded or nailed walls).

EN 1997 does not expand enough the interactive design method (so called "Observational Method") and the application of Prescriptive Measures – these are methods commonly used for verification of design in rock mechanics. Further, EN 1997 only describes actions where bearing capacity and load effect can clearly be separated. It does not cover the ground-structure interaction, which is the governing behaviour of all rock tunnels. The partial factors proposed for ground water loading are sometimes considered unrealistic – e.g. for the case of deep tunnels when the ground water table is close to the surface.

Moreover, although the impacts of a construction on neighbouring structures and ground environment are not formally recognised in the EN 1997 limit states, often they are one of the most important aspects in tunnel design for two reasons:

- primarily, due to technical reasons, as excessive deformation and/or vibration of the soil or rock due to construction activities or due to its presence in the final state, or lowering of the ground water level may cause exceedance of the serviceability limit state criteria or even the ultimate limit state in the neighbouring structures; and
- secondly, due to social and administrative reasons, since respecting the interests of third parties (e.g. neighbours) is a requirement for obtaining a building permit in many countries.

The general structural design concept for reinforced concrete structures in **EN 1992** is well covered, but developed for buildings (Part 1-1), bridges (Part 2) and liquid retaining and containment structures (Part 3). However, gaps exist, for example in the structural design of sprayed concrete lining for tunnels, the initial support design of rock tunnels, the ground-structure interaction with appropriate analysis methods and aspects of structural robustness (minimum reinforcement).

The **Eurocodes fire design parts**[17] are developed for buildings; thus for railway tunnels fire design, the Technical Specifications for Interoperability relating to 'safety in railway tunnels' of the rail system of the European Union are used. For the fire design of road tunnels, guidelines by the International Tunnelling Association (ITA) or by the World Road Association are mainly used.

When designing a tunnel for fire resistance, a number of points should be additionally addressed:

- An additional safety objective is the repairability. Different from a building, where from a regulator's perspective it is acceptable if the building collapses after safe evacuation and search by the fire brigade, or if the building needs to be demolished after the fire, this is generally not accepted for tunnels. The costs of fully replacing a tunnel, as well as costs for the society for non-availability of the tunnel, are so high that a tunnel structure needs to be repairable within an acceptably short period of time after a fire. This usually translates into much lower maximum temperature requirements for the concrete structure as well as the requirement that the concrete must not spall.
- The temperature development during a tunnel fire is usually much more severe than in a building fire. This relates to the rate of temperature increase (in a tunnel typically reaching 1000-1200°C within a few minutes) as well as the maximum temperatures (up to 1300-1350°C below the ceiling). Fire curves as currently provided in EN 1991-1-2 are not suitable for tunnels.

[17] Eurocodes fire design parts refer to EN 1991 Part 1-2: "Actions on structures exposed to fire" and Part 1-2: "Structural Fire Design" found in EN 1992, EN 1993, EN 1994, EN 1995, EN 1996 and EN 1999.

— Given the fast temperature rise and high maximum temperatures, in combination with a relatively high moisture content inside the concrete (compared to a closed and heated building), concrete tunnel structures are likely to suffer from spalling during fire. In case of unprotected concrete, it will normally start after a few minutes of fire exposure and progressively chip away layers of the cross-section, with rates of (very roughly) several millimetres per minute, and the steel reinforcement will become quickly exposed. Spalling is dependent on a large number of factors, including the concrete's mix ingredients to a level of detail (mineralogy, particle sizes etc.) that is normally not specified for a project but left to the concrete plant within certain limits. For this reason, once tested spalling-free mixes tend to change over time when applied to different projects, and the spalling sensitivity may drastically increase, as demonstrated by recent research of the Ministry of Infrastructure and Water Management in the Netherlands.

— Tunnel structures are generally of different geometries (mainly walls, slabs) and are to a certain extent restrained against thermal expansion. In order to evaluate the ability of a passive fire protection system to avoid spalling of a given concrete tunnel structure, dedicated fire tests are necessary. Such concrete spalling test procedures are described in different standards such as NFPA 502 (2017), ASTM E3134 (2017) and the RWS test procedure 2008-Efectis-R0695 (Breunese et al., 2008).

Regarding the seismic actions for underground structures, EN 1998–Part 4: "Silos, Tanks and Pipelines" specifies principles and application rules for the seismic design of the structural aspects of facilities composed of above-ground and buried pipeline systems and of storage tanks of different types and uses, as well as for independent items, such as for example single water towers serving a specific purpose or groups of silos enclosing granular materials, etc. Only one section in EN 1998-4 (Section 6) describes specific application rules for buried pipelines and Informative Annex B: "Buried Pipelines" is about seismic actions. EN 1998-4 covers safety requirements, seismic action, methods of analysis, verifications and design measures for fault crossing. The seismic design of underground structures is clearly not a major concern nor the main focus of EN 1998-4. For seismic design reference to ISO 23469 and ISO/TR 12930:2014 should be sought.

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 design of tunnels. The works on the second generation of the Eurocodes, as mandated by the European Commission, also do not encompass specifically the design of tunnels. However, some new developments in EN 1997 might accommodate some of the specific aspects of tunnel design – e.g. recently a Project Team within TC250/SC7 was established dealing with the compatibility of rock mechanics with the limits states concept. Future EN 1998-5 will provide a totally new extensive section on the definition of the seismic actions for underground structures like pipelines, tunnels and large underground structures like metro stations. Further, future EN 1992-1-1 is intended to provide non-member specific design rules whenever possible. Hence, design provisions in the second generation of 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 Austria, Germany, Finland, France, Italy, Norway, Sweden and the UK, some of the critical tunnel design aspects which are not covered by the Eurocodes, are covered by national standards, or guidelines (some of them developed by the client), or national and international technical recommendations. Other international and national guidelines or recommendations that can be used for tunnel design include the ITA-AITES (2000) used internationally, the JSCE (2005) in Japan, and FHWA (2009) in the United States. In 2017, AASHTO (American Association of State Highway and Transportation Officials) published a new document titled 'LRFD Road Tunnel Design and Construction Guide

Specifications'. This is based on the FHWA (2009) document, but specifically written for tunnels.

Moreover specific guidelines do exist for the segment lining design in the UK, published by the British Standards Institution (BSI), namely the PAS 8810 (2016) "Tunnel design – Design of concrete segmental tunnel linings – Code of practice". This document limits its application to segment lining's structural design. It is worth mentioning that the British Tunnelling Society (BTS) is currently drafting a design guide for sprayed concrete lining, whereas the American Concrete Institute ACI ComBSe 544 (ACI 544.7R-16, 2016) has recently published a design guide for precast concrete lining.

Some standards published by International Organization for Standardization (ISO) may be used as a basis for structural and geotechnical design of tunnels. However, they generally set up the basic framework for design rather than offering specific design rules. Therefore, they are rarely explicitly used and directly referenced in design.

ISO 2394 ('General principles on reliability for structures') presents the general principles on reliability of structures and covers issues like risk-informed and reliability-based decision making. Additionally, ISO 13824 ('Bases of design for structures – General principles on risk assessment of systems involving structures') presents general principles on risk assessment of systems involving structures, including consideration of hazards, consequences and risk estimation. This risk-oriented approach presented in these standards is in line with current trends and practice used in the design of underground structures, especially, when considering tunnels not as just structures, but as parts of larger infrastructural systems. Moreover, when impact of tunnelling on ground displacement and neighbouring structures is considered, also ISO 13822 ('Assessment of existing structures') and ISO 4356 ('Deformations of buildings at the serviceability limit states') can be used to define general framework on which the design or a new standard can be based. Most of those standards were updated in recent years or their new versions are currently being under development (e.g. ISO 4356).

Generally, even though tunnels are unique structures, their design is mainly being carried out by implementing design standards developed mainly for buildings and other common engineering structures. As a result, designers are many times forced to perform complex numerical analyses due to the complexity of the encountered problem.

3.3.2 National standards for tunnel design

Below, some details for existing technical documents for the design of tunnels at national level are presented. The information presented is not exhaustive but provides an idea for the existing documentation in the EU Member States and EFTA countries.

Austria

One of the few standards issued by the Austrian Standards Institute with a direct relation to tunnelling is the ÖNORM B 2203, which regulates in particular directives for tendering procedures and for the preparation of bids besides issues of billing. To cover other issues, such as design and construction, a variety of national guidelines and recommendations have been created.

The following entities that have developed such additional regulations are mentioned:

- Austrian Society for Construction Technology (OEBV) (http://www.bautechnik.pro/EN)
- Austrian Society for Geomechanics (OeGG) (https://www.oegg.at/en/)
- Austrian Research Association for Roads, Railways and Transport (RVS – FSV) (http://www.fsv.at/cms/start.aspx?LN=EN)

The EN 1997-1 design approach DA2* (characteristic material parameters with factorisation of the effects of actions for the concrete design) is commonly used by designers in Austria. According to the Austrian National Annex to EN 1997, DA3 can also be applied for numerical methods.

As a supplement to the Eurocodes and helping designers to avoid misinterpretations, the following guidelines and recommendations are available in Austria (in extracts):

Austrian Society for Geomechanics (OeGG) Guidelines:

- Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation
- Guideline for the Geotechnical Design of Underground Structures with Mechanized Excavation
- Recommendation for the design of sprayed concrete linings

Austrian Society for Construction Technology (OEBV) Guidelines

- Guideline for Sprayed Concrete
- Guideline for Concrete Segmental Lining System
- Guideline for Inner Concrete Linings
- Guideline for Tunnel Waterproofing
- Guideline for Waterproof Concrete
- Guideline for Fibre Reinforced Concrete
- Guidelines for Fire Design of Underground Structure

Austrian Research Association for Roads, Railways and Transport (RVS) Guidelines

- Guideline for Cut and Cover Construction Method
- Guideline for Shallow Tunnels in soil in Urban Areas
- Guideline for Tunnel Ventilation
- Guideline for Interior Construction
- Guideline for Tunnel Equipment

In coexistence with national guidelines, it has been possible in recent years to develop a more-or-less Eurocodes-compliant approach for the design of tunnels. Nonetheless, a harmonised approach set by the Eurocodes is the preference of the tunnelling community in Austria.

France

The French Tunnelling Association (AFTES) gathers all stakeholders involved in tunnels, providing exchange of knowledge between owners, transport operators, construction companies, designers, engineering consultants, suppliers and universities. The key goal of such exchange is to elaborate on key guidelines which aim at recommending organization processes and technical advices. Those are not mandatory for tender and contracts but reference to them is largely done within the projects.

AFTES provides a wide technical baseline for tunnels design which however is neither exhaustive nor complete and scientific guidance and/or research may be needed to implement correctly the recommended methods. AFTES recommendations are available at http://www.aftes.asso.fr/publications_recommandations.html .

The main recommendations about geotechnical data and structural tunnel design include:

- Geotechnical data: Characterization of rock masses useful for the design and the construction of underground structures (GT1R1A1 2004); The choice of geotechnical parameters and tests useful to the design, dimensioning and construction of underground structures (GTR4A1 1999); Characterisation of geological, hydrogeological and geotechnical uncertainties and risks (GT32R1A1 2012).

- Conceptual calculation methods: Considerations on the usual methods of tunnel lining design (GT7R2A1 1993), choice of tunnel support (GT7R1A2 1993), convergence-confinement method (GT7R6A1 2002), tunnelling-induced effects on neighbouring structures in the design and construction of underground works (GT16R2A1 2018).
- TBM, shields and segments: The design, sizing and construction of precast concrete segments installed at the rear of a tunnel boring machine (TBM) (GT18R1A1 2005), Design, dimensioning and execution of precast steel fibre reinforced concrete arch segments (GT38R1A1 2013).
- Conventional support and lining: design of sprayed concrete for underground support (GT20R1A1 2001), compatibility of AFTES recommendations with the Eurocodes for concrete final lining (GT29R2F1 2007 in French), design of radial rock bolting (GT30 R1F1 2018).
- Earthquake Design and Protection of Underground Structures (GT22R1A1 2002).

Germany

In Germany, there are no national technical standards for the design of tunnels but a lot of client-specific technical rules set up and applied by road and railway national authorities. Such specific technical rules partly refer to specific parts of related Eurocodes. In particular, a list of available rules for road tunnels, railway tunnels and general design recommendation is provided below.

Road Tunnels:

- Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten (ZTV-ING), Teil 5 Tunnelbau (Technical contractual terms and conditions and guidelines, part 5: Tunnel construction)
- Richtzeichnungen für Ingenieurbauwerke (RiZ-ING) (Technical drawings for infrastructure)
- Richtlinien für das Aufstellen von Bauwerksentwürfen für Ingenieurbauten (RAB-ING) [früher (RAB-BRÜ)] Guidelines for the design of infrstructure
- Richtlinie für die Ausstattung und den Betrieb von Straßentunneln (RABT) (Guidelines for the operations and the required layout / safety provisions / service provisions of road tunnels)
- Burbaum, U., Krajewski, W. & Seeger, K. J. (2006): Wirtschaftliche Aspekte bei Tunnelbauwerken in frühen Planungsphasen, Hessisches Landesamt für Straßen- und Verkehrswesen, Heft 52-2006, 60 Seiten (Guidelines for economical tunnel design in early tunnel project design phases, Hessian Road Authority, Germany, Publication nr. 52, 60 pages)

Railway Tunnels:

- Richtlinie (Ril) 853 – Eisenbahntunnel planen, bauen und instand halten (Deutsche Bahn: client standard for the design, construction and maintenance of railway tunnels)
- Ril – Anforderungen des Brand- und Katastrophenschutzes an den Bau und den Betrieb von Eisenbahntunneln Deutsche Bahn: client standard for fire protection and emergency management of railway tunnels)

General Recommendations:

- Empfehlungen des Arbeitskreises „Tunnelbau" ETB, DGGT (Deutsche Gesellschaft für Geotechnik) Recommendations for tunnelling of the German Society for Geotechnical Engineering, working team tunneling

- Empfehlungen zur Berechnung von Tunneln im Lockergestein, Empfehlungen des Arbeitskreises „Tunnelbau" ETB, DGGT (Deutsche Gesellschaft für Geotechnik) Recommendations for structural analysis of tunnels of the German Society for Geotechnical Engineering, working team tunneling
- Empfehlungen STUVA (Studiengesellschaft für unterirdische Verkehrsanlagen) / DAUB (Deutscher Ausschuss für unterirdisches Bauen) Recommendations of the STUVA (Research Association for Tunnels and Transport Facilities e. V.)

Italy

In Italy, tunnel design is performed using the general criteria and partial factors method according to EN 1997 (Eurocode 7), although tunnels are explicitly not addressed, being included in Geotechnical Category 3. Moreover, for aspects regarding the design of concrete structures, EN 1992 is being used.

As a matter of fact, the application of EN 1997 (and EN 1992) to underground structures has been fostered by the Italian Technical Code for Constructions (DM 17/01/2018) which defines general rules and performance according to the Structural Eurocodes for all civil constructions: buildings, bridges, geotechnical structures, and, among them, underground structures. It must be admitted though that some criteria, for example regarding the geotechnical investigation, the geotechnical report and observational method, have been fruitfully applied, giving a framework for common "best practices".

Nonetheless, many specific aspects of tunnel design are not covered by national Italian standards. In some cases (e.g. structural design of sprayed concrete lining and precast segment lining, seismic design and analysis) international guidelines or recommendations are used as reference. Other issues, such as the assessment of tunnel excavation effects on buildings or peculiarities of numerical modelling, are currently addressed by different guidelines issued by the Italian Transportation authorities such as:

- Ferrovie dello Stato Italiane (Italferr): Linee guida per la progettazione geotecnica delle gallerie naturali, 2015 [Guidelines for the geotechnical design of tunnels] (Italferr, 2015)
- Ferrovie dello Stato Italiane (RFI), 2017: Manuale di progettazione delle opere civili. Parte II – Sezione 4. Gallerie [Manual for civil works design –Section n° 4 Tunnels]

A general framework for tunnelling design and construction is provided by the guidelines published by the Italian Tunnelling Society (SIG) "Italian Guidelines for Design, Tendering and Construction on Underground Works" (SIG, 1997) that are currently undergoing an upgrading.

Other aspects related to tunnel durability and performance in operation phase are generally set up by the clients by means of technical guidelines, but coherent and specific guidelines do not exist. A general standard on the maintenance and rehabilitation of existing tunnels is not available as well.

The Netherlands

In the Netherlands the geotechnical conditions are mostly known for the very soft soil. As a consequence there is a lot of experience with cut and cover tunnels and immersed tunnels, but the oldest mechanised tunnel is only 20 years old. Up to the beginning of the nineties of the previous century it was questioned whether or not a TBM could be used in the Dutch soil conditions. The first mechanised tunnels in the Netherlands have brought a lot of measurements on the behaviour of this type of tunnels in soft soil conditions. But, there construction projects have not yet resulted in standards or regulations specific for these conditions.

The Dutch research centre for underground construction (COB[18]) gathers all stakeholders involved in underground construction (tunnels, deep excavations), providing exchange of knowledge between owners, construction companies, designers, engineering consultants and universities. Recently in 2017, COB has published a handbook on tunnel construction including cut and cover tunnels and immersed tunnels, but excluding mechanise tunnels. Handbooks and guidelines of COB are not mandatory for tender and contracts but reference to them is largely done within the projects.

Also in 2017, a project started focusing on the maintenance and refurbishing of the construction of existing tunnels. It may be worthwhile to include also these aspects in the European standards to be developed for tunnel design.

Nordic Countries

In Norway, Sweden, Finland and Iceland, the geotechnical conditions are mostly known for its hard and partly ancient bedrock, often allowing for very large underground constructions, where the rock itself is functioning as the tunnel main construction "material". The world largest underground constructions are mostly found in Northern Europe, like the Norwegian's Gjøvik Olympic hall with a span of 61m, Salmisaari underground Stone Coal Storage halls in Helsinki with a circular span of 4 times 42 m and Leppävirta's underground cross country ski hall in Central Finland with a span of 41 m.

During early design stages one often relies on the Norwegian Handbook of the Q-system[19]. In Norway there are also national guide books for road tunnelling (Håndbok N500 Vegtunneler[20]) and bolting reinforcements (Håndbok V224 Fjellbolting[21]). The empirical system of using Q-values allows having a good primary indication of the support necessary, as in most of the cases the primary lining of sprayed concrete with rock bolts also functions as the final lining, especially in more straight forward projects. In executive design stages three-dimensional modelling must be conducted to define tunnel engineering aspects more in detail. One of the important stages, nevertheless, is engineering judgement during execution, relying on observations of real conditions and adjusting design in real time. This is especially important in very changing conditions.

Very specific demands in the Nordic countries that need special attention in designing are freezing conditions during winter time, especially for open tunnels, high rock temperature related issues (e.g. in Iceland), very high horizontal stresses (e.g. in Finland's bedrock) and sealing against water leakage.

In coexistence with Norwegian guidelines, there is common understanding on the approach for the dimensioning of tunnels. Nonetheless, a harmonised approach set by the Eurocodes is the preference of the tunnelling design and construction communities in the Nordic Countries. It must be especially stressed out that the potential development of the Eurocodes for use in design of tunnels shall intrinsically focus to geotechnical conditions driven design approach.

In Sweden, there is no national standard for design of tunnels or underground openings. However, the Swedish Transport Administration has set up technical rules and advice for design of railways and road tunnels and tunnelling during 2016, which are used today for designing road and railways tunnels. The Swedish Commission for Implementing the Eurocodes has set up a document with rules for rock mechanical design. One objection of all these works is to get a better harmonizing with the Eurocodes. However, the problems of applying EN 1997 for design of tunnels was recognized. The above mentioned documents are as follow:

— TRV, TDOK 2016:0231 Requirements Tunnelling

[18] https://www.cob.nl/

[19] Using the Q-system. HANDBOOK, Rock mass classification and support design, Norges Geotekniske Institutt (NGI), Oslo, May 2015

[20] Vegtunneler Nr. N500 i Statens vegvesens håndbokserie, ISBN:978-82-7207-697-8, November 2016

[21] Fjellbolting Nr. V224 i Statens vegvesens håndbokserie, ISBN 82-7207-495-8, June 2014

— TRV, TDOK 2016:0232 Advice Tunnelling

— IEG: Report 5:2010 Rock tunnels and rock mechanics.

Poland

In Poland cut and cover tunnel design is performed using EN 1990, EN 1992 and EN 1997 with partial factors method. The specific situation with Polish geotechnical and mining standards and regulations of Ministry of Transport, Ministry of Environment and Mining Industry leads to many misinterpretations. TBMs tunnels and rock tunnels are classified as "mining works" and for this reason mining standards and regulations are adapted to this type of tunnels. That is why there is a great need of new Eurocodes (or European guidelines and standards) covering tunnel design (especially TBMs tunnels) in all aspects, namely structural, safety design, life time cycle, environmental impact etc.

Switzerland

Switzerland has a series of Swiss standards (SIA standards) for tunnels since the 1990's, namely:

- SIA 195 Pipe Push-Method (Rohrvortrieb)
- SIA 196 Ventilation
- SIA 197 Planning of tunnels (Projektierung)
- SIA 197/1 Rail tunnels
- SIA 197/2 Road tunnels
- SIA 198 Underground construction
- SIA 199 Assessment of rock for underground construction

Swiss standards for tunnel design refer for dimensioning of permanent reinforced structural concrete members to the Structural Concrete standard. For temporary unreinforced elements, the tunnel standard applies.

UK

In the UK, a number of different documents are being used for specifying tunnel lining in addition to other international and European publications.

— PAS BS 8810:2016. Tunnel Design of concrete segmental tunnel linings – Code of Practice, BSI (BSI, 2016).

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

— British Tunnelling Society, 2010. Specification for Tunnelling Third Edition (BTS & ICE, 2010).

— BS 6164:2011. Code of Practice for health and safety in tunnelling in the construction industry, BSI (BSI, 2011).

Major Clients – Asset Managers have their own guidelines such as Network Rail/London Underground, Thames Water, National Grid, etc.

4 Potential benefits of having a standard(s) and detriments in its (their) absence

In the section above, the market situation concerning the design and construction of tunnels, and the related future trends have been analysed. The status of standards for the design of tunnels and other underground structures in a European and international level has been reviewed and the potential for future development has been discussed. Thus, the impending multiple benefits of having a standard for the design of underground structures are becoming evident and are further discussed in this section.

According to data presented by the International Tunnelling Insurance Group (Reiner 2011), the main causes of underground construction failures can be categorised as:

— Design errors including wrong/inadequate specifications – 41%;

— Defective construction – 21%;

— “Force majeure” – 18%;

— Insufficient ground investigation – 12%;

— Lack of communication – 8%.

Although it is often difficult to distinguish a single cause of failure for any type of structure or construction work, the fact that 41% of the considered underground construction failures are believed to be related to design errors clearly underlines the importance of the design stage. Thus, the need for and importance of standardisation for the design of underground structures based on state-of-the-art methodologies and design approaches verified by long time experience is evident.

New design standards for tunnels could support the achievement of harmonized level of construction safety. This fact is even more important taking into account that many tunnels are part of the Trans-European Transport Network (TEN-T) and are being associated with very large infrastructural projects; thus they may be considered critical infrastructure. Considering their criticality on a European level implies the need for establishing a minimum level of reliability of such construction works. Therefore, having new standards should establish such common minimum reliability level and will increase the resilience of tunnels and the critical infrastructures of which they are a part of.

Current practice in some European countries that do not have national standards or widely recognized guidelines for the design of underground structures, results in design solutions based on individual decisions of designers or/and clients. In parallel, the complexity of the ground-tunnel support interaction often requires designers to undertake a complex numerical analysis route. In effect, such individual design approaches may lead to vast differences even in basic design assumptions, such as a targeted level of reliability and can complicate the design process. Even though new technologies are fast adopted in tunnelling industry, there is no design standard that covers fundamental elements of tunnel design.

New standards and/or guidelines for the design of tunnels will inhibit the use of standards which are not compatible with the tunnel design related problem. Also, they can ensure coherent design principles and will introduce a consistent design philosophy for the various design stages enhancing the transparency of the design process. Consequently, the design will become more efficient, simpler and quicker processes for engineers and checkers or other involved practitioners will be introduced. If properly set-up, new standards will introduce reasonable engineering approaches without limiting the required flexibility. In addition, it will be possible that common design aids (manuals, handbooks, etc.) and software will be prepared and used. As regards the asset owners, the streamlined design will result in improved reliability tailored to their needs and performance requirements.

Having common European standards will also clearly define the scope of the applicability of the concerned parts of EN 1990, EN 1992 and EN 1997. In current practice, with the lack of specific standards for tunnels, the industry gives preference to European standards, in their design. Therefore, as designers prefer to use Eurocodes beyond their formal range of applicability, extending them to tunnel design is a very practical choice. A new European standard or design rules for tunnel design would result in a formal approval of the current state-of-the-art in tunnel design by a collective decision of CEN member countries. Therefore, the Eurocodes could be supplemented by harmonized design rules specific for tunnelling purposes, which are now spread across literature, guidelines, specifications, as well as some national standards.

Affirmation of a general framework and design rules in a form of a complementary standard, or additional parts to the existing Eurocodes, can foster the spread of state-of-the-art practices in the industry. Further justification for such approach is provided by the fact that almost every tunnelling project involves various other structures (i.e. stations of new metro lines), which are designed based on the Eurocodes (when in Europe). In parallel, a new standard will cease the confusion of interpretations when applying different (and sometimes contradictory) rules, guidelines, standards, etc. in a specific project at national level.

Just as notable, is the fact that standardisation in tunnel design will ease communication between interested parties (designers, authorities, constructors and clients). Although some European countries and institutions responsible for infrastructure development have their own guidelines and specifications, a European standard would provide a common communication platform between the main stakeholders. Concerning international tenders, standards will ease the communication between the related parties and provide a common reference (and language) to define technical requirements and performance and common codes of practice.

A common standard could help increasing common market activities across informal national barriers that exist due to differing traditional design philosophies. It may also be supportive for industry activities and for co-operation of European joint ventures outside of Europe. Moreover, having one comprehensive European framework for tunnel design can represent a stronger reference in comparison to national standard. It can also become a reference standard for countries not being members of CEN[22] that are lacking their own national standards and wishing to adopt and use the European standards. This can increase the global competitiveness of the European construction sector and in particular can open or increase the market potential for European designers and contractors to international tenders and worldwide activities.

Tunnelling industry is one of the most innovative branches of engineering; the generation of new ideas is driven by the competition between specialized contractors and technical challenges encountered during tunnelling construction works. However, standardisation also plays an important role, not only in the process of harmonization, but also for transfer of innovation in the construction practice. The existence of standards will provide an opportunity of sharing technical expertise and best practices among European countries and developing new approaches and technologies based on common research topics. Moreover, countries and stakeholders, who lack resources to develop their own standards but are involved in tunnelling projects could benefit as well through a transfer of knowledge. Even the process of standard development itself may significantly contribute to the exchange of such expertise, as well as to fostering the scientific cooperation between countries and people involved in these activities.

The process of innovation adoption (in particular new and improved calculation models for the design process) is not only limited by technical constrains but also by the individual decisions of engineers willing to adopt or reject specific aspects of innovation. Although the entire process of innovation adoption is more complex (Rogers, 2003), the process can be represented by a cumulative distribution function as presented in Figure 1 for the geotechnical engineering. Its progression rate depends on a couple of factors, most notably, the relative advantage for an individual in adopting the innovation.

[22] European Standardisation Committee

Standardisation, considered by many designers as official recognition and formal acceptance of novel material presented by the geotechnical community, can significantly improve the process of spreading state-of-the-art ideas and practices. Moreover, standards may reflect also on new trends, which could bring solutions that are more economical for tunnel construction.

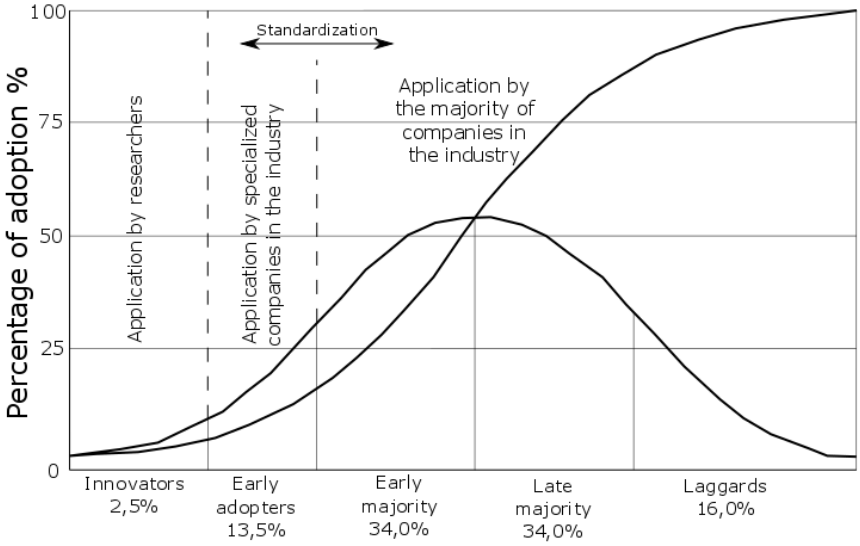

Figure 1. Idealized process of diffusion of innovations in geotechnical engineering and possible role of standardisation; based on the basic diffusion concept presented by Rogers (2003).

In summary, the main potential benefits of developing standards for the design of tunnels, can be summarized as in the following points:

- harmonized level of constructions 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).

As the process of developing standards involves various stakeholders, the result of the standardisation process can be considered as a collective decision, which usually gains easier acceptance among individual designers. Even though converging on a commonly acceptable solution, through standardisation, might be a difficult and iterative process sometimes, harmonization can be achieved with the participation of various stakeholders, especially designers and contractors working in the tunnelling industry and thus benefiting from standards with wide acceptance.

As discussed above, the lack of a standard for tunnel design, often leads to the application of the existing Eurocodes for underground structures despite tunnels being beyond their scope. The resulting inconsistencies may cause legal and economic risks. A new standard and clarifications for the applicability of the existing Eurocodes could alleviate these dispensable risks born by designers, clients and contractors today. Thus, unnecessary arguments between the designer and the checker (or the client), as well as legal misinterpretations and misconceptions, can be minimised. Further, having a new design standard might be used to promote a risk-management approach in geotechnical design that may indirectly influence contracting practices, thus, decreasing the number of claims and court cases between contractors and clients.

The absence of harmonized standards for the design of tunnels in Europe could result in the implementation of sub-standard procedures and design methods. Noted construction failures in tunnels and other underground structures (structural, operational etc.) could give the EU construction sector, and the EU construction industry in general, undesired negative publicity. Clearly, the longer the design of tunnels and other underground structures is allowed to be implemented using ad-hoc, non-standardised, technical solutions, the greater is the risk of failures (catastrophic or minor) occurring. Naturally, the implementation of harmonized standards may reduce this risk.

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:

— greater risk of failures for critical infrastructure;
— lack of harmonization 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 more difficult the cooperation in international projects and could be a serious obstacle in the case of cross-border tunnels where two (or more) European countries have to develop different sections of a common underground infrastructure guaranteeing a common level of safety;
— lack of broadly recognized document(s) that may serve as a reference when evaluating the quality and assumptions of the design;
— lack of clear guidance to designers when dealing with complex technical issues for the design and safety assessment of underground structures;
— difficulty of getting insurance coverage or excess insurance fees as a result of a perceived increased risk.

5 Future technical documents

5.1 Scope of new standards

It is easily understood that the development of a common structural design standard including all types of underground structures for all countries in the European Union could be a challenge. An important issue to address is an agreed definition of major technical terms (i.e. a "tunnel vocabulary/glossary") that will enhance the communication among all stakeholders involved in tunnels projects. In addition, interactions between the tunnelling construction, the existing geotechnical conditions and other civil engineering structures around the tunnel have to be addressed.

In parallel, it has become evident from the previous sections that the design of tunnels has some non-typical features that cannot be fully and correctly addressed by rules and criteria developed for other structures. Thus, a tunnel-specific standard(s) is necessary to define design criteria and to allow an appropriate level of flexibility to face with the specific setting and conditions related with the underground structures. Possible difficulties in finding a common approach, especially in case of atypical and complex configurations, are related to the broad definition of underground structures, different construction techniques and geological conditions, as well as construction in both soil and rock.

As it has been mentioned in previous chapters, even though there are currently no specific provisions given in the Eurocodes for tunnel design requirements - and in particular for the site geotechnical investigations -, they are commonly used in tunnel design. Thus, it will be beneficial if the concept of a new standard(s) for the design of tunnels is developed in consistence with the existing Eurocodes and also with the new developments for the second generation of the Eurocodes. Synergy should be sought with EN 1992 and EN 1997, which will allow the use of complementary standards in the absence of appropriate models within the standard.

For atypical and complex configurations, the definition of broad risk assessment criteria / methodology could ease the deployment, enhance the transparency and ensure a level playing field while reducing the average time-to-market of such infrastructures, with an overall socio-economic advantage for the EU, both in terms of effectiveness of the internal market and innovation.

Having in mind the vast variety of geological conditions in Europe, as well as the large variety of construction methods for tunnels, the elaboration of new guidelines based on existing ones shall be considered as an alternative to the creation of standard(s). A possible way ahead could be through the development of guidelines specifying which approaches of the Eurocodes shall not be used in tunnel design, and alternatively – which are the approaches suitable for the design of tunnels. Such guidelines can also provide assessment and analysis of failures due to inappropriate design. Alternatively, new tunnel design rules could be included as additional chapter(s) in the future generations of EN 1992 and EN 1997. Such approach could profit from the established editorial and maintenance environment by CEN/TC250 Sub-Committees 2 (SC7) and 7 (SC7), thus saving time and work compared with the approach of developing a separate standard(s).

The future technical documents shall cover the design of underground structures and common types of civil engineering tunnels. The new standard(s) or/and guidelines shall encompass new underground structures and the assessment and retrofitting of existing ones. While focusing on civil engineering tunnels, other underground structures may be examined as appropriate.

In order to be consistent with national specificities commonly practiced in a safe way, any standard or guideline, shared at the European level, has to be not too rigid and allow addressing specific national requirements. But such flexibility is present in the Eurocodes concept through the Nationally Determined Parameters.

Special attention must be given to the fact that tunnel design and construction require large experience as well as the application of the interactive design (the so-called “observational method”) during construction. Thus, the need for experience as well as the application of the interactive design during construction require special contractual and insurance philosophies that should be addressed by supplementary guidance.

In addition, the technical documents to be developed should especially:

- refer to tunnels safety aspects, both during construction and during operation;
- 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;
- be not too prescriptive so not to turn the tunnel standard as a barrier to 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 frame of developing new standard(s) for tunnel design, two main risks associated with standardization have to be recognized. Firstly, lack of consensus between various CEN member countries may arise due to differences in national practices and local geotechnical conditions. However, this may be resolved by the introduction of National Determined Parameters (NDPs) fixed by the National Annexes. Secondly, a very prescriptive standard may result in some unforeseen and unintended consequences for the industry. In order to avoid those risks, an iterative approach to standardization may be the most beneficial. Potential first edition of the standard(s) should be rather flexible and open. Based on its implementation, further refinement of design rules and adaptation to the expectations of the industry should follow.

5.2 Specific technical issues to be addressed in the new standard(s)

In Annex A to this report, different technical issues related to the design of underground structures are presented. In this section, the issues which are specific for the design of tunnels, are summarized and discussed more generally. A more detailed discussion will be possible when all details about of the revision of the Eurocodes (i.e. the Second Generation of the Eurocodes), primarily EN 1990, EN 1992 and EN 1997 are available after 2020.

The area of use for new standards for the design of underground structures has to be established. In this context, underground structures shall be regarded as all types of underground openings, tunnels and shafts in soil or rock excavated by mining methods.

A standard must cover all three types of structural bearing systems and relevant combinations of systems. These are (i) the ground itself, (ii) ground reinforced by structural elements or other types of improvements and (iii) supporting structures.

The geological uncertainties related to mining are a challenge. The general rules of ground investigations for foundation works are not applicable. A risk-based framework covering both design and construction are mandatory. Quality assurance work including monitoring should be related to the framework.

The design work must not only cover the underground structure itself but also the measures to be taken to fulfil the requirements of acceptable impact on environment. In this context, design situations are not only related to permanent structures but also to situations encountered during the excavation. The impact on the environment and stability during excavation for underground openings are more pronounced and, to some extent, unique.

The general rules in existing codes for verifying the design of geotechnical structures are applicable also for underground structures. Design by adapting prescriptive measures and applying the observational approach is frequently used. However, these verification methods have to be further elaborated. The complex ground-structure interaction, which characterizes many underground structures, has to be designed by applying numerical calculation methods. Partial factor method is in general more difficult to apply for this type of problems and thus guidelines have to be developed. Calculations based on probabilistic methods are foreseen to increase and, thus, guidelines have to be elaborated.

Fire resistance and impact from earthquakes for underground structures are not covered by the standards of today and thus have to be addressed in new standard(s). The same will be relevant, for example in relation to rock grouting, rock bolts and sprayed concrete which are frequently used to support underground openings.

6 Conclusions

Tunnel projects in Europe form a large portion of the infrastructure market and there is continuous demand for tunnels. However, **currently European tunnel design standards are not any available**. Thus tunnel design in Europe is being carried out based on the national knowledge and experience with the use of industrial/client standards and the application of the Eurocodes whose original scope does not include tunnel design.

New European tunnel standards and/or guidelines will provide the following main benefits:

- harmonized level of constructions 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 **development of design standards or guidelines for tunnels and underground structures is certainly feasible**, at least for typical configurations. As it was discussed in the previous sections, it would be advantageous to foster harmonisation of design rules between countries.

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.

It seems indispensable to fit the new tunnel design standards into the framework of the Eurocodes and delineate how to complete and/or restrict their use for tunnel design without limiting the required flexibility and having in mind the specificity and diversity of tunnels. Synergy and coordination with the current activities on the evolution of the structural Eurocodes (i.e. the second generation of the Eurocodes) is naturally necessary.

As next steps, it is important for the Expert Group to brief CEN/TC250 on its views on the standardisation needs for tunnels. Thus, the expert group will prepare brief material for CEN/TC250 with a list of issues: (i) covered in the Eurocodes and used for tunnelling; (ii) not covered in the Eurocodes but can be included in the future; and (iii) covered in the Eurocodes, but should not used in their present state for tunnelling.

In addition, the expert group will compile a list of existing documents and sources of guidance related to the design of tunnels. In the next two to three years, the goal is to prepare a report on the use of standards and guidance for design of tunnels in Europe, including the place of the first generation of the Eurocodes in the design of tunnels, issues not covered by the Eurocodes, sources for guidance and further standardization needs.

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List of figures

Annexes

Annex A. Technical issues to be addressed in the new standard(s) for the design of underground structures

Annex A. Technical issues to be addressed in the new standard(s) for the design of underground structures

In this Annex, some technical issues specific for the design of underground structures are discussed that shall be considered when developing a standard(s) and/or guidance for tunnel design. Naturally, the discussion of technical issues presented below is preliminary and cannot be considered exhaustive. Stakeholders to be involved in the concept and development of new standard(s) shall contribute with additional points and issues to be considered and further assessed.

It is noted again that tunnels are unique structures. The mean bearing element in tunnelling is the surrounding soils and rocks. One of the main aims in tunnelling is to keep these stable or to prevent them to get loose. Changes in 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 reduce changes in stress-state to a minimum. Therefore a 24/7 observational design method and construction process is mostly aspired wherever and whenever possible. This is one of the most important difference for tunnel design compared to other structures, e.g. buildings and bridges.

1. *Geotechnical investigation*

The general guidance given in the first generation of EN 1997 is not sufficient for tunnelling design purposes as it covers mostly standard structures and buildings, also with regards to the geotechnical investigation in soils and rocks. Only small tunnels are mentioned in the informative Annex B to EN 1997-2 "Ground investigation and testing". As geotechnical investigation is often conducted from the early stages of a design, i.e. at the feasibility study phase, the client rather than a designer or a contractor often contracts it. Moreover, due to the scale of the problem, identification of possible adverse geotechnical conditions is by far more important for tunnelling contracts than for other structures and buildings.

Prior to the selection of a tunnelling construction method, the geotechnical investigation report might not have to define the single correct interpretation of geotechnical conditions (Hatem, 1998). However, the design should include a definition of assumed geotechnical ground model, based on the investigations conducted at all stages of the project, in reference to the design parameters (i.e. cutter face pressure for Earth Pressure Balanced Tunnel Boring Machine EPB-TBM, amount of soil predicted for excavation, etc.) and the range of possible variations of those parameters. Such a ground model should represent a statement of the characteristics of the ground on which the design is based, in relation to identified possible failure modes (Muir, 2002).

Future standards and guidelines should not be limited to the type and minimum number of investigations required (field and laboratory testing program). Reference should also be made to the process of site investigation starting with a desk study, followed by several phases of field and laboratory work and closing by stating clearly that a geotechnical baseline report has to be provided by the clients as basis for tendering, design and construction. Major parts of the report are the description of the geotechnical model as well as the presentation of derived values of particular parameters.

New tunnel standard(s) shall reflect on the changes made in EN 1997 (i.e. the evolution of EN 1997) and make recommendations to which Geotechnical Complexity Class and to which Consequence Class the tunnels construction should belong. The current classes in the EN 1997 can lead to increase or decrease of partial safety factors.

2. *Tunnelling-induced ground movements and damage to existing structures*

It is commonly recognized that a construction of an underground structure may have a significant impact on structures located directly above it and in its vicinity. This is a subject of significant concern and a main inherent geotechnical risk in the execution of any underground project. Necessary limitations imposed on the designer, in some cases, may even be a major factor governing the choice of the construction method, specific design solutions, or the organization of construction activities.

As the subsoil is made of highly variable material and its behaviour is often controlled by non-linear relationships concerning stress- and strain-dependence, the soil-structure interaction for the case of underground structures is a difficult issue to analyse. An additional problem associated with this type of behaviour is the displacement of the surrounding area caused by a disturbance in the in-situ conditions due to the construction. The extent of the zone of influence may reach far beyond the area of the construction site, affecting other existing structures. Therefore, tunnelling projects at urbanized areas are associated with increased third-party exposure. This issue is covered extensively in literature on tunnelling in urbanized areas (e.g. Guglielmetti et al., 2007). Consideration of serviceability conditions of existing structures is especially important for elements of critical infrastructures, i.e. existing tunnels, metro lines, etc. Such structures often have their own strict serviceability and safety criteria imposed by authorities responsible for their maintenance and operation (e.g. Metro, 2014).

In the Limit State Design framework, for any design, a verification of all relevant Ultimate Limit States (ULS) and Serviceability Limit States (SLS) have to be conducted. For most typical geotechnical structures, all necessary analyses are limited to the structure itself and all its elements; however, when an underground structure (i.e. deep excavation, shallow tunnel, etc.) is considered, this also involves neighbouring structures in the expected influence zone. Although this issue is not detailed in EN 1997, it is often one of the most important aspects of a design

The verification of the impact on the neighbouring structures is composed of following main steps:

- Assessing the extent of the zone of influence - where structures are at risk of loss of stability due to the construction activities and also where minor risk of loss of stability exists but additional deformations due to underground construction can be expected; predicted boundaries may be used as an extent of the area to be monitored during construction of the tunnel - e.g. based on ITA-AITES (2014) (general) or other (local) recommendations.
- Quantifying the impact - i.e. as a predicted deformation of the ground surface, usually assuming greenfield conditions and assuming equivalent displacements of the structure.
- Verification of the limiting criteria concerning an allowable deformation for a given type of the structure.
- Design and preparation of the remediation measures, as necessary.
- Monitoring during construction.

Depending on the type of the structure and geotechnical conditions, an entire construction sequence, with various levels of simplifications, may have to be considered in the analysis to properly represent stress and strain changes which may involve: unloading (e.g. due to demolition of existing structures), dewatering, excavation (unloading of the subsoil and imposed strains due to deformation of a retaining structural elements), as well as final loading conditions. With regards to tunnelling, the process of excavation and lining installation is often critical for the assessment of ground movements.

As per EN 1997, three main types of calculation models may be used: analytical, semi-empirical, and numerical. The latter two are most commonly used for ground settlement prediction due to tunnelling. For some special design situations, none of those methods may be adequate.

Semi-empirical methods (e.g. Peck, 1969b) often assume tunnelling in greenfield conditions, where the opening caused by the tunnel construction is defined by a displacement profile of Gauss distribution with the centre at the tunnel axis. The inclusion of the building in the analysis tends to modify the ground movements (Yiu et al., 2017). Prediction of the extent of influence zone as well as the displacements, offered by simplified semi-empirical calculation models, can be regarded as safe and conservative within the boundaries of their applicability. However, the increasing complexity of the construction projects and the availability of more advanced prediction tools make it reasonable to conduct more advanced analysis (e.g. Finite Element Modelling FEM – an example of results given in Figures A1-A3). When complex soil-structure interaction problems are considered (Geotechnical Category 3 according to EN 1997), designers and investors should consider the complementary use of more advanced prediction models and calculation methods. The choice of appropriate calculation models should take into account the risk profile of the investment and possible consequences of failure (Bogusz & Godlewski, 2017a). Numerical methods should also be implemented for the assessment of the impact on underground foundation elements, i.e. piles (e.g. Mroueh & Shahrour, 2002).

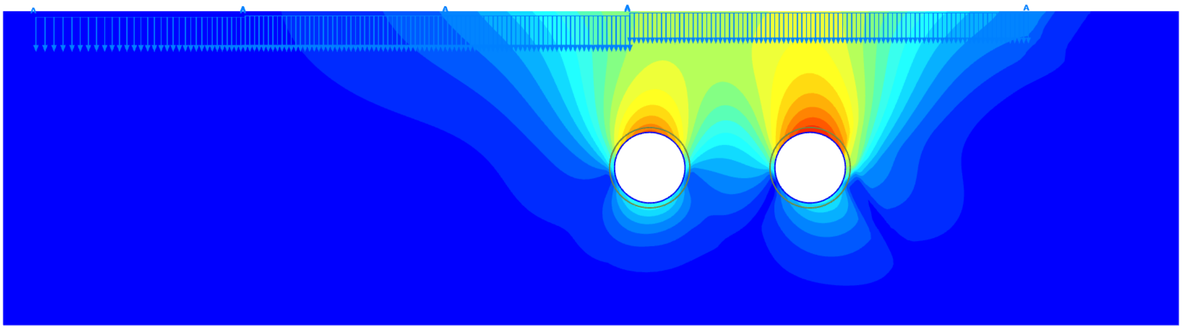

Figure A1. Example of a map of predicted displacements caused by twin tunnels (TBM - EPB) .constructed underneath existing buildings, simplified as distributed loads) (courtesy of W. Bogusz)

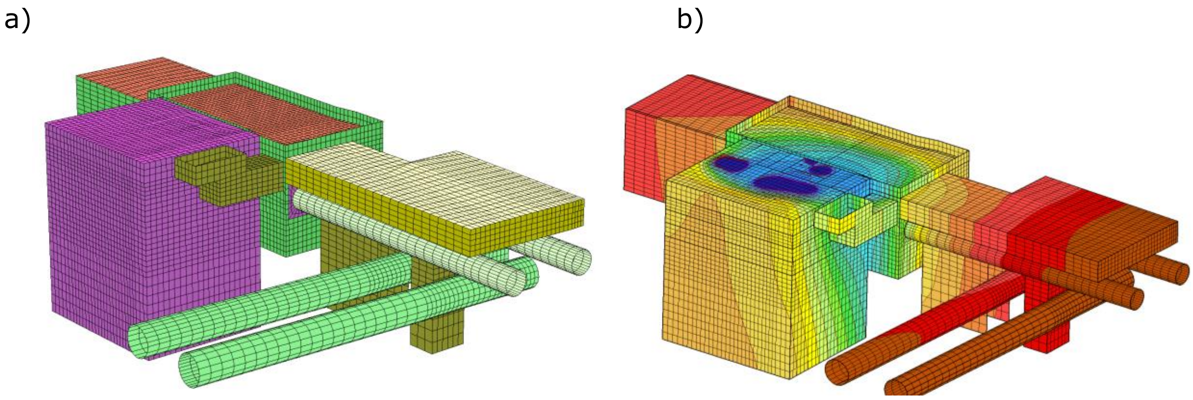

Figure A2. Example of finite element model for underground structures in close proximity: a) structural elements; b) map of predicted displacements due to execution of a new building next to the intersection of two metro lines (modified after Bogusz & Godlewski, 2017b).

Depending on local practice and type of the structure under consideration, the value of expected deformations may regard vertical displacements, tensile strain, differential deformation, etc. The limiting values are usually evaluated on a case-by-case basis as they need to include factors such as:

- type of the structure (buildings, tunnels, and installations);

— type of foundation and load-bearing structural elements (i.e. masonry or reinforced concrete walls, etc.);

— the condition and fatigue of load-bearing elements;

— possibility of ductile or brittle failure;

— consequences of damage, or even the value of a structure to the society (e.g. monuments).

Some default but conservative values are given in various papers and recommendations (e.g. Skempton & MacDonald, 1956; Polshin & Tokar, 1957; Burland & Wroth, 1974; Boscardin & Cording, 1989; Bogusz & Godlewski, 2017a). However, they are not related to risk-based framework and, in most cases, aim to avoid any damage rather than present a designer with a possibility of applying performance based design (PBD).

In some cases, predicted deformations may exceed allowable criteria for a given structure. After assessing the risk with a properly detailed analysis, this can be managed efficiently, i.e. by underpinning and strengthening of the existing structure prior to the execution of the works, or allowing for the damage to occur and proceed with repair afterwards. Providing sufficiently accurate analysis to allow certain level of deformation and possible damage may be considered as an example of Performance Based Design (PBD).

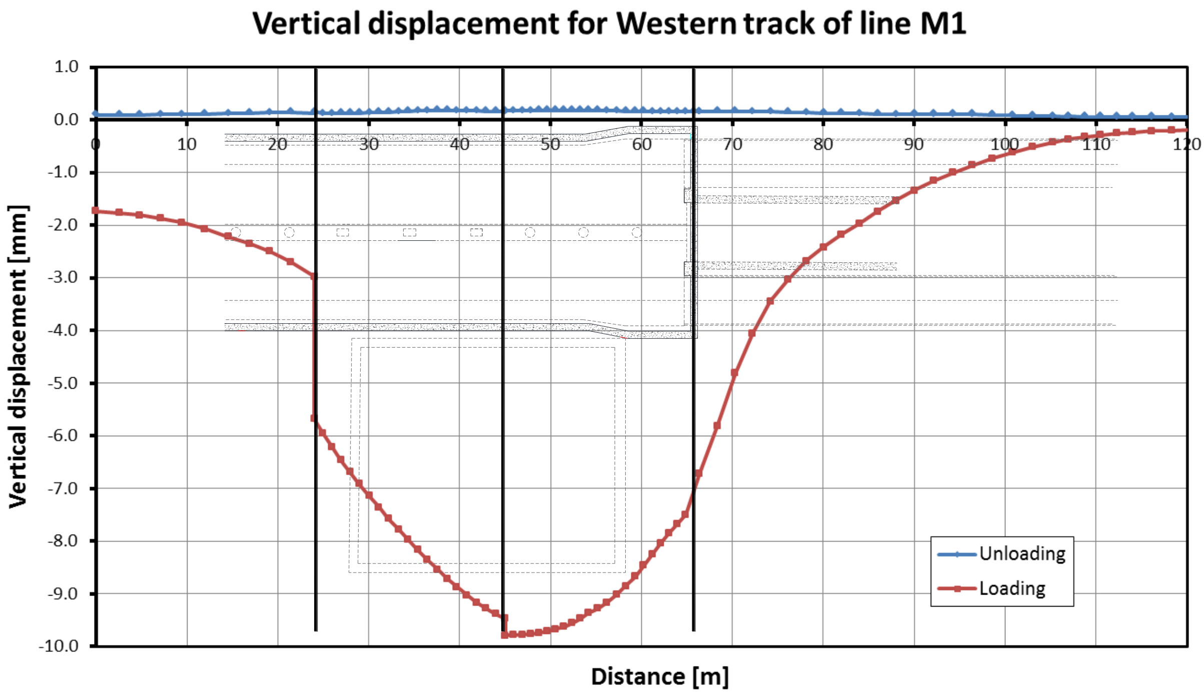

Figure A3. An example of displacement profile for a track bed of a metro line at different stages of a construction of a neighbouring building (modified after Bogusz & Godlewski, 2017b).

3. *Monitoring*

Monitoring of adjacent structures during tunnel construction is closely related to the prediction of ground movements. One of the most important issues is the range of monitoring and which structures should be subjected to it. The scope and the area of monitoring can be based on prescriptive and general rules [e.g. given ITA-AITES (2014), recommendations (ITB, 2002), etc.] or a more detailed analysis, usually associated with the extent of the zone of influence of a construction.

The plan and scope of monitoring is an important aspect for tunnelling projects; especially in urban areas extensive level of monitoring is required, including:

— ground deformations;

— neighbouring structures and utilities;

— groundwater levels;

— vibrations and noise;

— environment (i.e. plants, trees, soil contamination) ;

— constructed tunnels (i.e. measurements of deformations and stresses in lining).

The monitoring should include different levels of limiting values for measured parameters and for notification, alert and alarm, preferably with automatic verification and data distribution system. A tunnelling project in urbanized environments may involve hundreds or even thousands of measurement points. This is why observations, analysis of results, verification, notification, and undertaking remediation measures should be as efficient as possible, and have to be specified as a part of the interactive design (see point 13 of Annex A of this report).

Promoting the use of extensive and advanced monitoring systems, which can be influenced by a standard(s) describing the technical requirements, does not only increase safety, but also may provide important data, which may serve as a reference for future tunnelling projects.

Innovative use of emerging technologies in monitoring (sensors and data management) for critical tunnel infrastructure can contribute to optimisation in terms of efficiency, cost, low carbon footprint and service quality. Monitoring data can enable smarter and proactive asset decisions during construction/operation of new infrastructure or in relation to existing assets, improving resilience (Mair, 2015) and reducing uncertainties and risk. Condition-based maintenance is tailored to fulfil service life requirements, meaning that inspection and refurbishment programmes can be highly benefited by novel monitoring systems, which can be prescribed and installed during early design and construction phases of the project. Big Data and Internet of Things can also contribute to the transformation of infrastructure monitoring (Mair, 2015). Novel technologies comprise among others fibre optic sensing systems and wireless sensor networks.

The interest in fibre optic techniques as a viable sensing approach for civil infrastructure has been motivated by the advantages they offer over traditional sensors. Fibre optic sensors are: immune to electromagnetic interference, lightweight, small, easy to install, corrosion resistant, durable and can operate over a single cable or be daisy chained, considerably reducing the space they take and installation time. In contrast to electrical sensors, fibre optic sensors are passive and intrinsically safe, as they do not carry current but simply act as a wave guide for light pulses. This property is extremely beneficial for sewer systems, where the environment could be explosive. Various fibre optic sensor systems have been developed and applied in numerous geotechnical applications, such as soil nails, anchors, pipelines, piles, retaining walls, tunnels (Hong et al., 2016). Hauswirth et al. (2014) installed fibre optics for ground surface displacements during tunnelling, while Kechavarzi et al. (2016) reference several cases where fibre optics were used for underground structure monitoring. Other applications of fibre optics in tunnels and shafts are provided by Inaudi (1998), De Battista et al. (2015), Schwamb et al. (2014), Di Murro et al. (2016), Metje et al. (2006), Metje et al. (2008) and Moffat (2016). Fibre optic inclinometers and fibre optic tilt and crack meters are also applicable for monitoring settlements due to excavation and capture the inclination and cracks in tunnels (Pei, 2012; Metje et al., 2008).

Furthermore the adoption of Non Destructive Testing (NDT) techniques in Civil Engineering enables practitioners to tackle a number of design issues such as:

— Monitoring Defects in and Behind Sprayed Concrete and behind Precast Concrete Segments (tail skin grout validation);

— Ultrasonic Testing of Sprayed Concrete and Precast Concrete Samples;

— Strengthening Precast Segmental Lining Elements to Resist Crushing Under TBM Thrust;

— Lessons Learnt from Precast Segmental Lining Facilities.

4. *Structural design (ULS)*

EN 1997 in combination with EN 1992 and EN 1990 can be used as a basis for the design of sprayed concrete linings (Schweiger et al., 2017). Differences in loading will arise depending on the modelling approach. Commonly used linear elastic-perfectly plastic models may not be appropriate for the design of tunnel linings. Accounting for time-dependent and non-linear behaviour may result in more realistic predictions, as the choice of constitutive model has a significant impact on the results (Thomas, 2009).

The loading conditions to which a tunnel lining is subjected to are different than those for standard structures. Depending on geological and hydrogeological conditions at the site, as well as the construction method, loading can be highly time-dependent and may include additional pressures. e.g. due to swelling (Kovari, 1988) and tail void grouting. Additionally, for precast segmental lining, actions associated with transportation and installation (i.e. loads from TBM during installation) may be as important as final loads due to ground pressure.

Although precast concrete structures are covered by the rules of EN 1992, the influence and design of joints may be of concern. Segmental lining is characterized by the radial (longitudinal) and circumferential joints between neighbouring segments. The function and design of those joints differ. The joints are important as their stiffness affects geotechnical actions on the lining and their structural bearing capacity should be considered in the design (Maidl et al., 2008; Tvede-Jensen et al., 2017; Caratelli et al., 2018). Furthermore, they have an influence on the global stiffness of the tunnel lining.

Fiberglass reinforcement used for starting shafts of TBM does not follow standard design procedures of EN 1992. Moreover, fibre reinforced concrete design is not currently covered in EN 1992.

5. *Geotechnical design (ULS)*

For mechanized tunnelling using TBM, face stability verification is associated with a design of face pressure, i.e. for EPB TBM, to avoid loss of stability, reduce ground movements, and prevent the possibility of blow-out in the case of shallow tunnels. Various analytical methods were proposed for that purpose, i.e. by Broms & Bennermark (1967), Jancsecz & Steiner (1994), Anagnostou & Kovari (1996), among others. Uplift can be verified according to the requirements of EN 1997.

6. *Serviceability of tunnels (SLS)*

The basic equation governing verification of SLS according to EN 1997 can be used for tunnelling purposes as well, and it is expressed as:

$$E_d \leq C_d$$

where E_d is the design value of the effect of actions and C_d comprised the limiting design value of the effect of an action.

Equivalent verification criterion should be used for assessing possible damage or loss of serviceability when considering other structures which might be affected by tunnelling activities, as well. The possible future changes in the overburden, or an execution of new tunnels and other underground structures, might have an impact on serviceability criteria of a tunnel.

The main serviceability criterion for concrete tunnels, other than the ones associated with the specific purpose of the tunnel use, is often associated with its water tightness and durability. Furthermore, criteria for allowable crack width specified for buildings may not be applicable for tunnelling purposes.

7. Numerical modelling

Rapid adoption of advanced numerical methods, including FEM, in structural and geotechnical engineering design had a significant impact on tunnel design practice, where such methods are especially valuable. These methods are used for estimation of internal forces in tunnel lining, as well as prediction of the tunnelling-induced ground movements. However, it has to be recognized that results of any such analysis are highly dependent on the undertaken assumptions and simplifications introduced in the model. As the use of numerical methods in geotechnical design is not covered by the current Eurocodes and the next version of EN 1997 will cover them only in general terms, specifying tailor-made requirements for tunnelling purposes will be of benefit for the industry. Currently, all assumptions and simplifications for numerical modelling of tunnels are introduced at the discretion of designers, based on their personal previous experiences and the diverse guidance given in literature.

It is noted that the second generation of EN 1990 will include a specific guidance on non-linear analysis methods. It is expected to provide adequate basis for use in underground construction and also for tunnels.

From a practical point of view, the analysis can be conducted with the assumptions of various levels of simplifications, as a balance between the accuracy of prediction, the time necessary to obtain the results, the data availability and the underlying uncertainties. The commonly used assumption concerns the use of plane-strain conditions (2D) in the analysis, where a tunnel construction is represented by one of possible methods approximating 3D construction procedure, often based on empirically obtained volume loss values from similar projects or an unloading factor. Full spatial (3D) analysis of construction procedure requires a large number of excavation steps and is not feasible in design practice because of the high expenses. Even with significant improvements in FEM-based software used in geotechnical engineering and increase in the computational capabilities, this limitation has not yet been overcome.

Significant differences in calculated structural forces and ground displacements can occur between cases of wished-in-place tunnel lining without modelling stress redistribution, and accounting for full staged excavation sequence of a given tunnelling method. Furthermore, the use of advanced constitutive models for soils and concrete may be of great significance for the final result of calculations, thus, affecting the chosen design solution. For soils, stress- and strain-dependent stiffness should be accounted for. While for rocks, accurate modelling of their behaviour is still an issue in design practice.

For the design of sprayed concrete lining (SCL) tunnels, according to Paternesi et al. (2017) and Schweiger et al. (2017), the use of both DA2* and DA3 approaches[23], as defined by current EN 1997, is recommended. This is equivalent to dual-factoring approach postulated for the second generation of EN 1997, when numerical methods are applied. Furthermore, applying partial factors in FEM calculations could allow for implicit verification of structural limit state of such lining, without the need of verifying the results with moment versus axial force interaction diagrams (M-N charts). However, such approach may also complicate the verification of results by external personnel.

For segmental lining, an issue of joint stiffness and their impact on the global stiffness of the tunnel may have to be considered.

Numerical modelling might include a sensitivity analysis to assess the impact of various design parameters on the tunnel predicted behaviour.

8. Dynamics and Earthquakes

The effects of vibrations caused by tunnelling activities, as well as the future use of the tunnel, should be considered in the design. For example, in Poland (Polish Ministry of Infrastructure, 2011), it is required to use technical solutions in metro tunnels, which

[23] DA1, DA2 and DA3 refer to the different geotechnical design approaches mentioned in EN 1997 "Geotechnical Design".

protect adjacent structures and people from the influence of vibrations. It is assumed, on average, that a zone of dynamic influence reaches 40 m from the tunnel in both directions from the metro line. Within that zone, an assessment of the dynamic influences is necessary for the adjacent structures. Furthermore, during the maintenance phase, some continuous measurements should be taken, as the degradation of the tracks may cause an increase of vibrations.

Seismic design may be critical for tunnelling design in some countries. This is more pronounced for underground structures in soft soils or soils prone to liquefaction.

9. *Materials*

As tunnels have to remain in constant contact with the ground, with very limited access for external inspection, ensuring the resilience of the entire structure is connected with the durability of materials used for the tunnel construction.

No standard methods are available in Europe with regards to cement grouts used for tunnelling purposes (Rahman et al., 2017). Not only the extent of quality assurance and testing for grout is limited during tunnel execution but also the durability of grout is also of some concern. Subjected to degradation processes as well as the aggressive elements in the groundwater, permeability of the grout can be greatly increased during the lifetime of the tunnel (Laver et al., 2013; ITAtech, 2014).

Some existing tunnels (i.e. London Underground, or the 1st metro line in Warsaw) were constructed with the use of segmental cast-iron lining. This type of material is not standardized and in their case, the explicit use of the Eurocodes is not possible.

10. *Extending service life of existing tunnels*

As it is more probable that an existing tunnel will be refurbished or retrofitted rather than being decommissioned, procedures for assessment using the current codes should be defined. Especially for existing masonry tunnels (Kamel et al., 2016), and also for 50 year old immersed tunnels (e.g. the Maastunnel in Rotterdam), significant degradation over time may be of great concern.

The next generation of Eurocodes will include parts on Existing Structures: General part (material-independent) and Annexes in the material Eurocodes to supplement the general part with material-specific regulations. Hence, it may be the case that these parts will be useful also for assessing existing tunnels.

11. *Fire safety*

Guidelines for structural design, especially in case of fire in traffic tunnels, when people may become affected, must be given in terms of design rules, standard fire loads, specifications for construction materials, etc. (e.g. ITACosuf, 2014; IRACosuf, 2015)

12. *Rock engineering and tunnels in rocks*

Rock engineering is not covered to sufficient extent in the current version of EN 1997, both with regards to design and the geotechnical investigation. For tunnelling purposes, some guidance may be found in specialized literature (Maidl et al., 2008).

13. *The observational method (interactive design)*

The observational method (OM) or interactive design, as introduced by Peck (1969a), and defined now by EN 1997, plays a significant role in tunnelling industry. The use of the OM is especially beneficial for projects that cannot be quantitatively assessed beforehand with sufficient reliability.

In such situation, careful analysis of the results of the observations may provide invaluable guidance, especially for major geotechnical projects. However, the application of the OM poses a risk of slowing down the construction works. As most often tunnelling works are on the critical path of the project, this may be not acceptable by either the investor or the contractor, and more conservative but costly design assumptions are preferred, anyway. The OM is closely related to the issue of monitoring, but, often less effort goes to the significance of data obtained from monitoring than the preparation of formal reports and documents based on them (Peck, 1969a). Strengthening the role of the OM in a tunnelling standard may popularize this method, which in turn may lead to more cost-effective design solutions. Although the OM cannot be applied if no modification of the design is allowed at the execution stage, tunnelling projects often account for that possibility.

14. *Ground improvement techniques used with tunnelling*

Various soil improvement techniques (Mair, 2008; Chapman et al., 2010), can be used prior to tunnelling works, in order to reduce their impact on neighbouring structures or increase the stability of the ground during tunnelling works. This may include: compensation grouting, ground freezing, grouting, fore poling, face dowels, roof pipe umbrella, etc. Not all of those methods can be easily designed.

15. *Innovative and non-standard design solutions*

Development of new tunnelling methods or updating of existing ones should not be inhibited by the standardization, but should rather be encouraged. Currently innovative ideas implemented in tunnelling construction include, for example, thermally activated lining that allows tunnel to be used as a large-scale heat exchanger (Franzius & Pralle, 2009; Di Donna & Barla, 2016; Tini et al., 2017), as well as new types of segmental tunnel linings, which may include composite elements (Zhang & Koizumi, 2010). Such elements may be outside the scope of existing structural design standards (e.g. EN 1994), as well.

An area with profound safety and productivity benefit is the development of extruded linings. Extruded concrete lining methodologies (Maidl et al., 2014) comprise the continuous placing of the lining directly behind the tunnelling machine with the aid of a movable/detachable formwork. Extrude Concrete Lining (ECL) systems provide relief from troublesome works related to conventional segmental lining with backfill grouting; a primary support is no longer required. The tunnel is continuously supported by the ECL, leading to material and labour savings; Grouting is of no use; the elimination of the long-term rock/soil exposure minimises settlements. No cement powder flies around.

The aforementioned benefits led to a sharp increase in ECL patents, machine development and applications in Europe, Japan and Russia around the 1970s and more recently (Maidl et al., 2013). Nevertheless, extruded lining lost popularity the following years and it was only in 2004 that Japan went back to ECL, through the SENS methodology (Iida, 2006). Since then, 3 tunnels have been constructed in Japan in this way (ITA, 2014; Iida 2006; Noguchi et al., 2013; Sakata 2014), showing continuous improvement and better advance rates from project to project. Regarding microtunnelling, extruded tunnel lining concepts has recently been assessed by Royal (Royal et al., 2007). Notwithstanding this, the ideal form of placing only one continuous lining behind the tunnelling machine with the aid of a horizontal slipform is desirable. The availability of new materials, admixtures and equipment could provide the necessary boost for improvement in this method (Cyroň, 2014).

In the area of the asset protection due to tunnelling-induced ground movement one area of potential application is the use of expansive polyurethane resins. Their chemical reaction is accompanied by significant volume expansion (up to 30 times) and expansion pressure up to 10MPa. As the required injection pressures are low (100-200kPa), they are conventionally injected from the surface through small diameter tubes (10 mm tubes) and equipment and they are used for underpinning buildings, (Dei Svaldi, 2005; Mensueto, 2009; Gabassi, 2010), relevelling road pavements or railway slabs (Alsabhan, 2016) and other applications (Dominijanni, A. and Manassero, M., 2015). Combined with efficient monitoring, expansive polyurethane resins could be adopted in tunnelling or deep excavation applications, in order to provide real time displacement control and asset protection.

16. Other issues to be addressed

Other technical issues to be addressed in the standard and guiding documents are specific elements present in tunnelling works such as anchors, bolts, shotcrete, precast concrete, aerodynamics in tunnel, etc. and also rules for sealing against groundwater. Further, the need for guidance for the configuration and operation of tunnels in service in terms of safety during operation should be considered in the context of Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network.

17. Risk-based framework

The scope of the standard or guidelines should ensure that new structures are both sufficiently safe and cost-effectively constructed. This objective may be more efficiently achieved if the standard is developed within a risk-based framework. The fundamental challenge is to take decision(s) under uncertainty. This implies that risk management with its three fundamental steps (establishing the context, risk assessment and risk treatment) should be the base for the standard.

Another important issue to be addressed is the nature of uncertainty. In rock engineering uncertainties are mainly caused by lack of knowledge regarding the geological conditions at the site. This is called epistemic uncertainty and can be reduced by gaining additional information. This is in contrast to uncertainties caused by randomness, which cannot be reduced.

Based on the above-mentioned three issues, the risk-based concepts of the standard should be discussed and further assessed by the involved stakeholders. The level of ground investigation and quality control of the construction work is dependant to the decision of method for verifying the design. The procedure of using observations during construction in order to reduce uncertainties and risks, thereby ensuring structural safety is a fundamental aspect of the design of underground openings in soil and rock, with which the standard must be compatible.

In addition, most tunnelling projects are part of infrastructure development, involving construction processes and procedures, which are a combination of many different tasks, processes and requirements, and requiring the handling large amounts of information to be considered. Multiple Criteria Decision Analysis (MCDA) provide a decision-making mechanism for assisting the understanding of such complex scenarios. MCDA is being widely used to support decision making for problems that involve multiple criteria, both quantitative and qualitative (Roy & Vanderpooten, 1996). Its role in different application areas has increased significantly, especially as new methods develop and as old methods improve (Velasquez, 2013). The construction industry has embraced MCDA and adopted them in many cases (Espino et al., 2014; Sipahi and Timor, 2010). Infrastructure (Kabir et al., 2014) and Risk management has also benefited from these techniques (BS EN 31010; Sturk et al., 1996; Mustafa, 1991; Fouladgar et al., 2012; Aminbakhsh et al. 2013; Hong et al., 2009; Dey, 2010). Tools, such as decision trees (Eskesen et al., 2004), can also enhance the risk management process. Following the example of the Department for Communities and Local Government in the UK (Dogson, 2009) or the risk specific guidance issued by ITA (Eskesen et al., 2004), similar context guidelines on option appraisal evaluation from the early design stages and risk management could be developed. MCDA methods offer the potential of improving the transparency, analytic rigour, auditability and conflict resolution of decision makers (Kabir et al., 2014). In this way, designers, contractors, clients and other stakeholders/decision could better identify an alternative's weaknesses and strengths, justify their decision, gain consensus and prevent serious omissions in either design, construction or operation.

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doi:xx.xxxx/xxxx

ISBN xxx-xx-xx-xxxxx-x