AUSTRIAN
SOCIETY FOR
GEOMECHANICS

ÖSTERREICHISCHE
GESELLSCHAFT FÜR
GEOMECHANIK

# RECOMMENDATIONS
# for the design of reinforced sprayed concrete linings based on EN 1992 and EN 1997

2023

# RECOMMENDATIONS

## for the design of reinforced sprayed concrete linings based on EN 1992 and EN 1997

**Chair**
*(in alphabetical order)*

| | |
|---|---|
| Brandtner, Markus | IGT Geotechnik und Tunnelbau ZT GmbH |

**Members of the committee**
*(in alphabetical order)*

| | |
|---|---|
| Hofmann, Matthias | Brenner Basistunnel BBT SE |
| Paternesi, Alessandra | Marche Polytechnic University |
| Saurer, Erich | SKAVA consulting ZT GmbH |
| Schweiger, Helmut F. | Technische Universität Graz |
| Walter, Herbert | ZT Ingenieurkonsulent für Bauingenieurwesen |

**Layout**
*(in alphabetical order)*

| | |
|---|---|
| Kluckner, Alexander | Österreichische Gesellschaft für Geomechanik |

**Review**
These recommendations on the design of sprayed concrete shells of cavity structures based on EN 1992 and EN 1997 have been submitted to a selected panel of experts for the purpose of review. Any feedback was processed, suggestions for changes have been incorporated if necessary and the results have been made available to the reviewers.

# TABLE OF CONTENTS

## 1. INTRODUCTION

Both numerical and analytical methods are commonly applied to the design of permanent tunnel linings and temporary support measures. The anticipated in-situ stresses in the ground and the ground-structure interaction play a significant role. In the past, a global safety concept was typically used. Since the introduction of the Eurocode this concept became a topic of discussion. Although the verification of structural adequacy of tunnels is not directly covered by Eurocodes, the standards for reinforced concrete (Eurocode 2) and geotechnical design (Eurocode 7) are usually used. The current situation allows large room for interpretation. This document is intended as an aide in choosing a suitable verification method and the related partial factors of safety.

These recommendations are based on research and case studies, some of which have been published in [1] and [2].

## 2. SCOPE

These recommendations are solely valid for verification of the ultimate limit state (ULS) of reinforced sprayed concrete (SpC) linings of cavity structures for which numerical methods are applied. Verification of the serviceability limit state (SLS) is not part of these recommendations.

These recommendations apply to load bearing, reinforced sprayed linings of cavity structures. These recommendations cover both temporary and permanent spayed concrete linings.

The choice of a suitable constitutive model for the ground and the sprayed concrete is left to the reader and is not part of these recommendations.

The application of these recommendations presupposes that the designer strictly follows the rules of the Eurocodes (e.g. regarding ductility and stability), apart from the distinctions mentioned here.

# 3. MOTIVATION

Tunnels fall into either geotechnical category 2 or 3 according to the description of categories in Eurocode 7 (EN 1997-1). Tunnels are allotted to geotechnical category 2 when the following condition is met [3]:

“Tunnels in hard, un-fissured rock and without particular watertightness or other requirements.”

In general, tunnels in non-fissured rock present few difficulties, but such cases are rare. All other structures that cannot be assigned to geotechnical category 1 or 2 are assigned to geotechnical category 3. This category is described as follows in [3]:

“Structures assigned to geotechnical category 3 should generally be examined according to more demanding requirements and rules than those mentioned in this standard.”

This categorisation makes clear that Eurocode 7 is not primarily applicable to tunnelling.

Regardless of this fact, it has become standard practice in real-life engineering that the partial safety concept, based on the Eurocode, is used for verification of tunnels and cavity structures. This results in a leeway for interpretation, since the type of verification and the verification procedure to be applied are not regulated. Three verification methods are defined in Eurocode 7, which differ in the application of partial safety factors on actions, strength parameters and resistances. In Austria, according to the National Annex for geotechnical design, only design approach 2 (DA2) is to be used, with the exception of the stability of embankments. For the latter geotechnical design situation, the application of design approach 3 (DA3) is mandatory. Nonetheless, the Austrian national annex permits the use of DA3 for numerical analyses, even when DA2 would be used in conventional analysis [4]. Design approach 1 (DA1) is not practised in Austria.

# 4. LIMIT STATES TO BE VERIFIED

The verification of limit states can be undertaken in different ways, mainly:

- Testing of models
- Observational methods
- Calculations

The recommendations in this document solely focus on verification by calculation.

## 4.1. Verification of the Serviceability Limit State (SLS)

Verification of the serviceability limit state is not a subject of this recommendation.

## 4.2. Verification of the Ultimate Limit State (ULS)

Internal failure of the materials as dictated by their strength (STR) is usually the governing case for the resistance and therefore design of sprayed concrete linings. This implies that Eurocode 7 is to be used in conjunction with Eurocode 2.

According to the Eurocode, the application of a partial safety factor to the stiffness of the ground or the sprayed concrete is not intended. Therefore, the influence of stiffness on the verification is not dealt with any further.

Verification has to take into account partial safety factors for actions and resistances (e.g. internal forces in the sprayed concrete lining), ground and concrete properties (e.g. friction angle and cohesion for ground and compressive strength for concrete) and geoetechnical resistance (e.g. passive earth resistance).

The following chapters detail verification procedures which are in accordance with Eurocodes.

### 4.2.1. DA1 according to Eurocode 7

Two combinations are to be considered for DA1 (DA1-1 or DA1-2). In the first combination, partial safety factors are applied to the actions. In the second combination, factors are applied to variable actions and ground parameters. The unfavourable combination is governing.

### 4.2.2. DA2 according to Eurocode 7

In verification DA2 the partial safety factors are applied to the effects (of the actions) and to the resistance of the ground.

NB: Because of the difficulty in distinguishing between load and resistance in the ground, the factors for DA2 are often applied to the effects of the actions (e.g. internal forces). This alternative is also referred to as DA2* in the literature [5].

### 4.2.3. DA3 according to Eurocode 7

In this method the partial safety factors are applied to the variable actions (in the case of geotechnical actions, otherwise also to permanent actions) and the ground properties. However, Eurocode 7 does not specify how structural elements are to be treated. These recommendations also examine an alternative of the DA3 with factorisation of the strength of the sprayed concrete shell, which will be referred to as DA3+ for better distinction.

### 4.2.4. „Non-linear procedure“ according to Eurocode 2, Chapter 5.7

When verifying on the basis of the “non-linear method” in the sense of EN 1992-1-1 [6] and EN 1992-2 [7], material properties that realistically represent the stiffness and failure criteria of each structural component should be used for determining the internal forces. The actions should be increased using a global factor of safety, which covers the whole design.

The use of this process for sprayed concrete with numerical methods (e.g. FEM, FDM, DEM) is problematic as the ground load cannot be explicitly increased, rather it is implicitly derived through the calculation.

### 4.2.5. „ General procedure” according to Eurocode 2, Chapter 5.8.6

The “general procedure” is based on a non-linear calculation of the internal forces. The general rules for the “non-linear procedure” from Eurocode 2, Chapter 5.7 are valid. In this procedure the design values of concrete strength and actions are used. The reduction of the concrete stiffness is also prescribed.

This procedure corresponds to the logic of DA3 in Eurocode 7.

## 5. MODELLING OF SPRAYED CONCRETE

In addition to the verification procedures, the modelling of sprayed concrete plays a significant role in the lining design.

### 5.1. Time-dependent, elastic material model for sprayed concrete

It is common practice to model the time-dependent development of the strength parameters of sprayed concrete by changing the modulus of elasticity according to age. In addition, the tensile strength or the maximum allowed bending moments (plastic moments) can be limited.

It should be noted that the strain compatibility must be explicitly demonstrated if this is not covered by the material model (e.g. rotation capacity, to ensure ductile system behaviour under bending loads).

This procedure cannot replace a time-dependent, non-linear material model.

## 5.2. Time-dependent, nonlinear material model for sprayed concrete

A further refinement can be achieved by considering the time-dependency of the concrete strength and stiffness. This allows more realistic simulation of the transfer of load from the ground to the young, sprayed concrete at the face. If necessary, effects due to creep, shrinkage and constraints from the hydration process can be taken into account as well.

# 6. VERIFICATION METHODS FOR SPRAYED CONCRETE LININGS ACCORDING TO THE EUROCODE

Within the context of Eurocode 7, tunnels are essentially retaining structures. In principle this means limit states for structural capacity (STR) and in the ground (GEO) should be verified.

However, a difficulty is presented by the fact that the surrounding ground is both an action and a resistance. Distinguishing between these two in tunnelling is not generally possible and, therefore, the system behaviour as a whole is considered. This is taken into account in DA3 by reducing the resistances as well as increasing the actions by applying the partial safety factors. In general, e.g. in tunnelling, the verification of the expected system behaviour is preferably performed using a global model that also includes the geology.

A rough distinction can be made between common design approaches based on DA2 and those based on DA3.

In addition, a distinction must be made as to which material model is used for the sprayed concrete. This results in combinations of design approaches and concrete (material) models as described in the following chapters and summarised in Table 1.

*Table 1 Verification strategies in underground space engineering*

| Clause | DA | time-dep. nonl. mat. model SpC | $\gamma_M$ Cohesion | $\gamma_M$ tan (φ) | $\gamma_M$ SpC | $\gamma_E$ M-N [1)] | $\gamma_M$ M-N [2)] |
|---|---|---|---|---|---|---|---|
| 6.1 | DA2* | no | 1,00 | 1,00 | 1,00 | 1,35 | 1,50 |
| 6.2 | | yes | 1,00 | 1,00 | 1,00 | 1,35 | 1,50 |
| 6.3 | | yes | 1,00 | 1,00 | 1,35 · 1,50 [1) 3)] | - | - |
| 6.4 | DA3 | no | 1,25 | 1,25 | 1,00 | 1,00 | 1,50 |
| 6.5 | | yes | 1,25 | 1,25 | 1,00 | 1,00 | 1,50 |
| 6.6 | DA3+ | yes | 1,25 | 1,25 | 1,50 | - | - |

[1)] for permanent loads

[2)] check on the section loads by M-N interaction diagram and shear check

[3)] strictly not Eurocode-compliant, but opens up the possibility of using DA2 together with an implicit design method (see [8])

## 6.1. DA2* – Time-dependent, elastic material model for sprayed concrete

This is the most widespread combination and has also found its way into the Guideline for the Design of Tunnels in Soft Ground below existing Buildings [9].

In a separate verification step, the sprayed concrete shell is designed based on [6]. The calculated internal forces (M-N) are to be multiplied with the partial safety factor $\gamma_E$ according to [10].

The disadvantage of this method is that the stress redistribution due to the non-linearity of the sprayed concrete can only be considered within a particular cross-section, resulting in an overly conservative design in most cases. Furthermore, if the load-bearing capacity of the concrete cross-section is exceeded, the ultimate limit state verification can no longer be obtained (see Fig. 1 as example). An increased thickness is often not useful, as the resulting increased stiffness leads to a further increase in bending moments in the over-utilised area.

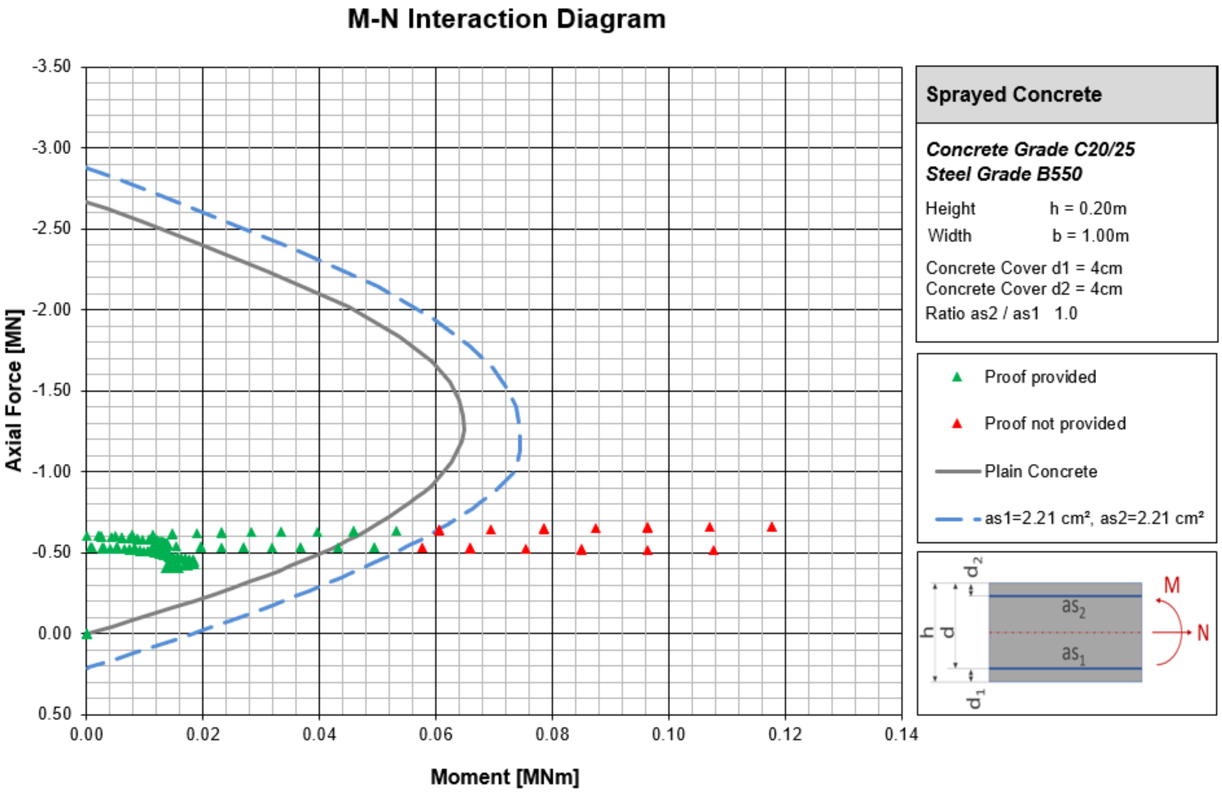


*Fig. 1 M-N-interaction diagram – ULS failure*

## 6.2. DA2* – Time-dependent, non-linear material model for sprayed concrete

The consideration of non-linear behaviour in sprayed concrete in lining design was introduced rather later than non-linear ground models. An exception is the visco-plastic model described in [11]. Visco-plastic models require a careful choice of parameters for time-dependency, as the creep or ductility of the sprayed concrete lining can otherwise be overestimated. In recent years sprayed concrete models based on [6] and [12] have been implemented in common software tools – see for example [13], [14] and [15]. These models typically allow time-dependent development of strength, creep and shrinkage to be considered.

Based on a study [2], it can clearly be stated that the choice of the material model for the sprayed concrete has the largest influence on the results. It was demonstrated that realistic material behaviour usually leads to lower internal forces. If the characteristic strength of sprayed concrete is used, 100% utilisation of some zones of the concrete and/or any reinforcing steel can nonetheless occur. This can be checked, e.g. with an N-M interaction diagram (see Fig. 1). In this case, an additional calculation for the assessment of the overall stability is strongly recommended, for which an assessment according to 6.3 or 6.6 is preferred.

## 6.3. DA2* – Time-dependent, non-linear material model for sprayed concrete with reduced strength

If partial factors for the material and the effects of the actions are applied to the sprayed concrete strength, it follows that the subsequent verification of the lining implicitly ensures no over-utilisation. As the stiffness is directly related to the strength in non-linear models, it must be noted that such a method assumes a relatively soft lining as long as the stress-strain relation is not adjusted with regard to the strain at the peak-stress. Within this procedure, the partial safety factor on effect of actions is shifted to the resistance side. Therefore, this method is strictly speaking not in accordance with the Eurocode. However, such a procedure makes it possible to assign partial factors, as with DA2*, exclusively to the stress resultants and the material of the supporting structures. This approach enables an implicit design [8].

## 6.4. DA3 – Time-dependent, elastic material model for sprayed concrete

Applying DA3 in connection with linear elastic material behaviour of the sprayed concrete is consistent with the Eurocode, though this is not recommended because of the disadvantages listed in section 6.1.

## 6.5. DA3 – Time-dependent, non-linear material model for sprayed concrete with characteristic strength properties

Applying DA3 in connection with non-linear material behaviour of the sprayed concrete with characteristic strength parameters is possible. However, the verification can only be carried out afterwards. Therefore, this procedure offers no significant advantages.

## 6.6. DA3+ – Time-dependent, non-linear material model for sprayed concrete with design values for the ground and concrete strength properties

In [2] it was demonstrated that DA2 can give too favourable results in certain circumstances (e.g., due to increased horizontal in-situ stresses). It is therefore advisable that DA3 with factored ground strength is used in addition to DA2 with non-linear material behaviour. In this way, the bearing capacity of the entire system is verified, and the design completed in an implicit manner. The calculated deformations based on design values are not meaningful.

## 7. ASSESSMENTS AND RECOMMENDATIONS

- In principle, all design approaches defined in EC7 for designing sprayed concrete shells in cavity structures are permitted.
- Modern software offers several options for consideration of non-linear material behaviour. It is recommended that a model considering the time-dependent (non-linear) development of strength, stiffness and creep is chosen. The use of linear elastic models for sprayed concrete is not recommended, even if the Young's moduli for fresh and hardened sprayed concrete are assigned different values.
- The study in [2] showed that modelling of the sprayed concrete in combination with the different design approaches plays an essential role in the assessment of the load-bearing capacity.
- Tunnels can be regarded as supporting structures. Therefore, they are usually verified with DA2*. This can still be considered as the standard design approach, for which the alternative according to section 6.2 is recommended.
- Please note that DA2* provides unreliable results in certain situations (see [2]). In these cases, an additional calculation with DA3+ can provide more clarity about the system behaviour in the ultimate limit state.
- The moments in time that can be critical for the design must be examined as intermediate construction stages, which must be determined on a project-specific basis. Intermediate states in which the early strength of the sprayed concrete is a governing design parameter are automatically consistently designed when using implicit methods. When verification methods other than those described under 6.3 or 6.6 are used, the current concrete strength must be explicitly specified in the verification of all intermediate construction stages.

# BIBLIOGRAPHY


[1] H. F. Schweiger, A. Paternesi und F. Tschuchnigg, „Eurocode 7-based design of SCL tunnels by means of numerical analyses,“ *Géotechnique,* Bd. 67, Nr. 9, pp. 837-844, 2017.

[2] M. Brandtner, M. Hofmann, A. Paternesi, E. Saurer, H. F. Schweiger und H. Walter, „Entwicklung einer geeigneten Nachweisstrategie für Spritzbetonschalen im Tunnelbau,“ *Geomechanics and Tunnelling,* Bd. 11, Nr. 5, 2018.

[3] ÖNORM EN 1997-1, Eurocode 7 - Entwurf, Berechnung und Bemessung in der Geotechnik - Teil 1: Allgemeine Regeln, Wien: Austrian Standards, 2014.

[4] ÖNORM B 1997-1, Eurocode 7: Entwurf, Berechnung und Bemessung in der Geotechnik - Teil 1: Allgemeine Regeln - Nationale Festlegungen zu ÖNORM EN 1997-1 und nationale Ergänzungen, Wien: Austrian Standards, 2013.

[5] R. Frank, C. Bauduin, M. Driscoll, M. Kavvadas, N. Krebs Ovesen, T. Orr, B. Schuppener und H. Gulvanessian, Designers' Guide to EN 1997-1 Eurocode 7: Geotechnical Design – General Rules, London: Thomas Telford Limited, 2005.

[6] ÖNORM EN 1992-1-1, Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken - Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau, Wien: Austrian Standards, 2015.

[7] ÖNORM EN 1992-2, Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken - Teil 2: Betonbrücken - Bemessungs- und Konstruktionsregeln (konsolidierte Fassung), Wien: Austrian Standards, 2012.

[8] H. Walter, „Implicit ULS design using advanced constitutive laws within the framework of Eurocode 7,“ in *ECCOMAS Thematic Conference on Computational Methods in Tunnelling (EURO:TUN 2007)*, Wien, 2007.

[9] RVS 09.01.42, Geschlossene Bauweise im Lockergestein unter Bebauung, Wien: Forschungsgesellschaft Straße-Schiene-Verkehr, 2013, März.

[10] ÖNORM EN 1990, Eurocode - Grundlagen der Tragwerksplanung, Wien: Austrian Standards, 2013.

[11] G. Meschke, „Consideration of Aging of Shotcrete in the Context of a 3-D Viscoplastic Material Model,“ *International Journal for Numerical Methods in Engineering,* Bd. 39, Nr. 18, pp. 3123-3143, 1996.

[12] Intern. Federation for Structural Concrete (fib), fib Model Code for Concrete Structures 2010, Berlin: Verlag Ernst & Sohn, 2013.

[13] J. Lee und G. L. Fenves, „Plastic-damage model for cyclic loading of concrete structures,“ *Journal of Engineering Mechanics,* Bd. 124, Nr. 8, pp. 892-900, 1998.

[14] B. Schädlich und H. F. Schweiger, „A new constitutive model for shotcrete,“ in *8th European Conference on Numerical Methods in Geotechnical Engineering*, Delft, 2014.

[15] M. Neuner, P. Gamnitzer und G. Hofstetter, „An Extended Damage Plasticity Model for Shotcrete: Formulation and Comparison with Other Shotcrete Models,“ *Materials,* Bd. 10, Nr. 82, p. 82, 2017.

# LIST OF TABLES



# LIST OF FIGURES

AUSTRIAN
SOCIETY FOR
GEOMECHANICS

ÖSTERREICHISCHE
GESELLSCHAFT FÜR
GEOMECHANIK

Innsbrucker Bundesstraße 67
5020 Salzburg, Austria

Tel.: +43 662 875519
Fax: +43 662 886748
H.: www.OEGG.at
E.: Salzburg@OEGG.at