EUROCODE and rock mechanics – the basics

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1 Introduction 2
2 Design procedures according to Eurocode-7 3
3 Main principles of Eurocode based calculations 3
4 Specific problems of the current Eurocode-7 for rock engineering 5
5 Eurocode-7: second generation (2024 any beyond) 7
6 References 11

1 Introduction

The EUROCODE regulations consist of a suite of codes:

- EN 1990 EUROCODE : Basis of structural design
- EN 1991 EUROCODE-1: Actions on structures
- EN 1992 EUROCODE-2: Design of concrete structures
- EN 1993 EUROCODE-3: Design of steel structures
- EN 1994 EUROCODE-4: Design of composite steel and concrete structures
- EN 1995 EUROCODE-5: Design of timber structures
- EN 1996 EUROCODE-6: Design of masonry structures
- EN 1997 EUROCODE-7: Geotechnical design
- EN 1998 EUROCODE-8: Design of structures for earthquake resistance
- EN 1999 EUROCODE-9: Design of aluminium structures

Although EUROCODE-7 is the most important one for geotechnical engineering, also the other play some role depending on the specific application, for instance:

- EUROCODE-7 plus EUROCODE-9 for geotechnical structures under earthquake impact
- EUROCODE-7 plus EUROCODE-6 for masonry based structures like shafts or foundations
- EUROCODE-7 plus EUROCODE-4 for steel reinforced foundations or support systems
- etc.

Please note that the Eurocode has developed over the last decades and will develop further as indicated by Fig. 1.1. The first generation of the Eurocode-7 has concentrated on soil, the second generation should also take into consideration the particularities of rock mechanics and rock engineering. The Eurocode is obligatory for the European Community, but also used in other countries worldwide.

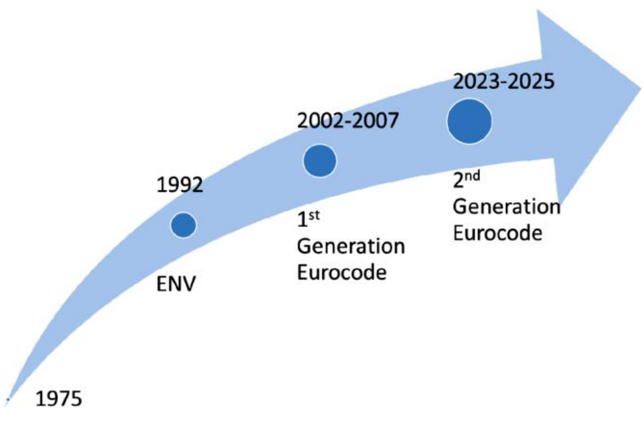


Fig. 1.1: Timeline of Eurocode (Franzen & Garin, 2021)

Please have a look also to our ebook “Risk management in rock engineering”, where the fundamentals of risk management according to Eurocode-7 are explained.

2 Design procedures according to Eurocode-7

According to the Eurocode-7 the following design methods can be used (stand-alone or in combination) for rock engineering design:

- Use of calculations based on design values, quantification of stabilizing and destabilizing actions incl. partial factors considering distribution functions for parameters (see chapter 3 ff.)

- Adoption of prescriptive measures based on rock mass classification and connected empirical rules for support and construction (see for instance discussion by Olsson & Palmström, 2014). They involve mainly conventional and generally conservative design rules and can be applied when comparable experience makes design calculations or application of the observational method unnecessary.

- Observational method as an interactive design process based on observations (monitoring) in conjunction with predefined contingency actions (see our ebook "Observational method")

- Proof by large-scale in-situ testing

3 Main principles of Eurocode based calculations

The EUROCODE demands to perform two different proofs by calculations:

- Ultimate limit state (ULS)
- Serviceability limit state (SLS)

ULS is a condition of a structure, if exceeded, immediately leads to global failure and collapse, respectively. The characterization of the ULS is mainly performed by comparing acting stresses with failure envelops.

SLS is a condition of the structure which, if exceeded, does no fulfill the requirements of usage. SLS is mainly characterized by certain values of deformation (e.g. strain, inclination, settlement etc.)

In general, the limit state conditions is defined as:

$$E \cdot \gamma_E \leq R \cdot \gamma_R$$

where:

E destabilizing actions (forces, stresses etc.)
γ_E partial factor for destabilizing actions (always > 1)
R stabilizing actions (support actions, counterforces etc.)
γ_R partial factor for stabilizing actions (always < 1)

We have to notice that E and R cannot be specified by single values. Both are characterized via distribution functions. Consequently also the limit state is characterized by a joint distribution of E and R as illustrated in Fig. 3.1. Therefore, the result of an ULS analysis is the probability that R < E or vice versa, or with other words the probability of failure.

The Eurocodes themselves but also specific national regulations deliver partial factors for certain constellations considering different geotechnical categories (see our ebook "Risk management in rock engineering"). This is applicable for soil mechanical structures, but only to some extend for rock mechanical ones.

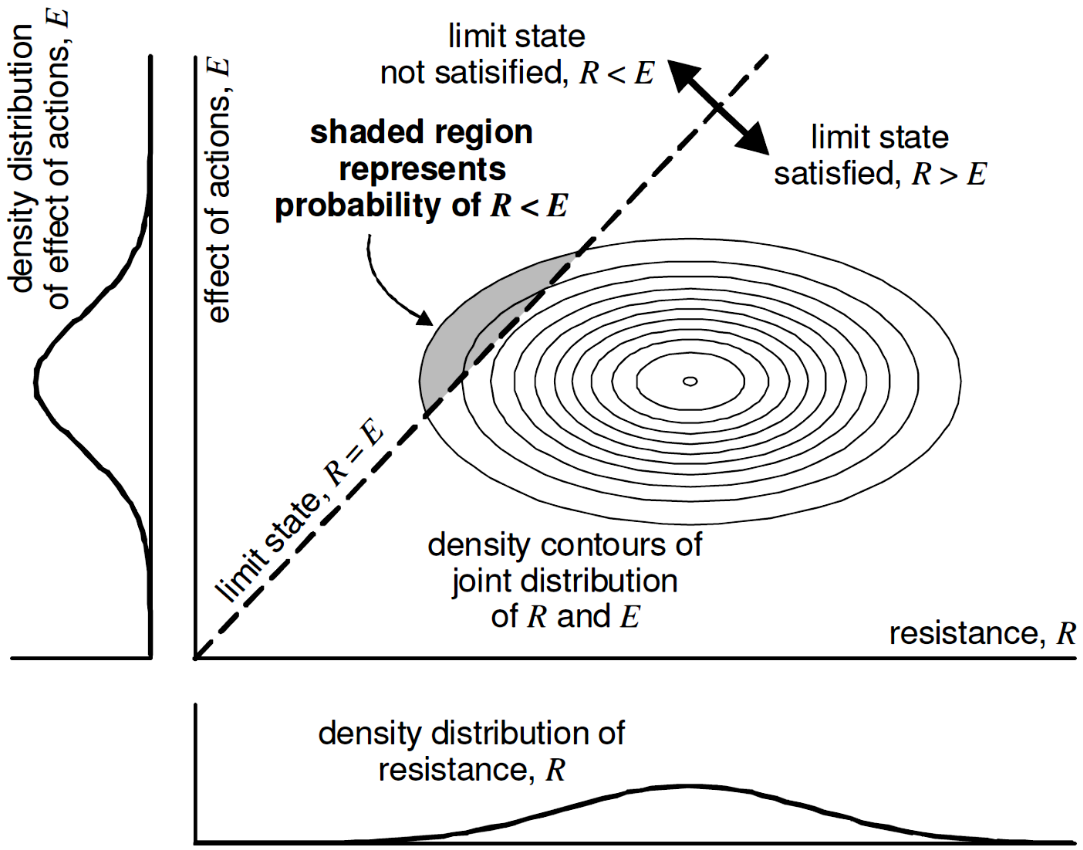


Fig. 3.1: Illustration of ULS (Lemaire et al., 2009)

The most common approach to proof the ULS is the so-called 'c-ϕ'-reduction method (also known as shear strength reduction method). If this method is applied to rock mechanics, the tensile strength has to be considered in addition. Therefore, this technique should then be called 'c-ϕ-σ_t'-reduction method (see our ebook "Factor-of-safety calculations in geomechanics").

Several examples are described in detail by Frank et al. (2005), however dedicated to soil mechanics. A comprehensive introduction into the stochastic concept of the Eurocode was already provided by Fischer (2001).

4 Specific problems of the current Eurocode-7 for rock engineering

Up to now the Eurocode-7 covers soil mechanics quite well, but does not address the specific characteristics of rock masses, which have to be considered in rock engineering (see for instance: Bedi & Orr, 2014; Ferrero et al. 2014; Lamas et al., 2020; Vagnon et al., 2020 or Franzen & Garin, 2021).

The main problems are the following:

The Eurocode concept with partial factors assumes that the uncertainty in stabilizing and destabilizing factors is of aleatory nature, that means that we can describe all the parameters with distribution functions based on measurements / observations. However, several parameters of rock masses are often epistemic (uncertainty due to restricted knowledge). This is mainly caused by the scale-dependent discontinuities inside the rock mass. For instance: it is very difficult to describe the DFN (discrete fracture network) incl. the corresponding properties on these joints and acting forces / stresses on them.
Also, specific rock engineering applications like rockfall protection are not covered by the Eurocode so far and may need another strategy, like replacement of forces/stresses by energy (see Vagnon et al., 2020).

Mathe & Ferentinou (2021) compared the classical factor-of-safety (FOS) concept with the Eurocode-7 concept based on partial factors using a simple analytical limit state design approach. The classical deterministic approach (limit equilibrium) delivers FOS values depending on assumed parameters. The approach according to Eurocode-7 assumes partial factors according to the corresponding geotechnical category. Fig. 4.1 shows the underlying rock slope geometry. Fig. 4.2 shows the results in terms of FOS values (classical FOS approach) and the ratio of resistance forces to action forces (according to Eurocode-7) for different parameter constellations.

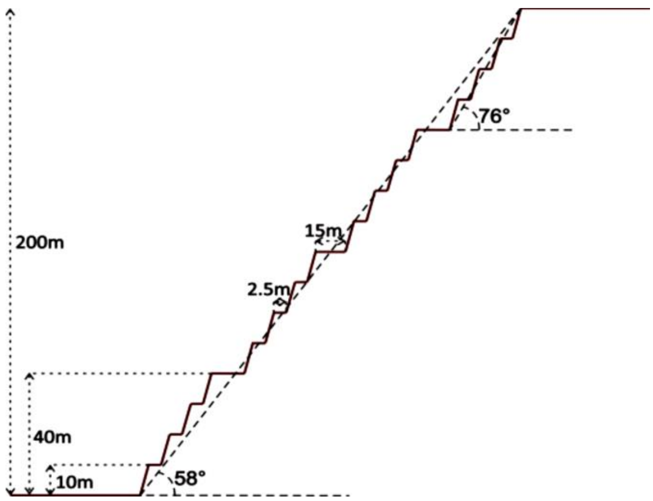
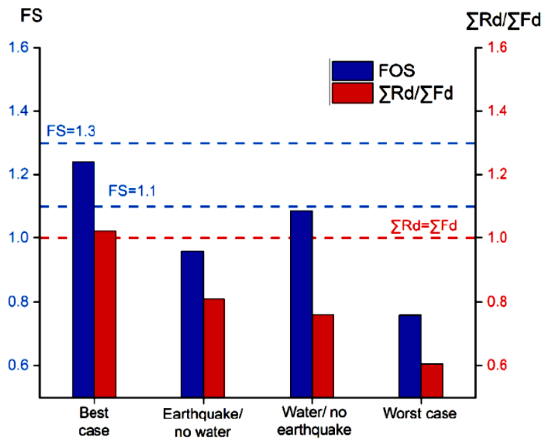


Fig. 4.1: Slope geometry for limit state and Eurocode-7 analysis (Mathe & Ferentinou, 2021)



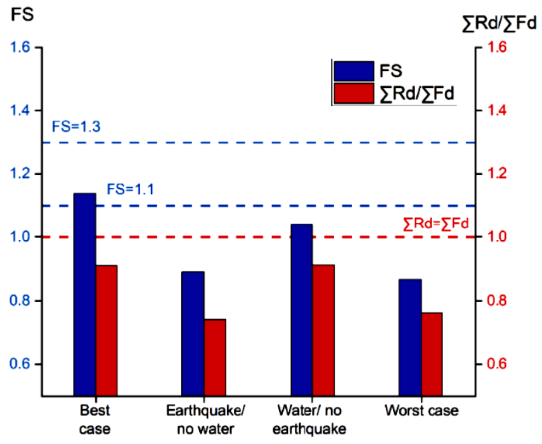


Fig. 4.2: Results for limit state analysis for different model constellations, blue: classical FOS approach, red: Eurocode-7 approach (Mathe & Ferentinou, 2021)

As Fig. 4.2 documents that the two applied procedures deliver different results, whereby the Eurocode based design is more conservative. This small study does not allow to draw general conclusions, but documents that the transition from a FOS-based design toward a stochastic based Eurocode design needs rethinking and new interpretations, because it can produce different results even for relatively simple calculation models.

The most advanced procedure based on Eurocode would be numerical simulations or classical limit-state-analysis based on Monte-Carlo-Simulations using a sampling procedure for picking parameters from distribution functions. The results should document a failure probability smaller then a certain acceptable values (e.g. 10^{-3} to 10^{-6}). The problem behind is, that even by using intelligent sampling procedures a huge number of calculations have to be performed (see our ebook “Risk management in rock engineering”). Therefore, in practical engineering the usage of partial factors is applied. A good compromise might be the application of the point estimate methods (see for instance Ahmadabadi & Poisel, 2016).

Despite all these current not yet solved problems, in future the FOS-values will be replaced by physical more sound values based on failure probability like propagated by the Eurocode.

For underground rock engineering structures the observational method is most appropriate one at the moment. It can be supplemented by numerical calculation methods, however it is unclear how partial factors can be applied (see also Harrison et al., 2023).

5 Eurocode-7: second generation (2024 any beyond)

As already mentioned, the Eurocode undergoes a permanent development. According to the schedule (Lamas et al., 2023), the second generation will be published latest in 2027 and the existing standards must be withdrawn in 2028. In the following the main items of EN 1990 and EN 1997 are given.

According to EN 1990 all constructions are classified by so-called consequence classes (see Tab. 5.1). Consequence classes are used to determine the consequence factors necessary to perform stability and serviceability analysis. EN 1997 describes so-called geotechnical complexity classes (see Tab. 5.2) and in combination with the consequence classes the so-called geotechnical categories (see Tab. 5.3) are defined.

Tab. 5.1: Consequence classes (CC)

Consequence class	**Loss of human life or personal injury**	**Economic, social or environmental consequences**	**Examples**	**Consequence factor**
CC4	Extrem	Huge	Dams, nuclear power plants	Not yet specified
CC3	High	Very great	Highrise buildings, concert halls	1.1
CC2	Medium	Considerable	Buildings not covered by CC1 and CC3	1.0
CC1	Low	Small	Storage buildings	0.9
CC0	Very low	Insignificant	Elements other than structural	Not yet specified

Tab. 5.2: Geotechnical complexity classes (GCC)

Geotechnical complexity classes	Complexity	General features
GCC3	Higher	▪ Considerable uncertainty regarding ground conditions ▪ Highly variable or difficult ground conditions ▪ Significant sensitivity to groundwater and surface water conditions ▪ Significant complexity of the ground-structure interaction
GCC2	Normal	GCC2 applies of GCC1 and GCC2 are not applicable
GCC1	Lower	▪ Negligible uncertainty regarding ground conditions ▪ Uniform ground conditions ▪ Low sensitivity to groundwater and surface water conditions ▪ Low complexity of the ground-structure interaction

Tab. 5.3: Geotechnical categories (GC)

Consequence classes	Geotechnical complexity classes		
	GCC1	GCC2	GCC3
CC3	**GC2**	**GC3**	**GC3**
CC2	**GC2**	**GC2**	**GC3**
CC1	**GC1**	**GC2**	**GC2**

Fig. 5.1 illustrates the interaction and relation between the different classes and categories.

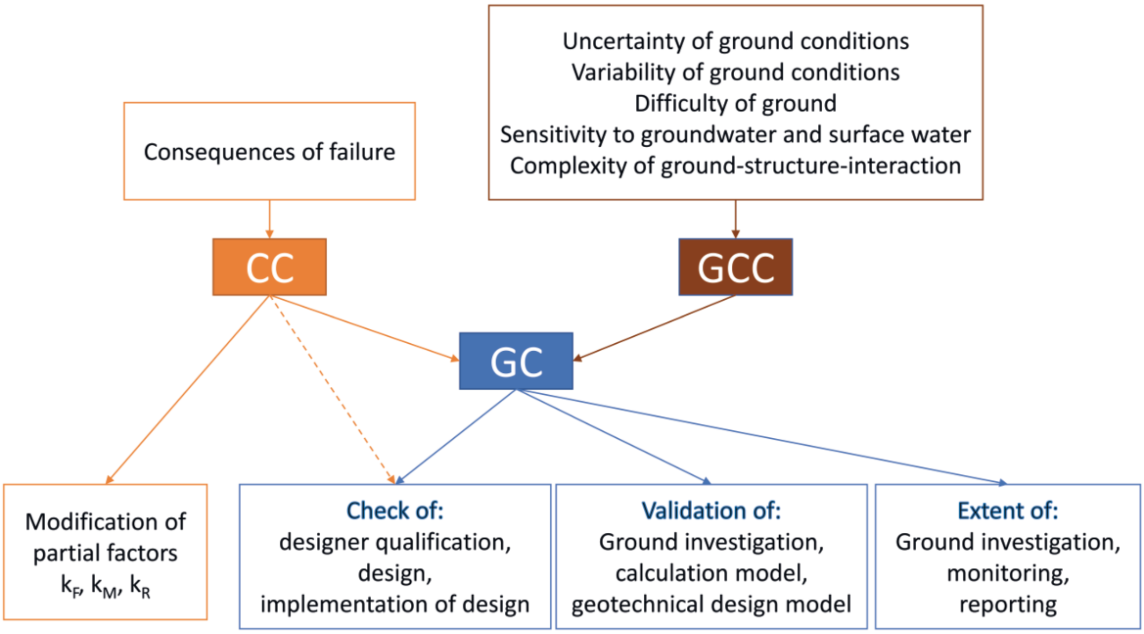


Fig. 5.1 Connection between CC, GCC and GC (Walter et al., 2023)

The design life categories are given in Tab. 5.4.

Tab. 5.4: Design life time

Category of building	Design life time in years
Monumental building structures	100
Building structures not covered by any other category	50
Agricultural and similar structures, replaceable structural parts	25
Temporary structures	≤ 10

The concept of partial factors (see chapter 3) is the preferred verification process. Tab. 5.5 show the partial factors for different verification cases.

Tab. 5.5: Partial factors (Lamas et al. 2023)

Action or effect *Einwirkungen oder Auswirkung von Einwirkungen*				**Partial factors γ_F and γ_E for verification cases** *Teilsicherheitsfaktoren γ_F und γ_E für Überprüfungsfälle*				
Type *Art*	**Group** *Gruppe*	**Symbol** *Symbol*	**Resulting effect** *Auswirkung*	**Structural resistance** [a] *Struktureller Widerstand* [a]	**Static equilibrium and uplift** [b] *Statisches Gleichgewicht und Auftrieb* [b]		**Geotechnical design** *Geotechnische Bemessung*	
Verification case / *Nachweisfälle*				**VC1** [a]	**VC2(a)** [b]	**VC2(b)** [b]	**VC3** [c]	**VC4** [d]
Permanent action (G_k) *Dauerhafte Wirkung* (G_k)	All [f] *Alle* [f]	γ_G	unfavourable / destabilizing *ungünstig / destabilisierend*	$1.35\,k_F$	$1.35\,k_F$	1.0	1.0	G_k is not factored *G_k wird nicht berücksichtigt*
	Water [l] *Wasser* [l]	γ_{Gw}		$1.2\,k_F$	$1.2\,k_F$	1.0	1.0	
	All [f] *Alle* [f]	$\gamma_{G,stb}$	stabilizing [g] *destabilisierend* [g]	not used	1.15 [e]	1.0	not used	
	Water [l] *Wasser* [l]	$\gamma_{Gw,stb}$			1.0 [e]	1.0		
	All *Alle*	$\gamma_{G,fav}$	favourable [h] *günstig* [h]	1.0	1.0	1.0	1.0	
Prestressing (P_k) *Vorspannung* (P_k)		γ_P [k]						
Variable action (Q_k) *Veränderliche Wirkung* (Q_k)	All [f] *Alle* [f]	γ_Q	unfavourable *ungünstig*	$1.5\,k_F$	$1.5\,k_F$	$1.5\,k_F$	1.3	$\gamma_{Q,red}$ [j]
	Water [l] *Wasser* [l]	γ_{Qw}		$1.35\,k_F$	$1.35\,k_F$	$1.35\,k_F$	1.15	1.0
	All Alle	$\gamma_{Q,fav}$	favourable	0	0	0	0	0
Effects of actions (E) *Auswirkungen von Einwirkungen (E)*		γ_E	unfavourable *ungünstig*	Υ_E is not applied *Υ_E wird nicht verwendet*				$1.35\,k_F$
		$\gamma_{E,fav}$	favourable *günstig*					1.0

[a] Verification case VC1 is used both for structural and geotechnical design. / *Der Nachweisfall VC1 wird sowohl für die statische als auch für die geotechnische Bemessung verwendet.*

[b] Verification case VC2 is used for the combined verification of strength and static equilibrium, when the structure is sensitive to variations in permanent action arising from a single-source. Values of γ_F are taken from VC2(a) or VC2(b), which ever gives the less favourable outcome. / *Der Nachweisfall VC2 wird für den kombinierten Nachweis der Festigkeit und des statischen Gleichgewichts verwendet, wenn das Bauwerk gegenüber Schwankungen der ständigen Einwirkungen aus einer einzigen Quelle empfindlich ist. Die Werte für γ_F werden aus VC2(a) oder VC2(b) entnommen, je nachdem, welcher Fall das ungünstigere Ergebnis liefert.*

[c] Verification case VC3 is typically used for the design of slopes and embankments, spread foundations, and gravity retaining structures. See the relevant part of EN 1997 for details. / *Der Nachweisfall VC3 wird in der Regel für die Bemessung von Böschungen und Dämmen, Flachgründungen und Schwerkraft-Stützbauwerke verwendet. Einzelheiten sind dem entsprechenden Teil von EN 1997 zu entnehmen.*

[d] Verification case VC4 is typically used for the design of transversally loaded piles and embedded retaining walls and (in some countries) gravity retaining structures. See EN 1997 (all parts) for details. / *Der Nachweisfall VC4 wird in der Regel für die Bemessung von quer belasteten Pfählen und eingebetteten Stützwänden sowie (in einigen Ländern) für Schwerkraft-Stützbauwerke verwendet. Für Einzelheiten siehe EN 1997 (alle Teile).*

[e] The values of $\gamma_{G,stb} = 1.15$ and 1.0 are based on $\gamma_{G,inf} = 1.35\,\rho$ and $1.2\,\rho$ with $\rho = 0.85$. / *Die Werte von $\gamma_{G,stb} = 1{,}15$ und 1,0 basieren auf $\gamma_{G,inf} = 1{,}35\,\rho$ und $1{,}2\,\rho$ mit $\rho = 0{,}85$*

[f] Applied to all actions except water actions. / *Angewandt auf alle Einwirkungen außer Wassereinwirkungen.*

[g] Applied to the stabilizing part of an action originating from a single source. / *Angewandt auf den stabilisierenden Teil einer Einwirkung, die aus einer einzigen Quelle stammt.*

[h] Applied to actions whose entire effect is favourable and independent of the unfavourable action. / *Angewandt auf Aktionen, deren gesamte Wirkung günstig und unabhängig von der ungünstigen Aktion ist.*

[j] $\gamma_{Q,red} = \gamma_{Q,1} / \gamma_{G,1}$ where $\gamma_{Q,1}$ = corresponding value of γ_Q from VC1 and $\gamma_{G,1}$ = corresponding value of γ_G from VC1. / *$\gamma_{Q,red} = \gamma_{Q,1} / \gamma_{G,1}$ mit $\gamma_{Q,1}$ = entsprechender Wert von γ_Q aus VC1 und $\gamma_{G,1}$ = entsprechender Wert von γ_G aus VC1.*

[k] For the definition of γ_P where γ_P is materially dependent, see other relevant Eurocodes. / *Für die Definition von γ_P, wenn γ_P materialabhängig ist, siehe andere relevante Eurocodes.*

[l] For water actions induced by waves and currents. / *Für Wassereinwirkungen durch Wellen und Strömungen.*

The design process according to EN 1990 and EN 1997 comprises in general 4 tasks:

(1) Reliability management: establishing geotechnical complexity classes, consequence classes and geotechnical categories

(2) Ground modelling: determination of geological, hydrological and geotechnical conditions

(3) Design verification: verification of ULS and SLS

(4) Implementation of design: supervision, inspection, monitoring, maintenance during execution and design service time

For geotechnical ULS design the following is valid in terms of the partial factors (see Tab. 5.5.):

- VC3: partial factors are put only on unfavourable variable actions
- VC4: partial factors are applied to action effects

There are 2 options to consider partial factors (for geotechnical engineering MFA is normally used):

- Partial factors on material strength parameters (material factor approach = MFA)
- Partial factors on resistance directly (resistance factor approach = RFA)

Tab. 5.6: Example for partial factors for materials: k_M=consequence factor (Walter et al., 2023)

	Ground property ***Baugrundeigenschaft***	**Symbol**	**M1**	**M2**
Soil and fill *Boden und Auffüllungen*	Shear strength in effective stress analysis (τ_f) *Schubfestigkeit mit effektiven Spannungen* (τ_f)	$\gamma_{\tau f}$	1.0	1.25 k_M
	Coefficient of peak friction (tan ϕ'_p) *Spitzenwert des effektiven Reibungsbeiwerts* (tan ϕ'_p)	$\gamma_{\tan\varphi,p}$	1.0	1.25 k_M
	Coefficient of friction at critical state (tan ϕ'_{cs}) *Reibungsbeiwert bei konstantem Volumen* (tan ϕ'_{cs})	$\gamma_{\tan\varphi,cs}$	1.0	1.1 k_M
	Shear strength in total stress analysis (c_u) *Schubfestigkeit mit totalen Spannungen* (c_u)	γ_{cu}	1.0	1.4 $k_{M<<}$
Rock material and rock mass *Gestein und Gebirge*	Shear strength (τ_f) *Schubfestigkeit* (τ_f)	$\gamma_{\tau f}$	1.0	1.25 k_M
	Unconfined compressive strength (q_u) *Einaxiale Druckfestigkeit* (q_u)	γ_{qu}	1.0	1.4 k_M
Rock discontinuities *Trennflächen im Gebirge*	Shear strength (τ_f) *Schubfestigkeit* (τ_f)	$\gamma_{\tau dis}$	1.0	1.25 k_M
	Coefficient of residual friction (tan $\phi'_{dis,r}$) *Restreibungsbeiwert* (tan $\phi'_{dis,r}$)	$\gamma_{\tan\varphi dis,r}$	1.0	1.1 k_M

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