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STIFTELSEN BERGTEKNISK FORSKNING
ROCK ENGINEERING RESEARCH FOUNDATION

UTREDNING AV RISKBASERADE PRINCIPER INOM BERGDIMENSIONERING:

Så bör en standard vara uppbyggd

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BeFo Rapport 190

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Investigation of risk-based approaches to rock engineering design:

Principles for design codes

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FÖRORD

Utformningen av bergkonstruktioner behöver normalt uppfylla en mängd olika krav. Dessa krav kan komma såväl från beställare, som genom lagkrav, miljödomar och byggnormer. Bergmekanikern som utför dimensioneringen har att ta hänsyn till alla dessa krav och ska samtidigt så långt som möjligt optimera konstruktionen så att beställaren får största möjliga nytta för pengarna. I den pågående revideringen av designkoden Eurokod 7 strävar man efter att förbättra tillämpbarheten inom bergbyggande. Det har dock saknats en vetenskaplig grund att stå på avseende just revideringen av reglerna för bergbyggande. Syftet med forskningsprojektet, som avslutas i och med denna slutrapport, har därför varit att vetenskapligt stödja de som arbetar med Eurokodrevideringen genom att publicera två vetenskapliga artiklar på området.

Forskningsprojektet har främst fokuserat på de övergripande dimensioneringsprinciperna och hur dessa behöver ses ur ett riskhanteringsperspektiv. I de två bifogade artiklarna visas hur dimensionering kan tolkas i enlighet med de generella riskhanteringsprinciper som finns i standarden ISO 31000. Med en sådan tolkning kan dimensioneringen utföras på ett transparent och strukturerat sätt. Därmed kan dimensioneringsarbetet även integreras i det allmänna hanterade av risker som utförs i byggprojekt. Det bör ge möjlighet till ett kostnads- och resurseffektivt bergbyggande, samtidigt som samhället får tillräckligt säkra konstruktioner.

Forskningen har utförts som ett seniorforskarprojekt på KTH:s avdelning för jord- och bergmekanik, där Arild Palmstrøm, Rock Mass AS, har bidragit med expertstöd. Författarna riktar ett särskilt tack till referensgruppen, som bestod av Robert Sturk (Skanska), Gunilla Franzén (Geoverkstan), Thomas Dalmalm (Trafikverket) och Per Tengborg (BeFo). Stiftelsen Bergteknisk Forskning – BeFo har stöttat projektet finansiellt.

Stockholm, 2019

Per Tengborg

PREFACE

The design of a rock engineering structure generally needs to satisfy a number of requirements that may originate from clients, as well as from laws, court rulings, and design codes. The designing rock engineer needs to account for all these requirements, while trying to optimize the structure to maximize the utility of the invested funds. In the ongoing revision of Eurocode 7, one main purpose is to improve the applicability with respect to rock engineering. A scientific basis for this work has however been missing. The purpose of this research project, which ends with this final report, has therefore been to support the revision work by publishing two scientific articles on rock engineering design principles.

The research project has mainly focused on the general design principles and how these by necessity needs to be viewed from a risk management perspective. The two appended articles discuss how design may be interpreted within the general risk management principles established by the international standard ISO 31000. Such a risk-based view facilitates both transparent and structured design work. This allows the design work to be integrated in the general risk management process that regardless is carried out in the construction project. This should facilitate cost-effective rock engineering design and construction, while the societal requirements regarding for example safety are satisfied.

The research has been carried out as a senior research project at KTH Royal Institute of Technology, at the Division of Soil and Rock Mechanics. Dr. Arild Palmstrøm, Rock Mass AS, has supported the project with his expertise. The authors acknowledge the reference group, which consisted of Dr. Robert Sturk (Skanska), Dr. Gunilla Franzén (Geoverkstan), Dr. Thomas Dalmalm (Trafikverket) and Per Tengborg (BeFo). The project was financially supported by the Rock Engineering Foundation – BeFo.

Stockholm, 2019

Per Tengborg

SAMMANFATTNING

Utformningen av bergkonstruktioner behöver normalt uppfylla en mängd olika krav. Dessa krav kan komma såväl från beställare, som genom lagkrav, miljödomar och byggnormer. Bergmekanikern som utför dimensioneringen har att ta hänsyn till alla dessa krav och ska samtidigt så långt som möjligt optimera konstruktionen så att beställaren får största möjliga nytta för pengarna. I Sverige gäller sedan 2010 de EU-gemensamma byggreglerna Eurokoderna inom i stort sett all byggkonstruktion – dock inte inom bergbyggnad. I den pågående revideringen av Eurokod 7 är dock ett syfte att förbättra tillämpbarheten inom bergbyggande. Det har dock saknats en vetenskaplig grund att stå på avseende just revideringen av reglerna för bergbyggande. Syftet med forskningsprojektet, som avslutas i och med denna slutrapport, har därför varit att vetenskapligt stödja de som arbetar med Eurokodrevideringen genom att publicera två vetenskapliga artiklar på området.

Forskningsprojektet har främst fokuserat på de övergripande dimensioneringsprinciperna och hur dessa behöver ses ur ett riskhanteringsperspektiv. Som vi ser det, är det väsentligt att den reviderade Eurokod 7 är uppbyggd enligt riskbaserade principer. Det innebär att dimensionering behöver ses som en del av det nödvändiga strukturerade riskhanteringsarbete som ska utföras i byggprojekt. I de två bifogade artiklarna visar vi hur dimensionering kan tolkas i enlighet med de generella riskhanteringsprinciper som finns i standarden ISO 31000. Med en sådan tolkning kan dimensioneringen utföras på ett transparent och strukturerat sätt. Därmed kan dimensioneringsarbetet även integreras i det allmänna hanterade av risker som utförs i byggprojekt.

I Artikel I diskuterar vi översiktligt de övergripande principerna för hur en designkod för bergbyggande behöver vara organiserad för att ge samhället ett kostnads- och resurseffektivt bergbyggande, som samtidigt ger tillräckligt säkra konstruktioner. Vi diskuterar särskilt betydelsen av att observationsmetoden integreras på ett jämbördigt sätt i designkoden tillsammans med övriga tillåtna verifieringsmetoder för gränstillstånd.

I Artikel II tar vi ett helhetsgrepp om frågan vad riskbaserad dimensionering egentligen innebär. Artikeln presenterar ett generellt ramverk för dimensionering av bergkonstruktioner, där en grundförutsättning har varit att dimensionering måste ses som beslutsfattande under osäkra förhållanden. Vi diskuterar och strukturerar de beslut och överväganden som behöver göras i dimensioneringsarbetet och visar hur besluten kan fattas ur ett riskperspektiv. För att stödja arbetet med revideringen av Eurokod 7 diskuterar vi också på vilket sätt som det presenterade ramverket kan implementeras i en designkod. En viktig grundprincip är att koden utformas så att bergmekanikern ges möjlighet att anpassa hanteringen av de risker, som identifieras under dimensioneringsarbetet, till de aktuella förhållandena i projektet. Kodförfattarna bör alltså avstå från att ange alltför detaljerade krav avseende exempelvis utformning av förundersökningar. I annat fall kan effekten bli att potentiellt dyra åtgärder behöver utföras inte för att de behövs ur ett riskperspektiv, utan endast för att koden kräver det. Det skulle enligt vår åsikt rimma illa med det övergripande målet om en långsiktigt hållbar samhällsutveckling.

Nyckelord: bergbyggande, risk, dimensionering, Eurokod 7, observationsmetoden

SUMMARY

The design of a rock engineering structure generally needs to satisfy a number of requirements that may originate from clients, as well as laws, court verdicts, and design codes. The designing rock engineer needs to account for all these requirements, while trying to optimize the structure to maximize the utility of the invested funds. The Eurocodes have been the current design code in Sweden for almost all construction work, except for rock engineering. However, in the ongoing revision of Eurocode 7, one main purpose is to improve the applicability with respect to rock engineering. A scientific basis for this work has however been missing. The purpose of this research project, which ends with this final report, has therefore been to support the revision work by publishing two scientific articles on rock engineering design principles.

The research project has mainly focused on the general design principles and how these by necessity needs to be viewed from a risk management perspective. As we see it, it is essential that the revised Eurocode 7 is structured in accordance to risk-based principles. This implies that design needs to be understood as a part of the necessary structured risk management work that is carried out in construction projects. In the two appended articles, we show how design may be interpreted within the general risk management principles established by the international standard ISO 31000. Such a risk-based view facilitates both transparent and structured design work. This also allows the design work to be integrated in the general risk management process that regardless is carried out in the construction project.

In Article I, we discuss synoptically the general principles for how a rock engineering design code needs to be structured to facilitate both cost-effective construction and sufficiently safe structures. In particular, we discuss the importance of integrating the observational method into the design code, so that this limit state verification method is equally treated as the others.

In Article II, we take a more holistic approach to the fundamental meaning of risk-based rock engineering design. The article presents a generic framework for rock engineering design, where it is presupposed that design by definition is decision-making under uncertainty. We discuss and structure the required decisions and considerations that are made in the design work and show how those decisions can be made from a risk perspective. To support the revision work of Eurocode 7, we also discuss how the presented framework can be implemented in a design code. An essential principle is that the code allows the designing rock engineer to manage the associated risks in a way that is suitable given the project at hand. This implies that code writers should refrain from putting too detailed requirements regarding for example the extent and quality of pre-investigations. Otherwise, we fear that potentially costly measures occasionally will need to be taken not because they are needed from a risk perspective, but only because the code requires them. This would in our opinion not be in line with the overall striving toward a long-term sustainable societal development.

Keywords: bergmekanik, sannolikhetsbaserad dimensionering, Eurokod 7, observationsmetoden

LISTA ÖVER BIFOGADE ARTIKLAR

Inom ramen för detta forskningsprojekt har följande artiklar publicerats. Artiklarna återpubliceras i sin helhet i denna rapport med villkor enligt CC-BY 4.0 Creative Commons licens: http://creativecommons.org/licenses/by/4.0.

Artikel I

Spross, J., Stille, H., Johansson, F. & Palmstrøm, A. 2018. On the need for a risk-based framework in Eurocode 7 to facilitate design of underground openings. *Rock Mechanics and Rock Engineering, 51*(8), 2427–2431. https://doi.org/10.1007/s00603-018-1463-8

Artikel II

Spross, J., Stille, H., Johansson, F. & Palmstrøm, A. 2019. Principles of risk-based rock engineering design. *Rock Mechanics and Rock Engineering*, in press. https://doi.org/10.1007/s00603-019-01962-x

INNEHÅLL

1. INLEDNING

1.1 Bakgrund

Undermarksanläggningar såsom tunnlar och bergrum utgör idag en väsentlig del av infrastrukturen i vårt moderna samhälle. Liksom vid allt byggande måste sådana anläggningar dimensioneras så att de under hela sin livslängd har förmåga att motstå de laster och påfrestningar som konstruktionen utsätts för, givet att de underhålls på ett tillfredsställande sätt. Likaledes finns normalt sett även miljökrav och ett antal praktiska begränsningar att ta hänsyn till. Utformningen ska därutöver också så långt som möjligt optimeras så att beställaren – ofta samhället genom någon beställande myndighet – får största möjliga nytta för pengarna. Bergmekanikern som utför denna dimensionering har alltså att beakta många olika tekniska och ekonomiska aspekter i sitt arbete med att utforma bästa möjliga undermarksanläggning givet förutsättningarna.

För att säkerställa att konstruktioner uppfyller samhälleliga krav på säkerhet och tillräckligt liten miljöpåverkan under hela konstruktionens livslängd, har man i de flesta utvecklade länder tagit fram standarder och normer som anger hur konstruktioner ska vara utformade. Dessa regler stammar i regel från århundraden av byggverksamhet. Länge utvecklade respektive land sina egna regler, men i och med det allt tätare europeiska samarbetet inom först den Europeiska Gemenskapen och sedermera den Europeiska Unionen insåg man att gemensamma byggregler länderna emellan skulle underlätta för den gemensamma marknaden. Resultatet blev Eurokoderna, som efter en lång och krokig resa under trettiotalet år ersatte respektive medlemslands nationella regelverk år 2010. Tanken var att så skulle ske även inom bergbyggnad: Eurokod 7 (EN1997, CEN, 2004) anger tydligt att avsett tillämpningsområde innefattar geotekniska konstruktioner i både jord och berg. I Sverige insåg man dock tidigt att tillämpbarheten inom bergbyggnad var tämligen begränsad. Boverket fastställde därför i sina föreskrifter och allmänna råd (2011:10) om tillämpning av europeiska konstruktionsstandarder att dessa inte är tillämpliga för tunnlar och bergrum (§2). I stället gäller Plan- och byggförordningens (2011:338) tredje kapitel, där det framgår exempelvis att:

> *7 § För att uppfylla det krav på bärförmåga, stadga och beständighet som anges i 8 kap. 4 § första stycket 1 plan- och bygglagen (2010:900) ska ett byggnadsverk vara projekterat och utfört på ett sådant sätt att den påverkan som byggnadsverket sannolikt utsätts för när det byggs eller används inte leder till*

1. *att byggnadsverket helt eller delvis rasar,*
2. *oacceptabla större deformationer,*
3. *skada på andra delar av byggnadsverket, dess installationer eller fasta utrustning till följd av större deformationer i den bärande konstruktionen, eller*
4. *skada som inte står i proportion till den händelse som orsakat skadan.*

Som synes nivån på kraven inte särskilt detaljerad. En uppsättning riktlinjer har därför utvecklats av Trafikverket för dimensionering av (främst) stora trafikinfrastrukturprojekt och samlats i en projekteringshandbok (Lindfors et al. 2015).

På europeisk nivå har man insett att situationen inte är tillfredsställande för dimensionering av konstruktioner i och på berg. I samband med initieringen av det första revideringsarbetet uttrycktes det därför en önskan om att dimensionering av bergkonstruktioner ska täckas fullt ut av Eurokod 7. En särskild utredningsgrupp, Evolution Group EG13, tillsattes därför under Teknisk Kommitté 250:s sjunde underkommitté inom Europeiska Kommittén för Standardisering. EG13 hade i uppdrag att tillse att frågor rörande bergbyggnad beaktades inom revideringsarbetet. (EG13 kom senare att omvandlas till Task Group TG3 med ett något förändrat mandat som innebar att man endast skulle understödja revideringsarbetet tekniskt med expertkunskap inom bergbyggande.)

1.2 Forskningsprojektets syfte och omfattning

För att vetenskapligt stödja TG3:s arbete initierades det forskningsprojekt, vars slutrapport du nu håller i handen. Forskningsprojektet har syftat till att belysa vikten av att ha ett riskbaserat synsätt vid dimensionering av konstruktioner i och på berg. Detta har främst skett genom publicering av två tidskriftsartiklar i välrenommerade vetenskapliga tidskrifter, eftersom diskussion av generella dimensioneringsprinciper inom bergbyggnad i princip helt saknas i internationell vetenskaplig press. Utan vetenskaplig grund att stå på, är det svårt att motivera det ena synsättet framför ett annat i revideringsarbetet, vilket kan leda till att framtidens dimensioneringsstandarder inte baseras på bästa möjliga vetenskapliga grund.

För att säkerställa att bergbyggande sker på ett resurseffektivt sätt, samtidigt som eventuell miljöpåverkan blir acceptabelt liten, är det, som vi ser det, väsentligt att den reviderade Eurokod 7 är uppbyggd enligt riskbaserade principer. Varför så är fallet redogör vi för i de två vetenskapliga artiklarna, vilka har bifogats denna slutrapport. Principerna har också sammanfattats i själva rapporten.

Genom internationell publicering hoppas vi även kunna väcka intresse hos andra forskare och praktiker över hela världen att bidra till att förbättra de principer som ligger till grund för framtidens regelverk och riktlinjer. Vi har också som en del av forskningsprojektet verkat för att införa framtagna riskbaserade principer genom att ge kommentarer på de utkast på nya klausuler, som tagits fram i det pågående revideringsarbetet för Eurokod 7, samt diskuterat detta inom TG3.

1.3 Översikt över innehållet

I denna slutrapport redogörs i Kapitel 2 för de riskbaserade dimensioneringsprinciper som vi anser ska ligga till grund för allt bergbyggande. I Kapitel 3 sammanfattas kort det generella ramverk för riskbaserad dimensionering av bergkonstruktioner som utvecklats i projektet. Eftersom artiklarna i sin helhet bifogats i slutet av rapporten, hänvisas till dessa för de fullständiga forskningsresultaten. I Kapitel 4 ges några avslutande kommentarer till resultaten.

2. RISKBASERAD DIMENSIONERING

2.1 Geologiska och geotekniska osäkerheter

Dimensionering av konstruktioner i berg skiljer sig på en viktig punkt från dimensionering av konstruktioner som byggs helt av tillverkade byggmaterial såsom stål och betong. Denna skillnad består i att de geologiska förhållandena och de geotekniska egenskaperna hos bergmassan till stora delar är okända i början av dimensioneringsarbetet, jämfört med stål och betong som kan beställas från en tillverkare med de egenskaper som önskas. Bergmekanikern har dock inte den möjligheten. Inför liknande svårigheter står även geoteknikern som dimensionerar konstruktioner i jord, men med skillnaden att geoteknikern ofta har större möjlighet än bergmekanikern att undersöka förhållandena i marken i början av dimensioneringsarbetet, eftersom jorden normalt sett är relativt enkelt tillgänglig för undersökning från markytan.

Denna geologiska och geotekniska osäkerhet avseende de verkliga förhållandena i marken brukar man kategorisera som *epistemisk* osäkerhet, det vill säga att osäkerheten beror på brist på kunskap, vilken man dock har möjlighet att öka exempelvis genom att utföra undersökningar (till skillnad från *aleatorisk* osäkerhet som avser ett helt slumpmässigt beteende där ytterligare undersökningar inte minskar osäkerheten); se vidare diskussion av dessa kategorier av osäkerheter i exempelvis Der Kiureghian & Ditlevsen (2009) och de två bifogade artiklarna.

Det är denna epistemiska osäkerhet som bergmekanikern har att hantera i dimensioneringsarbetet, som på ett övergripande plan syftar till att ge konstruktionen tillräcklig säkerhetsmarginal med avseende på dessa osäkerheter, för att de krav som beställaren ställt på konstruktionen ska uppfyllas (med tillräckligt stor sannolikhet).

2.2 Dimensionering är riskhantering

2.2.1 Vad är risk?

Som vi ser det, innebär dimensioneringsarbete beslutsfattande i ett osäkert läge, det vill säga att beslut ska fattas om lämplig utformning på konstruktionen, trots att bergmassans geologiska förhållanden och tekniska egenskaper inte är helt kända. Därmed faller dimensioneringsarbete inom ramen för byggprojektets riskhanteringsarbete, som syftar till att begränsa de risker som kan hänföras till byggprojektet och som kan få oönskade konsekvenser av något slag, ifall de faller ut. För att förstå vad dimensionering egentligen innebär behöver man alltså förstå de grundläggande principerna för riskhantering.

Risk kan enligt ISO 31000 (2009), som är en generell standard för riskhantering, definieras som *osäkerhetens effekt på mål*. Sett ur bergbyggandets perspektiv handlar det alltså i princip om hur mycket de geologiska och geotekniska osäkerheterna påverkar möjligheten att uppnå det övergripande målet att färdigställa en undermarksanläggning, som uppfyller beställarens alla krav och samtidigt håller budget och tidplan. Annorlunda uttryckt kan man säga att de geologiska och geotekniska osäkerheterna gör att det finns en viss sannolikhet att det inträffar en oönskad konsekvens (att målet inte uppnås). Dimensioneringsarbetet ska därför ses som ett sätt att *hantera* denna risk genom att man under arbetets gång kontinuerligt identifierar, analyserar och utvärderar de hot och möjliga konsekvenser som kan göra att målet inte uppnås, och att man i förekommande fall på olika sätt minskar risken, om den bedöms vara för stor (Figur 1). Principer för hur detta låter sig göras i byggprojekt redogörs för bland annat i metodbeskrivningen utgiven av SGF (2017), artikeln av Spross et al. (2018), samt det praktiska tillämpningsexemplet som presenterats av Spross et al. (2015).

2.2.2 Etablera kontext – att förstå det tekniska systemet

Då dimensioneringsarbetet inbegriper många olika dimensioneringsfrågor med olika svårigheter som medför risker, är det viktigt att arbeta med dessa frågor på ett strukturerat sätt. För att lyckas med detta krävs det att man först skaffar sig en god förståelse av hur byggprojektets mål samverkar med yttre faktorer och de geologiska och geotekniska förutsättningarna. Förståelsen av denna kontext är avgörande för om arbetet med de olika tekniska lösningarna som man överväger i dimensioneringsarbetet ska bli framgångsrikt. Denna förståelseuppbyggnad motsvarar etableringen av kontexten i Figur 1.

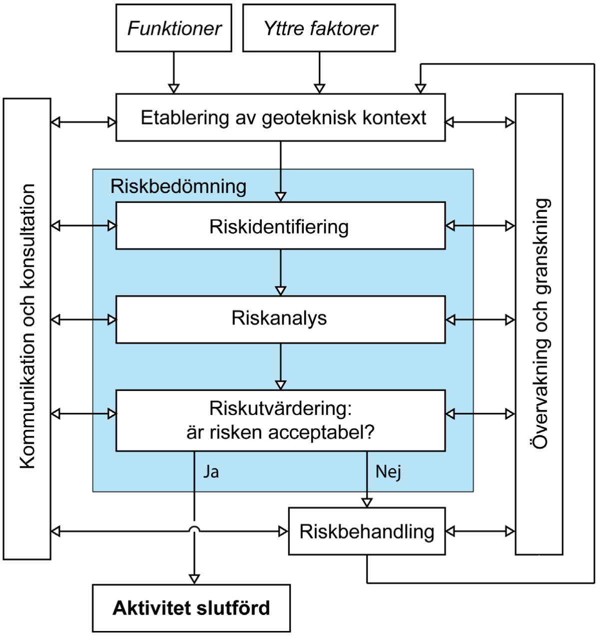
2.2.3. Riskidentifiering – vilka är de relevanta dimensioneringsfrågorna?

När man har denna förståelse är det första steget att identifiera vilka detaljerade dimensioneringsfrågor som behöver beaktas för de analyserade tekniska lösningarna. Varje dimensioneringsfråga har en direkt koppling till de ställda kraven. Detta motsvarar riskidentifieringen i Figur 1. I praktiken kan dessa frågor delas in i fem kategorier:

- Tillfredsställande säkerhet mot brott i konstruktionen i relation till samhällets krav,

- Tillfredsställande beständighet i relation till Beställarens krav på konstruktionens livslängd och förväntat underhållsbehov,
- Tillfredsställande brukbarhet i relation till Beställarens krav och förväntningar,
- Acceptabel miljöpåverkan i relation till samhällets minimikrav (eller Beställarens högre ställda krav i förekommande fall),
- Acceptabel arbetsmiljö i relation till arbetsmiljölagar (eller Beställarens högre ställda krav i förekommande fall).

Eftersom de geologiska och geotekniska osäkerheterna normalt utgör de största utmaningarna i dimensioneringsarbetet, utgör bedömningar av förväntat geologiskt scenario (bergmekaniskt beteende) bergmekanikerns kanske viktigaste uppgift. Notera att de dimensioneringsfrågeställningar som bergmekanikern ställs inför behöver beaktas utifrån både förhållandena för den permanenta konstruktionen och den temporära situationen precis vid berguttaget.



Figur 1. *Den cykliska riskhanteringsprocessen enligt ISO 31000. (Översatt version från Spross et al 2019, CC-BY 4.0)*

2.2.4. Riskanalys – hur stora är rådande osäkerheter och potentiella konsekvenser?

För varje dimensioneringsfråga behöver man identifiera vilka osäkerheter som kan påverka sannolikheten att vi uppnår de satta kraven avseende den analyserade frågeställningen. Viktig del i detta arbete är att identifiera vad som i Eurokoderna kallas dimensioneringssituationen (d.v.s. de fysiska förutsättningar som råder). Dessa osäkerheter behöver sedan kvantifieras, eller åtminstone klassificeras med avseende på deras storlek. Därutöver behöver man också bedöma storleken på konsekvensen som uppstår i fall man inte uppnår kraven. Utifrån en given konstruktionslösning kan man alltså analysera hur olika tekniska åtgärder och val av dimensionerings- och konstruktionsmetoder påverkar storleken på både rådande osäkerheter och konsekvenser. Detta motsvarar riskanalysen i Figur 1. I praktiken tar man hänsyn till en mängd olika typer av osäkerheter, där bristen på kunskap om de faktiska geologiska och geotekniska förhållandena i berget är den största. Andra osäkerheter som man behöver beakta inkluderar osäkerheter som introduceras i materialmodeller och beräkningsmetoder. Sådana modellosäkerheter representerar svårigheten att matematiskt och tekniskt beskriva komplexa fenomen i dimensioneringsberäkningar. För vidare diskussion av olika geologiska scenarion, vilka osäkerheter som är relevanta att beakta, samt deras respektive utmaningar vid dimensioneringsarbete, hänvisar vi till specialiserade publikationer för detta, såsom Palmström & Stille (2015) och Stille & Palmström (2018). Exempel finns även presenterade i Tabell 1 i den bifogade Artikel II.

2.2.5. Riskutvärdering – är föreslagen teknisk lösning acceptabel?

För att kunna avgöra om en viss konstruktionslösning eller annan åtgärd är lämplig att genomföra, behövs också tydligen kriterier för vilka risker som man är beredd att ta. Somliga kriterier fastställs av samhället i designkoder, exempelvis acceptabel brottsannolikhet för olika storlekar på konsekvenser, medan andra kriterier behöver fastställas av den som äger den aktuella risken (d.v.s. den som får stå för kostnaden i fall den inträffar). Denna utvärdering av huruvida en viss föreslagen konstruktionslösning är lämplig eller ej motsvarar riskutvärderingen i Figur 1. Principen är att man beroende av att storleken på osäkerheten och storleken på konsekvensen behöver olika mycket säkerhetsmarginal. Rent konkret blir därmed syftet med dimensioneringsarbetet att hitta en konstruktionslösning som ger rätt säkerhetsmarginal för var och en av de relevanta dimensioneringsfrågorna.

2.2.6. Riskbehandling – åtgärder för att minska risken vid behov

Om risken med den analyserade konstruktionslösningen bedöms vara för stor, beslutar man om att utföra riskbehandling (Figur 1), det vill säga att genomföra någon åtgärd för att minska risken. Man kan då i princip välja bland följande åtgärder, som även kortfattat diskuteras nedan (se artikel II för mer uttömmande diskussion).

- Ändra den tekniska lösningen
- Välja en annan verifieringsmetod för gränstillståndet
- Göra ytterligare geotekniska undersökningar
- Införa kontroll och granskning av dimensioneringsarbetet och under byggtiden

Ändringar av den tekniska lösningen kan påverka risknivån på två sätt. Mindre justeringar påverkar oftast säkerhetsmarginalen genom att göra designen mer eller mindre konservativ. Mer storskaliga ändringar kan även påverka storleken på eventuella konsekvenser vid brott i konstruktionen, exempelvis om man beslutar att flytta hela anläggningen till en annan plats.

Den tekniska lösningens säkerhet kan verifieras på olika sätt. I de flesta moderna designkoder definierar man otillräcklig säkerhet som ett överskridande av ett gränstillstånd. De vanligaste verifieringsmetoderna för att den tekniska lösningen inom bergbyggande är dessa: 1) analytiska, numeriska eller sannolikhetsbaserade beräkningar, 2) hävdvunna (empiriska) metoder såsom Q-metoden, 3) observationsmetoden. De olika verifieringsmetoderna är behäftade med olika grad av modellosäkerhet, vilket alltså påverkar bedömningen av risken.

Genom att utföra geotekniska undersökningar kan man minska den epistemiska osäkerheten, eftersom man ökar kunskapen om de geologiska och geotekniska förutsättningarna. Det är förstås också möjligt att man efter att ha analyserat resultaten från utförda undersökningar kraftigt behöver revidera sin uppfattning om de geologiska förhållandena: den bedömda osäkerheten kan även öka om man efter mer detaljerade undersökningar upptäcker att bergmassans kvalitet i ett område är betydligt sämre än vad man först antog.

Genom att kontrollera och granska utfört arbete kan man minska sannolikheten för fel. Under dimensioneringsarbetet kan användandet av tredjepartsgranskning (i Sverige ofta kallat GK3-granskning) medföra att exempelvis sannolikheten ökar för att alla relevanta dimensioneringsfrågor har blivit beaktade. Varje kontroll av utförandet, kvalitén på använt material, m.m., är att betrakta som en del i riskbehandlingen, dvs. att vi bygger som vi har tänkt.

2.3 Geoteknisk kategori som praktiskt verktyg att klassificera risk

Ett sätt att ge konstruktioner tillräcklig säkerhetsmarginal i dimensioneringsarbetet är att klassificera storleken på risken och koppla säkerhetskrav till respektive klass. Användning av sådana klasser syftar till att öka transparensen i dimensioneringsarbetet avseende de beslut som fattas för att minska risken. Vi föreslår att sådan klassificering görs genom att för varje dimensioneringsfråga ansätta en osäkerhetsklass (motsvarande har diskuterats i det pågående revisionsarbetet av Eurokod 7 och har då benämnts *Geotechnical Complexity Class*) och en konsekvensklass, baserat på den tillgängliga kunskap som man har för tillfället, och väga samman detta till en klassificering som anger den rådande risken. Ett vedertaget begrepp i Eurokod 7 som kan användas till denna riskklass är *Geoteknisk kategori*, som därmed skulle få en riskbaserad definition. I dagsläget kan dock de geotekniska kategorierna i Eurokod 7 inte fullt ut betraktas som riskklasser, då de inte kopplas till storleken på de rådande osäkerheterna, utan bara till konsekvenserna. De formella osäkerhetsklasser som vi förordar har dock än så länge bara introducerats som idé (Stille & Palmström 2018), även om liknande verktyg diskuteras i det pågående revideringsarbetet för Eurokod 7. Med en riskbaserad Geoteknisk kategori blir även de beslut som påverkas av den geotekniska kategorin fattade baserat på den rådande risken. Detta inkluderar krav och rekommendationer avseende exempelvis

- vilka verifieringsmetoder som bedöms lämpliga för gränstillstånd,
- omfattning på geotekniska undersökningar,
- omfattning på kontroll och granskning av dimensioneringsarbetet och under byggtiden,
- omfattning på dokumentation av förhållandena i marken.

Notera överensstämmelsen med listan över möjliga åtgärder för riskbehandling i avsnitt 2.2.6.

Vi anser att införandet av osäkerhetsklasser som underklasser till den geotekniska kategorin skulle stärka det riskbaserade synsättet i dimensioneringsarbetet, om de tillsammans med konsekvensklasserna kopplas till Geoteknisk kategori. Hur detta kan göras diskuteras i detalj i Stille & Palmström (2018) samt i Artikel II i denna rapport.

2.4 Minskning av osäkerheter med hjälp av observationsmetoden

Eftersom storskaliga förundersökningar av de geologiska förhållandena och geotekniska egenskaperna i berget ofta inte låter sig göras av ekonomiska eller praktiska skäl, har man i stället i stor utsträckning använt den så kallade observationsmetoden för att därigenom kunna minska osäkerheterna under byggtiden. I Eurokod 7 anges också observationsmetoden som en tillåten metod för att verifiera gränstillstånd (d.v.s. visa att tillräcklig säkerhetsmarginal har uppnåtts för respektive dimensioneringsfråga).

Observationsmetoden, som först beskrevs av Peck (1969), innebär att den framtagna designen endast ses som preliminär vid tiden för byggstart. I Sverige kallades metoden för aktiv design och började användas redan i början på 1970-talet (Stille 1986). Observationer av konstruktionens beteende och eventuella ändringar görs sedan enligt i förväg definierade mät- och åtgärdsprogram och fastställda larmgränser för oacceptabelt beteende. Det betyder att den slutliga tekniska lösningen inte är känd förrän projektet är klart. Att man redan i designskedet utreder konstruktionens möjliga beteende, samt fastställer gränser för acceptabelt beteende och ett åtgärdsprogram, är dock en förutsättning för att observationsmetoden ska kunna användas framgångsrikt. Enligt Palmström & Stille (2007) kan man annars lätt råka ut för förseningar och kostnadsökningar, eftersom man sannolikt inte har beaktat de stora osäkerheter som råder kring konstruktionens möjliga beteende från början. Ett strikt tillvägagångssätt enligt framtagna planer krävs också av Eurokod 7.

Ur ett principiellt perspektiv är det, som vi ser det, väsentligt att samtliga metoder som är tillåtna för att verifiera gränstillstånd i en standard behandlas på ett likvärdigt sätt. Bergmekanikern ska själv kunna avgöra utifrån det egna projektets unika förutsättningar vilken verifieringsmetod som är mest lämpad för att ge beställaren bästa möjliga kvalitet och kostnadseffektivitet i byggprojektet. Detta ställer särskilda krav på hur standarden utformas, eftersom den mest kostnadseffektiva mängden förundersökningar kommer att vara beroende av vilken verifieringsmetod som används: om observationsmetoden används, så att man kan minska osäkerheterna om geologin och de geotekniska egenskaperna under byggtiden, kan man sannolikt förvänta sig att man behöver mindre mängd i tidiga skeden än annars. Vilken mängd undersökningar som ska utföras i olika skeden bör alltså inte fastställas i standarden. Däremot kan man som designkodsförfattare förstås ge läsaren rekommendationer i bakgrundsdokument och handböcker, som då kan användas på samma sätt som jurister använder förarbeten till hjälp att tolka lagtext.

3. GENERELLT RAMVERK FÖR DIMENSIONERING AV KONSTRUKTIONER I BERG

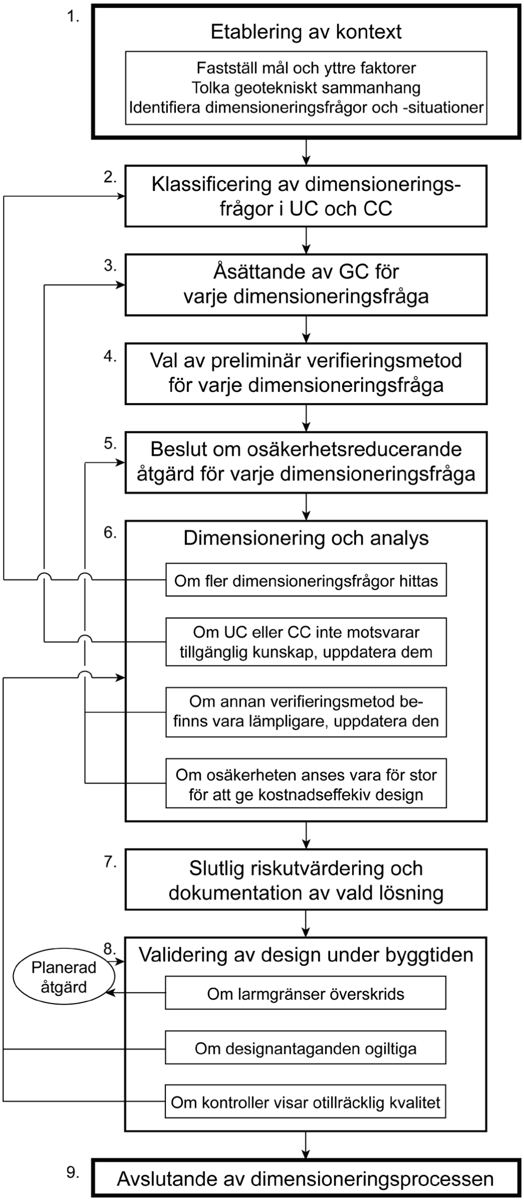
3.1 Översikt över ramverket

Vi har i detta projekt analyserat dimensioneringsprocessen inom bergbyggande ur ett riskperspektiv. Baserat på denna analys har vi formulerat ett generellt ramverk för hur dimensionering bör utföras, för att uppnå målet att färdiga konstruktioner kostnadseffektivt ska uppfylla ett krav just på en acceptabel risk. Ramverket visar på behovet av att hantera osäkerheten, konsekvenserna och därmed risken på ett stringent sätt i dimensioneringsarbetet. Ramverket kan beskrivas som en algoritm (Figur 2) och är giltigt för dimensionering av både temporär och permanent konstruktion. I följande avsnitt ger vi en översikt över de principer som ramverket är uppbyggt på. För en detaljerad genomgång av respektive steg i algoritmen och fördjupad diskussion av ramverket hänvisas till Artikel II.

3.2 Viktiga principer för riskbaserad dimensionering

Till skillnad från Eurokoderna anser vi att dimensioneringsfrågorna ska ligga i fokus för dimensioneringsarbetet, inte de olika konstruktionsdelarna. Det innebär exempelvis att samma konstruktionsdel enligt vårt synsätt bör kunna få olika geoteknisk kategori för olika dimensioneringsfrågor. Därmed kan man hantera frågeställningar med liten risk på ett enkelt sätt, medan komplexa frågeställningar kan hanteras i enlighet med den omfattning på åtgärder som den identifierade höga risken kräver, trots att båda frågeställningarna avser samma konstruktionsdel. Det ska jämföras med dagens Eurokod, där man sätter konstruktionsdelens konsekvensklass baserat på den största konsekvensen hos de analyserade dimensioneringsfrågorna.

Eftersom geotekniska undersökningar och andra osäkerhetsreducerande åtgärder spelar stor roll inom bergbyggande, är det viktigt att dessa utförs just i den omfattning som är befogat utifrån den bedömda risken. Vi menar att frågan om undersökningarnas omfattning ska hanteras av den som utför dimensioneringen som det beslutsteoretiska problem som det är – d.v.s. är potentiell kunskap värd kostnaden för undersökningen? Det beror på att den optimala mängden undersökningar beror både på respektive projekts egenheter och på vald verifieringsmetod för gränstillståndet. Det innebär att om en designkod skulle upprätta specifika krav på miniminivå av undersökningar baserat på den aktuella risken, så kan det lätt uppträda situationer när undersökningar framtvingas av koden trots att de potentiella



Figur 2 *Generellt ramverk för dimensionering av bergkonstruktioner. De numrerade stegen diskuteras i detalj i Artikel II. (Översatt version från Spross et al 2019, CC-BY 4.0)*

undersökningsresultaten sannolikt inte påverkar den aktuella risken. Det gäller särskilt när observationsmetoden används för att verifiera gränstillstånd.

Eftersom denna metod bygger på att mätningar och observationer utförs för att minska osäkerheterna under byggtiden, så blir det olyckligt ifall designkoden skulle framtvinga undersökningar i designskedet för att minska samma osäkerhet. Vårt föreslagna ramverk behandlar därför de olika verifieringsmetoderna för gränstillstånd på ett likvärdigt sätt. Bergmekanikern kan därmed välja den verifieringsmetod som bäst passar det aktuella fallet – till skillnad från Eurokoderna som tydligt favoriserar partialkoefficientmetoden.

3.3 Möjligheter till implementering i designkoder

Vi ser goda möjligheter att formulera en designkod baserat på det presenterade ramverket i Figur 2. Det bygger dock på att kodförfattarna endast reglerar de övergripande principerna och överlåter åt den dimensionerande ingenjören att bestämma hur riskerna bäst hanteras i det egna projektet. Notera att detta också lägger ansvar på ingenjören: att ignorera uppenbara risker – exempelvis genom att besluta om en design baserat på extremt få undersökningar – måste anses vara grov oaktsamhet, såvida man inte lagt på mycket stora säkerhetsmarginaler förstås. Återigen: här finns naturligtvis möjligheter för kodförfattare att bistå den enskilda ingenjören genom att bilägga designkoden med förklarande bakgrundsdokument och ta fram handböcker med rekommendationer.

4. SLUTORD

I detta forskningsprojekt har vi utrett möjligheterna att införa riskbaserade förhållningssätt till dimensionering av bergkonstruktioner i designkoder. Inom ramen för projektet har vi publicerat två vetenskapliga artiklar på temat, vilka har bilagts denna slutrapport. Artikel I diskuterar varför riskbaserade förhållningssätt är nödvändiga i en designkod för att tillse att dimensionerade bergkonstruktioner uppfyller samhällets säkerhetskrav på ett kostnadseffektivt sätt. Artikeln diskuterar särskilt de utmaningar som man står inför i det pågående revideringsarbetet avseende Eurokod 7.

I Artikel II utreder vi riskbaserad dimensionering av bergkonstruktioner i ett vidare perspektiv och sätter dimensionering i sitt sammanhang i byggprojektets riskhantering. Ur detta perspektiv presenterar vi ett generellt riskbaserat ramverk för dimensionering av bergkonstruktioner. Ramverket är uppbyggt så att dimensioneringsprocessen ger konstruktioner som kostnadseffektivt uppfyller kravet på acceptabel risk. Detta krav på acceptabel risk avser såväl säkerhet mot brott i konstruktionen som konstruktionens beständighet, brukbarhet och eventuell miljöpåverkan. Artikeln syftar till att ge kodförfattare en vetenskaplig grund för de principer som de använder när de formulerar krav och rekommendationer i koden, eftersom detta helt saknas i den vetenskapliga litteraturen för bergbyggande.

Vi hoppas att dessa två artiklar ska sporra en fortsatt diskussion av dimensioneringsprinciper i både svenska och den internationella forskningsgemenskapen inom bergbyggande. Vi tror att användandet av ett stringent riskbaserad synsätt vid dimensionering av tunnlar och bergrum gör arbetet mer transparent och att det går lättare att integrera det i det allmänna hanterande av risker i dessa typer av projekt.

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Artikel I

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ORIGINAL PAPER

On the Need for a Risk-Based Framework in Eurocode 7 to Facilitate Design of Underground Openings in Rock

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Abstract

The European design code for geotechnical engineering, EN-1997 Eurocode 7, is currently under revision. As design of underground openings in rock fundamentally differs from design of most other types of structures, the revised Eurocode 7 must be carefully formulated to be applicable to underground openings. This paper presents the authors' view of how a design code for underground openings in rock needs to be organized to ensure that new structures are both sufficiently safe and constructed cost-effectively. The authors find that the revised version of Eurocode 7 carefully must acknowledge the fundamental decision-theoretical connection between design and risk management that should permeate all geotechnical design work. Otherwise, if the revised code is not given a risk-based framework, the authors fear that, as a consequence, the observational method will not be favorable to use in excavations of underground openings in rock. Then, cost-effective construction will be very difficult to achieve.

Keywords Eurocode 7 · Risk · Design · Structural safety · Rock

1 Introduction

The European design code for geotechnical engineering, EN-1997 Eurocode 7 (CEN 2004), is currently under revision. In principle, the code covers design of structures located both in soil and in rock, although it has not yet been fully implemented for rock structures. However, one of the many aims with the revision is to incorporate design of rock structures fully in the new version of Eurocode 7, which is planned for publication in 2020. To arrange for the incorporation of rock engineering in the revised version, an Evolution Group for rock mechanics (EG13) was appointed under Technical Committee 250's Sub-Committee 7, which is in charge of Eurocode 7 within the European Committee for Standardization (CEN). (EG13 was later reorganized into a Task Group (TG3) with a slightly revised mandate to support the revision work only technically with expert knowledge in rock engineering.)

Naturally, the evolution of a common structural design code for all countries in the European Union is a challenge and compromises are of course required. However, in developing a modern design code, there are, in our opinion, some fundamental principles that must not be violated to ensure a stringent and logic hierarchy between the many stated requirements in the code. The aim of this paper is therefore

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A first version of this paper was presented at the Workshop on Rock Mechanics in Eurocode 7 held on October 11, 2017, in the course of the 66th Geomechanics Colloquium in Salzburg and published in the workshop proceedings edited by Schubert and Kluckner (2017). The present paper is a revised and expanded journal version that provides further context for a wider readership. We believe that the ongoing revision of Eurocode 7 needs more involvement of both the rock engineering research community and practicing rock engineers, as the revised Eurocode 7 will affect the rock engineering practice in Europe for a long time in the future. Therefore, we encourage further discussion on this topic.

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to establish our view of what needs to be the theoretical basis for the revised Eurocode 7 and, in addition, to encourage rock engineers to contribute to the discussion of the current revision work. Comments or replies to this paper are most welcome! We believe that the active participation of the rock engineering community is utterly important to ensure the highest quality in the revised Eurocode 7, as its principles will affect all geotechnical construction work within the European Union in the foreseeable future.

As underground openings constitute a major part of engineered rock structures, we in this paper present our view of how a design code for such structures needs to be organized to ensure that they are both sufficiently safe and constructed cost-effectively: We strongly believe that Eurocode 7 must be developed on a risk-based framework. This view is in line with our previous discussions on the topic (e.g. Stille 2017; Stille and Palmstrøm 2017). Thereafter, we discuss some critical aspects that we believe must be addressed in the revised code, if it is to be applicable to rock structures.

2 The Risk-Based Design Philosophy

2.1 Design as a Decision Under Uncertainty

In our opinion, design of underground openings in rock differs fundamentally from design of structures made of manufactured materials such as concrete and steel. The main difference lies in the magnitude of the uncertainties regarding the material properties: There is much less uncertainty in the assessment of the properties of steel and concrete than that of rock. Design of underground openings in rock differs also from design of excavations and other structures in soil. This difference lies in the level of difficulty to carry out pre-investigations. The amount of pre-investigations that normally is carried out for excavations in soil is simply not feasible for most underground openings in rock. Instead, the rock engineer will start the design process with few investigations at a large distance from each other in a geological setting that, in addition, likely is more variable than that of the geotechnical engineer.

These differences accentuate the fundamentals of the design process. As we see it, the choice of design is essentially a decision made under uncertainty. For design of underground openings, this concept becomes much clearer, because of the large uncertainties. Consequently, the design decision must be made in light of all other decisions that affect the construction process, implying that the choice of design is only one part of the decision maker's overall risk management work. This means that design of underground openings in rock must not be detached from all the other decision making in the project, which includes environmental and social considerations regarding, for example, impact on groundwater levels and unpleasant vibrations caused by blasting.

2.2 Design is Part of the Project's Risk Management

With this view, design becomes subject to the general risk concept, defined as the *effect of uncertainties on objectives* in ISO 31000 (ISO 2009). This ISO standard defines a general procedure for risk management (Fig. 1); its applicability to geotechnical construction work has been shown by, e.g., van Staveren (2006, 2009, 2013) and Spross et al. (2015). Additionally, the Swedish Geotechnical Society recently published a methodology for geotechnical risk management (SGF 2017; Spross et al. 2017), which is based on the principles in ISO 31000.

In the context of geotechnical engineering, an *objective* may be to complete a structure that satisfies both the client's requirements and the society's requirements on structural safety and environmental impact. *Uncertainty* is mainly caused by the lack of knowledge regarding the geological conditions at the site. Such uncertainty is known as epistemic uncertainty, which implies that it can be reduced by gaining additional information about the geological conditions; in contrast, we have aleatory uncertainty that is caused by randomness, which cannot be reduced. The importance of this distinction is further discussed by Der Kiureghian and Ditlevsen (2009). Lastly, *effect* (of the uncertainty on the objectives) indicates that the uncertainty may cause a consequence of some sort. This shows the link to the possibly more well-known definition of risk

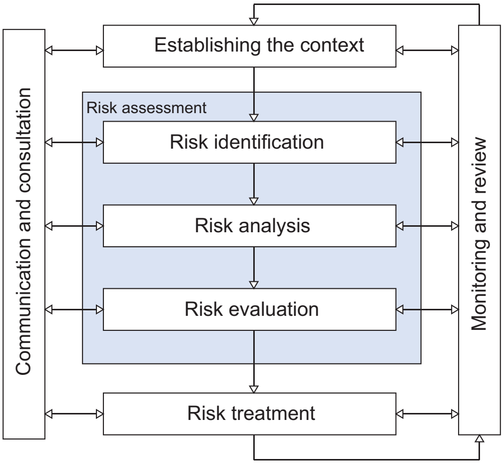

Fig. 1 The cyclic process of risk management, according to ISO 31000. (© Spross et al. 2015 and IOS Press 2015. CC-BY-NC 3.0: https://creativecommons.org/licenses/by-nc/3.0/deed.en_US)

as a measure of the combination of probability of an event and the severity of its consequences; though, note that the definition of "risk" varies between different research fields, as discussed by Aven (2012).

In designing underground openings in rock, it is important to understand that not only can magnitude of the (epistemic) uncertainties change during the project, but there may also be different objectives to satisfy at different times. For example, during construction, one objective is to facilitate a sufficiently safe and economic excavation progress. The associated uncertainty is then mainly caused by a significant lack of information of the rock mass properties. In contrast, when the rock has been excavated, the rock mass properties are much better known, but the objective is then changed to ensure a safe and functional facility for public use. Consequently, it is only at this point, where it must be shown that the structure actually satisfies the safety requirement of the applicable design code. Clearly, the acceptable risk is different for these two objectives.

Accepting that decisions regarding the design are part of the project's risk management implies that the design work becomes a tool for the rock engineer to analyze the risks involved in the construction. This means that the design that in the end is put forward to the decision maker before construction is started is, in principle, the result of a risk analysis (cf. Fig. 1). *Decision maker* here refers to the person that has been appointed to make decisions regarding risks, which is done in establishing the context of the risk management. As discussed in Spross et al. (2017), this person—the *risk owner*—needs to represent the entity that both is responsible for achieving the objective (that is affected by uncertainties) and carries the related economic risk. Consequently, the decision maker will belong to either the client or the contractor, depending on project organization and contract type.

Based on the result of the risk analysis, the decision maker assesses the risk associated with the proposed design and makes the decision either to accept the design (including the associated risks) or to resend the proposed design to the engineer with the objective to reduce the risks. The making of this decision is known as risk evaluation. In principle, risk reduction can then be done either by reducing uncertainties or by reducing the expected consequences, seeing that risk inherently consists of these two components as previously discussed. We find that a fundamental aspect of design is to understand its role in the general risk management work of the project. The implications of taking this risk-based view when designing underground openings in rock are discussed in the following.

2.3 Observational Approaches are Fundamental to Underground Excavation in Rock

The risk-based view on design highlights the effect of uncertainties on the design decisions. Considering the significant uncertainties involved in rock engineering projects, we find that a rational management of the involved uncertainties is of the utmost importance to ensure cost-effective construction, as well as to ensure acceptable structural safety both during construction and for the completed structure.

Traditionally, design of rock structures has largely been based on observational approaches in combination with prescriptive measures (e.g., rock mass classification systems). The reason is that experience has indicated that the risk caused by geological uncertainties is best managed by reducing these uncertainties. This can be done either through investigations in early phases or by monitoring structural behavior during construction. As large investigation programs often are costly in rock engineering, it has proven favorable to reduce a significant part of the uncertainty during construction. The design method known as the observational method (Peck 1969) is based on this principle. Its application to design of underground openings has been discussed by for example Brantmark et al. (1998), Stille and Holmberg (2008, 2010), Serra and Miranda (2013), Bozorgzadeh and Harrison (2016), Spross and Johansson (2017), and Bjureland et al. (2017).

In short, the observational method implies that the design is only preliminary at the start of the construction. Observations of geological conditions and structural behavior are then used to reduce uncertainties during construction. If the observations indicate that the design is insufficient, predefined contingency actions are put into operation. Consequently, the final design is not known until the project is completed. Note that this does not mean that the observational method should be seen as a learn-as-you-go approach; Palmstrom and Stille (2007) find that such interpretations often lead to unexpected time delays and cost increases. Instead, careful analysis of the expected possible range of structural behavior is required, so that situations for which there are no prepared contingency actions can be avoided. This stricter approach is required by the current Eurocode 7 (CEN 2004).

We find that the procedure of using observations during construction to reduce uncertainties and risks, thereby ensuring structural safety, is a fundamental aspect of design of underground openings in rock, with which Eurocode 7 must be compatible. How the principles of the observational method in the current version of the Eurocode 7 can be satisfied has been discussed by Prästings et al. (2014), Spross et al. (2016), Spross and Johansson (2017), Bjureland et al. (2017), and Fuentes et al. (2017).

3 Challenges that Need to be Addressed in the Revision Work

3.1 Ensured Connection Between Design Work and Risk Management

Presuming that the risk-based approach to design is fundamental to design of underground openings—we encourage discussions on this presumption!—we find that the revised Eurocode 7 must have a stringent hierarchy that ultimately facilitates designs that target the *risk*. If this is not achieved, design decisions will, as a consequence, not be aimed toward cost-effective risk reduction.

A typical effect of targeting the risk in the design work is that the required effort in uncertainty-reducing measures (i.e. the amount of performed investigations) will depend on both the present uncertainties and the expected consequences of failure. Although a lack of knowledge regarding the ground conditions often justifies elaborate ground investigations to avoid problems during construction, the amount of performed investigations should also be affected by the expected consequences of failure. To make an example: if there are existing structures sensitive to subsidence caused by groundwater drawdown as an effect of expected groundwater inflow to an underground opening, more elaborate ground investigations of the groundwater conditions should be required by the design code, than if the construction work took place in an area with no sensitive structures.

An important issue is who decides on the amount of investigations in a project. Should the code specify requirements on minimum investigation effort or should it be left to the decision-making engineer to decide? Looking at design of underground openings in rock from a risk-based perspective and in the context of the project's risk management, we believe that the amount of performed investigations should be for the decision maker to decide. In other words, the code should refrain from interfering in what we believe is one of the engineer's main tasks: to decide how risks (uncertainties and consequences) are most efficiently managed in the context of the problem at hand (Spross et al. 2015). For example, deciding on less pre-investigation will instead require more effort in monitoring and control during construction in order to satisfy the design criteria of the completed structure. This highlights that the decision on where to make the uncertainty-reducing effort in fact only is an economic consideration from a safety point of view. Therefore, it should not be regulated in a design code.

3.2 Need for Stringent Hierarchy

We find that an effect of having a risk-based view on design is an implicit requirement on stringent hierarchy in the framework of the code. Presupposing that the overall aim of Eurocode 7 is to satisfy the safety requirements of EN 1990 (Table 1) (CEN 2002), the hierarchy of Eurocode 7 must acknowledge this fundamental aspect of design. In the current version of Eurocode 7, there are four acceptable design verification methods: design by calculation, verification by prescriptive measures, verification by experimental models and load tests, and verification with an observational method. In order to have a risk-based design code, selection of design verification method must be superior to any prescriptions on how uncertainties are to be reduced. The reason is that the selection of verification method is much related to how the engineer chooses to accommodate the design to the present risk. For example, if the observational method is used, uncertainty is mainly reduced during construction, which implies that the required amount of pre-investigations likely is less, than if the same design were verified by calculation. Naturally, some investigations in early phases are needed also when using the observational method, to allow definition of for example the range of possible behavior and limits of acceptable behavior with respect to the preliminary design.

If the new version of Eurocode 7 instead was to put prescriptions on uncertainty-reducing measures superior to the selection of design verification method, the benefits of using the observational method in excavations of underground openings in rock would be completely lost, as the code would need to prescribe the same amount of pre-investigations regardless of the amount of performed measurement and observations during construction. For rock engineering applications, we find that such a development would be very unfortunate, as much of underground works in rock rely on the principles of the observational method.

Table 1 Recommended minimum values for reliability index, β, according to EN 1990 (CEN 2002)

Safety class	Minimum values for β	
	Reference period 1 year	Reference period 50 years
RC3	5.2	4.3
RC2	4.7	3.8
RC1	4.2	3.3

4 Concluding Remarks

To summarize, we have discussed how a design code for underground openings in rock needs to be organized to ensure that new structures are both sufficiently safe and constructed cost-effectively. We believe that Eurocode 7 must be developed on a risk-based framework to be applicable to rock structures, if designs are to be both sufficiently safe and cost-effective to construct. It is our strong belief that having another basis for design than the risk-based will increase future project costs, because the code may require additional support measures, investigations, and inspections, even though they may not be needed from a risk perspective. We may then end up with a revised code that is worse than its predecessor was; therefore, we hope that these aspects are carefully considered in the ongoing revision work.

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Compliance with Ethical Standards

Conflict of interest Prof Håkan Stille is a member of Task Group 3 for Rock Mechanics in the revision of Eurocode 7 and a member of the ISRM Commission on Evolution of Eurocode 7.

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ORIGINAL PAPER

Principles of Risk-Based Rock Engineering Design

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Abstract

In comparison with other types of construction, the development of rock engineering design codes has been slow. Codes must, however, be developed with relevant discipline-specific characteristics in mind. This paper, therefore, presents a generic design framework for rock engineering. The framework is based on the presumption that rock engineering design must be viewed as decision-making under uncertainty, which makes the design process subject to general risk management principles, as risk is defined as "effect of uncertainties on objectives" (ISO 31000). Thus, rock engineering design codes ultimately need to facilitate design processes that target the risk, to enable design of structures that not only are sufficiently safe and durable and cost-effectively constructed, but also imply safe and healthy work conditions during construction and an acceptably low environmental impact. The presented framework satisfies this fundamental requirement and the authors find codification of its principles to be rather straightforward, as long as the level of detail in the code is governed by a strict application of ISO's general risk management principles. Further details on methods and practical recommendations can instead be supplemented in separate handbooks and application guidelines.

Keywords Risk · Design · Structural safety · Rock · Code · Risk management

1 Introduction

1.1 Challenges of Rock Engineering Design: Code Development and Practice

As with all structural systems, rock engineering structures need a satisfactory engineering design to withstand loads and deterioration processes caused by use and the surrounding environment. In general terms, the designing engineer's objective is to maximise the expected utility of the facility; though, given the large scale and complexity of many rock engineering structures, this objective can certainly be a challenge. Moreover, there are constraints that the designing engineer needs to consider, of which compliance with public safety requirements is possibly the most important, while others include, for example, aesthetic considerations and availability of construction material, machinery, and labour.

In many countries, structural design codes have been established to provide the foundation of good engineering practice, based on past experience inherited from centuries of construction. A rather recent fundamental code improvement was the shift from allowable stress design to the limit state design concept, on which most modern structural design codes are built. Examples include the Eurocodes (CEN 2002), the American ACI 318 Building Code Requirements for Structural Concrete (American Concrete Institute 2014), and the Canadian Highway Bridge Design Code (Canadian Standards Association 2014; Fenton et al. 2015). The code development in rock engineering design has, however, been lagging behind. The introduction of the Eurocodes provides a striking example: although the EN-1997 Eurocode 7 (CEN 2004) claims to include rock engineering structures in its scope, its practical applicability to rock engineering has been questioned (e.g., Ferrero et al. 2014; Harrison et al. 2014; Lamas et al. 2014; Spross

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et al. 2018b). In fact, even such a fundamental concept to the Eurocodes as limit state design has been found unsuitable or difficult to apply to some design issues in rock engineering, mainly because of the difficulty in defining analytical limit state functions and characterise the variability of involved variables. As a consequence, corresponding target failure probabilities for the analysed design problems are currently lacking (Bjureland et al. 2017a, b; Harrison 2017). Although some deficiencies in Eurocode 7 may be corrected in upcoming revisions, developing a functional design code for engineered rock structures has clearly proven a substantial challenge.

As it turns out, constructing rock engineering structures poses some specific challenges on the design that is not present for other types of structures. A fundamental difference is the origin of the construction material itself: while manufactured construction materials can be ordered with rather specific properties, rock is a natural material with considerably larger property variability. Moreover, the geological conditions not only vary in space physically, but also are more or less uncertain in terms of both magnitude and variability—this lack of knowledge is known as epistemic uncertainty (Der Kiureghian and Ditlevsen 2009). A key aspect of rock engineering design is, therefore, to increase the knowledge about the rock mass through geotechnical investigations or other observations, thereby reducing the epistemic uncertainty. Consequently, the rock engineer will often start the design process with rather limited information, possibly coming from a synoptic study of available geological maps and a few boreholes drilled at a considerable distance from each other. Thus, the rock engineer needs to be aware of that there may be unknown geological features with fundamentally different geotechnical properties in between the boreholes. This epistemic uncertainty will prevail until the rock mass is excavated; only then can the geotechnical properties be investigated in detail.

The other engineering challenge is caused by the excavation process required in underground construction projects. In contrast to excavations in soil, where the execution goes from safe conditions at the beginning towards less safe conditions as the excavation depth increases, the highest probability of structural collapse of an underground facility can be attributed to the temporary design situation right after the excavation, before the support prescribed by the design has been installed (Fig. 1). Thus, a successful rock engineering design needs to consider not only the permanent design situation when the facility has been completed, but also the temporary design situation right after the rock excavation sequence. Note here the significant difference in available knowledge for the respective designs of the temporary and permanent situations: the design of the permanent structure can in principle take into account any information gained

Fig. 1 Escalator shaft at the Odenplan commuter train station in Stockholm, Sweden. Temporary design situation during construction of the shaft (left) and permanent design situation when the station is in use (right)

during the excavation, while that information was unavailable to the designer of the temporary structure.

1.2 Purpose and Structure of Paper

Given the expected increased use of the underground space, we find it crucial that future design codes for rock engineering are developed with its discipline-specific characteristics in mind. The purpose of this paper is, therefore, to present a generic design framework for rock engineering and, in light of this, discuss how a modern design code needs to be structured to be applicable in current rock engineering practice.

Unlike previous generic descriptions of the rock engineering design process (Bieniawski 1993; Feng and Hudson 2004; Hudson and Feng 2015), our framework is based on the presumption that a risk-based approach is fundamental—not contributional—to the rock engineering design process. The need for this presumption was established and discussed in depth in our previous papers (Spross et al. 2018b; Stille and Palmström 2018, and Stille 2017). Note that risk-based design principles naturally are applicable also to other engineering disciplines than rock engineering; however, the implementation of such principles may be different depending on the characteristics of the respective disciplines.

2 Risk: a Fundamental Concept in Rock Engineering Design

In general terms, engineering design is an iterative decision-making process of devising a system to meet desired needs, by optimal conversion of resources through the application of basic sciences, mathematics, and engineering sciences (ABET 2013). This definition highlights the key aspects of the design process:

- It is iterative,
- It is driven by needs,
- It strives toward optimisation of the product, and
- It requires decision-making regarding the adequacy of the design.

As rock engineering is inherently associated with significant epistemic uncertainty, the rock engineering design process can essentially be interpreted as decision-making under uncertainty. Consequently, the design process must also be recognised as a part of the project's risk management, seeing that risk is defined as the *effect of uncertainties on objectives* in ISO 31000 (ISO 2009). In a rock engineering context, *objectives* can be exemplified with the completion of an underground facility that corresponds to the client's needs and wishes, as well as to any societal requirements on, for example, structural safety and environmental impact; in other words, to leave the client with a product that provides sufficient quality during both excavation and operation. The word *effect* indicates that the prevailing uncertainties in any external factors may be linked to consequences, which makes ISO's definition well aligned with the possibly more well-known definition of risk as a measure of the combination of the probability of an event and the severity of its consequences (Spross et al. 2018b).

The standard ISO 31000 defines a general procedure for risk management that has been found applicable to geotechnical engineering projects (van Staveren 2006, 2009, 2013; SGF 2017; Spross et al. 2018a). In a risk management context, key components of the design process are to identify risks associated with different design alternatives, and subsequently to analyse the probability of occurrence of their potential consequences (Fig. 2). Furthermore, risk management is an essential continuous process that is needed in all phases of the construction project, from the preliminary study until completion of the structure (Fig. 3). To clarify: design does not need assistance from risk management, but design is risk management! This is, therefore, discussed in depth in Sect. 4.6.3.

We note that in practice, strictly risk-based structural design is rarely performed in the sense of allowing tailored trade-offs between different types of consequences for individual structures (see Sect. 4.1). Instead, design codes often require facilities to satisfy some absolute requirements, such as allowable failure probabilities when it comes to hazards

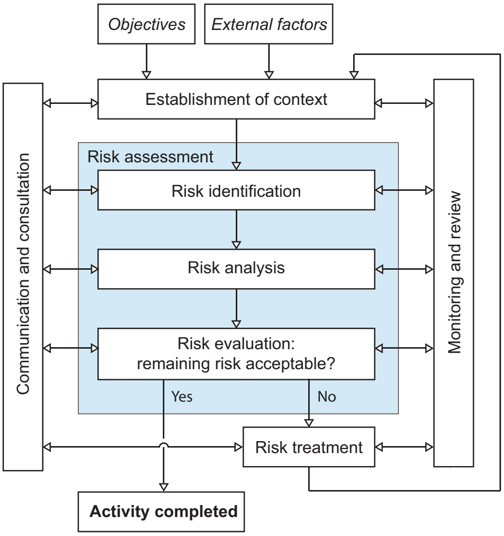


Fig. 2 The cyclic process of risk management in geotechnical engineering projects modified after ISO 31000

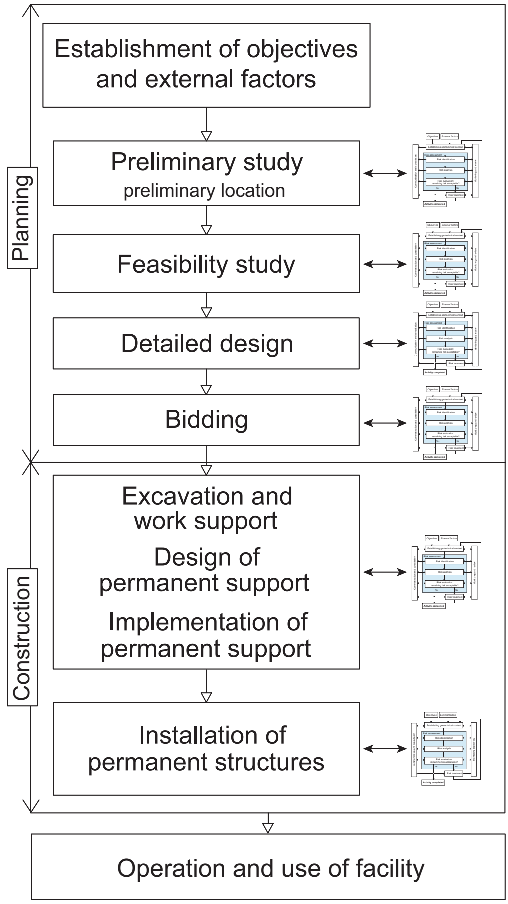


Fig. 3 Design studies during planning and construction. Risk management, as detailed in Fig. 2, is essential in all design studies

for the general public. This means that the decision to accept a developed design in the risk evaluation (Fig. 2) also needs to take such absolute code requirements into consideration. While this may seem suboptimal at first glance, the purpose is clearly to ensure that the interests of the general public are protected.

Risk management in rock engineering is by no means limited to ensuring satisfactory performance of the facility. Risk can also, for example, be the probability of having selected an unsuitable excavation method because of limited understanding of the geological conditions, combined with the associated cost increases and delays as the corresponding consequences—or with ISO terminology: how much can the present uncertainty regarding geological conditions affect our objective to not exceed the budget, given a certain choice of excavation method? In this paper, however, we only consider the design work.

3 Rock Engineering Design Issues

A satisfactory design of a rock engineering structure needs to consider many aspects. We denote these aspects *design issues*. Based on the client's needs in terms of design requirements such as size, shape, and restrictions regarding location, the design needs to address five fundamental categories of design issues:

- Satisfactory *structural safety* with respect to societal requirements,
- Satisfactory *durability* in relation to the client's requirements on life length and maintenance frequency,
- Satisfactory *serviceability* with respect to the client's performance requirements,
- Acceptable *environmental impact* with respect to societal requirements (and sometimes also client's stricter policy), and
- Acceptable *work environment* with respect to societal requirements (and sometimes also client's stricter policy) on workers' safety and health.

Durability can be considered subordinate to the issues structural safety, serviceability and environmental impact. However, design issues related to durability are so important to account for in the design that a separate category is warranted.

For all five categories of design issues, geology (including any associated epistemic uncertainty and natural variability) has a major impact, as geology generally is the main source of uncertainty in the design work, and therefore contributes with significant hazard to rock engineering projects. This geological uncertainty can be attributed to several factors, where the most important is the difficulty to predict the large-scale behaviour of a jointed rock mass, based on limited pre-investigations, small-scale laboratory tests on intact rock, investigations during excavation, and empirical assessments. Predicting the right type of geological scenario, i.e., rock-mechanical behaviour, has, therefore, become a key task in the design work; three main categories are

- Gravity-driven behaviour,
- Stress-induced behaviour, and
- Water-influenced behaviour.

Underlying factors include the rock mass composition, tectonic stress conditions, groundwater conditions, and influence from excavation features such as size, shape, and rock–support interaction (Palmström and Stille 2007; Stille and Palmström 2018).

In addition to geological factors, there are also others that may affect the risk related to the critical design issues of a project. Table 1 shows examples of design issues connected to such underlying factors in the five categories. Notably, identified design issues often need to be considered both for the permanent design situation of the completed structure and for the temporary design situation occurring during excavation.

4 The Risk-Based Rock Engineering Design Process

4.1 Sources of Uncertainty and Types of Consequences

As established in the previous sections, the rock engineering design process needs to take into account several types of underlying uncertainty and variability. The larger the magnitude of the uncertainty, the larger is the probability of having negative consequences—i.e., the larger is the risk.

In addition to the previously discussed uncertainty in expected geological scenario and limited knowledge about the geotechnical properties, there are also uncertainties related to imperfect material models and imperfect calculation models. Model uncertainties reflect the engineer's inability to describe a complex phenomenon in adequate technical terms. Thus, model uncertainties can in fact also be characterised as epistemic, because they are caused by a lack of detail in the description of the material properties or the mechanical behaviour. In practical design work, there may also be uncertainty in whether the used model is applicable to the case at hand—and sometimes there is even erroneous use of inapplicable models because of a lack of competence in the design team. Moreover, there is sometimes also a temporal component to the uncertainty, for example, in terms of an uncertain rate of degradation of a structural component.

Consequences can generally be categorised based on the nature of the unwanted event: economic consequences imply a loss in monetary value and affect the project, the society, or both; social consequences imply a loss of human life (fatality) or a negative impact on health and well-being; and environmental consequences imply a negative environmental impact. Note the correspondence to the three dimensions of sustainable development: economic, social, and environmental sustainability.

The severity of economic loss can be expressed in both absolute terms and relative terms with respect to the project cost. The choice of view is always dependent on the circumstances, for example, in terms of whom the consequence affects: a certain cost could be perceived as a large consequence, if it were imposed on a third party; while the same cost could be perceived as a smaller consequence, if it were carried only by the client or the contractor and the potential gain or profit from the project were much larger than the cost. Time is another complicating factor. For example, how

Table 1 Examples of design issues in the five categories

Example of design issue	Design situation[a]	Examples of underlying factors
Structural safety		
Cave-in of unsupported rock	Temporary	Highly jointed or crushed rock
Running ground of unsupported rock	Temporary	Zone of crushed or soil-like material under the ground water level
Time-dependent overstressing of rock support	Permanent	Creep caused by overstressing of rock with clay or micaceous minerals (squeezing)
Durability		
Degradation of cement grout	Permanent	Chemically aggressive ground water
Loss of shotcrete adhesion	Temporary/permanent	Ravelling ground from slaking of rock minerals
Serviceability		
Settlements of foundations	Permanent	Inhomogeneous weak rock
Loss of free space	Permanent	Creep caused by overstressing of rock with clay or micaceous minerals (squeezing)
Environmental impact		
Drainage of overlying groundwater reservoirs	Temporary/permanent	Highly permeable (zones in) rock mass
Settlements of surface buildings	Permanent	Small aquifers connected to normal consolidated clay soils
Work environment		
Unhealthy air quality	Temporary	Radon gas solved in ground water

[a] For reference, EN1990 (CEN 2002) instead use the four design situations persistent (normal use), transient (temporary conditions, e.g., during construction), accidental (exceptional conditions caused by, e.g., fire or explosion), and seismic (when subject to seismic events)

should the effect of potential future durability problems that may require repair and unplanned maintenance be assessed in terms of severity?

The severities of societal and environmental consequences are generally more difficult to assess.

4.2 Classification of Uncertainty Magnitude and Consequence Severity

The uncertainty magnitude and consequence severity can be grouped into classes to increase transparency regarding the made design decisions. Consequence classes can, for example, be used to adjust the required safety margin in structural design codes; an example from the Eurocodes is presented in Table 2. In essence, structures associated with large consequences at failure require higher safety against failure. Notably, the Eurocodes, for example, allow different consequence classes to be assigned to different structural components (clause B3.1(3) in EN-1990 (CEN 2002)). However, in rock engineering, one structural component can be subjected to different types of consequences, if it provides capacity for more than one design issue (see Table 1). Stille (2017), therefore, identifies a need to separate consequence severities with respect to design issues, so that the classification of consequence severity not necessarily is the same for all design issues of a structure or structural component. An example is provided in Table 3. The implications of separation with respect design issues are discussed in Sect. 4.6.1. Other types of consequence classification schemes are discussed in Eskesen et al. (2004).

Table 2 Consequence classes and corresponding recommended minimum values for reliability index, β, according to EN 1990 (CEN 2002)

Consequence Class	Description [fatality/economic, societal, or environmental consequences]	Minimum values for β^a
CC3	High/very great	5.2
CC2	Medium/considerable	4.7
CC1	Low/negligible	4.2

[a] Reference period 1 year

Similar to the classification of consequence severity, the uncertainties accounted for in a design can be of different magnitude. As discussed in Sect. 3, the largest sources of uncertainty are typically related to the expected type of geological scenario and the engineer's limited knowledge about the corresponding geotechnical parameters. The magnitude of the uncertainty may differ from case to case, depending typically on the level of difficulty to acquire information about the ground conditions. The largest uncertainty is normally encountered in the design of underground excavations, in particular in the temporary design situation, as much information about the geological scenario and geotechnical properties will be revealed upon excavation and therefore known for the design of the permanent structure. For surface structures such as rock slopes and rock foundations, geological uncertainties are generally smaller, but may still have a considerable impact on the design.

Model uncertainties are normally smaller in magnitude and can be interpreted as the ability to fine-tune the design calculations, once the correct geological scenario has been identified. Uncertainties related to the execution of the design are also normally small in comparison. The difference in magnitude of the respective uncertainty sources is important to recognise, so that uncertainty-reducing measures are directed to where they are most beneficial.

To facilitate the accounting of the present level of uncertainty in practical design work, we believe like Stille and Palmström (2018) that defining *Uncertainty Classes*, UC, can be convenient, similar to the already established concept of consequence classes. Noting the need to consider both the temporary and permanent situation in the design, two sets of uncertainty classes are required for design of

Table 3 Examples of consequence classes with respect to design issues related to the grouting of a highway tunnel in a rural setting

Example of design issue	Consequence class	Description of potential consequence
Structural safety		
Shotcrete failure caused by low adhesion	High	Block fall or cave in
Durability		
Degradation of cement grout caused by aggressive chemical environment	Medium	Increased maintenance cost
Serviceability		
Inflow causing icicle formation in tunnel roof during winter	High	Fatality or human injury caused by falling icicles into traffic and increased operational costs to avoid icicle formation
Environmental impact		
Drainage of overlying groundwater reservoirs	Low	Drainage of single wells

rock engineering structures. Stille and Palmström (2018) denote them *Ground Uncertainty Classes* and *Ground Quality Classes*, respectively (Table 4). This effectively highlights that the epistemic uncertainty regarding the ground conditions constitutes the main challenge before excavation, while the difficulty to handle the revealed ground conditions constitutes the main challenge after excavation. In a general sense, both sets of classes address the present level of uncertainty and reflect the current level of understanding of the situation at hand. Similar concepts for uncertainty classification have been discussed in the currently ongoing revision work for Eurocode 7. Note that to manage the risk related to each design issue stringently, each design issue needs to be assigned an uncertainty class.

4.3 Methods and Tools to Manage the Risk in a Design Process

4.3.1 Design is Decision-Making Under Uncertainty

To successfully manage risks in a design process, it is fundamental to attain comprehensive understanding of the geotechnical and geological setting and its interaction with the potential technical solutions that are considered. In essence, this is achieved by systematic analyses of the identified design issues, with respect to how any associated uncertainties and potential consequences are affected by different design measures in the established setting. To facilitate well-justified decisions regarding the suitability of the analysed design options, clear criteria for risk acceptance are required, as the prevailing risks potentially are substantial (cf. risk evaluation in Fig. 2). If the prevailing risks with a certain design solution are found too high, measures are needed to reduce the risks, for example, through design changes or further geotechnical investigations—otherwise, the solution must be discarded. A key consideration is how to manage the project risk of not meeting the budget requirements in the project; as an effect, this generally facilitates cost-effectiveness in the proposed design alternatives. When the optimal design solution has been found, the construction phase may be initiated.

In this systematic management of design risks, the designing engineer has to consider how the following aspects affect the risk level associated with the planned structure:

- Selected design solution
- Design (limit state) verification method to ensure satisfactory performance,
- Extent of geotechnical investigations, and
- Extent of control and inspection during design and construction.

In the following subsections, we elaborate on the effect on the risk of these four aspects. In Sect. 4.5, we propose a generic risk-based framework for how to carry out this selection process in the design of rock engineering structures.

4.3.2 Effect of Adjustments to the Technical Design Solution

Adjustments to the technical design solution can affect the risk level in two ways. The design is either adjusted so that it becomes more or less conservative, which affects the calculated probability of unsatisfactory performance, or fundamentally changed so that the structure can be reclassified in terms of consequence severity. The latter include, for example, damage-limiting measures on existing nearby structures, relocation of the planned facility itself, as well as restrictions of access to and use of the facility and the surrounding area.

In the selection of a technical design solution, the robustness and resilience of the technical system are key aspects.

Table 4 Separation of uncertainty classes into two sets: Ground uncertainty classes for the temporary situation and ground quality classes for the permanent situation Reprinted from Stille and Palmström (2018) with permission from Elsevier

Classes of geological and ground uncertainty (before excavation)	
Low	Clear and simple geology and ground conditions. Ground parameters can be easily found. Experience from construction in similar ground conditions
Medium	Clear geology and ground conditions. Methods exist both to assess ground conditions and for dimensioning. Experience from construction in similar ground conditions can be documented
High	Unclear geology and/or ground conditions with potential for problematic tunnel excavation. There are limited possibilities to assess the ground conditions before excavation starts
Classes of ground quality (after the ground has been encountered in the tunnel, shaft or cavern)	
Good	Good or very good ground conditions and stability as documented from tunnel mapping using, e.g., classification systems (RMR, Q, RMi, etc.)
Fair	Fair ground conditions and stability as found from tunnel mapping and, if found necessary, supported by investigations
Poor	Poor or very poor ground conditions and stability as found from tunnel mapping and description supported by investigations and tests

Robustness implies that the structure does not suffer from disproportionately large failure in case of accidental loading—progressive structural failure through tunnel collapse into tunnel parts far from a fire-devastated area is, for example, not acceptable. Resilience, on the other hand, implies that the structure is able to absorb or avoid damage so that complete structural failure is avoided. Reinforced shotcrete can be regarded as more resilient than unreinforced, as the reinforcement can redistribute loads even if the shotcrete has cracked for some reason.

4.3.3 Effect of Choice of Design Verification Method

The performance of the design needs to be verified, to ensure satisfactory structural safety, durability, serviceability, work environment, and that the environmental impact is acceptable. Defining unsatisfactory performance as violation of a limit state, which is common in modern structural design codes, the design is verified with a limit state verification method. In selecting verification method, the designing engineer needs to consider that each method introduces different amount of model uncertainty and parameter uncertainty to the design. The most common methods in rock engineering include design by

- Calculation, including
  - Analytical design with the partial factor method (Bedi and Orr 2014; Nomikos and Sofianos 2014; Bjureland et al. 2017b),
  - Design using numerical modelling (Jing and Hudson 2002; Jing 2003); its combination with the partial factor method is currently a debated topic in geotechnical engineering (Potts and Zdravkovic 2012; Paternesi et al. 2017; Lees 2017; Schweiger et al. 2017), but there is little discussion of rock engineering applications,
  - Reliability-based design (Lü et al. 2011; Langford and Diederichs 2013; Bjureland et al. 2017a, 2019; Napa-García et al. 2017),
- Empirical methods and other prescriptive measures (Barton et al. 1974; Bieniawski 1989; Stille and Palmström 2003; Olsson and Palmström 2014),
- Design by the observational method (Spross and Larsson 2014; Miranda et al. 2015; Spross et al. 2016; Bjureland et al. 2017a; Spross and Johansson 2017).

Note that all design issues may not be possible to describe with a quantifiable limit state function. This is typically the case for complex processes (Palmström and Stille 2007); examples of such design issues are degradation of cement grout or formation of icicles in Table 3.

As the different design verification methods allow the design issue to be modelled in different ways and account for different types of available knowledge, the selection of design verification method can be used to adjust the prevailing uncertainty in the design. Prescriptive measures, for example, are empirical rules of thumb that generally generate simple but conservative design solutions for some specific application. Conversely, the observational method allows the designing engineer to take into account not only knowledge gained from pre-investigations, but also observations of the structural behaviour during construction. The observational method is, therefore, often suggested for cases when the structural behaviour is difficult to predict. Uncertainty and errors can, however, also be introduced, for example, through inappropriately designed monitoring plans.

4.3.4 Effect of Extent of Geotechnical Investigations

By performing geotechnical investigations, knowledge is gained about the geotechnical conditions, which implies that the epistemic uncertainty is reduced, and so is also the present risk, as the prevailing geotechnical conditions are indicated with more certainty. Complete uncertainty elimination is, however, not possible; there is always a remaining possibility of encountering worse conditions than expected. Finding the optimal extent of geotechnical investigations is a decision-theoretical problem, which implies that such decisions in principle can be based solely from an economic standpoint, considering whether the potential gain of information is worth the cost (Einstein 1996; Zetterlund et al. 2011, 2015). Note that the level of epistemic uncertainty is related to the knowledge of the project team. The involvement of an experienced engineering geologist is in many cases crucial. Generally, however, all projects need sufficient knowledge about the site conditions to identify which design issues that need to be considered in the design. From a risk management perspective, this is part of establishing the context (see Fig. 2).

4.3.5 Effect of Control and Inspection

Control and inspection during construction have multiple purposes:

- To check that the design assumptions are valid and that the design requirements are fulfilled,
- To detect construction errors,
- To reduce the probability of human errors in design and construction.

Thereby, the probability of achieving sufficient quality in the product increases. As discussed by Stille et al. (1998) and Stille (2017), rock engineering requires a dualistic quality system: in addition to ensure that things are *done right*, the large epistemic uncertainties emphasise the need of the quality system to ensure also that the *right things* are done. The latter can entail, for example, external reviews of the design to check the validity of design assumptions and applied mechanical models. Extensive control of the design work is more relevant for complex or uncommon design issues, where erroneous assumptions are believed to be more likely to occur, and for structures associated with severe consequences at failure. Grouting is an example where the work should be controlled in both ways. The mixing and pumping procedure should be checked to be done right, but it should also be checked that the grouting is carried out where it is needed—and only there—i.e., that the right thing is done.

Control and inspection during construction are performed to ensure that the structure is constructed in accordance with the design specifications (i.e., that things are done right). Important tools for active control during construction are the use of milestones and tollgates, which reduce the risk caused by malfunctioning communication between design team and production (Stille 2017).

4.4 Risk-Based Geotechnical Categorisation as a Tool

A straightforward method to manage in practice the complex interaction of the aforementioned four aspects (discussed in Sects. 4.3.2–4.3.5) is to assign a *Geotechnical Category* (GC). They are based on assessments of consequence severity and uncertainty magnitude. The purpose is to facilitate efficient and consistent decision-making with respect to all four aspects.

Stille and Palmström (2018) argue that while the current Eurocode 7 (CEN 2004) introduces three Geotechnical Categories, they are not only vaguely formulated in terms of risk, but also unsatisfactorily defined, as most underground excavations in rock will fall within the highest category GC3. Stille and Palmström (2018) therefore propose that Geotechnical Categories for rock engineering should be strictly based on a combination of consequence severity and either the prevailing ground uncertainty (before excavation) or the established ground quality (after excavation). The outcome is illustrated in Table 5.

The Geotechnical Category can then be connected to recommendations and requirements regarding

- Extent of documentation of the ground conditions,
- Selection of design verification method,
- Extent of geotechnical investigations
- Extent of control and supervision of the design, and
- Extent of control and inspection during construction.

Note that for selection of design verification method and extent of geotechnical investigations, the Geotechnical Category normally only provides guidelines; decisions regarding these aspects need to consider much more, such as access to the investigated rock mass, limitations in applicability of the verification method, and competence and organisation of the project.

4.5 Conceptualisation of the Rock Engineering Design Process

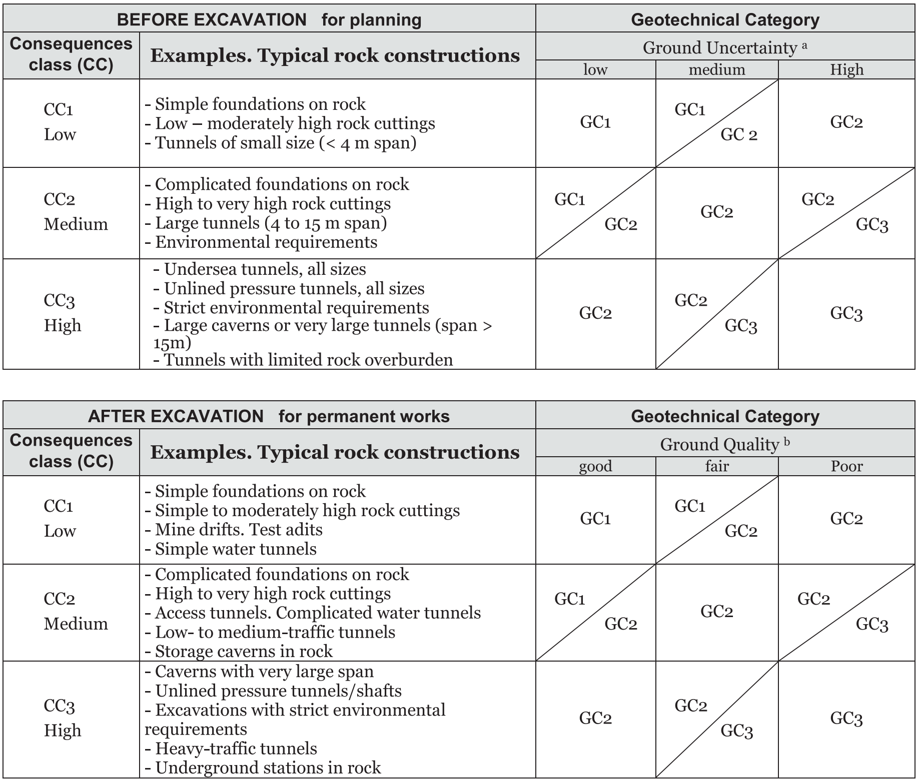
Managing risks by assigning Geotechnical Categories (Table 5) based on separately analysed consequences (Table 3) and uncertainties (Table 4) makes it possible to generalise and conceptualise the general rock engineering design process into a generic risk-based design framework. The framework highlights the need to have a stringent hierarchy between the concepts uncertainty, consequence, and risk. This allows the designing engineer to let all design decisions target the current level of risk, making this the cornerstone of the rock engineering design process. The generic design framework can be described by the following iterative algorithm and its key features are discussed in the next section. An overview is provided in Fig. 4. Note that the framework can be applied to the respective analyses of both the temporary and the permanent design situations. The analyses are then performed in two separate processes, as these design situations in practice are analysed at different times in the project execution. The reason for this separation in time is that information gained in the execution of the temporary structure can provide valuable input to the design of the permanent structure.

1. Establish the general context:
    - Clarify the objectives of the project and the external factors that can pose threats against the fulfilment of the objectives.
    - Interpret roughly the geotechnical conditions in light of the objectives and external factors, based on information gained from e.g., preliminary and feasibility studies.
    - Identify relevant design issues and design situations to address in the design work (see Sect. 3). Determine at what point in time that steps 2–9 are to be followed for each design situation.

Follow steps 2–9 for the design situation at hand.

2. For every design issue that is relevant to consider in the analysed design situation:
    - Determine the current Uncertainty Class based on the available knowledge (if there is a severe lack of knowledge about the ground conditions, assign UC3 to all design issues).
    - Determine the expected Consequence Class.

Table 5 Proposed Geotechnical Categories based on Consequence Classes and Stille and Palmström's proposed Uncertainty Classes (denoted Ground Uncertainty and Ground Quality) Reprinted from Stille and Palmström (2018) with permission from Elsevier



BEFORE EXCAVATION for planning		Geotechnical Category		
Consequences class (CC)	Examples. Typical rock constructions	Ground Uncertainty [a]		
		low	medium	High
CC1 Low	- Simple foundations on rock - Low – moderately high rock cuttings - Tunnels of small size (< 4 m span)	GC1	GC1 / GC 2	GC2
CC2 Medium	- Complicated foundations on rock - High to very high rock cuttings - Large tunnels (4 to 15 m span) - Environmental requirements	GC1 / GC2	GC2	GC2 / GC3
CC3 High	- Undersea tunnels, all sizes - Unlined pressure tunnels, all sizes - Strict environmental requirements - Large caverns or very large tunnels (span > 15m) - Tunnels with limited rock overburden	GC2	GC2 / GC3	GC3

AFTER EXCAVATION for permanent works		Geotechnical Category		
Consequences class (CC)	Examples. Typical rock constructions	Ground Quality [b]		
		good	fair	Poor
CC1 Low	- Simple foundations on rock - Simple to moderately high rock cuttings - Mine drifts. Test adits - Simple water tunnels	GC1	GC1 / GC2	GC2
CC2 Medium	- Complicated foundations on rock - High to very high rock cuttings - Access tunnels. Complicated water tunnels - Low- to medium-traffic tunnels - Storage caverns in rock	GC1 / GC2	GC2	GC2 / GC3
CC3 High	- Caverns with very large span - Unlined pressure tunnels/shafts - Excavations with strict environmental requirements - Heavy-traffic tunnels - Underground stations in rock	GC2	GC2 / GC3	GC3

[a] Stille and Palmström's (2018) term for Uncertainty Classes before excavation (see Table 4)

[b] Stille and Palmström's (2018) term for Uncertainty Classes after excavation (see Table 4)

3. Based on the current Uncertainty Classes and Consequence Classes, establish the current Geotechnical Category (Table 5) for each relevant design issue. This provides a number of requirements and recommendations to consider in the design work (Sect. 4.4).
4. Select a *preliminary* design verification method for each relevant design issue (Sect. 4.3.3).
5. Decide on whether uncertainty-reducing measures, e.g., geotechnical investigations, shall be carried out with respect to each relevant design issue (Sect. 4.3.4) to possibly reduce its current uncertainty level (i.e., the UC); carry out these measures if so was decided.
6. Work on the design for the analysed design situation, but consider the following:

    (a) Add a new (or disregard a non-relevant) design issue, if the available knowledge indicates that this is necessary. For new design issues, start over from 2.
    (b) Revise the current UC or CC, if the available knowledge indicates that this is necessary with respect to some design issue, and start over from 3.
    (c) Select another design verification method, if it is believed to be more suitable than current one, and start over from 5.
    (d) If it is found that the current uncertainty level is too high to facilitate efficient design work, start over from 5.

7. Perform a final risk evaluation by deciding that any remaining risks are acceptable in the current design solution. This implies showing that the safety margin of each considered design issue is satisfactory using a suitable design verification method (see Sect. 4.3.3), and also that any budget and time plan constraints are sufficiently likely to be met. Then document the following:

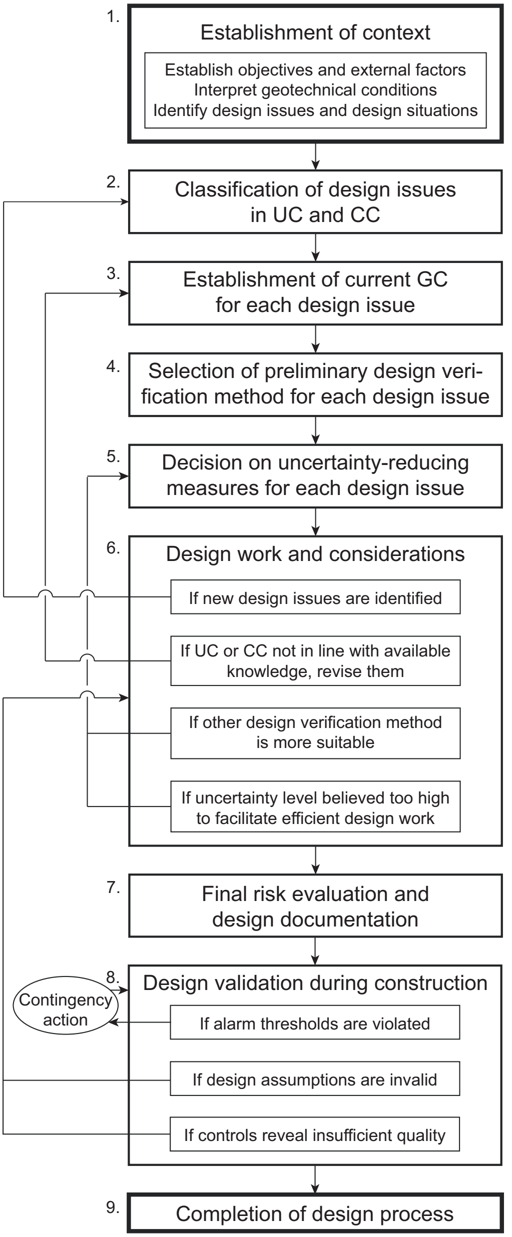


Fig. 4 Flowchart describing the risk-based rock engineering design process. The process is valid for both the temporary and the permanent design situation. UC = uncertainty class, CC = consequence class, GC = geotechnical category

  - Required level of quality assurance during construction, as defined by the current Geotechnical Category,
  - Applied design verification method in the used design solution,
  - Plans for how to validate the made design assumptions, and
  - Monitoring and contingency action plans (if the observational method is applied).

8. Validate the design solution during construction and follow all prepared plans regarding monitoring and quality assurance, as well as predetermined tollgates.
   - If alarm thresholds are violated, put prepared contingency actions into operation, as prescribed by the observational method.
   - If the design assumptions turn out not being valid, re-design based on revealed conditions.
   - If the performed control and inspection reveal insufficient quality, re-design or re-construct the defective component.

9. Complete the design process formally by confirming that the control has shown that all design issues have been accounted for satisfactorily, to ensure that the client is provided with a facility of high quality. Produce and archive as-built drawings to document any changes that were made in comparison to the planned design solution in step 7.

4.6 Key Features of the Generic Risk-Based Rock Engineering Design Process

4.6.1 Design Issues in Focus—not Structural Members

Using the design issue as the feature of interest in the design framework allows the designing engineer to attend to each design issue in relation to what its accompanying risk warrants. This is facilitated by the fact that each design issue may be assigned a separate Geotechnical Category. This arrangement contrasts to, for example, the Eurocodes, which instead revolve around "structural members" as the feature of interest [see clause B3.1(3) in EN1990 (CEN 2002) and clause 2.1(20) in EN1997 (CEN 2004)]; however, we find the separation with respect to design issues more favourable, because the designing engineer would then not have to manage all design issues within a structural member with the same high attention. This is reasonable, since they potentially carry very different levels of risk. For example, there may be little uncertainty (UC1) regarding the structural behaviour of a concrete lining, but large uncertainty

(UC3) regarding potential long-term deterioration effect on the lining, because of aggressive chemical compounds in the groundwater. Unless these design issues are treated separately, both design issues could be recommended to be subjected to external review during the design, even though such measures would only be relevant to manage the latter issue.

4.6.2 Design Verification Method Affects the Uncertainty-Reducing Efforts

Pre-investigations and other uncertainty-reducing measures play a key role in the rock engineering design. In our opinion, however, the amount of uncertainty-reducing effort that is made in a rock engineering project should be completely free for the designing engineers to decide themselves. As shown by Spross and Johansson (2017), this is a decision-theoretical problem that the engineer solves from an economic standpoint: what information can potentially be gained by performing further investigations and is it worth the cost, or is it more favourable to go with a more conservative design to account for the lack of knowledge? The optimal amount of uncertainty-reducing measures depends in fact largely on project-specific features, as well as on the selected design verification method. Consequently, design guidelines and codes must not put specific requirements on minimum amount of uncertainty-reducing measures based on the prevailing risk. In our opinion, such code regulations would at best be pointless recommendations without substance and at worst strict requirements that potentially increase project costs, owing to uncertainty-reducing measures that are not needed from a risk perspective.

For example, if the observational method is selected as preliminary design verification method, the observations made during construction can be expected to provide a lot of information. Less uncertainty-reducing measures (pre-investigations) are then likely to be required during the design phase, than if the design was to be verified by calculation based only on what was known in the design phase. Though, the amount of investigations needed to identify the relevant design issues would depend on the geological conditions at the site as well as the scale of the project.

The favourability of reducing the prevailing uncertainties is reflected in the proposed design process by letting all design work start in the highest Uncertainty Class when there is a severe lack of knowledge, which drives up the Geotechnical Category. Performing uncertainty-reducing measures will, therefore, likely reduce the Uncertainty Class—and in the remaining cases highlight complexities that indeed warrant a high Uncertainty Class.

As the designing engineer can manage the prevailing risk with several different tools, we find it important that the designing engineer is allowed to choose freely between them. Thus, the proposed design framework is carefully defined to treat all design verification methods equally, without favouring or discriminating against any method. If it is not allowed to select design verification method and uncertainty-reducing effort independently, the designing engineer loses the opportunity to optimise the design with respect to the prevailing risk and expected project cost.

4.6.3 Risk Management with the Proposed Design Process

A key feature of the proposed risk-based rock engineering design process (Fig. 4) is that it is fully compatible with ISO's (2009) general risk management framework. This highlights how the design work is an integrated part of the project's risk management. Comparing the risk management framework in Fig. 2 with the steps in Fig. 4, the *context* is established by interpreting the geotechnical conditions in light of the project objectives and affecting external factors (step 1). The identification of relevant design issues and design situations (step 1) corresponds to the *risk identification*. The assessment of Uncertainty Classes and Consequence Classes (step 2), the establishment of Geotechnical Categories (step 3), the selection of a preliminary design verification method (step 4), the analysis of performed uncertainty-reducing measures (step 5), and the consideration of different technical solutions (step 6) all correspond to the *risk analysis*. The potential revisions that are listed in step 6a–d imply that the risk at some point has been found unacceptably large in a *risk evaluation* and that *risk treatment* is needed through any of the listed options. As noted in Sect. 4.3.1, a key risk to assess is the potential exceedance of the budget, which will drive the decisions toward cost-effective treatment options. The feedback loops highlight the cyclic nature of the risk management process. Note also the final risk evaluation in step 7, where it is decided that all remaining risks are acceptable and that no further risk treatment is needed with respect to the design.

5 Can the Rock Engineering Design Process be Codified

To be of any practical use, the proposed design process must be allowable by the applicable design code. Consequently, the design process ought to conform to the common code formats used for rock engineering design. Noting the current ongoing revision of the Eurocodes, we discuss in this section specifically how the proposed design process can be codified in terms of the format used in Eurocode 7.

Regarding the definition of Uncertainty Classes, Consequence Classes, and Geotechnical Categories (steps 2 and 3 in the framework), we believe that implementation should be rather straightforward. Regarding the selection of preliminary design verification method (step 4) and uncertainty-reducing effort (step 5), the key issue lies in allowing these decisions to be made solely by the designing engineer. From a code-writing perspective, this should in fact ease the work, as there is no need to specify requirements or recommendations regarding, for example, minimum amount of pre-investigations for different design verification methods and geotechnical categories. The principle is clear: The role of the code is not to educate engineers, but civil engineers who use the code need to have the capacity to determine themselves what effort of pre-investigations is needed to ensure high quality in their designed structure. Note that accepting a design based on extremely little information regarding the geotechnical conditions, in our opinion, should be treated as serious negligence—a gross human error made by the decision maker—unless, of course, very large safety margins that correspond to all conceivable conditions have been applied. The absence of requirements and recommendations on these matters in the code does not, however, prevent the code writers from issuing separate handbooks and application guidelines, as, e.g., Frank et al. (2004), if they find relevant to do so.

Seeing that the main purpose of a structural design code is to protect health, safety and general welfare of the general public that occupy the constructed facilities after their completion, the main challenge in implementing risk-based design lies in how to make the code to facilitate—and not to obstruct—the required iterative process (step 6) through its set of clauses, as codes generally only regulate final design requirements and not the design process. In addition, code writers must not forget to regulate also the temporary situations that inevitably occur during construction, as they in rock engineering often are more critical than the permanent situations. One solution is once again to provide suggested design procedures and corresponding executions in handbooks and application guidelines. A key concept is the application of the observational method, as most underground work relies heavily on the possibility to gain information about geological conditions and structural behaviour during construction (Schubert 2008; Palmström and Stille 2015).

Lastly, we note that limit state design may be difficult to enforce to all rock engineering design issues. This needs to be recognised by the design code and alternative design approaches should be allowable in such cases.

6 Concluding Remarks

In conclusion, we find that design codes ultimately need to facilitate design processes that target the risk, to enable design of structures that not only are sufficiently safe and durable and cost-effectively constructed, but also imply safe and healthy work conditions during construction and an acceptably low environmental impact. The presented generic design process for rock engineering structures satisfies this fundamental requirement and agrees well with ISO's (2009) established risk management procedure. We believe that having a risk-based design code improves transparency of the decision-making in the design process and highlights that design and construction are interconnected in rock engineering. Moreover, by integrating the design work into the project's risk management, a common language is created, which we believe will reduce the risk for human errors. We find codification of the proposed generic process to be rather straightforward, as long as the level of detail in the code is governed by a strict application of ISO's general risk management principles. This allows the designing engineers fully to treat the design work as decision-making under uncertainty. Details on methods and practical recommendations should, in our opinion, instead be provided in separate handbooks and application guidelines.

Lastly, we hope that this article will inspire to other contributions on rock engineering design principles, in particular in light of the ongoing revision of Eurocode 7—comments or replies to this article are most welcome.

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Compliance with Ethical Standards

Conflict of Interest Prof Håkan Stille is member of Task Group 2 (General Rules) and Task Group 3 (Rock Mechanics) in the revision of Eurocode 7, member of the ISRM Commission on Evolution of Eurocode 7, and member of the expert group on the design of underground structures formed by Joint Research Centre (JRC) on the initiative of the European Commission.

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