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Principles of structured risk management in rock engineering

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Summary This article, based on a keynote lecture given at the Finnish Rock Mechanics Day 2019, discusses how structured risk management can be implemented to rock engineering projects. The suggested procedure is based on ISO 31000 and a recently published methodology for practical implementation of the standard to geotechnical engineering projects. The main message is that structured risk management is a key tool to achieve high-quality rock engineering structures. A key component for many projects will be the use of the observational method to cost-effectively reduce the lack of knowledge of the ground conditions during construction of the facility.

Key words: risk management, ISO 31000, observational method

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Introduction

The construction of rock engineering structures constitutes a large part of the construction industry, but many projects face cost increases and time delays as the project moves from feasibility studies through the design, bidding and the construction phases. Many problems can be attributed to unexpected and unforeseen geotechnical conditions, as well as to design errors and erroneous execution of the design in the construction phase.

A well-known Swedish example is the design and construction of the Hallandsås railway tunnel on the West Coast Line in south-western Sweden (Figure 1), which was constructed between 1992 and 2015. In addition to a cost increase of *11 times* the initial predictions, the project caused considerable environmental damage to local fish and cattle, as well as suspected nerve damage to person, due to use of toxic grouting chemicals in trying to make the tunnel watertight. A main issue was that the rock quality turned out to be considerably worse than first estimated, so the original TBM was not able to create enough resistance against the tunnel walls, making it unable to move forward: The TBM was completely stuck after only 13 m of drilling. The groundwater ingress was also substantial and exceeded soon the allowed thresholds by far. The first contractor, Kraftbyggarna, was unable to complete the tunnel under such conditions and went into bankruptcy, making the construction works to come to a halt.

Figure 1. The Hallandsås tunnel during construction.
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Later, Skanska took over, but seems to have been equally surprised by the heavy groundwater inflow; Skanska was the contractor that introduced the now infamous sealing compound Rhoca-Gil, which contained the toxic chemical acrylamide that poisoned both animals and possibly also construction workers. After an emergency halt in 1997, the construction works were once again resumed in 2005; this time by the contractor consortium Skanska–Vinci, who also completed the tunnel 10 years later.

The story of the Hallandsås tunnel illustrates the need to create a comprehensive understanding of the present geological and geotechnical context, when rock engineering structures are planned, designed, and constructed. If the difficult hydrogeological conditions had been understood, better technical solutions to manage the water ingress could have been implemented already from the outset. Creating this understanding is the first fundamental step in the risk management work procedure that was the topic of my keynote lecture at the Finnish Rock Mechanics Day 2019. In this supplementary article, I introduce the key concepts of this work procedure and discuss its application to rock engineering projects.

Key concepts of structured risk management

Quality

To understand the purpose and benefits of risk management, the overall objectives of the project at hand must be clear. In general terms, the objective of a rock engineering project is to provide the client with a high-quality product, i.e., a structure that satisfies or exceeds the client's explicitly or implicitly stated, justifiable requirements and wishes [1, 2]. This includes anything from structural safety to serviceability, construction costs, environmental impact, future maintenance costs, completion on time, and aesthetic design considerations. The purpose of the risk management is to facilitate that high quality is achieved in the project, by eliminating the risks that threaten this objective.

Risk as a concept

The origin of the word *risk* is not fully clear, but it is believed to originate from the Latin word *risicum* ('danger, hazard'), derived from *resecare* ('that which cuts'), which may refer to sharp reefs or cliffs at sea. Another possible origin is the Arabic word *rizq*, which can be translated to 'fortune, luck, destiny, chance of profit'.

The modern use of the word risk is also elusive. Aven [3] has in fact found many different meanings in everyday and technical language (Table 1). A common technical definition is the 'combination of probability and severity of consequences', which is favorable in assessing the magnitude of the risk. For identifying the risks relevant to a project, the last definition by ISO 31000 in Table 1 is however, in my opinion, the most useful: 'effect of uncertainties on objectives' [4].

Table 1. Examples of use of the word risk in everyday and technical language.

Style	Meaning
Everyday language	1. Exposure to the possibility of loss, damage, injury, or other unwelcome circumstance
	2. A hazardous journey, or course of action
	3. A person or thing regarded as likely to produce a good or bad outcome in a particular respect
Technical language	4. Expected loss (negative outcome)
	5. Probability of an undesired event
	6. Uncertainty (about a cost or loss)
	7. Combination of probability and severity of consequences
	8. Effect of uncertainty on objectives (ISO 31000)

Risk in a rock engineering context

As in all structural design work, design of tunnels and other rock engineering structures requires that safety margins are applied to ensure that sufficiently high quality is achieved. Here, the concept of risk plays an important role. Although the ISO definition of risk may seem abstract at a first glance, it highlights clearly the engineering challenge to manage the fact that there are uncertainties that may affect the project objectives. With this understanding, the risk of a rock engineering project can then be defined as follows:

> *"To what degree geological, geotechnical and other uncertainties affects the possibility to achieve the objective to complete the rock engineering structure, so that it satisfies all of the client's requirements including the budget and time plan."*

This definition can also be interpreted in line with the seventh example of use in Table 1, as the present uncertainties imply that there is a *probability* that an unwanted *consequence* occurs (i.e., that the objective is not fulfilled).

Development of risk management procedures for rock engineering

The introduction of risk as a theoretical concept to consider in rock engineering design was quite recent. Mostly, it followed the development of reliability-based methods to design of structures in soil, with an early rock engineering application discussed by Kohno et al. [5]. Other risk-related research contributions in rock engineering can be attributed to the development of decision-theoretical methods, where two pioneering articles were Einstein and Baecher's [6] and Einstein et al.'s [7] introduction of statistical decision theory to engineering geology in rock tunnel exploration around 1980. Sturk et al. [8] discussed its application to specific problems related to the Stockholm ring road project in Sweden in the 1990s.

Regarding the procedural aspects of managing risks in projects (in contrast to only analyzing its magnitude), the development has however been slower. In lack of formal procedures and economical resources most risk management in the early days were performed informally and intuitively, based on engineering judgement [9]. In line with this, Tengborg [10] notably reported in 1998, that the general understanding in Sweden at the time was that one of the main success factors in tunneling was to have skilled workers at the tunnel front. Moreover, decisions ought to be made on the right organizational level by knowledgeable people. According to Carlsson [11], the awareness of the risk concept started growing within the construction industry in the 1990s, following the increasing number of complex civil engineering projects in urban areas.

Carlsson [11] also provides one of the few detailed case studies on the use of risk management procedures in a rock engineering project, namely the construction of the road tunnel under the fjord Hvalfjörður on Iceland in during the late 1990s, which turned out successful despite the many challenges associated with tunneling in a region with active volcanoes. For example, they encountered inflow of hot water (up to 60°C) at the tunnel front. A main success factor was the fact that the involved parties *understood* that they entered a project with high uncertainties and little previous experience from similar projects. As a consequence, the risk management became a priority in the project, using a combination of formal risk analysis methods (e.g. fault trees) and engineering judgement. The tunnel opened for traffic approximately four months before the originally estimated completion date. Note that this success story incidentally took place at the same time as the second attempt to tunnel through the Hallandsås ridge in Sweden.

As late as in 2009, van Staveren [12] wrote a scientific journal paper with the objective of assisting geotechnical professionals with advancing from analyzing risks to actually *managing* risks. This is also the current status in my opinion: the geotechnical construction industry has started to show interest in learning how to manage risks in a more structured process. It should be noted that the number of researchers on the topic of risk and reliability of rock engineering structures is very small compared to the corresponding number of researchers for similar research issues in soil, which makes the scientific development of risk management in rock engineering even slower in comparison.

Regarding future development, it seems that the use of artificial intelligence (AI) will enter also the geotechnical construction industry. A telltale sign is the recent establishment of the technical committee TC309 for machine learning within the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE). Learning how to incorporate AI methods into the risk management of rock engineering projects will be a key issue for the industry in the future. The application of artificial neural networks to predict tunnel boring machine performance is for example an emerging research topic; see e.g. the articles by Koopialipoor et al. [13, 14].

Geological and geotechnical uncertainties

Identifying and understanding the sources of geological and geotechnical uncertainties is a central aspect in any rock engineering project. The fact that the ground conditions exhibit a considerable challenge to geotechnical construction has been known for centuries – even millennia. An antique example is provided by the Greek historian Herodotus as early as 430 B.C., when he described how people from different nations failed to build a channel without having slopes collapsing, except the Phoenicians who learnt from their mistakes and made the slopes less steep based on their observations [15].

Of course, geotechnical uncertainty was for a very long time treated in design work only with experience and engineering judgement. It took until the 20th century before soil and rock mechanics became scientific fields of their own. Among the pioneers, the engineers in the Geotechnical Commission of the Swedish State Railway (1914–1922) should be mentioned, considering their deep understanding (for the time) of how to deal cost-effectively with the effect of geotechnical uncertainty on the safety of railway embankments [16]. (It is in fact believed that this commission introduced the word *geotechnical* to the world [17]). Regarding how geotechnical uncertainty historically was dealt with in rock engineering, there is however little to no scientific literature available to my knowledge, but the experience and judgement of the involved individuals likely played a key part in this, considering the aforementioned report by Tengborg [10].

The most important uncertainty in rock engineering is the difficulty to predict a large-scale behaviour of a jointed rock mass, i.e., the geological scenario, as there is typically only limited information available from for example pre-investigations, small-scale laboratory tests on intact rock, and empirical assessments [18]. Examples of underlying factors to uncertainties include the rock mass composition, tectonic stress conditions, groundwater conditions, as well as influence from excavation features (i.e., size, shape, and rock–support interaction) [19, 20]. Spross et al. [18] provide a comprehensive table of factors that may contribute with uncertainty to the design work in a rock engineering project.

In addition to the uncertainty regarding the geological scenario, there are also other categories of uncertainty present, such as imperfect material models and imperfect calculation models. Model uncertainties are introduced when the engineer is not able to (or choose to not) describe the analyzed phenomenon in exact detail.

Ways to interpret and understand uncertainty

Uncertainties can be divided into two general categories: aleatory uncertainties and epistemic uncertainties [21]. Aleatory uncertainties represent randomness and can therefore, by definition, not be reduced with more knowledge, just like casting a die five times does not help in predicting the result of a sixth cast. (*Aleator* is Latin for dice player, gambler.) Epistemic uncertainties, on the other hand, represent a lack of knowledge, and can therefore be reduced by collecting more information about the issue. (*Episteme* is Greek for knowledge.) In a rock engineering context, aleatory uncertainty can be exemplified with the uncertainty of the expected properties of not yet casted concrete, and epistemic uncertainty with the potential presence of a fault zone in a rock mass, as a geotechnical investigation would reveal whether it is there or not. The uncertainty regarding the actual rock mass properties along the planned alignment of an underground excavation is another example of epistemic uncertainty.

To understand how these epistemic uncertainties are dealt with in rock engineering design, yet another concept needs to be introduced: the Bayesian interpretation of probability and statistics. Originating from Bayes classic paper from 1763 [22], a new definition of probability has emerged and gained popularity in many fields, including structural and geotechnical engineering. To explain this new definition, we can compare with the traditional understanding of probability as a long-term frequency of recurring random events. The traditional interpretation, however, implies that only repeatable random events actually can have a probability. This causes a problem for the engineer that designs and builds a structure: how can it be estimated how likely the quality requirements are to be met, considering that the structure will only be built once in this exact location?

The Bayesian interpretation of probability offers a solution by defining probability as the degree of belief in an event (e.g. not meeting the quality requirements). The fundamental difference between the two interpretations of probability is that the frequentist view implies that the world is full of unknown constants that can be found only after many repeated trials, while the Bayesian view acknowledges that the state of nature has a random behavior, to which probability statements can be assigned.

The Bayesian interpretation of probability and statistics is fundamental to rock engineering design, because it provides a rational way of dealing with the epistemic uncertainty of the rock mass properties by letting the engineer assign probability distributions to them. As geotechnical investigations are carried out, more information is gained and the epistemic uncertainty is reduced. While this may sound intuitively correct, the actual uncertainty reduction can in fact be quantified through the calculation procedure known as Bayesian updating. Its mathematical details are not presented here, but conceptually the updating process can be used to show that precise measurements reduce the initial (prior) uncertainty more than less precise measurements do. Examples of using Bayesian updating in rock engineering include the articles by Miranda et al. [23], Feng and Jiemenez [24], and Bozorgzadeh et al. [25], who suggested different Bayesian frameworks for characterization of geomechanical data, as well as Bjureland et al. [26], who used Bayesian updating to verify the structural behaviour of a rock tunnel.

Methods and tools to manage geological and geotechnical risk

To achieve high quality in a rock engineering project, we need to organize the project activities so that we continuously control the risks. The key to this work is to continuously identify risks that may threaten the project objectives and account for these in all decisions. This work needs to be a structured, integrated part of the involved engineers' everyday work (and not a side-task to be performed occasionally). Thereby, we create a *risk-aware culture* in the project.

Achieving such a culture is a difficult, but necessary, task in a rock engineering project. There are however published methodologies and guidelines readily available to provide assistance in this work. The SGF [1] methodology for geotechnical risk management provides a set of requirements on the risk management work to be satisfied to achieve a high quality risk management process in accordance with ISO 31000. Its practical application has been studied in two recent development projects that resulted in guidelines and extensive application examples; see refs. [27-30].

The cyclic risk management procedure

In essence, the recommended procedure can be divided into a number of steps that are repeatedly performed (Figure 2):

The *establishment of context* means to create an understanding of how external factors may affect the possibility to achieve the project objective (e.g. a high-quality structure). The geological and geotechnical setting at the site needs to be interpreted in light of the features of the planned structure. How to create this understanding and interpret the geotechnical context has been discussed extensively in ref. [30].

Risk identification implies identifying the threats that the external factors may cause and describing how they can lead to consequences; in design work this means identifying the issues that need to be considered in the design. The design issues can be divided into five categories: structural safety, durability, serviceability, environmental impact, and work environment [18]. Table 2 gives some examples of design issues for each category. Additionally, there are risks concerning economical aspects and time plans, including contractual issues, delays, logistics, market situation, et cetera. There are also risks concerning the execution of the project, related to for example the use of chemicals, third-party disturbance, worker's safety, and ergonomic issues for the workers.

Risk analysis implies analyzing how likely the identified risks are and how serious the consequences can be for the considered setting. Potential chains of events are also investigated. The risk analysis step is a challenging task. In design work, some issues are controlled by following the relevant design code, but many remaining risks can today in practice only be analyzed with engineering judgement. This is however not a reason to ignore the risk analysis; when no other tools are available, engineering judgement is far better than nothing. The result of the risk analysis needs to be documented in a clear manner, so that the decision maker in the risk evaluation step can make an informed decision. This documentation is also crucial, if someone later would like to know why some specific decisions were made.

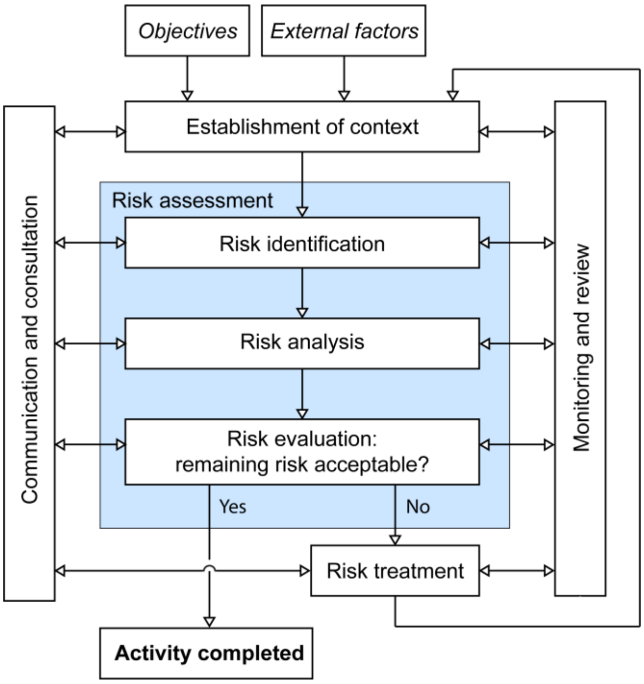

Figure 2. The cyclic work process for risk management.
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Risk evaluation refers to the decision that is made to either accept or not accept the present risks. Design codes and other laws and regulations typically provide evaluation criteria for, for example, design issues and acceptable work environment conditions. Evaluation of economic risks should be based on the organization's risk policy. Stille [31] discusses how economic consequences in a rock engineering project can be classed based on their magnitude.

Risk treatments are implemented to mitigate the unacceptable risks. In design work, this implies typically a re-design of the structure to better deal with the identified threat by making the structure more conservative, i.e., making failure less likely. Other options include performing additional geotechnical investigations to reduce uncertainties or performing measurements and observations during construction with the observational method [32]. The observational method implies that the suitability of an initial (preliminary) design is confirmed by measurements or other observations that are performed during the construction phase. The suitability is determined by comparing the measurements to pre-defined thresholds: if the thresholds are violated, prepared contingency actions to change the design must be put into operation. This allows the designing engineer to account formally, already in the design phase, for knowledge that potentially will be gained during construction. As previously discussed, this gain of knowledge is in fact a reduction in epistemic uncertainty. In underground excavations, it is generally much more cost-effective to use the observational method than to base a design solely on pre-investigations [33]. The link between observations during construction and reduced epistemic uncertainty is discussed extensively in refs. [34, 35]. Recent discussions of the use of the observational method to rock engineering design include refs. [26, 36].

Table 2. Examples of design issues in five categories.
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Design issues category 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	Raveling 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 ground-water 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, the Eurocodes 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).

The magnitude of potential consequences is often more difficult to reduce than uncertainties are, but it may sometimes be possible to move sensitive objects away from the site or prepare evacuation plans and alarm systems that get people out of harm’s way. The probability of human errors can be mitigated through control and review during the design and execution of the project [31].

Throughout the process, both internal and external *communication* is necessary to ensure the involvement of anyone that needs to know about risks or that can provide input to the risk management work. Documentation of the risk management work is necessary, as rock engineering projects often involve many people and last for many years: Some identified risks may not be relevant to treat until several years later. In some complex projects, external support from experts may also be required (*consultation*). The risk management process must also be *monitored and reviewed*, to ensure that it is performed with high standards (e.g. that it follows the SGF [1] methodology).

Concluding remarks

In this article, I have discussed the practical implementation of general risk management procedures to rock engineering. My main message is that implementing a structured risk management is a key tool to achieve high quality in rock engineering construction work. This implies that a work procedure is used that ensures that all potential threats are considered in a structured manner. ISO 31000 [4] provides a framework for such a structured process and SGF [1] provides a detailed methodology for its implementation to geotechnical engineering projects. I find it crucial that rock engineering design work is performed with a risk-based perspective. This implies that design codes need to comply with the concept of risk, as discussed in ref. [37]. For rock engineering, the principles of the observational method are fundamental in managing large epistemic uncertainties. Inventing better structured strategies for implementing the observational method to different rock engineering design issues will be an important research task to improve the risk management work in future rock engineering projects.

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