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Risk Management of Cost Overrun and Delay in Underground Excavation in Rock

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Abstract: This bright spark lecture opens by noting that geological and geotechnical uncertainty affects not only a tunnel's structural safety but also its cost and time plan. Cost overruns and delays of underground excavation projects in rock are, in fact, a huge problem worldwide, and neglecting the effect of geological uncertainty in the project planning can be an important reason for this. As a consequence, both clients and contractors need sensible risk management tools and contractual frameworks that facilitate fair risk sharing between the involved parties and reduce the number of contractual disputes. The lecture will highlight a number of such tools, like probabilistic time and cost assessments and Geotechnical Baseline Reports, as well as discuss their use from a risk management perspective.

Keywords: Risk management; Tunnel; Geotechnical Baseline Report; Time and cost estimation.

1 Introduction

Underground excavation projects in rock are often large, complexly organized, and occasionally also technically challenging. Based on the expected functionality expressed by the client, the rock engineer needs to come up with a design that satisfies requirements for structural safety, serviceability, durability, environmental impact, and acceptable work conditions. These requirements are typically clear from a design code or other relevant legislation. However, in addition, the rock engineer also faces a considerable economic optimization challenge: how shall the construction works be carried out so that they are completed without delay and cost overrun?

Previous experience indicates that this is not an easy task. Reports about the cost overrun and time delay of tunnel projects are frequent, and the attempts to explain the underlying causes have in a way formed their own research field. About 20 years ago, Flyvbjerg et al. (2002, 2003, 2004) analyzed cost overrun in a sample of 258 transport infrastructure projects and found that nine out of ten projects experienced cost overrun. Analyzing the statistics of the sample, they tried to find the underlying explanation for the overruns, considering technical, economic, psychological, and political explanations. Flyvbjerg (2006) later concluded that the cost overrun of transport infrastructure projects is mainly an effect of optimism bias (psychological explanation) and strategic misrepresentation (political). While this conclusion has been controversial among other researchers who believe in technical explanations of cost overrun (see, e.g., the criticism by Bolan 2015, Love and Ahiaga-Dagbui 2018, and Mohammadi 2021), it is nonetheless quite clear that cost overrun concerning tunnels has not been specifically analyzed in depth. Locatelli et al. (2017) observed, however, that projects with underground structures tend to experience overbudget more often than other transport infrastructure projects.

Comparing underground structures with other civil engineering structures, one difference is particularly notable: the degree of uncertainty about ground conditions is much more significant in the planning of an underground project than for projects above ground. The reason is that geotechnical investigations are typically more expensive and technically challenging to perform deep inside a rock mass. This lack of knowledge affects not only structural design work but also estimations of construction time and cost. Negligence or lack of understanding concerning this geological and geotechnical uncertainty can be one underlying technical explanation for the occurring budget overruns of underground projects. The connection between uncertainty about ground conditions and economic risk of underground projects is, however, rarely studied in the literature.

In this article, I therefore discuss how clients and contractors with sensible risk management tools can improve their understanding of the effect of geological and geotechnical uncertainty on time and cost estimations, as well as on their own risk-taking, in underground excavation projects. One such risk management tool targeting economic risks is the Geotechnical Baseline Report (GBR), the characteristics of which I analyze specifically from a probabilistic perspective. The article is organized with one chapter for each step in the ISO 31000 standard for risk management, which is introduced in the next chapter.

2 Risk management in underground excavation projects

2.1 The concept of risk

Stringent management of risk in a construction project requires an unambiguous definition of this term. In studying the literature, it soon becomes clear that "risk" can have many meanings, even in technical use (Aven 2012). The international standard ISO 31000 (2018) has nevertheless decided on the following definition:

Risk: *effect of uncertainty on objectives*

While this definition may seem abstract at first, it is in my opinion very useful for underground projects, because it clearly links the considerable uncertainty about the ground conditions with the project objective. Using this definition, the total risk of an underground project can be described as follows:

"the *effect of* the *uncertainty* about the project context *on* the *objective* to complete the structure without delay or cost overrun and, at the same time, satisfying all functional requirements."

Note that the ISO-31000 definition of risk can also be used to describe single risks in any project activity by determining the affected objectives and the nature of the affecting uncertainties. Moreover, as discussed by Spross et al. (2018b), ISO 31000 is also well aligned with the traditional definition of risk as a combination of the probability of an event and the severity of its consequences, because not satisfying the project's objectives would have consequences and they would occur with some probability due to the prevailing uncertainty.

ISO 31000 also provides a general procedure for managing risks (Figure 1). Its applicability to different types of geotechnical engineering projects has been discussed by, e.g., van Staveren (2009, 2013) and Spross et al. (2018a, 2020). However, most of the discussion has until now concerned design aspects, so in the following I therefore show how the procedure is relevant for the risk of time delay and cost overrun, concerning specifically underground excavation projects in rock.

2.2 A model to describe and understand risk

A structured framework for risk management requires that the risks themselves are described and organized in a stringent manner in the risk management work. Sturk (1998) proposed the risk model shown in Figure 2, which was recently discussed by Stille (2017), Tidlund et al. (2022) and Mohammadi et al. (2022a). The risk object is a component of the project, within which one or more hazards are present, constituting weaknesses in the risk objects. A hazard can be defined as a threat of potential (uncertain) damage, where damage is an unfavorable consequence expressed in terms of economic loss, time delay, negative health effects or fatalities. The damage event is the incident that causes the damage.

As risk is an abstract concept, it is vital to the risk management work that the terminology is clearly defined and applied with precision to all risks in the project; the outcome can otherwise become ambiguous and lose its relevance for the decision-making. However, successful risk management work requires not only a stringent use of a theoretical framework but also substantial engineering knowledge and skills. These skills can be illustrated by the warning bells in Figure 2, which are indicators of approaching damage events; Stille (2017) exemplifies warning bells with unexpected changes in geology, poor production rate, and malfunctioning rock support. Engineering knowledge and skills also become important, of course, in practical risk assessment work, which must be based on a thorough understanding of the geotechnical context (introduced in chapter 3).

A key aspect in the modelling of risk is the nature of the uncertainty of the hazard: is the uncertainty aleatory or epistemic? According to Der Kiureghian and Ditlevsen (2009), aleatory uncertainty is presumed to be "the intrinsic randomness of a phenomenon", while epistemic uncertainty is presumed to be "caused by lack of knowledge (or data)".

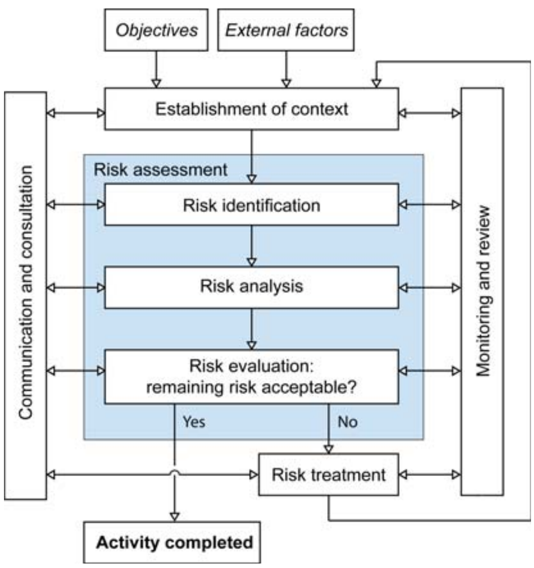

Figure 1. The cyclic process of risk management in geotechnical engineering projects modified after ISO 31000 (Spross et al. (2020), CC-BY-4.0, http://creativecommons.org/licenses/by/4.0/)

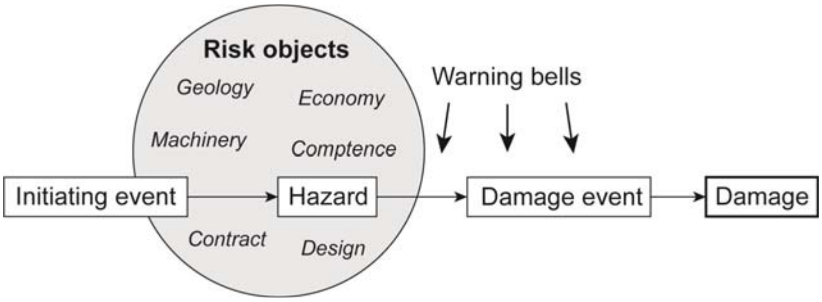

Figure 2. Risk model for underground excavation projects, developed from Sturk (1998). The circle of risk objects exemplifies some domains in which risk objects can be present.

For underground excavation projects, it is clear that all ground-related uncertainty is in principle epistemic, as we can reduce the uncertainty by improving our knowledge about the ground through investigations. A typical example is uncertainty about the variation in rock mass quality along a tunnel route. This uncertainty can greatly affect the probability of delays, as poorer quality requires the installation of more complicated support measures.

There is, however, also aleatory uncertainty in underground excavation projects. They are typically related to construction performance and future events, for example the time it will take for the workers to perform a certain work task, or the diesel price two years from now. Notably, geotechnical design work deals typically almost exclusively with epistemic uncertainty, while aleatory uncertainty is common in time and cost estimations (alongside some large epistemic uncertainties). Understanding the difference between aleatory and epistemic uncertainty is important in the last steps of the risk management procedure, as this may determine what can be done about risks that are deemed too large.

3 Establishment of the geotechnical context

3.1 Interpreting the geotechnical context

Considering the client's general expectations on the functionality of the end product – let us say a road tunnel with a certain traffic capacity passing through a mountain – the engineer needs early on to achieve sufficient understanding of the geotechnical engineering problem at hand, so that a suitable design solution, construction method, contractual format and project organization can be chosen, with respect to the situation at hand. Spross et al. (2021) call this activity *interpreting the geotechnical context*. In a tunnel project, examples of such considerations include decisions, such as:

- Construction method: TBM, drilling & blasting, or cut-and-cover?
- Sealing method to reduce water inflow during and after construction: Grouting or waterproofing?
- Contractual format and payment method: turnkey contract paid with lump sum, general construction contract paid based on re-measurement of the work, or a partnering contract paid on a cost-plus basis?
- Organization of the work: e.g., analysis of the critical path, and choice of machinery and staff.

Many external factors may contribute with uncertainty to these decisions, but the most notable are the geological, hydrogeological and geotechnical conditions of the ground. Predicting the correct geological scenario is therefore a key task in the planning phase; Palmstrom and Stille (2007) discuss the identification of possible ground behavior types and how their uncertainties can be dealt with in design and execution. The uncertain underlying factors that govern the ground behavior include rock mass composition, tectonic stresses, groundwater conditions, and influence from the excavation itself, including size, shape, and rock–support interaction.

3.2 The role of the contract in the geotechnical context

The geotechnical context is not limited only to the technical aspects of the project; it also has an economic component. Which excavation and sealing methods are likely to be the most cost-efficient for this project? Is there perhaps one that is more robust in terms of performance, i.e., disruption caused by adverse geological conditions is less likely?

Another possibly even more challenging decision is the client's selection of a suitable contractual format and payment method, so that they facilitate bids that strengthen the project's management of the prevailing risks. Although some geotechnical investigations may have been carried out already at this early stage in the project, there is still a considerable lack of knowledge regarding the actual ground conditions along the tunnel. As both construction time and cost are greatly affected by the prevailing ground conditions, there is a substantial economic risk associated with the project. But what contracting strategy should the client take to receive favorable tenders from contractors that are able to construct a tunnel that meets the client's expectations? This decision should be based on a thorough understanding of, what I call, the *geotechnical–contractual system*, which can be seen as a part of the geotechnical context.

The geotechnical–contractual system is very complex. The client's previous experience from past projects can therefore today often have a significant impact on the selected contracting strategy, but even individual experiences within the decision-making body can affect the decision, as the complexity of the issue makes it difficult to objectively compare advantages and disadvantages.

3.3 Who owns the risk?

A key aspect of the analysis of the geotechnical–contractual system is the recognition of *risk ownership*. Palmström and Stille (2015) illustrate conceptually in Figure 3 how the ownership of technical risks is divided between the client and the contractor in different contractual formats. For example, in a turnkey contract, the contractor takes on a substantial amount of risk regarding the geological conditions, for which the client will be expected to pay a substantial risk premium. This can be a favorable arrangement if the client is inexperienced in organizing and managing underground projects and happy to let the contractor take care of as much as possible. Moreover, the freedom of a turnkey contract allows the contractor to compete for the contract with innovative technical and organizational solutions to manage the risk.

In a partnered cost-plus contract, the client is much more involved and can even take on some production risks, even though they are typically allocated to the contractor. This happens, for example, when a contractor suggests a supposedly better production method and the client approves its use. As a consequence, the risks related to the suitability of the production method with respect to the ground conditions come to lie with the client, as the client pays for its related costs. (Some production risks are, however, always allocated to the contractor, e.g., machinery breakdown due to lack of maintenance.)

Although the contract is supposed to regulate risk ownership in a clear manner, claims and disputes are not uncommon in underground excavation projects. For example, Essex (2014) notes that accurately described uncertainties about the ground conditions in a geotechnical design report, as is required to ensure structural safety, can instead be exploited as ambiguity in the contract in a legal setting. A good solution to avoiding this problem is to have a *Geotechnical Baseline Report* in the contract. This document is analyzed specifically from a risk perspective in chapter 6.

4 Risk identification

Risk identification is possibly the most important activity in the risk management framework (Chapman 1998). If a risk has not been identified, no action can be taken to reduce or eliminate it. The risk identification shall be seen as an engineering task, where hazards and their potential damage events are specified. The model in Figure 2 can serve as aid to facilitate stringent use of the terminology. The people involved must have sufficient technical competence in the relevant field. For further details of practical risk identification techniques, e.g., brainstorming, I refer the reader to Chapman (1998). For the following steps in the risk management framework, two groups of risks common in underground excavation are discussed in greater depth:

- Risks related to delays and cost overrun
- Risks related to the allocation of incurred costs, should a damage event occur

5 Tools to analyze the risk for delay and cost overrun

Having identified as a hazard the uncertainty regarding the ground conditions along a tunnel route, which makes the prediction of project time and cost difficult, the magnitude of this uncertainty should be analyzed. If this is done quantitatively, it is in fact possible to calculate the probability of experiencing a delay beyond the planned

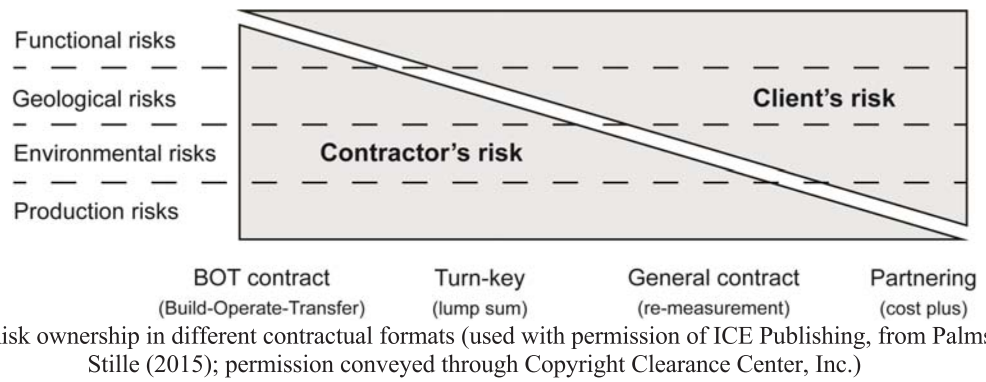

Figure 3. Risk ownership in different contractual formats (used with permission of ICE Publishing, from Palmström & Stille (2015); permission conveyed through Copyright Clearance Center, Inc.)

completion date, as well as the probability of budget overrun. While this is a much less studied field than reliability-based design, some advances have recently been made.

5.1 KTH's probabilistic time and cost estimation model

At KTH Royal Institute of Technology, we (i.e., Mohammadi et al. 2022b) are currently working to improve a probabilistic time and cost estimation model originally published by our former colleagues Isaksson and Stille (2005). The model estimates the tunnel project's time as a sum of two components: normal time and exceptional time, i.e., $T = T_{\mathrm{N}} + T_{\mathrm{E}}$. The basis of the model is the assumption that the required construction time of a tunnel section depends greatly on the actual geological and geotechnical conditions in that section. Therefore, the model introduces the parameter *production effort*, Q [h/m], which describes the time it takes to complete the construction of one unit length, l. Being the inverse of advance rate (constructed tunnel length per time unit), the use of production effort significantly simplifies the calculations in the model, as all installed material quantities and work times can easily be converted to time per unit length, regardless of the advance rate.

Letting the uncertain geological and geotechnical conditions in a tunnel section l be described by a vector $\mathbf{x}(l)$, the production effort in that section can be described by the function $Q_l = g[\mathbf{x}(l)]$. Note that the vector $\mathbf{x}(l)$ contains qualitatively described ground conditions; thus, the function is purely conceptual. The main assessment work instead concerns determining a reasonable distribution for Q_l. Mohammadi et al. (2022b) proposed that this be done by breaking down all work into unit activities, to which experts can assign probability distributions describing their estimated duration and cost (Figure 4a,b).

As the time it takes to construct the whole tunnel is the sum of all production efforts, we obtain the normal production time by integrating over the tunnel length L:

$$T_{\mathrm{N}} = \int_L g\left[\mathbf{x}(l)\right] dl \approx \sum_{l=1}^{L} Q_l \tag{1}$$

If the geotechnical conditions vary along the tunnel, Q_l can be obtained as a mixture distribution of underlying production efforts assessed for different geotechnical conditions, weighed with respect to their proportions of the tunnel.

In addition to T_{N}, disruptive events can occasionally occur in the project, delaying the project. This can be modelled as an additive exceptional time:

$$T_{\mathrm{E}} = \sum_{i=1}^{n} \sum_{\upsilon=0}^{m_i} p_{\upsilon,i} \left(\upsilon K_{\upsilon,i}\right) \tag{2}$$

where n is the number of different types of disruptive events, m_i is the largest possible number of events for each type, $p_{\upsilon,i}$ is the probability of having exact υ number of events occurring of this type, and K_υ is a stochastic variable representing the assessed time to handle one occurrence of the event before production is back to normal. A typical estimation result of total time, T, is presented in Figure 4c.

Isaksson and Stille (2005) discussed also how the model can be used to assess uncertainty in the cost of a tunnel project. In theory, this is achieved for normal production by simply introducing a set of cost factors z_j, which describe how the production effort in a section relates to incurred costs in j number of cost categories:

$$C_{\mathrm{N}} = \sum_j \int_L z_j g\left(\mathbf{x}\right) dl \tag{3}$$

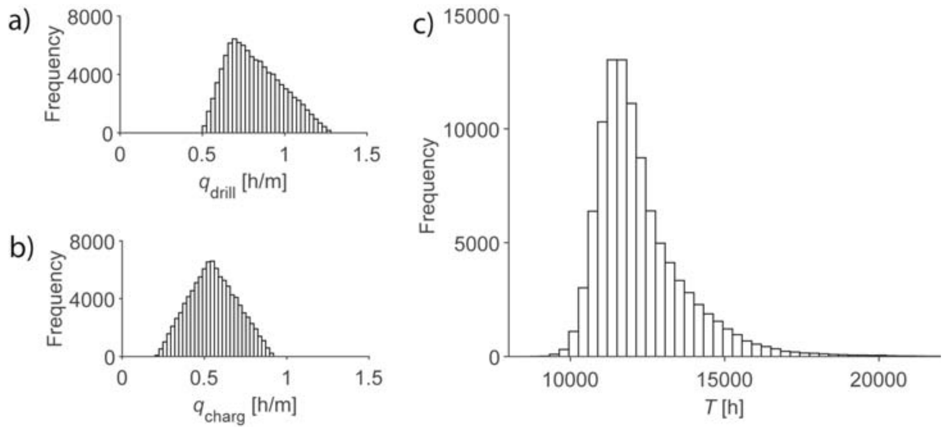

Figure 4. Probabilistic modelling of tunnel time. a) Assessed drilling time per unit length. b) Assessed charging time per unit length. c) Simulated total time of a tunnel project.

The cost C_E related to disruptive events is straightforwardly achieved by letting K_v in Eq. 2 instead represent a stochastic variable for the cost incurred by the occurrence of one event. This gives the total cost of the tunnel project: $C = C_N + C_E$. Note that cost is something different than price. The price is the agreed compensation to the contractor for completing the project, and this normally includes a profit. As a general comment, estimating cost accurately should be more challenging than estimating construction time, because the final cost is also much affected by the market situation, in addition to all other aspects that affect construction time.

5.2 Other probabilistic time and cost estimation models

There also exist other models to estimate the time and cost of a tunnel project. Einstein et al. (1999) summarize the principles of a tool called Decision Aids for Tunneling, which has its basis in a probabilistic ground class profile. A Markov-chain Monte Carlo (MCMC) simulation procedure is used to model the transition between the different ground classes along the tunnel. Following work in the 1970s (e.g. Moavenzadeh and Markow 1976), several updates and application examples have been presented (e.g., Einstein 2004, Min et al. 2008, Min and Einstein 2016). Another MCMC-based procedure to model tunneling cost was presented by Guan et al. (2014).

Another modelling approach was taken by Špačková et al. (2013), who presented a time and cost estimation model that uses a dynamic Bayesian network. A particularly interesting feature in their work is a "human factor", H, which is a variable representing factors that can systematically affect the production rate, for example the quality of design and planning or the organization of construction works. Notably, the potential threat of such aspects on the production rate can be described as hazards within the risk object domain Competence in Figure 2.

Uncertainty in time and cost estimations can also be analyzed using the Successive Principle (Lichtenberg 2000). The Successive Principle is, strictly speaking, not an estimation model that results in probability distributions of estimated time and cost, but rather a method to investigate and understand the relative magnitude of the uncertainties that might have an effect on the outcome. Mohammadi et al. (2022a) note that a key difference between the Successive Principle and probabilistic estimation models is that the estimation models take a bottom-up approach, assigning input values to identified unit activities to simulate total time and cost, while the Successive Principle takes a top-down approach, trying to break down identified uncertainties into smaller underlying uncertainty components. The Successive Principle therefore serves a different purpose than the estimation models, namely to draw decision makers' attention to risk and uncertainty and facilitate appropriate risk treatment action. Thereby, the decision maker can possibly reduce the deviation of the completed project's actual time and cost from any (deterministic) estimations made in the planning phase.

6 Risk treatment tools to mitigate economic risk in contracts

6.1 Risk allocation using Geotechnical Baseline Reports

Having analyzed how the uncertainty about the ground conditions affects the variability in production time and cost in a planned tunnel project, the client also needs to consider how to deal with the related risk in the contract with the contractor. The *Geotechnical Baseline Report* (*GBR*) is a risk allocation tool that can be used to clarify, but also mitigate, the parties' economic risk in a contract. In ISO-31000 terminology, a decision to use a GBR can be seen as a risk treatment measure, but note that this decision in turn introduces new risks related specifically to the GBR which now must be assessed (i.e. identified, analyzed, and evaluated) by both the client and the contractor. This chapter discusses this additional risk assessment work.

The use of GBRs has gained increasing attention over the last decades; Essex (1997) provided the first practical guidelines, which were published by ASCE, and, recently, GBR was adopted as the key risk allocation tool in FIDIC's (2019) "Emerald book", which suggests general conditions of contract for underground works, drafted by a joint FIDIC–ITA task group. The general purpose of a GBR is to facilitate a fair sharing of the geological risk between the client and the contractor, which means that these risks should be allocated to the party best suited to manage them (Gomes 2020). This means, greatly generalized, that geological risks tend to be allocated to the client, while production risks are normally allocated to the contractor (see Figure 3). Essex (2014) notes that this principle should restrain clients' earlier tendency to allocate as much risk as possible to the contractor, which – somewhat counterproductively – mostly served to increase contractors' risk premiums in their bids, making clients pay for the risk anyway.

The main purpose of a GBR is to facilitate resolution of disputes regarding the ground conditions, but Essex (1997) also notes some other benefits of using a GBR: 1) improvement of the contractor's understanding of the project scope, and 2) highlighting important considerations and constraints that must be addressed in bid preparation as well as during construction. Thus, by adopting a GBR, the client can implicitly facilitate better risk management in the contractor's bid preparation and construction.

GBRs are particularly important in turnkey contracts paid with a lump sum, as the contractor then is expected to take on more geotechnical and geological risk, but GBRs are also useful in re-measurement contracts, to regulate, for example, when a priced approximate bill of quantities can be renegotiated.

6.2 Theoretical principles of geotechnical baselines

The function of a geotechnical baseline lies in its translation of facts and assessments about ground conditions into precise, explicit statements that allow a binary determination of whether the encountered ground conditions agree with the statements. The use of a geotechnical baseline has the following components, which are also illustrated in Figure 5:

1) An identified, uncertain geotechnical factor that can affect the construction cost or time of the project. Gomes (2020) uses the term "baselined characteristics" for such factors. Unless the factor itself will be directly observable during construction, a related measurable parameter is also chosen, which will be used to determine indirectly the actual state of the nature of the geotechnical factor during construction.

2) Estimation of the possible range of the parameter.

3) The baseline limit value, established by the client. The baseline limit value determines what measured outcomes of the uncertain parameter should be managed by the contractor within the contract ("systematic conditions" in Gomes (2020)), and what outcomes result in the client paying the contractor additional compensation for adverse ground conditions ("non-systematic conditions").

4) Optionally, the parameter range can be complemented by an estimation of the parameter's probability distribution.

In practice, it can be expected to have several geotechnical baselines, as believed relevant with respect to identified hazards and performed construction activities. For example, it is likely necessary to have different baselines for grouting and support, as different rock mass properties cause challenges for different construction activities.

6.3 Client's considerations in establishing a geotechnical baseline

6.3.1 Choice of parameter

The choice of measurable parameter to regulate the allocation of geological risk is a technically challenging task. The analysis should be based on a thorough understanding of the "geotechnical–contractual system" within the geotechnical context (section 3.1). It is essential to consider that geotechnical characteristics of high relevance to structural safety may be of little relevance to the time and cost, and vice versa. The establishment of geotechnical baselines must therefore be initiated already before geotechnical investigations are planned, so that information relevant for time and cost estimations is revealed, in addition to information relevant for the structural design. Hatem (1998) points out that the parameter should not be dependent on human factors. Thus, "advance rate" would not be a suitable parameter, as a poor advance rate can equally well depend on machinery breakdown or an ineffective organization of the works, which should, of course, not trigger additional compensation from the client.

6.3.2 Analysis of parameter range and distribution

Before the limit value can be determined, the parameter's possible range needs to be estimated, i.e., the parameter's most pessimistic and optimistic values. If a more rigorous analysis is wanted, the parameter's probability distribution is estimated as well. Analyzing the probability distribution over the possible range provides decision makers with more complete information about the prevailing risk, as it facilitates the calculation of the probability of exceeding the baseline value, i.e., the probability of encountering non-systematic

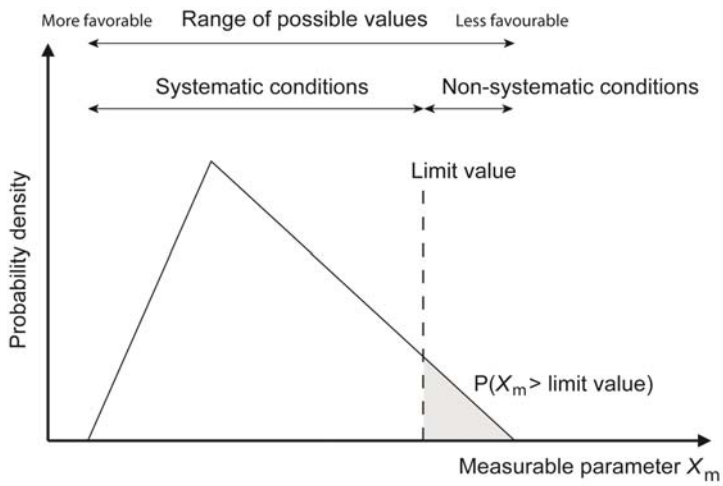

Figure 5. Theoretical principles of a geotechnical baseline, which determines what possible outcomes that fall within the contract and what outcomes that trigger extra compensation to the contractor.

conditions. The probability distribution should represent the present knowledge about the parameter, so depending on the level of knowledge, different distribution types will be relevant. Uniform distributions can be used to indicate that no value is known to be more likely than any other, while triangular distributions (Figure 5) are useful for expert assessments when there is subjective knowledge about the most likely value. Normal distributions are well-known by most engineers and therefore convenient but have the disadvantage of being symmetric around the most likely value. There are, of course, many other potential distributions; the choice of distribution type should, however, be carefully considered, as the distribution type itself can have considerable effect on any calculated probability of non-systematic conditions (due to model error).

6.4 Client's risk evaluation of the limit value in a geotechnical baseline

The limit value cannot be established objectively solely based on observations in geotechnical investigations; in fact, the limit value does not even need to be likely at all. Instead, the client must decide the limit value based on their own risk management strategy or risk policy. How much risk does the client want to allocate to the contractor? This decision corresponds to the risk evaluation in Figure 1. The closer the limit value is to favorable ground conditions, the lower the bid price from the contractor can be expected; however, the client should then also be prepared to pay out extra compensation for adverse conditions with larger probability (and vice versa). This means that the client can, at least in theory, trade later claims against a higher bid price, which would turn this into a mathematically solvable decision-theoretical problem. The total cost of the project can in such an analysis be estimated using probabilistic time and cost estimation models, in which estimated probabilities of encountering different ground conditions are input parameters to obtain the mixture distribution of Q_l (Eq. 1).

In practice, however, the client may also need to consider aspects other than the modelling results. The theoretical connection between the limit value, bid price, and claims for extra compensation assumes that the contractor has entered the contract based on a thorough understanding of their own risk, so that the contractor is prepared to handle rather adverse conditions without complaint. Otherwise, there is an incentive for the contractor to fight for additional compensation, even if the encountered conditions were meant to be within the systematic conditions.

6.5 Contractor's risk analysis and risk evaluation of the baseline

A contractor intending to submit a tender to a project using GBR needs to make their own risk assessment of the baselines. The key issue is to assess the probability of encountering systematic and non-systematic conditions and analyze the construction time and cost of different possible ground conditions. Probabilistic time and cost estimation models can be a useful tool also for the contractor, but note that the contractor only needs to consider the systematic conditions in the time and cost analysis, as the client takes the risk for non-systematic conditions. It is here important to recognize that what is economically favorable and unfavorable for the contractor does not necessarily coincide with the systematic and non-systematic conditions, respectively. If a risk-adverse client has also determined that rather challenging (heavily cost-increasing) geotechnical conditions shall be systematic, it can be very unfavorable for the contractor if the actual ground conditions turned out to be systematic, just below the limit value. If the contractor assesses this to be a likely case, the contractor needs to plan the work carefully so the challenging conditions can be handled cost-effectively.

If the client has instead chosen to take on more risk by making the geotechnically challenging conditions non-systematic, the contractor can safely assume good systematic conditions for the tender but should also prepare for a likely need to claim additional compensation, as the contractor believed non-systematic conditions to be likely to occur. (For a successful claim, the contractor will, however, need to show the client that encountering non-systematic conditions actually caused delay or cost increase.)

7 Other risk management tools for underground excavation

There are also other risk management tools that can assist in achieving a successful underground excavation project that is delivered in time and within budget. Regarding the handling of a large geotechnical uncertainty, the framework of the observational method allows a flexible but still safe method of underground excavation. Once established by Peck (1969), it has now become an accepted part of Eurocode 7 (CEN 2004) and other design codes and guidelines. Its value as a risk management tool is clear from the case study by Tidlund et al. (2022), which discusses how the observational method facilitated a safe and cost-effective construction of a road tunnel in very challenging geotechnical conditions in Iceland. In terms of future development, efforts are now made to combine the observational method with reliability-based design approaches (e.g. Bjureland et al. 2017, Spross et al. 2022), which can potentially provide an even better understanding of the prevailing risk levels when applying the method.

Lastly, the value of quality control and review must not be forgotten. Stille et al. (1998) discussed the need for a *dualistic* quality *system* in underground excavation: quality control cannot only check that things are done right, i.e., in accordance to plan; perhaps even more important is to review that the *right things* are done! For the latter purpose, a board of experts can contribute with a critical eye and new insights.

8 Concluding remarks

The management of economic risks in underground excavation projects is hardly a simple task, for clients or contractors. This is evident from the large number of time delays and cost overruns in tunnel projects all around the world. However, while risk management methods addressing the structural safety of geotechnical engineering structures have been researched extensively over the last decades, for example in conferences like the ISGSR, I note that we as researchers in the geo-risk field have put considerably less effort into studying the risk for time delay and cost overrun. There are, however, useful risk management tools emerging, like probabilistic time and cost estimation models, and contractual documents facilitating fair risk sharing, like Geotechnical Baseline Reports (GBR).

In this paper, I discussed how such tools can be used within a general risk management framework (ISO 31000) to target economic risks in underground excavation projects. I note that while some good work into developing the probabilistic time and cost estimation models has been done, they still need further development to consider more realistically complex projects, such as the construction of tunnels using multiple faces. There is also a need to develop more stringent methods to determine the input variables to these models, for example the experts' assessments of probability distributions for the time and cost of unit activities in tunnel production, as well as the probability of encountering different geotechnical conditions along the tunnel length.

To be able to achieve a fair risk sharing in a tunnel project, both clients and contractors need to understand how their tender documents and submitted tenders affect their own risk-taking. Introducing and promoting GBRs to underground works, as proposed by FIDIC (2019), is one step forward, but such contractual frameworks will only meet its full potential when both parties understand the practical implications of the contractual terms. This can only be achieved by integrating the GBR preparations fully into the project's risk management work, as the GBR needs to emerge from a thorough understanding of the project's geotechnical context. Otherwise, a GBR can never be expected to reflect properly the client's intended degree of risk-taking.

Probabilistic time and cost estimation models can form a theoretical basis for the risk analysis, but both the client's and the contractor's respective planning teams will also need to have knowledge in contractual law, in particular when analyzing the effect of the contractual format and payment method concerning risk allocation. To make this viable in practice, the tunnel construction industry will likely need to educate further the engineering geologists and other professions that today prepare and analyze tender documents, so that they become professionally comfortable in assessing uncertainty, probability, and risk in the context of time and cost estimations. While challenging, I believe this can facilitate clearer risk allocation in the client's tender documents, which in turn facilitates more sustainable pricing strategies among contractors. This should benefit both clients and contractors in terms of fewer disputes about unfavorable and cost-increasing ground conditions.

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