Does Geological Investigation Reduce Risks in Tunnelling Projects?

E. Bieth¹, C. Gaillard¹, F. Rival¹, A. Robert¹
¹Centre d'études des tunnels (CETU), Bron, France

1. Introduction

The underground works projects include a share of uncertainty, often significant, and related to the knowledge of ground which can only be partial before carrying out the work. Consequently the forecast construction budget must include in addition to the work costs estimate a margin to protect against the uncertainty, the evaluation of which comes under the responsibility of the contracting authority.

The increase in the size of infrastructure projects (Lyon – Turin rail link includes for instance a total length of 120 km of tunnels [1]) is accompanied by an increase in overall projects costs, and mechanically in the amount of the uncertainty margins, up to levels never attained before. The financing of such operations requires sufficient guarantees and can only be considered if a quantified risk analysis has been carried out.

This paper presents a method of risk assessment applied to geology, which is the main source of uncertainty for underground works. The interest of performing geological investigations is analysed in terms of risk analysis.

2. A few definitions

2.1. General vocabulary


When conducting studies, each feared and identified event is characterized according to two aspects:

– its likelihood (L): “chance of something happening”, expressed in qualitative or quantitative terms;

– its consequence (C): “outcome of an event affecting objectives”.

The level of risk (R) associated to an event is the "magnitude of a risk, expressed in terms of the combination of consequences and their likelihood", approach conventionally summarized by Equation 1:

\[ R = L \times C \] (Eq. 1)

2.2. Vocabulary specific to tunnels

The sources of risk related to geological uncertainty (that is the lack of knowledge or understanding concerning lithological nature of terrains, their acquired structure, their relative...
layout, their geomechanical characteristics, the nature and properties of contact surfaces, the hydrogeology and all phenomena that are likely to develop, such as karsts for instance) can be classified in three subsets [4] according to the criterion of identifiability\(^1\) and the feared consequences of the event:

- **Imprecisions**: sources of risk related to the occurrence of identifiable events whose consequences are marginal (minor error in the exact position of contacts between two geological formations or an incorrect evaluation of the homogeneity of a formation for instance).

- **Unexpected events**: sources of risk related to the occurrence of identifiable events which can cause considerable modifications of the project. In case of occurrence, treatment of unexpected events can require the mobilization of resources and methods in addition to those foreseen under the initial conditions of the contract.

- **Unforeseen events**: sources of risk related to the occurrence of events which are not identifiable by a competent professional and whose impact on the running – and incidentally on the cost – of the work can sometimes be considerable.

The treatment of these three categories having been tackled in earlier papers [5, 6], we will only present here the recent developments relating to the single category of unexpected events.

3. Risk assessment

Geological risk consists in the effect of uncertainties attached to the geological model on the design and construction of the underground structure. The level of risk is estimated as a financial provision included in the overall budget of the operation and intended to cover the meeting of unexpected events during the course of construction. It may change through the different phases of study of a project because it is directly related to the level of knowledge at a given time.

The concepts discussed below are illustrated with an example extracted from the new freight / high speed rail link project between Lyon (France) and Turin (Italy): a part of the Chartreuse tunnel (24.7 km) for which the uncertainties are numerous and significant, given the complex geological context, the large overburden and the low density of surveys.

The example shown in Figure 1 below is that of the Outheran massif, an area with an anticline-shaped geological structure. Unexpected events that can induce significant consequence on the course of work have been highlighted. In order to perform the analysis, the tunnel is broken down into several sections having the same length.

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\(^1\) An event is called identifiable if it can be named and described before it occurs (known physical phenomenon, situation which can be foreseen by a reasonably skilled professional...). On the contrary, a phenomenon which is totally unknown or completely uncommon in the crossed formations is called non-identifiable.
3.1. Estimating the level of knowledge (Lk)

The quantity of information available at different locations in the model is heterogeneous: some areas have been investigated previously and show a very high level of available information whereas other are only poorly known, based on a general interpretation of the geological context. Furthermore, all data can provide different amounts of information for the overall level of knowledge of the model, depending on the complexity of the geological context, the nature of investigations and the distance separating the surveyed/studied zone from the projected tunnel. We propose to define an index for the level of knowledge of the geological model that is a measure of both the complexity of the geological context and the quality of information used in its preparation.

Quantifying the level of knowledge of the geological context therefore involves an exhaustive list of all the knowledge of the massif. The method described below is based on previous work [7, 8, 9], whose main concepts are taken up.

A grade is attributed simultaneously to the geological context (Gc) and the reliability of sources of knowledge (Rs) performed in order to estimate the level of knowledge (Lk) of the geological model using Equation 2:

\[ Lk = Gc \times Rs \]  
(Eq. 2)

First, the complexity of the geological context (Gc) is quantified using a simplified characterization that takes into account the lateral variation, the uniformity of the geological formation being crossed, the assumed structural organization (ductile, brittle), the depth of the tunnel and the percentage of outcrop at the vertical of the studied area.

All types of investigations do not provide the same level of information. A second grade (Rs) thus characterizes the nature and closeness of sources of knowledge and reflects the reliability of this information (investigations such as bibliography, geological surface survey, galleries, addits, access galleries, core drilling, destructive sampling, logging, geophysics).

In this example, the evaluation of the level of knowledge is performed for every analysed section, using three categories (good, medium or low) in order to obtain a simplified zoning of the tunnel. Figure 2 shows the zoning of the level of knowledge of the geological model of the Outheran anticline.

![Figure 2: Level of knowledge of geological model on the Outheran sector of Chartreuse tunnel](image)

3.2. Estimating the level of risk

In the following we propose to estimate the unexpected events inherent to a project by taking up the three phases of the process of risk assessment: identification, analysis and evaluation.

3.2.1. Risk identification

The design engineer performs an analysis of the geological model. Based on his/her knowledge of the area (bibliography, previous studies, etc.) and on the geological context, he/she lists all sources of risks that are likely to lead to unexpected events, that is all events that are not taken into account in the initial definition of construction methods and therefore represent a significant part of risk. This task requires the most exhaustive possible review of all themes related to geological, geotechnical and hydrogeological context.
3.2.2. Risk analysis

The feared events are positioned on the longitudinal profile, according to the break-down pitch (in this example, all sections are 100 m long). For each event, the analysis consists in specifying its location, likelihood and evaluating the associated consequences.

The likelihood of unexpected event that depends on the geological context is determined, first, by geological expertise according to a voluntarily extremely simple grading (only three categories) with the following associated probabilities: very unlikely (1/200), unlikely (1/50) and possible (1/5). This probability depends on the lithology of the section, level of knowledge of the geology available at the vertical of this section and the length of this section. In first approximation and in the absence of specific investigation to reduce these risks, all identified unexpected events can be considered for instance as situations that are “possible” in the concerned sections. The eventual achievement of later specific investigations will lead to change the probability of occurrence of these events, either by directly integrating them into the project if they are considered as likely (probability greater than or equal to 1/2), or by demonstrating their low probability and considering them as unlikely or very unlikely.

For each unexpected event, a multiplicative factor whose value ranges from 1 to 1.5 depending on the level of knowledge of the geological model is applied to likelihood. As a consequence of this operation, the level of risk is increased in the zones where few data are available.

The estimate of the consequence related to each unexpected event is obtained separately, according to the constructive measures foreseen and the section under consideration. Each unexpected event is considered in terms of the consequence it could have, should it occur, on: the course of construction works in terms of additional studies, modified organization, implementation of specific methods and / or new means and finally extension of lead times. These various consequences are estimated financially and the total forms the economical impact of the unexpected event.

This consequence (economic impact) of a given unexpected event is then multiplied by its likelihood to obtain the level of risk.

3.2.3. Risk evaluation

At the end of risk analysis, each unexpected event is characterized by its location and its extent on the geological model, in terms of likelihood and consequence.

To estimate the overall risk of all unexpected events considered, the most simplistic approach consists in considering all identified events as independent. Although it naturally leads to an overestimation of the overall level of risk, this intentionally simplified approach already highlights sections where stakes are the most important.

However this approach is unsatisfactory, insofar as at fact :

– on the one hand, a link exists between geotechnical conditions encountered existing at a point and that of the sections located immediately before or after this position ;

– on the other hand, the likely consequences of a given event decrease each time it is met, methods of treatment being increasingly controlled by the teams.

Our analysis also relies on a discretization over the whole length of the tunnel in elementary sections. The length of these should naturally be adapted to that of the tunnel and the level of geological uncertainty (100 m break-down pitch in our example, for a 24 km long tunnel). The decomposition of the whole work into sections of finite length then allows the location of areas with the highest level of risk.

The estimation of the overall level of risk for a tunnelling project can thus be seen as the calculation of a mathematical expectation of the drift of costs and lead times, obtained by considering a set of independent events and a suitable break-down pitch.

Risk analysis can be summed up in a graph (Figure 3) showing the financial provision for all identified unexpected events (shown as a histogram, scale on the ordinate at left) and the index
of level of knowledge of the geological model (plotted as a curve, scale on the ordinate at right) for each section of the tunnel.

The results of this synthesis highlight the “tough sections” of the project for which provisions for unexpected events are high. If the overall level of risk is deemed too great by the building owner, geological risk can be better limited through a new investigation campaign. Moreover, site investigation is the only means available to the building owner to adjust the financial provision for unexpected event assigned to the project.

Figure 3: Synthesis of the risk analysis and investigation simulations carried for Chartreuse tunnel (Outheran massif)

3.3. Site investigation

3.3.1. Objectives and benefits of investigations

The main goal of site investigation is to refine the geological model from both geological, hydrogeological and mechanical points of view and especially characterize as finely as possible the crossed massif in order to forecast all construction methods adapted to the context. Defining a detailed geological model necessarily requires successive surveying campaigns, the content of which is intimately linked to the geological and geotechnical context and to previously obtained results. Each tunnel being a prototype, no precise directive can be given concerning the amount of investigations to perform.

Nevertheless, if we follow the indications of the U.S. National Committee on Tunnelling Technology [10] according to which the ratio between the total length of the drillings performed and that of the tunnel must be at least equal to 0.6, the cost of these explorations can represent large sums to invest during the study phases (about 500 k€ for a 500 m long tunnel). Although the
contracting authorities pretend to be convinced by the usefulness of explorations, they nevertheless sometimes doubt their economical profitability.

In this context, risk analysis helps to rationalize this observation by attempting to prove the usefulness of explorations according to a criterion of risk reduction. Thus a global analysis is to be performed, simultaneously taking into account both the geological risk identified and investigation techniques, the effectiveness and profitability of which are very different depending on the type of investigation (boreholes, field surveys, geophysics, bibliography, investigation galleries, etc.) [8].

3.3.2. Effect of ground investigations on the determination of the level of risk

The valuation of consequences of each unexpected event is determined by taking into account:

- the direct costs resulting from adjustments to the constructive methods defined initially;
- the cost of specific studies needed to develop adaptations (additional investigations, expertise, calculations ...);
- the cost induced by the disruption in the process of construction and a potential extension in construction time.

The last two items form the additional costs associated with the unexpectedness of an event during the course of work.

In the proposed approach for determining the level of risk, conducting a investigation campaign refines risk analysis through a change in the estimated likelihood: either the probability is increased and the event is now almost certain and integrated in the project (the cost of surprise disappears), or it is lowered and the level of risk decreases proportionally.

To illustrate this, let us consider the area of the Couz valley, for which the risk of encountering swelling marls was identified. This geological context may lead to special design specifications (invert, steel reinforcement of the lining). In the absence of investigation, based on bibliographic data only, the areas identified as likely to contain marly levels can be considered as potentially swelling. The likelihood associated with this event in these conditions is "possible", which is a "reasonably conservative" position given the data available.

If ground investigations are conducted and assuming the new data confirm the swelling potential, then the likelihood becomes "probable". Changes must be made to the project in order to fully integrate the feared event which is no longer considered as a unexpected event (event that may occur) but becomes an almost-certain event. If on the contrary the investigation does not show the presence of swelling minerals, then the likelihood is reduced to "very unlikely" and the level of risk is considerably lowered.

4. Simulations of site investigation on the geological model

Through several simulations, the potential impact new site investigations could have on the financial provision for unexpected event can be assessed. These simulations assume investigations reach indeed their goal of identifying and characterizing the unexpected event.

Three scenarios are presented in Figure 3:

- Scenario C: it presents the results of the initial risk analysis. The level of knowledge in the studied section is very heterogeneous. The estimated provision for unexpected event for this 3500 m long section is approximately 9.9 million €.
- Scenario A: a survey at the heart of the Outheran anticline is realized from Kilometer Point 70.7. The level of knowledge increases in the sections located below the survey and it is considered that the survey results regarding the nature and position of marls allow to reduce the likelihood of the unexpected event. The provision for unexpected event for the whole section is reviewed and lowered to approximately 8.8 million €.
– Scenario B: a survey in the Couz valley is carried out at KP 69.4. The level of knowledge increases in the sections located below the survey and it is considered that the survey results regarding the swelling behaviour of marls allow to reduce the likelihood of the unexpected event. The provision for unexpected event for the whole section is reviewed, again approximately to 8.8 million €.

Site investigations conducted in each of the scenarios A and B allow reducing the provision for unexpected event in the studied studied by 1.1 million €. The drill hole made in Scenario A has a length of 770 m while that of scenario B has a length of 150m. The cost of investigation is about five times higher in scenario A than in scenario B.

The effectiveness of the campaign for recognition of Scenario B is considered more important than that of scenario A by looking at the ratios between the cost of investigation and the cut in provision for unexpected event they generate.

This type of simulation makes it possible to retain and programme only the investigations that are most relevant in terms of risk reduction.

5. Conclusion et perspectives

Underground works always involve a part of geological uncertainty inherent to the complexity and/or variability of the natural environment constituted by the geological context and to the necessarily partial knowledge gained through ground investigation. To control as much as possible the effects of this part of uncertainty, several risk management approaches have been developed, aimed at evaluating the level of risk. This task consists in identifying, analyzing and assessing risks and finally summing them. The total amount thus obtained is the financial provision for risk that the building owner must have at its disposal in addition to the amount retained for the construction contract. Obviously the building owner tries to minimize this provision to limit the overall budget of the operation.

The approach presented in this paper is based on a graphic showing all along the tunnel project the level of risk for successive sections of constant length (100 m) as a function of the location. The interest is to visualize the areas with the highest level of risk and seek opportunities to reduce it. The principle is to consider for each area the benefit of specific investigations by comparing their cost to the reduction they provide in the evaluation of risk. The usefulness of additional investigations is then considered in light of their relevance and effectiveness: only those resulting in a significant reduction of risks are performed. Risk assessment keeps on going until the amount corresponding to the residual risk becomes acceptable to the building owner funding the work, ie to the point where he/she reckons that investing in further investigations becomes too costly with respect to the expected gain.

To be efficient, the evaluation of the level of risk requires on the one hand to determine the likelihood of events unforeseen in the project but likely to occur during the course of works and on the other hand to assess the technical and economic consequence the occurrence of such events would produce if they happened. From this point of view the objective of geological investigations is to reduce the likelihood of feared events and to specify the magnitude of their consequences. In terms of methodology it is important to ensure that each of the investigation campaigns conducted during the various phases of study is subject to a rigorous synthesis and that for each phase of study a new risk assessment is performed, the results of which will allow “targetting” the most appropriate additional investigations for a real reduction in risk.

With the benefit of the insight, it appears that the ways of bettering the approach lies primarily in improving the accuracy in determining the value of the likelihood through a reasoned assessment of the reliability of the geological model, but also in taking into account the interdependence of events, the consequence of which are not identical from one occurrence to the next.
References

[1]. J.-Cl. Daumarie and M. Schivre, “Lyon-Turin link – Section from Lyon to the alpine valley – design of several tunnels with a total length of 45 km” in Proceedings of Tunnels for High Speed Railways 1 and 2 October 2009, FEUP, Porto, 2009


