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Preliminary Investigations and the Financial Sustainability of Underground Project

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Abstract. Tunnels upgrade connectivity and mobility, with an all-out venture cost that mostly depends on the financial support given by significant lenders. Financial sustainability is related to Risk and Sensitivity Analysis, which in turn depends the level of knowledge of the geology of the project site. The target of this paper is twofold: depict the cycle of i) a well define comprehension of the geo-related model and ii) represent the impact of geo-related uncertainties into the Risk and Sensitivity Analysis. Key elements for assessing the economic sustainability of the investment are here outlined. The undeniable degree of financing preliminary investigations because of high forthright expenses is regular for the vast majority of the underground and tunnel projects. However, there are additional risks such as the geological uncertainty mainly related to the robustness of the preliminary investigations. Significant investment is needed prior to arriving at solid comprehension of the geological model and the connected hazards. Geological uncertainties can be characterized into two significant classes: epistemic and aleatory. Fundamental investigations are normally scant and don't cover the epistemic vulnerability related to the chosen tunnel alignment or underground facility location. For an underground infrastructure project, the geological uncertainty exerts the highest impact on the project and financial sustainability. Variables must be surveyed and contrasted with the assessed cost in order the project being eligible to some kind of financing. Depending on the result of the risk analysis, solutions can differ: i) withdrawal from the project or restructuration, ii) chances ensures, iii) dividing the risks between parties and phases, and more significant, iv) a powerful undertaking readiness. Last option being the most efficient method for risk mitigation however depends on fundamental examination by specialists. Blended finance presents a risk sharing approach.

1. Introduction

Worldwide, underground transport infrastructure facilities (long and deep tunnels as well as metro lines) are greatly increasing.

A recent European study [1] defined the standard cost per kilometer of built tunnel as approximately 35 Million Euros within a range of plus or minus 12 Million Euros per kilometer. To this cost, environmental safeguarding and muck management should be added. The study [1] shows approximately 50% of the total final costs are related to the costs for the excavation works. Excavation costs are key drivers in a tunnel project.

The estimated excavation unit costs (per m³) range between €225/m³ for ordinary tunnels, and €330/m³ for basis tunnels. This difference is mainly due to increases in the transport of muck, working environment constraints, difficult geological conditions and residual uncertainties.



Costs and time control are dependent on the robustness of the geological and geomechanical models. Residual geo-related uncertainties must be estimated on the basis of the geomechanical cross-section of the tunnel. Risk and Sensitivity Analysis (RSA) can be then further developed.

Thorough geological preliminary investigations are mandatory for a reliable project cost estimation, because, as outlined by [2] cost overruns in tunnelling projects are deeply impacted by geological and geotechnical investigations.

The objective is to reduce geological uncertainties and frame the remaining estimate in the Risk and Sensitivity Analysis.

2. Risk evaluation

ITA-AITES and the International Tunnelling Insurance Group [3] have published a code of practice for risk management in tunnel work. These guidelines and recommendations are necessary but not sufficient. According to [3], understanding the effects of geological uncertainties and gaps is crucial.

It is recommended that the analysis should:

- define the uncertainty of the geological data available
- predict all remaining geological uncertainties/gaps
- predict the behavioural variability of the rock mass

In driving the preliminary investigations, the approach is based on the definition of the RMZ (Rock Mass Zone, ISRM 1981) crossed by a tunnel and the following aspects should be considered:

- a core of 12 cm Ø only represents 0.01% for a tunnel of 12 m Ø
- rock samples are few and scattered and only represent the intact rock portion of the rock mass and could represent only a small percent of its overall composition
- lab data is usually few, and its collection and analysis are time consuming and costly.

Samples have their own variations; therefore, more lab tests may be needed in order to have a reliable geo-statistical distribution.

Geological features follow a fuzzy logic and have statistical distribution (random, probabilistic, normal, beta, exponential, lognormal [4]) which must be correctly captured. The applied value for rock mass quality should be assessed taking into account the project scope (table 1).

Table 1. Project scope v/s rock mass condition to be considered in a design.

Cat.	Scope	Reference Value for the Rock Mass to be considered
A	Temporary Mining Shafts	Favourable
B	Vertical Mining Shafts	Favourable
C	Permanent mining openings, hydraulic tunnels (excluding pressure), pilot, directional and head tunnels for large excavations	Intermediate – Favourable Intermediate
D	Storage rooms, water treatment plants, tunnels for secondary roads and railways, access tunnels	Intermediate
E	Power stations, primary roads or railways, portals, intersections, civil protection chambers, pressurised hydraulic tunnels	Intermediate - Intermediate Unfavourable
F	Underground railway stations, factories, underground nuclear power stations	Unfavourable – Extremely Unfavourable

3. The geological model

The geological and geomechanical model are cornerstones of any underground project [5, 6, 7, 8, 9]. The geo-models must be established at the earliest stage of project preparation as recently highlighted at the 2019 ISRM International Congress - Iguazu (Brazil), where the slogan was: “Back to the field!”

A recent analysis on tunnel failures [10] highlighted the key role played by the robustness and reliability of geological data in project risk management, which generally had its main weaknesses in limited preliminary investigations.

The main tools for defining geomechanical models are the preliminary investigations, intended as any type of direct or indirect geological, geophysical, hydrogeological, geotechnical, geomechanical survey, in situ or laboratory tests at any stages of project implementation (including investigations performed at the tunnel head).

The aim of preliminary investigations is to assess the correct geological-geomechanical-geotechnical-hydrogeological models along the tunnel axis and the area of interference. The different stages of targeted surveys and investigations will allow the design of the final geological model, evaluate the residual uncertainties, and provide all the technical data for tunnelling within safety, cost and time risk management parameters.

Most of the residual geological uncertainties are linked to a lack of preliminary investigations (figure 1a). As a general rule, for a reliable and sustainable tunnel project, the cumulative length of boreholes should tend towards the tunnel length and about 10% of the total costs should be allocated for the phases up to the final design phase [11] (figure 1a). Preliminary investigations must be well addressed and planned throughout the project development (figure 1b).

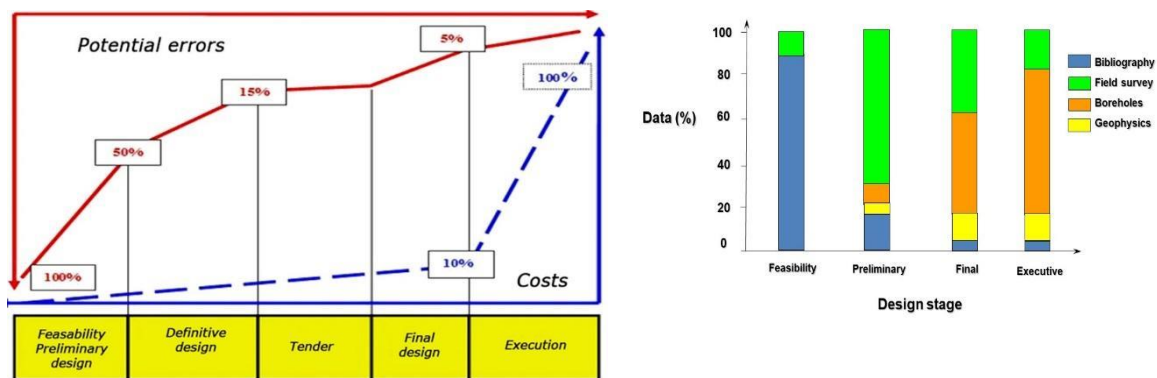


Figure 1. a) Costs and errors during the development of a design, b) Preliminary investigations distribution through a design.

4. Uncertainties

The *in situ* geological conditions are largely unknown and shall be assessed at project level using limited and expensive time-consuming surveys. The main uncertainties are related to the accuracy of the preliminary investigations and their impact at the scale of the project.

In subsequent design phases, geological uncertainties must be addressed and investigated, and residual uncertainties should be defined before implementation. This requires an accurate anticipation of issues and appropriate mitigation measures. Here including engineering solutions to be incorporated into the final design.

A sustainable underground project requires thorough and robust preliminary investigations and investment cost estimation that are of key importance for the success of the project (figure 2), particularly before starting the execution of the project.

Poorly addressed geological hazards have direct implications for cost increases, time delays and safety risks during project implementation.

Geological uncertainties can be of two types: epistemic and aleatory (table 2) [12].

- Epistemic risks are related to lack of knowledge and can be considerably reduced through targeted preliminary investigations.
- Aleatory risks are related to random uncertainties that can be verified only during the progress of the excavation's stages, their location or occurrence cannot be predicted, but their typology and expected range can be defined. Aleatory risk management should be included in the design phases.

Uncertainties in the geological-geomechanical models are mainly linked to a lack of surveys, of judgment, of geological knowledge and poor geostatistical modelling.

Uncertainties in the rock mass behavioural model for the tunnel are mainly deductive and related to well-defined starting conditions, together with reasonable behaviour models developed in other well-defined contexts.

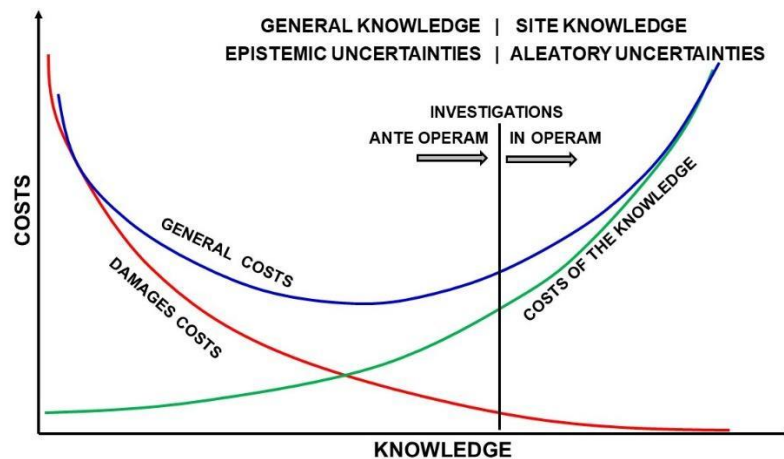


Figure 2. Roles and costs of the knowledge.

Table 2. Summary for Epistemic and Aleatory uncertainties.

<i>Epistemic (from the Greek episteme, knowledge)</i>	<i>Aleatory (dependent on chance, an uncertain outcome, from the Latin alea, game of chance)</i>
<ul style="list-style-type: none"> - Uncertainty due to lack of general knowledge, or partial data - Reduced through general surveys, in site investigations, by experts - Conceptually solvable with a model - Can be expressed as a degree of reliability in a [statistical] distribution - Sensitivity analyses can lead to defining the degree of uncertainty - Relates to assumptions made about rock mechanics processes in, e.g. the computer model 	<ul style="list-style-type: none"> - Random uncertainty - Due to the intrinsic geological variability of the site - Not conceptually solvable - Definable in its variability through probabilistic and statistical analysis - Need for large territorially significant data archives - Definable with any reliability only through specific site analysis
Example: Lack of understanding of coupled phenomena, lack of data	Example: Variability in fracture density, variation in life of tunnel boring machine cutters
Example: what type of geological structure the tunnel will encounter?	Example: at exactly what chainages will the tunnel encounter water-bearing fractures?
Example: will an earthquake damage the tunnel?	Example: when will the next earthquake occur?
Problem: Knowledge all the factors involved	Problem: Appropriately representing variability

5. Cost assessment

Financial sustainability and project maturity criteria require proper project preparation and a comprehensive understanding of the geological uncertainties. The relation between construction risks and the increase of construction costs is shown in figure 3.

Project risks are the same as in any infrastructure project: completion or delay risks, offtake risk, anticipated traffic or user demand, operational risk and any regulatory/environmental risk. However, the main risks may be related to residual geological uncertainties due to a lack of exhaustive preliminary investigations.

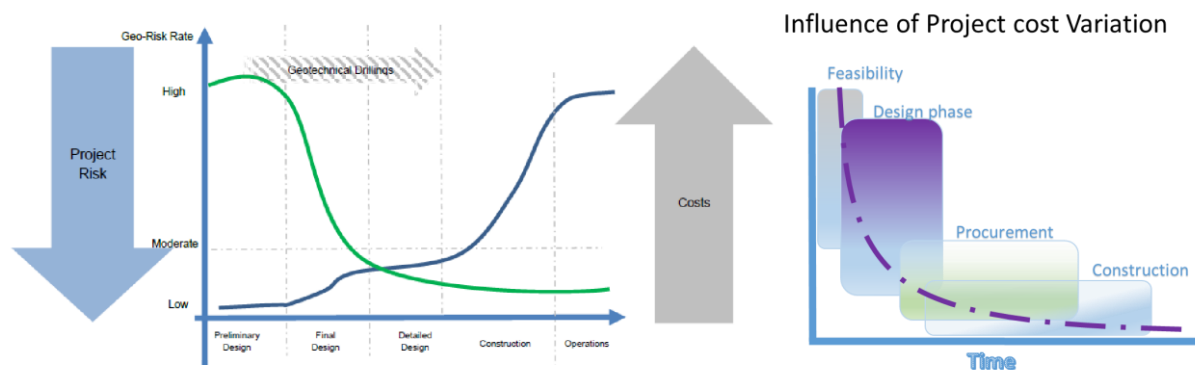


Figure 3. Project costs and risk at development stages for a large underground project. In green, the risk trend and in blue, the construction costs trend.

A high level of financing risk due to high upfront costs is common for most underground projects. Costs can be optimised following the different project main phases (Feasibility, Design, Procurement and Implementation) shown in the figure above.

Following NATM and ADECO-RS principles, in order to industrialise the tunnelling process and ensure safety, a number of behaviour type classes for each geomechanically homogeneous tunnel stretches have to be defined in a detailed geomechanical cross section (figure 4).

The costs for each behaviour type class can be calculated including its predicted variability and cost implications.

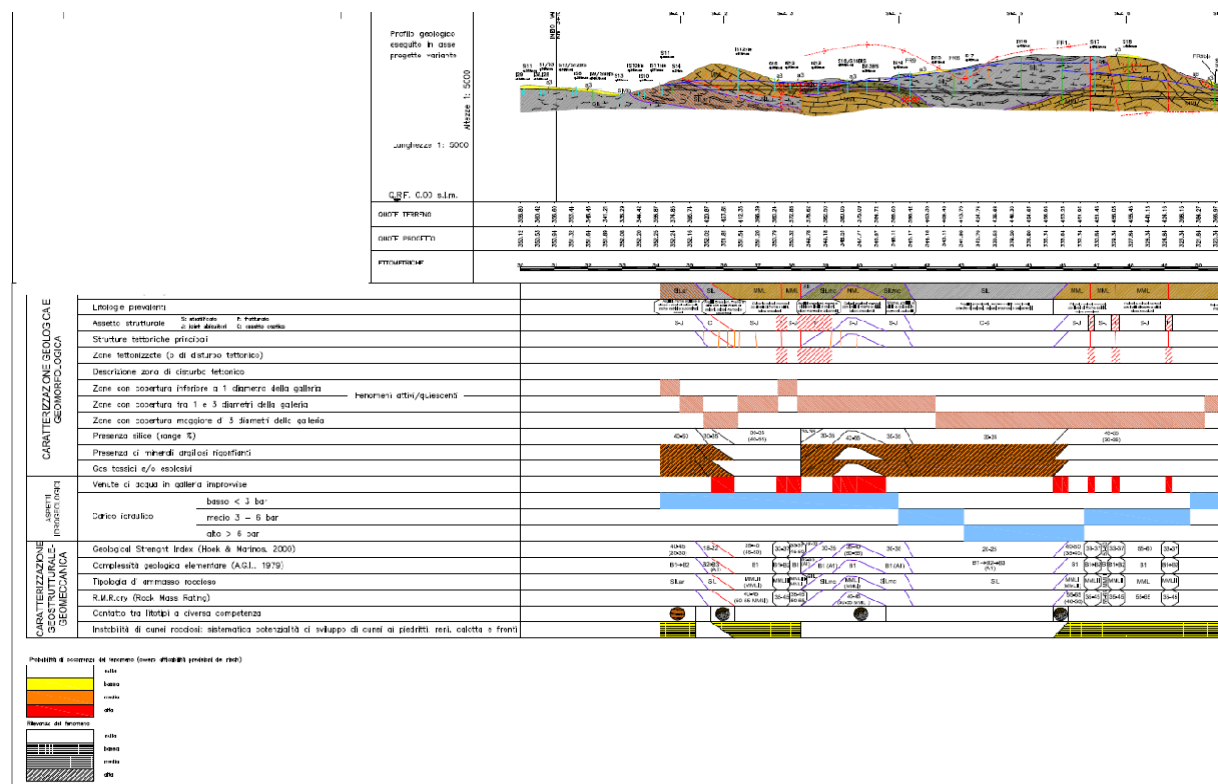


Figure 4. Geomechanical cross-section along a base tunnel in the Apennines (Italy) with all the geological hazards outlined and their forecast for tunnel stretches.

6. Risks and Sensitivity Analysis

Scenarios can then be identified by varying unit costs as a function of the geological conditions. As a result, the cost per km of a tunnel can vary. Cost estimates vary depending on the behaviour type classes.

A relatively small increase in the length of the most expensive type sections leads to a significant increase for the overall project cost.

For each identified risk category, risk impact and probability should be assessed against reliability and residual risks.

As an example, for a transportation project, the EU Cost and Benefits Analysis manual [13] considers four categories of key performance indicators having a direct impact in its economic and financial performance:

- Investment costs (IC)
- Operating and maintenance costs (O&M)
- Changes in Accident Risk (CAR)
- Environmental impacts (EI)

Each of these should have their value adjusted in the analysis, together with the estimated effect (as a percentage change) on results of financial and economic performance indexes.

Based on the sensitivity analysis, each type of cost must be considered as having a critical effect or not, with respect to the economic performance indicators of the project.

Sustainable successful tunnelling can be defined as producing a satisfactory finished facility for no additional money, in no more time than is required to deal with the existing ground conditions and very limited negative environmental impacts.

Considering a standard type of tunnel project of an amount €600 M estimated costs, for fixed benefits, the variation of the ratio EIRR/Tunnel and ENPV/Tunnel costs increase has been simulated, in relation to unplanned costs for uncertainties (figure 5).

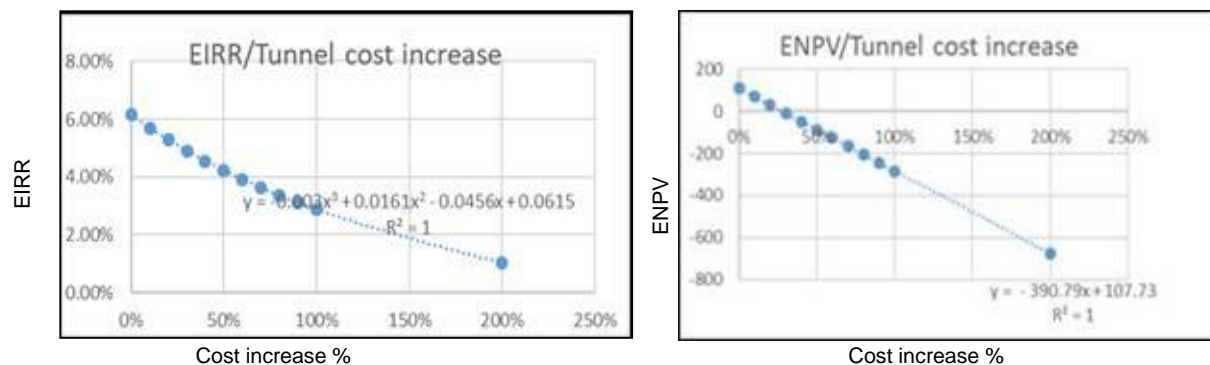


Figure 5. Benefit decreases in respect to the tunnel cost increase; left respect to EIRR, right respect to ENPV.

It appears that a small variation in the percentage of the different excavation classes have a direct impact in lowering EIRR and ENPV.

From the figure above, at a 25% cost increase (equal to a 5% economic discount [13]), the project becomes economically unsustainable. Costs for disruptions, claims, variations may be added.

7. Findings

A correct evaluation of the geological risks is required by means of preliminary investigations, and variables must be assessed and their influence on cost estimation verified.

The prediction of the foreseen and foreseeable geological uncertainties is the basis for the risk analysis.

Hence, the question becomes, “How well do you know the existing ground conditions?”

The answer that stays within a reliable geomechanical profile can lead to high reliability between:

- tunnel design

- excavation rate forecasts
- “as-built” data.

That is particularly true for the mechanized method (TBM), the use of which is now rapidly increasing. TBM design and construction take time and sizable investment prior to implementation. TBM must be tailored to the real in situ geological setting and therefore demands all the data needed to be well known in advance. Any deficiency in that implies failure in the use of TBM and a substantial increase of costs and long delays.

For TBM (the mechanised method) a good indicator of sustainability is the theoretical average rate of progression (ARA_T), which is expressed in meters per day (m/d). ARA_T considers the net daily advance without any stops or delays not related to geological concerns.

The robustness of a model is evidenced by the comparison of effective ARA_T with the as-built data and the forecasted ARA_T .

A good example of a reliable model is the Santa Lucia motorway tunnel (7.5 km length - Florence) executed with the largest TBM in Europe (figure 6). For this project, the ARA_T was estimated at about 15 m/d and the as-built data reflects this figure [14].



Figure 6. TBM-EPB, 15.965 m diameter for the 7,548 m Santa Lucia tunnel, A1 motorway, Italy.

8. Conclusions

Accurate preliminary investigations and work plans are the key drivers for a robust risk analysis. The risk analysis is of major importance for the successful implementation of a large-scale underground infrastructure project and for safeguarding natural water resources [15]. This article focuses on the impact of a lack of reliable geological data on the economic feasibility of the project. Unreliable data has a direct impact on risk analysis. An increase in costs may result in decrease of EIRR (see table 3).

The authors highlight the need to have a robust understanding of geological uncertainties for a reliable risks analysis.

Risk analysis can recommend solutions for risk mitigation such as:

- a) withdrawal from the project or fundamental adjustment of certain project components;
- b) risk guarantees;

- c) risks sharing among parties;
- d) robust project preparation, which is the most efficient method for risk mitigation.

Finally, blended finance may represent in some cases a risk sharing approach for the development of financial sustainable underground infrastructures.

Disclaimer

The comments and opinions expressed in this paper reflect the views of the authors and do not necessarily state or reflect the views of JASPERS and its partners (European Commission and EIB). In particular, the views expressed herein cannot be taken to reflect the official opinion of the European Union.

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