GEOHAZARDS – COST HAZARDS
A NEW METHOD FOR EVALUATION OF RISKS IN UNDERGROUND STRUCTURES

Rurdolf Pöttler[1], Helmut F. Schweiger[2], Gerd Peschl[3]
[1]ILF Consulting Engineers, Feldkreuzstraße 3, 6063 Rum / Innsbruck, Austria,
Phone: +43 (512) 2412-0; Fax: +43 (512) 2412-5902; Email: rudolf.poettler@ilf.com
[2]Technische Universität Graz, Institut für Bodenmechanik und Grundbau, Rechbauerstraße 12, 8010 Graz, Austria, Phone: +43 (316) 873-6231; Fax: +43 (316) 873-6232; Email: helmut.schweiger@tugraz.at
[3]INSITU Geotechnics, Gartengasse 19/II, 8010 Graz, Austria, Phone: +43 (664) 8405030; Fax: +43 (316) 225312-15; Email: gerd.peschl@insitu.at

Abstract

The realisation of large transport infrastructure projects is influenced by a wide range of different factors. It is a fact that cost overruns in infrastructure projects which are mainly dominated by tunnel structures are extremely high. An overrun of budget results in cost hazards which can be managed only by extraordinary input of not foreseen money. One of the most important factors are the widely unknown and varying geological and hydro geological conditions in which tunnel excavation has to be performed.
The general expectation that a project should be carried out within the planned period and on budget requires a high level of design, planning and controlling. To meet these requirements it is necessary to first to define and evaluate the risks for the project and secondly to compile the different risks to an overall risk assessment in terms of money.
The first part of this paper deals with the evaluation of costs of tunnel driving taking account of the scatter of the geotechnical parameters. In order to account for uncertainties in determining material parameters and the scatter of in situ behaviour these parameters are usually given in terms of ranges. In numerical calculations this is commonly replaced however by deterministic analysis with characteristic values and a limited variation of different parameter combinations. It is shown in this paper that the Random-Set-Finite-Element-Method (RS-FEM) provides a convenient tool to account for the scatter in material and model parameters and thus can increase the value of numerical analyses significantly. In addition, the comparison between calculation and field measurements (both available in terms of ranges) allows an assessment of the quality of the geotechnical model.
The second part of the paper discusses standardised comprehensible fundamental rules and guidelines for defining project costs and project budgets of infrastructure projects taking into account risk assessment and risk management. Adhering to these guidelines and rules contributes to ensure that the structure can be built in the required quality, on schedule and on budget, as well as to estimate the predicted margin of the budget.
For the evaluation of risk costs two different methods are described in detail: The deterministic method of risk cost evaluation is based on a certain percentage of the basic costs which is sufficient for simple projects. For complex projects a qualitative risk cost evaluation based on identified risk scenarios is necessary to get a sound basis for determining the budget of the project.

Introduction

Project costs of infrastructure projects which contain considerable technical, financial and time-related risk cannot be calculated in advance, but have to be estimated over a long project phase based on not yet consolidated knowledge of the project. Frequently there is a lack of suitable comparable data, as large-scale transport infrastructure projects often constitute prototypes on account of project-specific boundary conditions. The expected costs often can only be assessed and realistically predicted after all permits have been obtained and projects have been designed in detail. That is why a technically competent determination of potential cost risks and careful consideration of not yet specifically known but important cost influencing factors during the design phase play a decisive role in transport infrastructure projects. Cost and budget overrun in complex infrastructure projects up to 50-100% are quite common as can be seen from Figure 1.

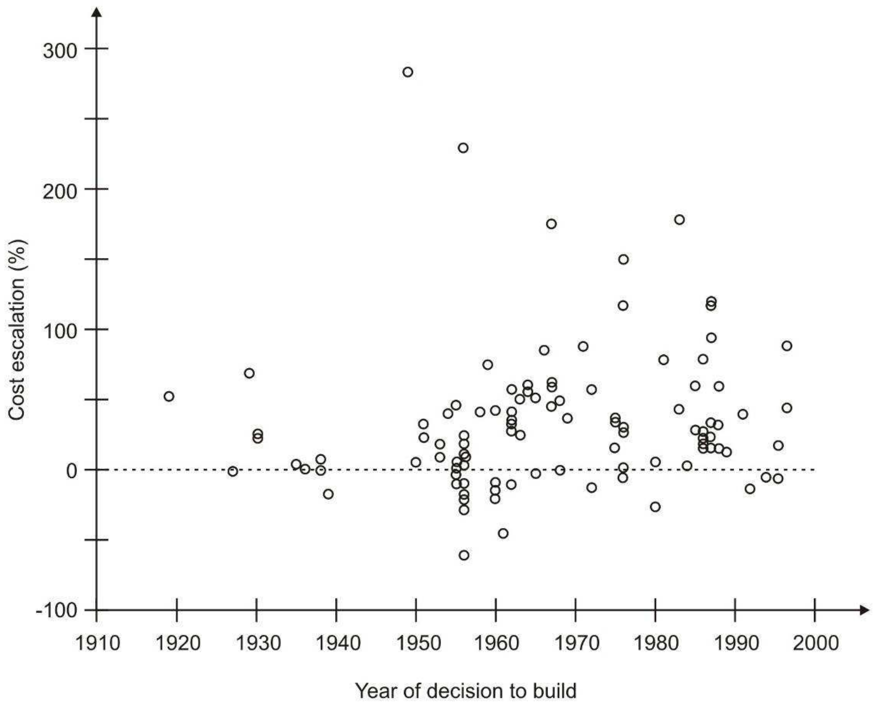

Figure 1: Budget overruns of large railway infrastructure projects [Flyvbjerg, Holm, Buhl, 2002]

The basic idea for each project realisation has to be that the real costs of a project have to be known from the very beginning to form a sound basis to decide whether the project should be pursued or not. Costs are to be evaluated in term of life cycle costs to make sure that the investment is in line with long term overall profitability and sustainability. The total costs of a project especially in the very first project phases are influenced by significant uncertainties as the most decisive boundary conditions are often not well defined. This is especially true for large infrastructure project dominated by underground structures. Costs of underground structures are governed by geotechnical boundary conditions. Unknown or uncertain boundary conditions may lead technically to geohazards and financially to costhazards in case no provisions for such cases have been foreseen. The present paper gives guidelines to perform cost evaluations for infrastructure projects taking account project risks. The method is based on an open book philosophy given all involved parties knowledge, transparency and influence to the cost evaluation.

The same aspects apply for brownfield projects revitalising old industry sites (Klapperich, Pöttler, 2006).

1. Fundamentals

The project has to be divided into (time dependent) project phases which are separated by milestones. There has to be a logical connexion between project phase, scope of project phase, milestones, accuracy and method of cost evaluation. Depending on the project it may be necessary and useful to adjust the phases and milestones, or to introduce further phases and milestones (Pöttler, Schweiger, 2006).

The total costs (TC) are divided into:

- Basic costs (B),
- Cost estimation of risks (R),
- Cost estimation in respect of financial issues: project financing, value adjustment and valorisation (F)

$$TC = B + R + F \qquad (1)$$

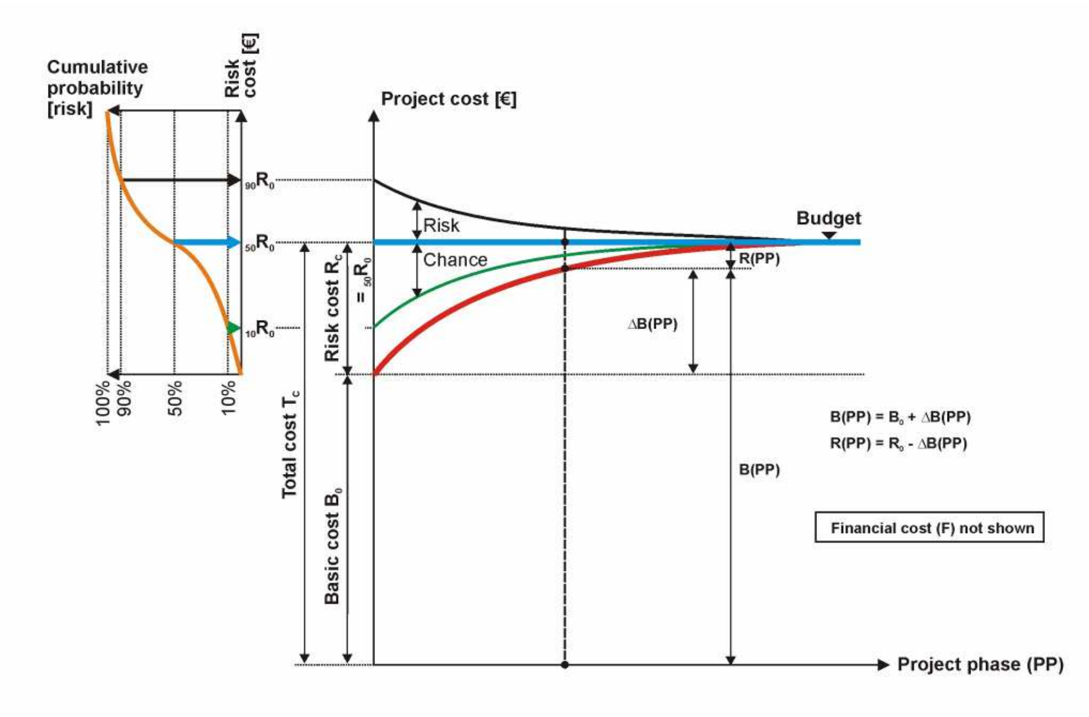

Figure 2: Schematic development of costs

This paper deals with basic costs (B) and risk costs (R). In Figure 2 the development of basic costs and risk costs is shown in a schematic way. With more profound knowledge of the project the basic costs increase and the risk costs decrease. In an ideal case the overall costs (TC) remain constant. As risk costs vary and are statistically distributed the investor and the engineer have to determine the value of R in terms of a fractile value to be added to B. According to engineering judgment the value of the 50% fractile (as shown in Figure 2) should be added, with a maximum 75% fractile. The difference between the added risk costs (R) and the 10% fractile and the difference between R and the 90% fractile of R can be assumed to be the chance or real risk of the project in terms of money. Cost estimation has to be done continuously during the planning, design and implementation stage of the project. Details are given in ÖGG 2006 [Nutzen und Herausforderung bei der Anwendung der ÖGG Richtlinie „Kostenermittlung für Projekte der Verkehrsinfrastruktur" im Ingenieurbüro] and [Pöttler, Schweiger and Peschl, 2006].

2. Cost Evaluation

The cost evaluation can be done using deterministic or probabilistic methods. It depends on the complexity of the project which method will be applied (see Table 1). For simple project basic cost and risk costs will be evaluated by using deterministic methods. For projects with high complexity both costs will be calculated according to probabilistic methods.

	Basic costs (B)	**Risk costs (R)**
Small projects	Deterministic (see 3.1)	Deterministic (see 4.1)
Big and/or complex projects	Deterministic or probabilistic (see 3.2)	Probabilistic (see 4.2)

Table 1: Method for evaluation of basic costs and risk costs depending on the complexity of the project.

The total costs are determined from the sum of the basic costs (B), cost estimation for risks (R), cost estimation in respect to financial aspects (F). The summation method depends on the chosen approach for determining these individual cost components.

The following cases may occur:

Case 1: If the basic costs and the costs for risks are calculated deterministically, the total costs are a deterministic value, with deviations in percent which are based on experience in most cases. No probabilities can be assigned to the indicated upper and lower limits.

Case 2: The combination of probabilistic determination of basic costs and deterministic evaluation of costs of risk provision does not make sense.

Case 3: Deterministic evaluation of basic costs and probabilistic determination of costs of risk provisioning is to be used for complex construction projects. Added to fixed basic costs, the cost of the risk is determined by means of statistical distribution. Theoretically it is possible, in this case, to make statements about the probability of exceeding the costs of provision for risks. This only applies when all risks can be quantified with sufficient accuracy.

Case 4: Determining the basic costs and the costs of provision for risks on a probabilistic basis will be justified and/or required for large, complex projects. A simplification of the methodology can be done in such a way that a fixed value (5 %, 50 %, 95 % - fractile) is used for the determined basic costs. This value is determined based on the probabilistic calculation according to engineering judgement. Thus the value of the basic costs corresponds to a deterministic value. For determining the budget cost Case 3 applies.

3. Basic costs (B)

3.1 Deterministic method for evaluation of B

The basic costs (B) are based on the design of the relevant project phase (degree of knowledge of the project), project sequence and market conditions, and can be calculated from the corresponding design status. Different methods are available for determining the basic costs depending on the project phase and data base available.

When using a deterministic method, the basic costs are calculated as the sum of element costs. Typical elements in tunnel construction are the costs for the excavation classes, site equipment, final lining, ventilation, etc. For projects with standard elements the calculation is based on a deterministic reference value of the element. This is sufficient, as the interval of element costs compared to the interval of risks is of secondary importance and can be covered by appropriate provision for risks.

3.2 Probabilistic method for evaluation of B

In complex and extraordinary construction projects, with elements depending on largely unknown boundary conditions such as detailed geological conditions, element costs can only be defined within larger intervals or statistical distributions. When combining such element costs it does not suffice to carry out a simple summation of the mean values with upper and lower limits. In order to be able to do an appropriate combination in such cases, probabilistic principles of combination have to be applied. The result of such a cost evaluation is a statistical distribution of the basic costs (Fig. 3).

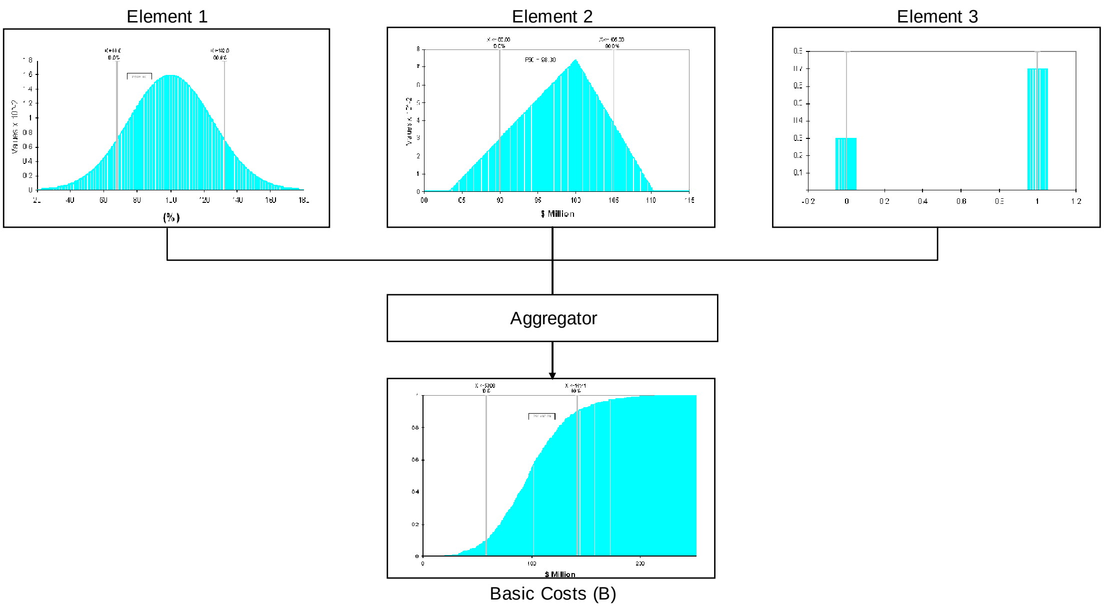

Figure 3: Schematic determination of basic costs using a probabilistic approach

In addition to standard probabilistic methods, the Random Set Method (RSM) has recently proved to be very practical and efficient [Pöttler, Schweiger, Peschl, 2006]. Instead of statistical distributions of costs, intervals are used as calculation basis, which eliminates the disadvantage of commonly used probabilistic methods which require a sufficient amount of basic data in order to obtain a stochastic distribution.

In contrary to classical probabilistic methods uncertainties resulting from lack of knowledge can be considered when applying e.g. the random sets which belongs to a class of methods which are based on concepts dealing with imprecise probability [Dempster, 1967; Shafer 1979]. The Random Set Method (RSM) [Tonon, Bernardini, Mammino, 2000a & 2000b; Peschl, 2004] does not use the usual probability density function but employs sets of input parameters (Fig. 4a). Definition of these sets representing bandwidths of "probable" values for a given parameter is done by experts and in case of costs on basis of offers provided by contractors. When using RSM the number of different sets is not limited and the more information available the closer the results are to classical probabilistic calculations. The result of a RSM-analysis is an upper and lower bound of costs presented in form of a cumulative distribution function (Fig. 4b).

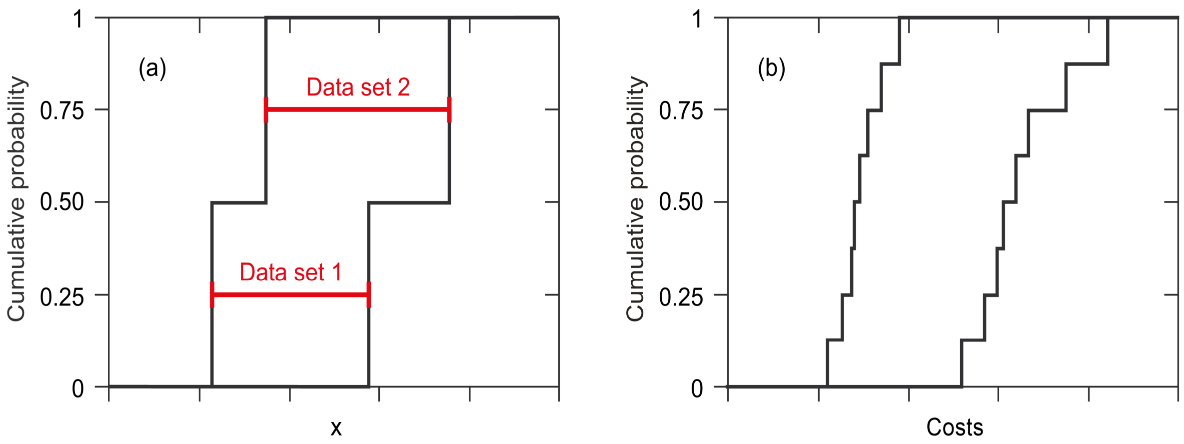

Figure 4: RSM - a) Range for input parameter, b) Range for typical results (e.g. costs)

Fig. 5 shows schematically the procedure for obtaining a cost estimate based on RSM. In the first step random sets are defined, based on the current knowledge on this parameter, and then a probability is assigned to this set. Due to the uncertainties involved and the lack of knowledge it is not possible to define the precise probability but only upper and lower bounds as shown in Fig. 5.

An example of this procedure is presented in the following for the case of a top heading excavation for a tunnel considering 3 support classes (K 6.1-R, K 6.2-R and K 6.2-RS) [Pöttler, Schweiger, 2006; Pöttler, Schweiger, Peschl, 2006].

Fig. 6 lists an example for input values and their graphical representation for support class K 6.1-R whereas the following parameters with their respect bandwidth have been considered:

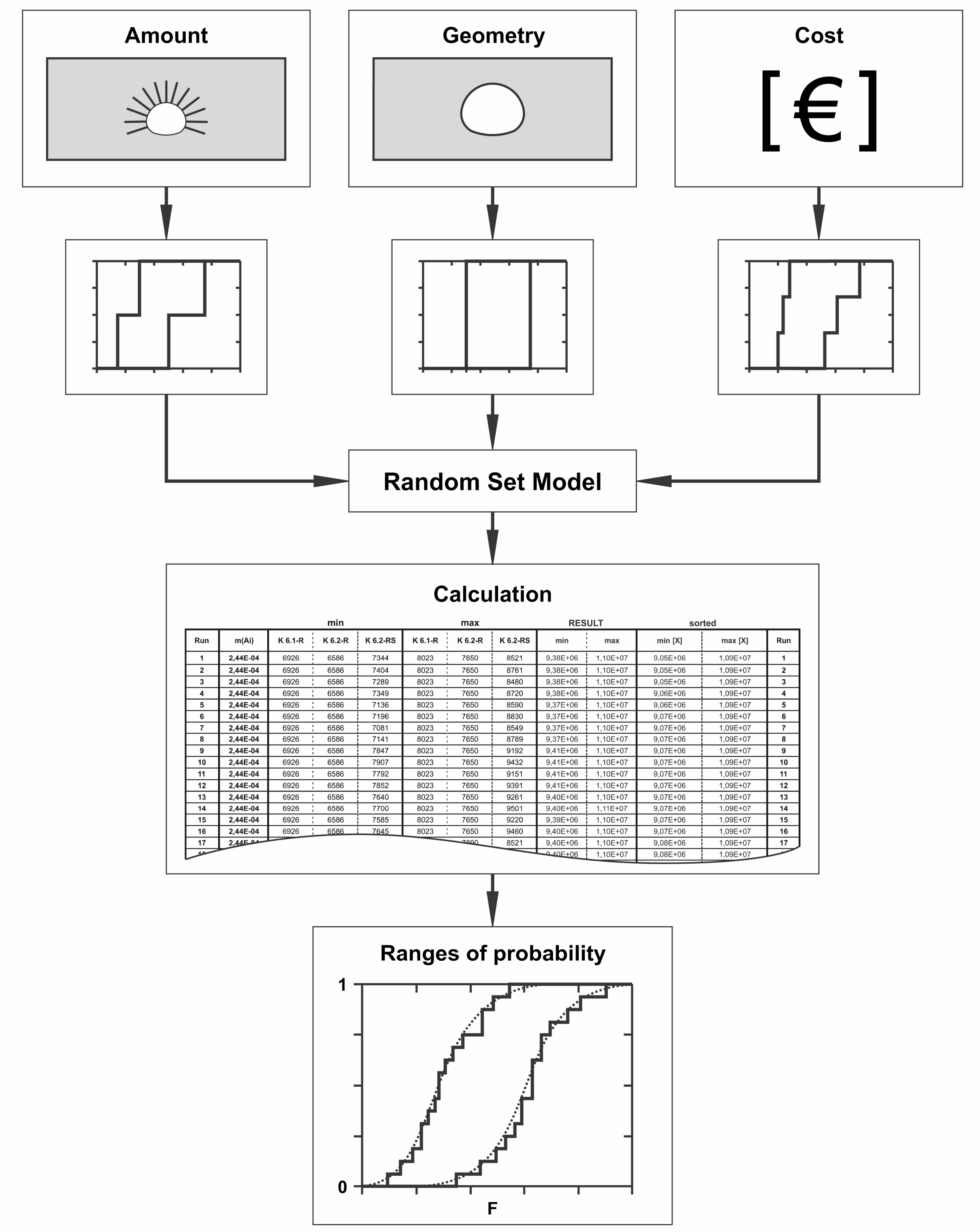

Figure 5: Schematic representation of RSM analysis

Input - RSM / Costs - Top heading (K 6.1-R)
Cost / m Tunnel [€]

Source	min	max	Prob.	min	max	Prob.
Amount/m:	*69,91*	*69,91*				
	Excavation (€ / unit)			Excavation (€ / m Tunnel)		
1	49,0	57,0	0,5	3426	3985	0,5
2	55,0	65,0	0,5	3845	4544	0,5
Amount/m:	*3,94*	*4,93*				
	Shotcrete (€ / unit)			Shotcrete (€ / m Tunnel)		
1	155,0	170,0	0,5	611	837	0,5
2	120,0	180,0	0,5	473	887	0,5
Amount/m:	*52,50*	*52,50*				
	Anchor (€ / unit)			Anchor (€ / m Tunnel)		
1	23,0	25,5	0,5	1208	1339	0,5
2	21,0	24,0	0,5	1103	1260	0,5
Amount/m:	*120,00*	*120,00*				
	Spiles (€ / unit)			Spiles (€ / m Tunnel)		
1	10,0	11,5	0,5	1200	1380	0,5
2	10,5	13,5	0,5	1260	1620	0,5

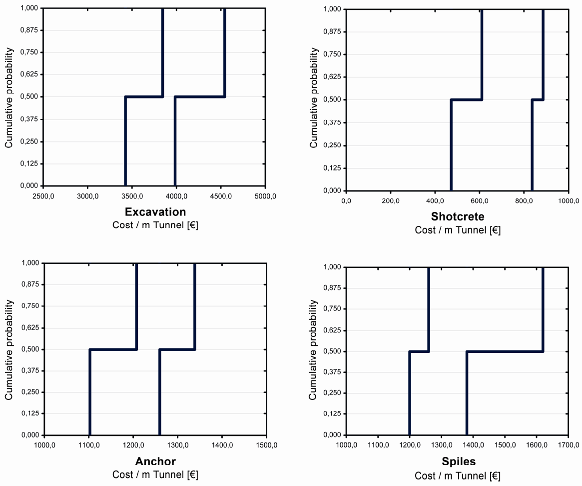

Figure 6: RSM - Input parameters for support class K 6.1-R

Cost for excavation

Data set 1: 49 bis 57 €/m^3
Data set 2: 55 bis 65 €/m^3

Cost for support measures

Shotcrete

Data set 1: 155 bis 170 €/m^3
Data set 2: 120 bis 180 €/m^3

Anchor

Data set 1: 23.0 bis 25.5 €/m
Data set 2: 21.0 bis 24.0 €/m

Spiles

Data set 1: 10.0 bis 11.5 €/m
Data set 2: 10.5 bis 13.5 €/m

Thickness of shotcrete lining

K 6.1-R: 20 to 25 cm
K 6.2-R: 25 to 30 cm
K 6.2-RS: 30 to 35 cm

Distribution of support classes (estimated length)

K 6.1-R: 1043 to 1275 m (= 1159 +/- 10%)
K 6.2-R: 13 to 265 m
K 6.2-RS: 56 to 76 m (= 66 +/- 15%)

Following the definition of the random sets the calculation matrix is established (Random Set Model, Fig. 7) and the required calculations are performed. Because the functions involved are continuous and monotonically increasing only a number of extreme combinations have to be actually evaluated. The result is a bandwidth of costs for support class K 6.1-R (Fig. 8).

RSM - COSTS per m tunnel [€] (K 6.1-R)

		min				max						RESULT		sorted	
Run	m(Ai)	Exca	Shotc	Anchor	Spiles	Exca	Shotc	Anchor	Spiles	Shotc face	Anchor face	min	max	min	max
1	0,063	3426	611	1208	1200	3985	837	1339	1380	420,55	61,20	6,93E+03	8,02E+03	6,68E+03	7,94E+03
2	0,063	3426	611	1208	1260	3985	837	1339	1620	420,55	61,20	6,99E+03	8,26E+03	6,74E+03	7,99E+03
3	0,063	3426	611	1103	1200	3985	837	1260	1380	420,55	61,20	6,82E+03	7,94E+03	6,79E+03	8,02E+03
4	0,063	3426	611	1103	1260	3985	837	1260	1620	420,55	61,20	6,88E+03	8,18E+03	6,82E+03	8,07E+03
5	0,063	3426	473	1208	1200	3985	887	1339	1380	420,55	61,20	6,79E+03	8,07E+03	6,85E+03	8,18E+03
6	0,063	3426	473	1208	1260	3985	887	1339	1620	420,55	61,20	6,85E+03	8,31E+03	6,88E+03	8,23E+03
7	0,063	3426	473	1103	1200	3985	887	1260	1380	420,55	61,20	6,68E+03	7,99E+03	6,93E+03	8,26E+03
8	0,063	3426	473	1103	1260	3985	887	1260	1620	420,55	61,20	6,74E+03	8,23E+03	6,99E+03	8,31E+03
9	0,063	3845	611	1208	1200	4544	837	1339	1380	420,55	61,20	7,35E+03	8,58E+03	7,10E+03	8,50E+03
10	0,063	3845	611	1208	1260	4544	837	1339	1620	420,55	61,20	7,41E+03	8,82E+03	7,16E+03	8,55E+03
11	0,063	3845	611	1103	1200	4544	837	1260	1380	420,55	61,20	7,24E+03	8,50E+03	7,21E+03	8,58E+03
12	0,063	3845	611	1103	1260	4544	837	1260	1620	420,55	61,20	7,30E+03	8,74E+03	7,24E+03	8,63E+03
13	0,063	3845	473	1208	1200	4544	887	1339	1380	420,55	61,20	7,21E+03	8,63E+03	7,27E+03	8,74E+03
14	0,063	3845	473	1208	1260	4544	887	1339	1620	420,55	61,20	7,27E+03	8,87E+03	7,30E+03	8,79E+03
15	0,063	3845	473	1103	1200	4544	887	1260	1380	420,55	61,20	7,10E+03	8,55E+03	7,35E+03	8,82E+03
16	0,063	3845	473	1103	1260	4544	887	1260	1620	420,55	61,20	7,16E+03	8,79E+03	7,41E+03	8,87E+03

Figure 7: RSM - Calculation matrix for support class K 6.1-R

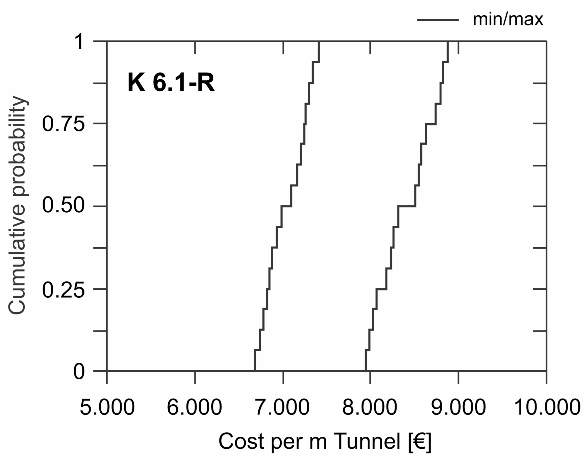

Figure 8: RSM - Result for support class K 6.1-R

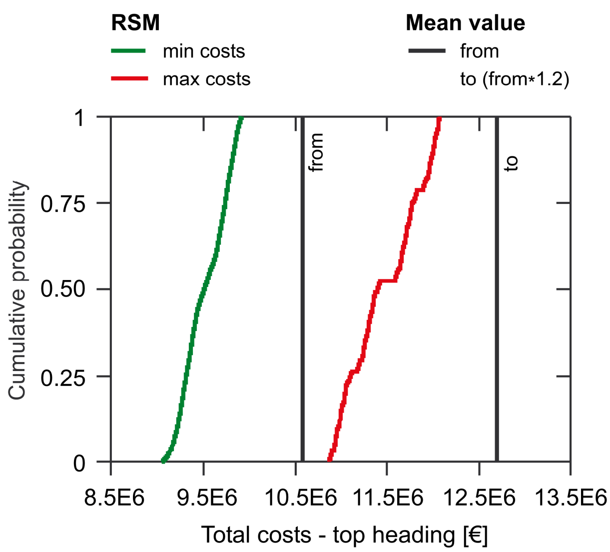

Figure 9: RSM - Range of total costs compared to deterministic analysis

In the same way costs for the other support classes are determined. Finally a combination of all support classes is considered whereas the individual length of each class is treated as random set too, of course with constant total length of the tunnel. The result are two cumulative distribution functions which represent the lower and upper bound of costs for top heading excavation (Fig. 9). Further cost calculations can be performed by taking a certain fractile of the bandwidth (e.g. 50%).

For the sake of comparison Fig. 9 indicates the result of a deterministic cost calculation based on mean values and an assumed 20% increase. It should be mentioned at this stage that this procedure is only recommended when the basic costs are determined by a large extent by uncertain ground conditions.

4. Risk costs (R)

The total costs also have to include appropriate provision for risks in the form of an appropriate cost estimation of risks. Principal risks are:

- **Design risks:** change of cost due to the results of the detailed design in the course of the project.
- **Right-of-way risks:** change of cost resulting from right-of-way issues.
- **Risk due to change of element cost:** change of cost due to new estimation of cost of services. The reasons for such a change of cost are, amongst others, services which were not considered in the original cost calculation. Another reason is e.g. the deviation of an individual result of award of contract from the pertinent cost estimate.
- **Contract risks:** change of cost, which results from the implementation of the contract under the specific conditions of services.
- **Risks due to change of scope of work:** change of cost due to the modification of the project and boundary conditions. They include changes of e.g. project requirements, state of the art, as well as changes of legislation, regulations, and guidelines.
- **Geotechnical risks:** change of cost due to unknown or only insufficiently known geotechnical conditions (geological and hydrogeological conditions, abandoned hazardous waste sites, …).
- **Approval risks:** change of cost resulting from the handling of permit application procedures.
- **Financing risks:** change of cost due to time and procedure of providing financial means
- **Market risks:** change of cost which results from the general development of prices on the procurement markets.
- **Force majeure risks:** change of cost which results from the effects of force majeure (earthquakes, floods, environmental disasters, acts of war, strikes and the like, in so far as such events exceed long-term averages).

4.1 Deterministic evaluation of R

Determining the costs for risks (R) is generally done on the basis of standard values for small- and medium-sized projects (Characteristic value method). Input parameters are:

- basic costs of the project (B),
- part of (B), which is affected by the geotechnical risk (Bgeotechnical),
- design status and
- assessment of the complexity of the project.

The cost R is calculated from the sum of costs for general project risks ($R^{general}$) and the cost for geotechnical risks ($R^{geotechnical}$):

$$R = R^{general} + R^{geotechnical} \quad (2)$$

For estimating the cost R for the project a percentage u is multiplied with the basic costs B:

$$R = u \times B \quad (3)$$

The percentage u is determined based on the corresponding design state and the complexity of the project as indicated in Table 2. The given percentages are the result of many years' experience in design, planning and handling of railway infrastructure projects in Austria. Thus they provide a good starting point for the scope of cost needed to cover the relevant risks. In individual cases it may become necessary to foresee deviating costs for risks on account of specific boundary conditions. [ÖGG, 2005].

	Complexity of the project		
Design status	**Simple**	**medium**	**complex**
Conceptual Design	11.5%	18.0%	24.5%
FEED	8.0%	13.5%	19.0%
Detailed Design	4.5%	9.0%	13.5%

Table 2: Percentages u for provision for risks in the design stage

While the cost for general project risks depends on the total basic costs of the project (B), the cost for the site risks is calculated only from that part of the basic cost affected by the geotechnical risk ($B^{geotechnical}$). This results in the following formula for calculating R:

$$R = u^{general} \times B + u^{geotechnical} \times B^{geotechnical} \quad (4)$$

	Complexity of the project		
Design status	**simple**	**medium**	**complex**
Conceptual Design	10%	15%	20%
FEED	7.5%	11.25%	15%
Detailed Design	5%	7.5%	10%

Table 3: Percentages $u^{geotechnical}$ for the provision for geotechnical risks in the design stage

3.2 Method based on discrete risk scenarios

Complex projects require a quantitative determination of the provision for risks based on defined risk scenarios.

The parties involved in the project shall identify, in a first step, all those risks which could have an impact on the project costs. It has to be kept in mind that risks may not only have negative but also positive effects on cost and time ("chance"). Such risks shall also be taken into consideration. For risks which have to be assessed in more detail as part of the risk considerations, it would be appropriate to establish risk scenarios. Based on the results and potential causes of risks these scenarios describe the consequences of a risk occurrence. In order to identify the risk in cost and time, it is important to define a clear separation between the standard case covered by the basic costs and the special case resulting from a risk occurrence.

Identified risk	*Risk potential*	*Risk scenarios*
Stability of the construction site ***(Z_1)*** [1]	➢ Locally confined failure – such as outbreaks from the crown area or small-scale failure of the excavation face	➢ Outbreak up to 5 m³ (X_1)[1] ➢ Outbreak up to 20 m³ (X_2) ➢ Local face failure up to 20 m³ (X_3) ➢ Local marked deformation (>50 mm heading, L = 20 m) (X_4)
	➢ Extensive failure – from collapses (scope 500m³) to cave to the surface or extensive failure	➢ Collapse 500 m³ ➢ Extensive face failure >20 m³ (X_5) ➢ Cave to the surface
	➢ Geogenic and anthropogenic phenomena	➢ Blowout ➢ Discharge of suspension
Excavation and support ***(Z_2)***	➢ Impairment of excavation – such as alteration of the calculated lengths of rounds of the excavation classes	➢ Change of excavation classes (X_6 / X_{10}) ➢ Clogging of excavation tools ➢ Machine defect/breakdown of mechanical equipment and vehicles
	➢ Support requirements – such as alteration of the calculated lengths of support classes	➢ Stresses and strains due to large swelling pressure (X_7 / X_{11}) ➢ Stresses and strains due to small swelling pressure ➢ Water pressure on primary lining ➢ Water pressure on secondary lining ➢ Uncontrolled loads (X_8)
	➢ Excavation and support concept	➢ Failure of the excavation method ➢ Failure of support method (X_9)
Difficulties ***(Z_3)***	➢ Impairment by water or gas	➢ Water ingress >10 l/s ➢ Water ingress 3 – 10 l/s ➢ Gas-impairment ➢ Discontinuation of excavation
	➢ Obstacles – such as unexpectedly frequent appearance of boulders and/or anthropogenic inclusions (steel, tree trunks, wells, etc.)	➢ Boulders up to 1.5 m Φ ➢ Boulders > 1.5 m Φ ➢ Anthropogenic foreign bodies (steel well pipes) ➢ Wood (trunks 20 m long / crossways to the direction of advance)
Special construction measures ***(Z_4)***	➢ Above-ground measures, non-scheduled – such as local groundwater lowering, soilcrete columns (vertical jetting) etc.	➢ Lowering of local groundwater level (L = 100 m) ➢ Local freezing ➢ Soilcrete columns (50 m)
	➢ Below-ground measures, non-scheduled – such as pipe arches, soilcrete columns (horizontal jetting), pressure relief measures, etc.	➢ Pipe arch (L = 30 m) ➢ Soilcrete columns (L = 30 m) ➢ Water pressure relief ➢ Injections/Grouting
Environmental impacts ***(Z_5)***	➢ Unexpected environmental impacts – such as oil leaks, impact of construction method on the environment, noise, vibrations, dust, etc.	➢ Groundwater impairment (oil accident) ➢ Truck collision with fire
	➢ Expected environmental impacts– due to noise, vibrations, dust, etc.	➢ Noise during excavation ➢ Vibrations (obstruction over a length of 200 m) ➢ Air in the tunnel ➢ Water ➢ Settlements

[1] ***Z_i; X_i*** : referred to example

Table 4: Examples for the identification of risks and risk scenarios

Examples for the identification of risks (Z_1 to Z_5) and risk scenarios (X_i to X_n) are provided in Table 4 for a twin-track railway tunnel with an excavation cross section of 115 m² [ÖGG, 2005].

In a 2nd step during risk assessment the risks determined in the risk identification process have to be quantified. Such a quantification should be based on a uniform evaluation basis [Vigl et. al, 2002]. In order to be able to determine the costs, the risks have to be quantified in terms of money. The assessed risk (Ri) of an incident (i) is the product of the probability of occurrence (Wi) multiplied by the effect (Ai) on costs and/or time.

$$R_i = W_i \times A_i \tag{5}$$

Quantitative determination of risks and/or probability of occurrence and effects on costs and/or time are generally difficult. On the one hand, the underlying processes have to be accurately known and on the other hand, it is difficult to determine the exact distribution (or density) function of the probability of occurrence and the effects on cost and/or time. Thus probabilities of occurrence and effects are only estimates and thus depend significantly on the assumption made [Vigl et. al, 2002].

Even if all risks have an effect on the costs, not all risks can be determined quantitatively and taken into consideration in the cost planning. The effort involved would not be justified. For assessing the identified and estimated risk, it should be considered which risks can be neglected, which risks can be controlled by monitoring them, which risks require measures (provision for risks through prevention, reduction, change) and which risks can be determined in a qualitative incident analysis only.

This decision is based on consequence classes defined for each project and agreed between the respective parties involved. An example for the definition of consequence classes is given in Table 5. The effect of risk is determined to be disastrous, severe, serious, considerable or insignificant. This depends on the type of incident and magnitude of consequences.

The combination of risks by means of an appropriate mathematical model serves to combine and depict potential risk effects of different, mostly interdependent causes. This provides an overview over the different risks and enables measures to be quantified.

Based on the identified risks (Table 4) and on the statistical distribution of the cost, as well as on the probability of occurrence and possible mutual dependencies, the costs of provision for risks are determined.

The following example shows the cost calculation for provision for risks identified in Table 4 (Z_1 to Z_5). The identified risks are combined to an overall risk in terms of money. Every single identified risk (Z) can be described in more detail in risk scenarios (X_i), e.g. the stability of the ground (Z_1) can be split into local and extensive failure. Local failure can be subdivided into categories, e.g. outbreaks of up to 5 m^3 (X_1), up to 20 m3 (X_2), local failure of the working face up to 20 m3 (X_3) and significant local deformations (X_4). Extensive failure is a collapse of up to 500 m^3 (X_5) or extensive failure of the working face, which, however, has already been taken into account in the mentioned collapse.

The intensity rates λ_1, ..., λ_5 identified in the project, and the expected value of the follow-up costs per category X_1,...,X_5 are aggregated to a distribution of risk Z_1 using the Panjer method. Using the stability of the ground as an example, a simple Poisson model is used for describing the individual risk Z_1.

$$Z_1 = \frac{1}{\lambda}\left(\lambda_1 X_1 + \lambda_2 X_2 + \lambda_3 X_3 + \lambda_4 X_4 + \lambda_5 X_5\right)$$
$$\lambda = \Sigma\lambda_i \quad (6)$$

The costs for extraordinary events $X_1,...,X_5$ are incorporated into the model as lognormal LN(.,.) and are given a coefficient of variation VX = 0.10 (Table 7).

Incident	**λ [Incident/Tunnel]**	**E[X] [€/Incident]**	**D[X] [€]**
X_1	13	1450	150
X_2	1.3	5810	580
X_3	5.3	1450	150
X_4	2.0	53700	5400
X_5	0.13	1090000	109000

Table 7: Stability of the ground: intensity rates (λi), expected value (E[X]) and spread of construction cost risk (D[X]) in €

The sequential tunnelling method may result in extra cost or reduced cost, particularly in the risk category 'Excavation and Support' (Z_2). For calculating the discrete risk these two items are calculated separately by means of a Poisson model.

The change of excavation class may lead to extra cost (X_6) or reduced cost (X_{10}). The same applies for the stresses and strains due to little swelling pressure (X_7) and (X_{11}). Further hazard scenarios are uncontrolled loads (X_8) and failure of the excavation concept (X_9) (Table 8).

The two components are then combined by means of a Frank Copula. Between the events which result in extra cost and less cost a correlation has to be taken into account which is assumed to be θ = 0.3 in this case. Figure 4 shows that this type of individual risk has a negative range.

$$Z_{2a} = \frac{1}{\lambda}\left(\lambda_6 X_6 + \lambda_7 X_7 + \lambda_8 X_8 + \lambda_9 X_9\right)$$
$$Z_{2b} = \frac{1}{\lambda}\left(\lambda_{10} X_{10} + \lambda_{11} X_{11}\right) \quad (7)$$
$$f_{X,Y}(x,y) = C_{Frank}\left(f_{Z_{2a}}(z_{2a}), f_{Z_{2b}}(z_{2b}); \theta\right)$$

Incident	**λ[Incident/Tunnel]**	**E[X] [€]**	**D[X] [€]**
X_6	1	48500	4850
X_7	0.26	3500	3500
X_8	0.1	2900	290
X_9	0.13	100	10
X_{10}	0.5	-48500	4850
X_{11}	0.26	-3500	3500

Table 8: Excavation and support: intensity rates (λ_i), expected value (E[X]) and spread of construction cost risk (D[X]) in €

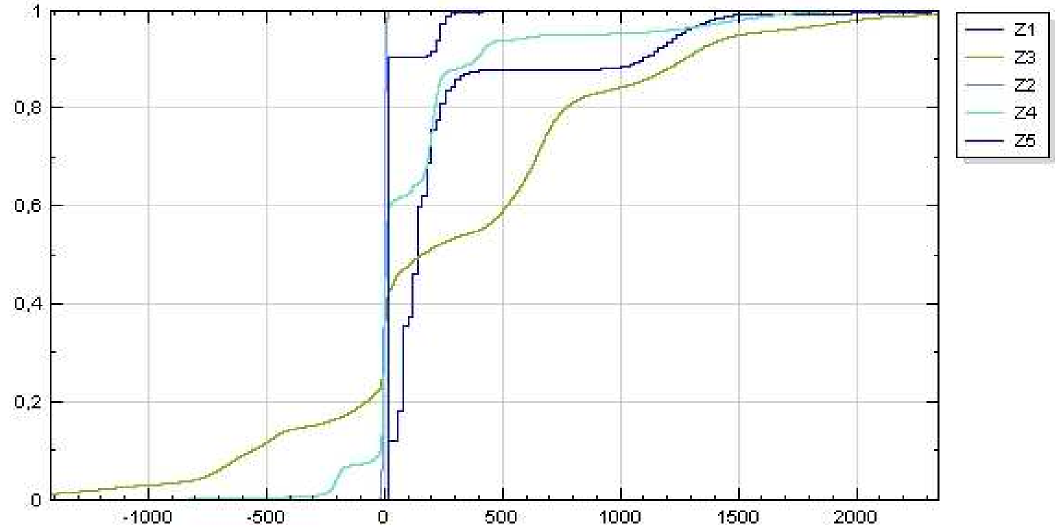

Figure 10: RV_{KE1} Distribution of discrete risks $Z_1,...,Z_5$, cost in [1000 €]

The same approach is used for the risks ‘Difficulties’ (Z_3), ‘Special Structures’ (Z_4) and ‘Environmental Impacts’ (Z_5). The overall result for all Zi is depicted as a cumulative size distribution in Fig. 10.

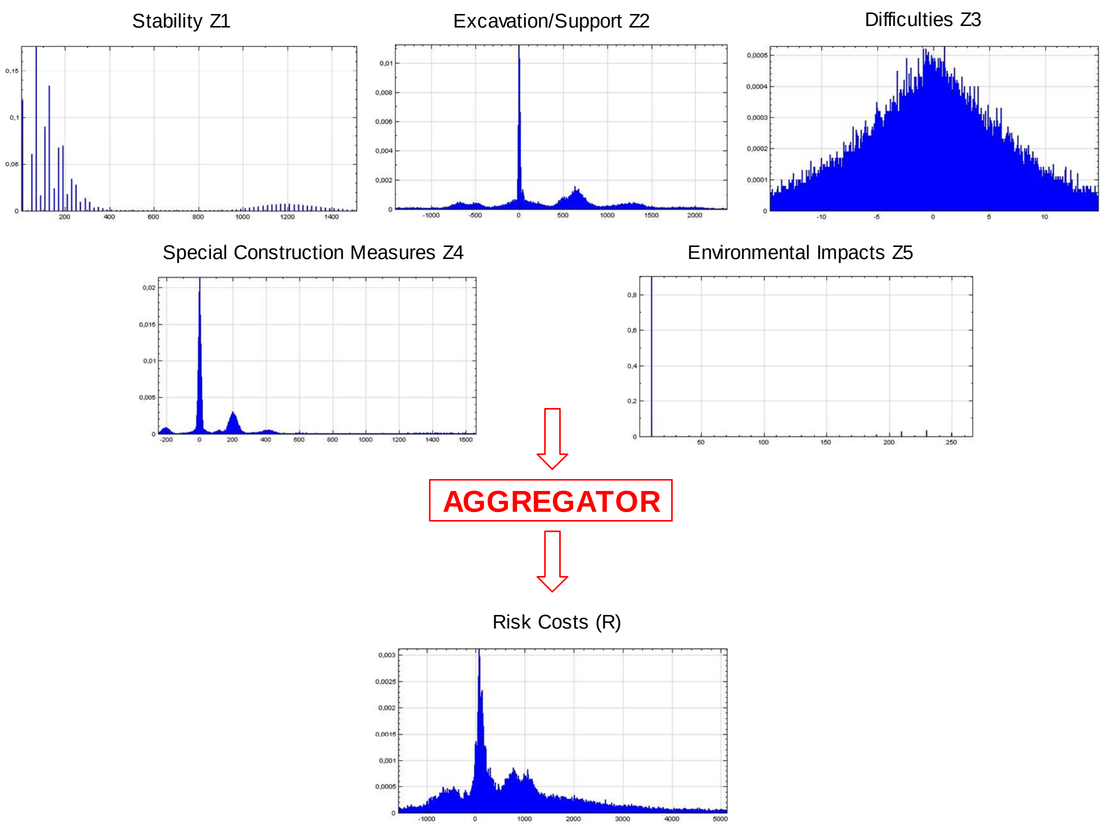

Figure 11: Distribution of total risk, cost in [1000 €]

The individual risks are combined by means of a Frank Copula. The correlation between the individual risks is described by the parameters $\theta_1,\theta_2,\theta_3,\theta_4$ and has to be determined empirically. In this example every $\theta_i = 0.5$.

$$f_Z(z) = C_{Frank}\left(f_{Z_1}(z_1), f_{Z_2}(z_2), f_{Z_3}(z_3), f_{Z_4}(z_4), f_{Z_5}(z_5); \theta_1, \theta_2, \theta_3, \theta_4\right) \tag{8}$$

This formula is calculated by means of a Monte Carlo simulation. At every simulation step, realisations of C(.;.) are generated and converted into risk costs using the inverted functions $Z_i = F_{Z1}^{-1}(u_i)$. The individual risks are summed up to a total risk and yield the cumulative distributions shown in Fig. 11.

Summary

It is only when the cost estimation and the cost control are based on objective boundary conditions understood from all parties involved, including provisions for risks, that the budgeting of a project will be done in such a way that there will be no budget overrun because countermeasures can be implemented at the right time and in the appropriate way. This is for the benefit of the project, investors, bankers, insurance companies, client, construction companies and consulting engineers.

The evaluation of costs depends on the knowledge and availability of element costs and risk costs and their progression from the beginning of the project to its implementation. It is up to the investors and consulting engineers to create a sound and well defined data basis for each project to gain reference values for future projects and thus to avoid budget overruns of 100 – 200% as have recently occurred in infrastructure projects.

Literature

Dempster, A.P. (1967): Upper and lower probabilities induced by a multivalued mapping Annals of Mathematical Statistics **38**, 325–339

Eskesen, S. D., Tenborg, P., Kampmann, J., Veicherts, T. H. (2004). *Guidelines for tunnelling risk management,* International Tunnelling Association, Working Group No. 2. Tunnelling and Underground Space Technology 19, 217-237

Flyvberg, B., Holm, M. S., Buhl, S.: (2002). “Underestimating Costs in Public Works Projects.“ *APA Journal Summer 2002, Vol. 68.*

Klapperich, H.; Pöttler, R. (2006): Flächenrecycling und Flächenmanagement – Altlastensanierung / interdisziplinär. 21. Christian Veder Kolloquium. Herausgeber: Gruppe Geotechnik Graz: M. Dietzel, W. Schubert, H.F. Schweiger, S. Semprich, Heft 28. 245-260.

ÖGG Richtlinie Kostenermittlung für Projekte der Verkehrsinfrastruktur unter Berücksichtigung relevanter Projektrisiken. 2005

Peschl, G.M. (2004): Reliability Analyses in Geotechnics with the Random Set Finite Element Method. Technische Universität Graz, Gruppe Geotechnik Graz, Heft 25.

Pöttler, R.; Schweiger, H.F. (2006): Cost evaluation for traffic and transport infrastructure projects taking account of project risks. "Geohazards", Farrokh Nadim, Rudolf Pöttler, Herbert Einstein, Herbert Klapperich, and Steven Kramer Eds, ECI Symposium Series, Volume P7 (2006). http://services.bepress.com/eci/geohazards/30

Pöttler, R.; Schweiger, H.F.; Peschl, G. (2006): Nutzen und Herausforderung bei der Anwendung der ÖGG Richtlinie „Kostenermittlung für Projekte der Verkehrsinfrastruktur“ im Ingenieurbüro. Felsbau **24**; 103 – 110.

Shafer, G. (1979): A Mathematical Theory of Evidence. Princeton: Princeton University Press.

Tonon, F.; Bernardini, A.; Mammino, A. (2000a): Determination of parameters range in rock engineering by means of Random Ret Theory. Reliability Engineering and System Safety **70**, No. 3, 241–261

Tonon, F.; Bernardini, A.; Mammino, A. (2000b): Reliability analysis of rock mass response by means of Random Set Theory. Reliability Engineering and System Safety **70**, No. 3, 263–282

Vigl, A., Benedikt, J., Eder, M., Ruegg, Ch., Lemmerer, J. (2002). “Vergleichende Risikoanalyse für konventionellen Vortrieb und TBM Vortrieb.“ *Felsbau 20*