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Model for Estimation of Time and Cost for Tunnel Projects Based on Risk Evaluation

By

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Summary

In the planning and procurement phases of tunnelling projects, numerous decisions have to be made regarding tender price and budget. Many case studies have shown that, in practice, the predicted costs and time schedules are often exceeded. This paper describes a study of the various risk factors in machine tunnelling and their differing impacts on cost and time. It has been concluded from the study that it is important to make a clear distinction between *normal cost and time*, and the *undesirable events* that cause *exceptional* cost and time. Existing decision-aid estimation models consider variation of the risk factors, but do not consider normal cost or time separately from undesirable events. Usually, estimations of project cost and time are made in a deterministic manner, but this does not allow one to consider uncertainty in cost and time variables. However, if the variables are treated probabilistically, the total cost of tunnelling can be expressed as a distribution curve, and a decision can be made on the tunnelling method by comparing the respective cost and time distributions. Based on such decisions, the budget and tender price can be determined separately, both by the client and contractor respectively. To meet the demands placed on decision-making for tender and procurement for currently favoured construction-contracting methods, a new model for estimating tender price and budget has been developed, and is described in this paper. This estimating technique has been applied to a case study of the Grauholz Tunnel. The predictions obtained from the estimation model are shown to be realistic, as the total construction cost and time obtained from the model correspond fairly well to the actual construction cost and time. The separate estimation of normal cost and time and exceptional cost and time contribute to the clarity of the results. The use of the proposed model also shows that the tunnelling method most suitable for the actual geological and hydrogeological conditions can be selected by this method.

Keywords: Risk, estimation, cost, time, Monte Carlo simulation, tunnelling.

1. Introduction

The objective of this paper is to present a probabilistic model for the estimation of construction cost and time for tunnelling projects, in order to improve the quality of data used in making decisions about tender price, budgets, and construction time. One important objective of the model has been to transparently handle and quantify the risks associated with different construction-contracting methods.

The impact of a probabilistic approach on cost and time estimations as an aid to management and decision-making for construction projects has been considered by various authors, e.g. (Moavenzadeh and Markow, 1976; Salazar, 1985; Lichtenberg, 1990; Nelson et al., 1994). The Decision Aids in Tunnelling (DAT) (e.g. Einstein et al., 1987) simulation programme is described in a later section.

Estimating the basic cost of a project from unit cost variation alone does not provide an adequate basis for decision making. However, using a model that incorporates the impact of different geological factors and risks into the estimation might do so. Such an estimation model has been developed and is described in this paper. The model has the same purpose as the DAT simulation programme, but considers risk more explicitly. For a complete description of the proposed model, see Isaksson (2002).

2. Demands on Estimation Models for Tunnel Projects

2.1 Introduction

The aim of this section is to point out the requirements of any system intended to take project specific risks into consideration during the estimation of cost and time for tunnelling projects.

Tunnelling can be seen as a cyclical process, with the main activities executed in series. As with all construction projects, tunnelling is affected by disturbances. The disturbances that affect the cyclical, in-series tunnelling process often have a larger impact on cost and time than those affecting other types of projects. Disturbances in tunnelling are caused by factors like the prevailing geological, technological (equipment and machinery) and economic conditions, and may lead to significant increases in actual costs and times when compared with those expected.

Figure 1 illustrates the impact of the higher levels of uncertainty inherent in tunnelling when compared with other types of construction. This figure shows that surface-built projects with a relatively simple production process, such as pipeline projects, have less variability in their range of tenders than the more complex underground projects. The spread between the mean tender value and the engineer's cost estimate is also larger for tunnelling projects.

Several reports state that cost and time overruns commonly occur in infrastructure projects that include tunnels (Kastbjerg, 1994; Andreossi, 1998; Nylén, 1999; HSE, 1996). Furthermore, world-wide experience in tunnel construction shows that major cost and time overruns can occur due to factors not considered in the planning or tender stages (Kovari et al., 1991; HSE, 1996; John et al., 1987). These factors do occur with a higher than negligible probability and often have great consequences for the success of the project.

The studies mentioned above show that, when compared with the expected outcome, substantial increases in the cost and time of a tunnelling project often occur. This indicates that there may be shortcomings in the methods used today for predicting these fundamental project parameters.

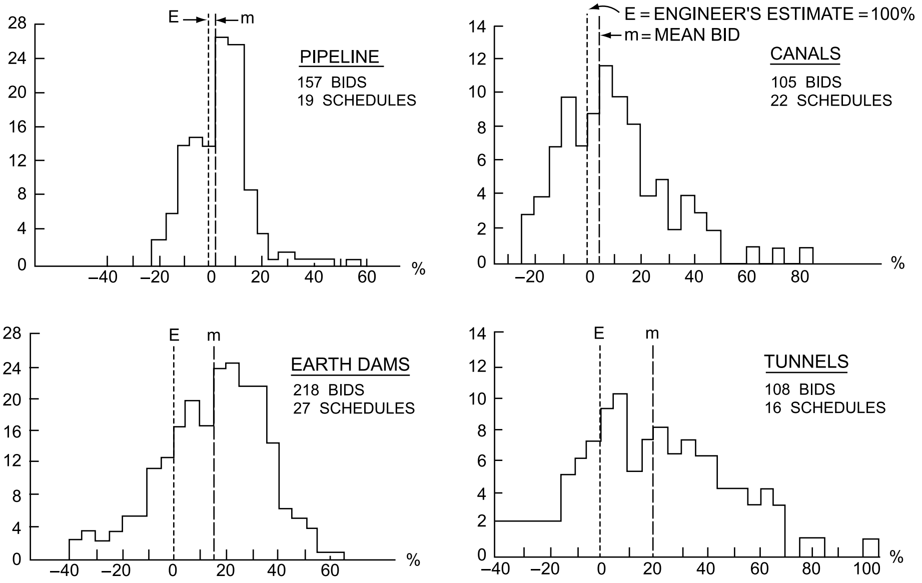

Fig. 1. Tender data for four types of heavy-construction projects (Bureau of Reclamation Projects, 1965–70). Histograms showing the number of tenders vs. percentage difference from the engineer's estimate (Moavenzadeh and Markow, 1976)

In current practice, the estimation of budget and tender prices for construction projects often is done deterministically. The principle of deterministic estimation of construction cost and time budgets has been discussed in the literature (Quellmelz, 1987; Platz, 1991). There are many different cost types to consider, including basic costs and overhead costs (Drees and Bahner, 1992; Bunner et al., 1981).

In a deterministic estimation, only one value is input for each parameter, despite the many assumptions required in fixing its value. The predicted outcome does not consider the uncertainties in the data. In addition, the deterministic approach often neglects substantial risks. This may be one reason for the common occurrence of cost and time overruns in tunnel projects. All this leads to the conclusion that improving the quality of estimations used in tendering and budgeting is imperative (RRV, 1994). One means of improving the quality of these estimations may be through using a system that considers risk in a structured way.

2.2 Risks in Tunnel Projects

2.2.1 Introduction

In this section, the characteristics of tunnelling projects are discussed, together with the risk factors that may have an impact on them, and the effect of the construction-contracting method on the individual parties' responsibilities for cost increases that may occur during the project.

2.2.2 Characteristics of Tunnel Projects

Tunnel projects are characterised by a number of different factors. One of these is the way the construction process is executed. According to Salazar (1985), Müller (1978), and other investigators, the tunnel construction process can be described as a "series" system, where the main activities lie in series along the critical time path. When one of these activities comes to a standstill, for example due to failure in a machine component such as the main bearing in a TBM, this often results in a stoppage in the construction process (Kovari et al., 1991; Maidl, 1988). In such circumstances, it is not possible to change the current work site, as each metre of tunnel has to be excavated sequentially.

The total cost and time can thus be regarded as the sum of cost and time of a great number of sequential events, in geological conditions more or less correlated from round to round. It follows that one way to reduce construction time is to increase the number of tunnel faces available for work.

However, the total time elapsing from the decision to commence planning until the completion of construction is often not controlled just by the construction method, the geological conditions or other project-specific factors, but by the time frame provided by the clients or financiers (Andreossi, 1998). As the construction time often has to be compressed in order to fit into the imposed time constraints, there may be insufficient buffer time to overcome unexpected interruptions, or "disturbances", to the planned schedule.

Another characteristic of tunnel projects is the high initial capital expenditure for construction. One reason for this is the increasingly mechanised excavation process, which requires investment in expensive machinery and equipment, and also a well functioning organisation with fast information flow (Tengborg et al., 1998; Stille et al., 1998).

All these factors indicate that tunnelling projects are much more vulnerable to disturbance than construction projects above ground.

2.2.3 Risk Factors in the Tunnelling Process

When planning a tunnelling project, the many work steps involved require assumptions and estimations to be made. For example, the ground itself has to be investigated before the tunnel can be designed. Soil and rock conditions and corresponding ground support measures for construction need to be worked out. The quantities of construction material and volume of ground to be excavated need to be estimated. The right machinery and equipment need to be selected for the job.

Different risk factors can affect the assumptions and estimations in various ways. The risk factors can be divided into different categories of risk, for example geological, construction, performance, contractual, financial and economic, political and social, and physical (Charoenngam and Yeh, 1999; Chapman et al., 1981).

Terms describing different risk factors have been used in a somewhat confusing way in the literature (Chapman et al., 1981; Charoenngam and Yeh, 1999).

The following definitions will be used in this study.

Ordinary risk factors can be defined as "factors causing deviations in the normal time and cost range". Variations in cost and time caused by ordinary risk factors can be described by a continuous distribution, and can be related to construction (for example, the quantities of construction material or the advance rate of the tunnelling method).

Table 1. Factors causing changes in costs and time used in this study

Type of factor	Definition	Description of probability	Consequence	Example
Ordinary risk factors.	Factors causing deviations in the normal range.	Normal occurrence, as physical conditions or processes cannot all be described and specified with complete certainty.	Normal variation in cost and time.	Construction material prices, labour costs, advance rate.
Undesirable events.	Events that cause major unplanned changes in the tunnelling process.	Likely to unlikely to occur but cannot be completely ignored based on physical or other reasons.	Exceptional cost and time.	Tunnel collapse, failure in main machinery components, flooding.

We use the term "*undesirable event*" in this study, and this can be defined as *an event that causes major and unplanned changes in the tunnelling process*. Such events can be taken into consideration in the estimation, but there are few statistical data available concerning their probability and consequences. They cause additional increases called *exceptional* costs and time, and can be regarded as single, non-continuous events.

A summary of the factors causing variation in costs and time is shown in Table 1.

Construction-contracting usually involves a payment and award system, and affects the responsibility for various risks of each of the parties to the contract. For most construction methods, the contractor is responsible for the ordinary risk factors. However, for undesirable events, risk responsibilities very much depend on the specific contract. In an unit price contract, an event unidentifiable from the Bill of Quantities will normally be classified as unforeseeable by an experienced contractor, and is normally the client's responsibility. By contrast, all eventualities will be the contractor's responsibilities in a turn-key project. The contractual basis is important for both the client and the contractor when estimating cost and time for a project, and emphasises the importance both for the client and the contractor of having a transparent means of handling risk. If risks are not allocated reasonably, claims and disputes may be some of the consequences of construction (Reilly et al., 1999; Isaksson et al., 1999a, b).

Using risk factors in the estimation process allows the cost and time for a project to be regarded as a stochastic variable, with an associated distribution curve. Decisions then can be made based on the results of the calculations of time and cost concerning, for example, the tunnelling method, budgeting and tender pricing. How these decisions can be made, as well as the factors affecting them, is discussed in the next section.

2.3 Decision Making

There are numerous decisions that have to be made whilst planning a tunnelling project. Two of the major decisions are:

- the tunnelling method, and
- the budget and tender pricing.

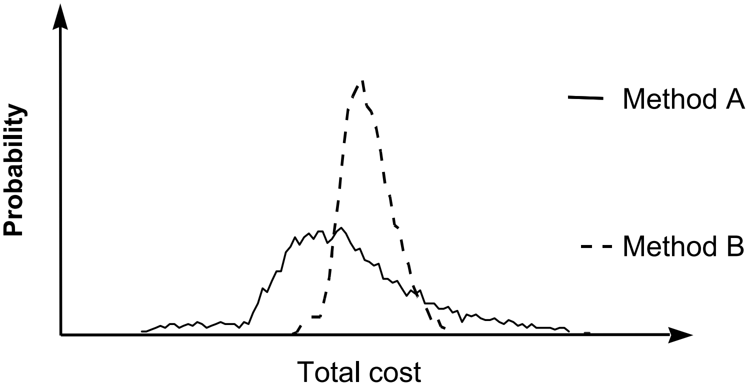

Fig. 2. Example of cost distribution for two different tunnelling methods

As discussed above, the total time and cost for a project can be described as a distribution. Many factors affect the shape of the distribution. Clearly, different distribution curves will correspond to different tunnelling methods, because of method-specific factors such as the necessary tunnel supports and the machinery and equipment required. The particular tunnelling method and risk factors being considered will affect the distribution of the total cost and time. Figure 2 shows assumed distribution curves of the total cost for two assumed methods, A and B.

Different decision criteria are available for deciding on the tunnelling method and the tender or budget cost. The minimum expected total cost (min E[C]) is one example. This can be used for making decisions between distribution curves such as those in Fig. 2 (Benjamin and Cornell, 1970). However, using just the expected value as a decision criterion often leads to erroneous conclusions and misunderstandings (Haimes, 1985). The decision about which tunnelling method to use may not necessarily be just a matter of finding the one with the lowest expected cost. Instead, it may also involve considering the probability of exceeding a certain value.

Several other decision criteria exist in which other types of utility for the decision-maker can be considered. As various parties are involved in tunnel projects, psychological factors are important considerations in decision-making. Decision-analysis methods that consider how an individual decision-maker faces a choice involving uncertainties have been discussed in the literature by, for example, Bell et al. (1988). The next section presents a detailed structure of an estimation model for tunnelling projects, taking into consideration the requirements just discussed.

3. Modelling of Time and Cost

3.1 Introduction

This section presents the theoretical background to a probabilistic estimation model, and some practical applications. The principles for the estimation of time and cost are discussed, as well as establishing the input data required. As with all modelling, it is important to realize that this model is just a representation of reality, with the purpose of providing an efficient tool for assisting decision-making.

There are already a number of decision-support tools used for the estimation of construction costs and time that take uncertainties into consideration. The “Decision Aids in Tunnelling”, e.g. Einstein et al. (1987) and “Successive Method”, e.g. Lichtenberg (1990) tools have been applied to tunnel projects in Europe.

The Decision Aids in Tunnelling (DAT) utilize the Monte Carlo Simulation technique. They were developed at the Massachusetts Institute of Technology (MIT) by Einstein and Vick (1974); Einstein et al. (1991, 1996); and Salazar (1983). They have been applied in projects in Switzerland, Italy and France, such as the Gotthard Base Tunnel and the Lötschberg Tunnel. The result of the Monte Carlo simulation is a scatter diagram, showing each simulated time and cost as a separate point. The DAT consider variation of the input data such as geology, construction performance as well as effects of unexpected mishaps, and time for unscheduled maintenance. The impact of undesirable events as defined in this study, i.e. undesirable events that cause major unplanned changes in the method, can also be considered in the DAT estimation.

The Successive Method is another management tool dealing with uncertainty. It was developed for building projects but can also be used to estimate cost and time for other types of construction projects. The Successive Method was developed in Denmark in the 1970s, and has been applied to tunnel projects in Denmark, Norway and Sweden, including the City Tunnel in Malmö, (Lichtenberg, 1990; Nilsen et al., 1999; Wallis, 1993). In the Successive Method, subjective estimates are treated with statistical rules. A Taylor approximation is used in the estimation of uncorrelated stochastic variables. The Taylor approximation can handle variation in one variable, for example unit prices, reasonably easily. Variables are assumed to be uncorrelated. In tunnel projects, however, variation has to deal with several correlated variables, e.g. quantities and unit-prices.

Another limitation of the method is that undesirable events that cause major unplanned changes in the method are not directly considered in the estimation. However, factors affecting the whole project, the so-called “general conditions”, are treated as separate items. Examples of general conditions are wages, problems with authorities, weather, and quality. To obtain the true extreme values in the estimation of these items, lower and upper limits are set at the 1^{st} and 99^{th} percentiles respectively. Further tunnel-specific factors, such as the probability of different geological conditions and their impact on the advance rate, are not considered in this model. These issues have to be evaluated separately and the results incorporated into the model indirectly.

3.2 A Theoretical Estimation Model

3.2.1 Expressing Parameters

As in all geotechnically-based problems, many of the parameters are best expressed as stochastic variables. The total time or cost can therefore be expressed as a function of all the variables considered, both deterministic (a_i), and stochastic (b_i):

$$C = f(\ldots, a_i, \ldots, b_i, \ldots) \tag{1}$$

Some of the variables in the function are correlated; consequently there is a need for incorporating this fact in the estimation of total time and cost.

As discussed in Section 2, *normal* time and cost is best considered separately from *exceptional* time and cost. In principle, the total time or cost (C) for a project can be expressed as the sum of the normal time or cost (C_n) and the exceptional time or cost (C_e):

$$C = C_n + C_e \tag{2}$$

As discussed in Section 2, the definition of undesirable events and ordinary risk factors is subjective, which can clearly be seen from the definition used here for an undesirable event as "a factor that causes major unplanned changes in the tunnelling process".

The term *advance rate* is used to express "the length of excavated tunnel per unit time" (for example m/day). However, in the estimation model, the inverse of the advance rate, is used, i.e. "the time consumption for excavating a tunnel unit using a certain tunnelling method" (for example in h/m). This facilitates the mathematical calculation. In this study, the term used for this inverse is the *production effort*. We have also chosen to use this term to describe quantities that have to be carried out per tunnel unit, e.g. the amount of shotcrete applied.

3.2.2 Normal Time and Cost

The normal time and cost can be expressed as a function of the production effort required by the method, i.e. the work carried out in constructing a unit length of tunnel. For estimation of the time taken, the production effort is the total effort for the activities lying on the critical path, expressed in working hours per unit of length. For calculation of the cost, different types of production efforts have to be considered, based on the quantities to be carried out as well as the working hours per unit of length.

The production effort of a tunnelling method depends on the geotechnical characteristics. Knowledge about the geotechnical characteristics is limited, due to the limited number of samples obtained by site investigation, (Salazar, 1985), so these are best expressed as probabilistic variables.

The geotechnical characteristics tend to vary from one point to another. At each point in the tunnel, the production effort for a given method depends on the geotechnical characteristics, expressed as $x(l)$, with a given distribution, $f_x(x)$. The relationship between these characteristics and the production effort can be expressed as a stochastic function, $g(x(l))$. When estimating the normal time and cost for a tunnel, it is necessary to add together all the production efforts to arrive at the total production effort (Q) for the tunnel length studied. It is important to realize that the production effort for each length can be regarded as a stochastic variable.

It is assumed that the characteristics at each point in the tunnel section under study are uniformly distributed, but not necessarily uncorrelated. This results in a uniformly distributed production effort at each point (but with a different distribution than that for the geotechnical characteristics). In this study, the term "fully correlated" means that the geological conditions are homogenous and there is a strong correlation from one point to another along the whole tunnel length. This may result in a large standard deviation in the total production effort. The term "partly correlated" means that the lengths with homogenous conditions are limited (over just a part of the tunnel length), which may result in a smaller standard deviation.

In principle, the expectation $E(y)$ and standard deviation σ_y of the production effort $y = g(x)$, can be estimated from the following equation (after Benjamin and Cornell, 1970):

$$E(y) = E[g(x)] \approx g(E(x)) \tag{3}$$

and

$$\sigma_y = \left[\frac{dg(x)}{dx} \bigg|_{E(x)} \right] \sigma_x, \tag{4}$$

and the probability density function, as:

$$f(y)_y = \left| \frac{dx}{dy} \right| f_x(x). \tag{5}$$

The production effort over the tunnel length L, can then be estimated from:

$$Q = \int_L g(x(l))\, dl. \tag{6}$$

The mean production effort will then be:

$$E(Q) = L * E(y) \approx L * g[E(x)] \tag{7}$$

and the standard deviation of the production effort will (if fully correlated) be expressed by:

$$\sigma_Q = L * \sigma_y = L * \left[\frac{dg(x)}{dx} \bigg|_{E(x)} \right] \sigma_x, \tag{8}$$

where L is the tunnel length.

As the length (L) over which the production effort is summed is increased, the standard deviation of the total production effort tends to be reduced in the process of averaging. Methods used to estimate the reduced standard deviation have been described in the literature, e.g. by Vanmarcke (1977) and Olsson (1986). Figure 3 illustrates the production effort (y), the standard deviation at a point (σ_y), and the "scale of fluctuation" (δ_l), which means the distance within which the geotechnical characteristics show relatively strong auto-correlation from one point to another along the tunnel length (L).

The reduced standard deviation (σ_Q) can be expressed as the product of a reduction factor $\Gamma(L)$ and the standard deviation with respect to each point (σ_y):

$$\sigma_Q = \Gamma(L) * L * \sigma_y. \tag{9}$$

The reduction factor depends on the zone length and the scale of fluctuation. If the zone length (L) is less than the "scale of fluctuation" (δ_l), then the standard deviation is not reduced, see Eq. (10). However, when the zone length exceeds the scale of

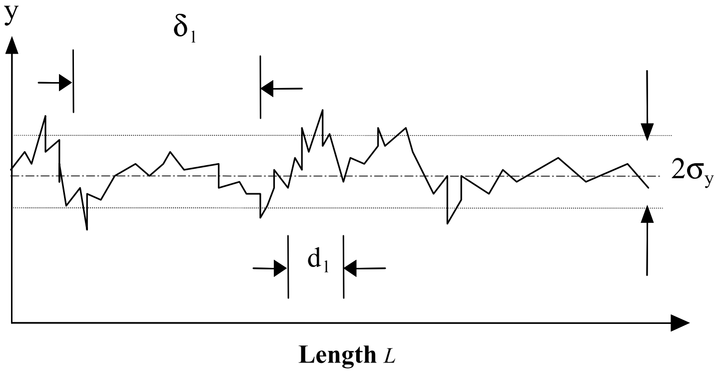

Fig. 3. Illustration of the production effort (y), the standard deviation at a point (σ_y), the "scale of fluctuation" (δ_l), and distance between "mean crossings" (d_1) for the tunnel length (L), after Vanmarcke (1977)

fluctuation, the reduction factor can be estimated as the ratio between the scale of fluctuation and the tunnel length, see Eq. (11).

$$\Gamma^2(L) = 1\_for\_L \leq \delta_l, \tag{10}$$

$$\Gamma^2(L) = \frac{\delta_l}{L}\text{-}for\_L \geq \delta_l. \tag{11}$$

The determination of the scale of fluctuation is described by Vanmarcke (1977). One way is to use the distance between "mean crossings" (d_l) using the following:

$$\delta_l = \sqrt{\frac{2}{\pi}} d_l. \tag{12}$$

When δ_l is less than L, the standard deviation of the production effort over a tunnel length L can be reduced to the following:

$$\sigma_Q = \sqrt{L} * \sqrt{\delta_l} * \sigma_y. \tag{13}$$

However, where conditions are very homogenous ($\delta_l \approx L$), the standard deviation may be high, and the uncertainty in the estimation correspondingly higher. See Eq. (8).

$$\sigma_Q = L * \sigma_y. \tag{8}$$

Thus, the total production effort (Q) over a certain tunnel length (L) can be regarded as a sum of a large number of random, uniformly distributed variables. The total production effort has a Gaussian distribution, and the central limit theorem can be used:

$$Q = N(m_Q, \sigma_Q). \tag{14}$$

Q is equivalent to the normal time for the case it has been based on, for all the activities on the critical path.

The normal cost can be estimated from Eq. (15):

$$C_n = \int z * g(x(l))\, dl, \tag{15}$$

where z is a cost variable relating to the production effort.

In the most general case, z may be a stochastic variable depending on the production effort, $g(x(l))$. For many tunnel projects, z can be considered to be independent of the production effort $g(x(l))$, e.g. when the production cost is proportional to the production effort. In this case, the normal cost can be expressed as:

$$C_n = Q * z, \tag{16}$$

where z can be regarded either as a constant or as a stochastic variable. Equation (16) can be used both for time and cost estimation if the variable z is set to 1 for the time estimation.

Benjamin and Cornell (1970), state that, if the cost z is independent of $g(x(l))$, the statistical parameters normal time or cost can be estimated as.

$$E(C_N) = m_Q m_z, \tag{17}$$

$$\sigma_{C_N} = \sqrt{m_Q^2 \sigma_z^2 + m_z^2 \sigma_Q^2 + \sigma_Q^2 * \sigma_z^2}, \tag{18}$$

where m_z is the mean value of the cost variables and σ_z is the standard deviation of the cost variables.

3.2.3 Exceptional Time and Cost

As discussed in Section 2, different tunnelling methods are affected by different undesirable events. The definition of an undesirable event (see Section 2) is a factor that causes a major unplanned change in the tunnelling process. For example, undesirable events can occur due to geological conditions or failure in machinery or components. In the model, exceptional time or costs caused by undesirable events are a function of the probability and consequences of undesirable events.

The probability that an undesirable event occurs can be described using Boolean variables (Toft-Christensen and Baker, 1982). In the present application, the random variables can exist in two conditions: (1) that the undesirable event k occurs, or (2) that the undesirable event k does not occur. The undesirable event occurs with the probability p and does not occur with the probability $(1-p)$, as seen in Eq. (19):

$$S_{ik} = \begin{cases} 1\_event\_k\_occurs\_with\_probability\_p \\ 0\_event\_k\_does\_not\_occur\_with\_probability\_(1-p). \end{cases} \tag{19}$$

If an undesirable event occurs, this results in exceptional time and cost. The time or cost consequence can thus be expressed as:

$$C_{e_k} = S_{ik} * C_{ik}. \tag{20}$$

Thus, the total exceptional time or cost can be expressed as the sum of all undesirable events in the expression:

$$C_e = \sum_{k=1}^{n} C_{e_k}. \tag{21}$$

3.2.4 Concluding Comments on the Theoretical Model

For a particular tunnelling method and a given tunnel length (L), the total time or cost can be expressed as the sum of normal time or cost and exceptional time or cost, as in Eq. (22).

$$C_{\text{tot}} = C_N + C_e = \int z * g(x(l))\, dl + \sum C_{e_k}. \tag{22}$$

The expected value for the total time or cost can be expressed as:

$$E(C_{\text{tot}}) = L * g[E(x)] * E(z) + \sum p_k C_k. \tag{23}$$

The practical application of the theoretical model is discussed in the next section.

3.3 Practical Modelling

3.3.1 Introduction to Practical Modelling

It has been concluded that it is important for the client and contractor to have a good basis for making decisions about budgeting, tender pricing or selecting a tunnelling method from those at their disposal. Both parties benefit from being able to utilise the estimated distribution of total time and cost as a basis for making decisions. To this end, estimations can be made according to the theoretical model described above, to provide a basis for making decisions about tender price and budget.

In the model, a separate estimation is made for the normal and exceptional time and cost. Exceptional time and cost is estimated for each identifiable undesirable event. This increases the options available to the various parties (client and contractor) for using the results in a variety of contractual and organisational situations.

Normal and exceptional time and costs that can be expected in a particular project are estimated for different tunnelling methods and various geological and hydrogeological conditions. Various degrees of "robustness" in the different tunnelling methods, (defined here as *capability to deal with a range of encountered conditions*), can be considered in the estimation.

3.3.2 Modelling of Normal Variation of Cost and Time

The modelling of normal variation in cost and time is described in detail by Isaksson (2002), but will be briefly described in this section.

The production effort of a tunnelling method is affected by the geological conditions along the tunnel. One way to facilitate the handling of the estimation of time and cost is to subdivide the lengths of tunnel into specific intervals called *geotechnical zones*; in other words, to discretize the tunnel. A geotechnical zone can be defined as "a section of tunnel that can be modelled as having similar geotechnical conditions, and in which it is intended to use the same tunnelling method". Clearly, the geotechnical characteristics of a zone are based on the geological conditions anticipated in the zone.

In principle, to assess the production effort that expresses the time or quantities taken for tunnelling per metre tunnel, input data can be obtained from back analyses of previously executed projects with similar geotechnical characteristics. When no such data are available, subjective estimations have to be made.

One general problem in rock engineering is that of being able to establish a relationship $g(x)$ between production effort and geotechnical characteristics. The division of the production effort into production classes can be used to facilitate the handling of the components in the relationships. One important component in the task of characterising production classes is to define the range of the geotechnical characteristics, or the group of geotechnical characteristics that correspond to a certain production class.

The cost variables used for the calculation of the normal costs are the costs per produced unit applicable to construction under normal tunnelling conditions for the project, such as time dependent costs, quantity dependent costs and fixed costs.

In the model described here, the cost variable z is regarded as an independent constant or a stochastic variable, which can be obtained by subjective estimation, (expert judgements), or by experience from other projects.

3.3.3 Modelling Undesirable Events

"Exceptional" time and costs can be estimated from knowledge about the probability and consequences of undesirable events. Different undesirable events will have different probabilities and consequences. Some will depend on the productivity of the construction method. Others might not.

Undesirable events may have a low probability, but a major consequence, for instance, when the actual geotechnical characteristics differ significantly from those in the normal range applicable for the method, so that the method may have to be changed. By contrast, other undesirable events may have a high probability, but a minor consequence only, for example, a minor breakdown of machinery.

A division into different event types has been made in order to, (a) obtain a distinct division between causes, probabilities and consequences, and (b) enable a relation between undesirable events and production effort.

Our suggestion for the classification of types of undesirable events is shown in Table 2. Undesirable events not covered by the first four types of undesirable event

Table 2. Classification of types of undesirable events

Type of undesirable event	Definition	Example
Production-dependent geological events.	Exceeding the limit of geotechnical characteristics for which the method works satisfactorily.	Joints, compressive strength, water pressure/permeability.
Randomly-occurring geological events.	Locally-significant deviations in geological conditions.	Water-bearing zones, fault zones.
Randomly-occurring mechanical events.	Component failure in the machinery or equipment used.	Main bearing failure.
Randomly-occurring gross errors.	Consequences of lack of competence.	Incorrect design, insufficient organisation, quality control or experience; insufficient knowledge about the method's working range.
Miscellaneous		

defined in Table 2 fall into the category "Miscellaneous". Clearly, other classification systems are possible, but this is the one that has been used in the estimation model. Clearly, which events should be considered in the estimation depends on the contractual situation between client and contractor, and the division of responsibility.

Estimations of the probability and consequences of each type of undesirable event can be made using risk analysis (Rausand, 1991), and involve:

- a description of the system,
- risk identification,
- estimation of the probability,
- estimation of the consequences.

3.3.4 Simulation

Using the model just described, the construction time and cost for a tunnel project can be estimated using data from experience. However, when this process becomes too complicated, Monte Carlo simulation can be used to solve it. Monte Carlo simulation has been discussed extensively in the literature by, for example, Harr (1987), or Ang and Tang (1984).

4. Case Study: The Grauholz Tunnel

4.1 Introduction

In this section, the model described in Section 3 is applied to the Grauholz Tunnel near Bern, Switzerland. The Grauholz Tunnel has been chosen because it is a well-defined project, for which different types of tunnelling machines were considered.

The total construction time and cost results obtained from using the estimation model are compared with the actual construction time and costs from the case study. As discussed in Section 2, factors such as the degree of correlation, the contractual situation and organisation, and the machine type and its robustness all affect decision-making as well as the outcome. The impact of these factors is also discussed in this section.

Initially, estimates for the project were prepared from data based on prior experience and case studies of similar tunnelling methods in similar geological conditions. No detailed information on costs was obtained from the people involved in the project. Estimates were prepared as if the project were in the planning stage. All the data input to the cost variables and production efforts are related to actual performance at the time the tunnel was built. The data were taken from a database built up between 1988 and 1995, when one of the authors was working as quantity surveyor for different contractors in Germany and Austria. In order to make the estimates realistic, increases in working capacity (such as the increased number of working hours available per month) have been taken into account. These were applied in two of the three geotechnical zones identified along the tunnel line, (see Section 4.2.2), to keep the construction schedule given by the client at start of the construction.

4.2 Description of the Project

4.2.1 Introduction

The Grauholz Tunnel was built between 1990 and 1993. It is 5500 m long, and passes through soil and rock. The tunnel is part of the Mattstetten-Rothrist Railroad Link, and is situated near Bern in Switzerland. The tunnel was built by Schweizerische Bundesbahnen, (SBB), to enable traffic to by-pass the junction at Zollikofen, and is a part of the plan known as "*Bahn 2000*".

4.2.2 Geology and Hydrogeology

The geological conditions in the vicinity of the Grauholz Tunnel are very complicated. The soil in the area consist of material of glacial origin containing deposits of glacio-fluvial sand and gravel covered by a substantial thickness of moraine. The rock was of a special type, called the Lower Fresh Water Molasse consisting of sandstone and marl. SBB tried to minimise the length of the tunnel excavated through water bearing moraine deposits, so the major part of the tunnel was routed through rock. This led to the tunnel being divided into three geotechnical zones, each consisting of relatively homogeneous geological conditions (see Fig. 4).

The first part of the tunnel, denoted East (Zone 1), consisted of hard and compact soil sediments. The overburden covering the tunnel was low. The geological and hydrogeological factors that made tunnelling in this zone complicated were the presence of boulders, high contents of fines and high groundwater pressure in an area with limited possibilities for dewatering works. The second part of the tunnel (Zone 2) consisted of soft marl and sandstone (the Lower Fresh Water Molasse), with an overburden of nearly 120 m. The third part, denoted West (Zone 3), consisted of silty-gravel moraine containing clay and sand. Stones and boulders were also found throughout this soil section, which was situated above the groundwater level.

4.2.3 Tunnelling Methods and Corresponding Measures to Increase Robustness

SBB envisaged that the tunnel would be excavated from both ends using open shields, combined in places with ground reinforcement or dewatering measures. Temporary

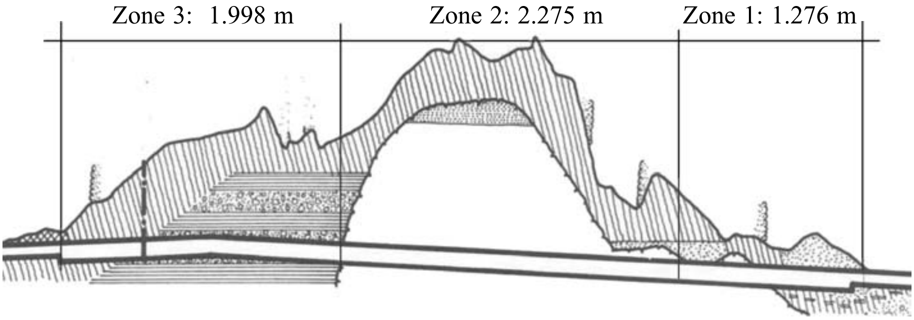

Fig. 4. Geological section through the length of the Grauholz Tunnel, after Harsch (1990)

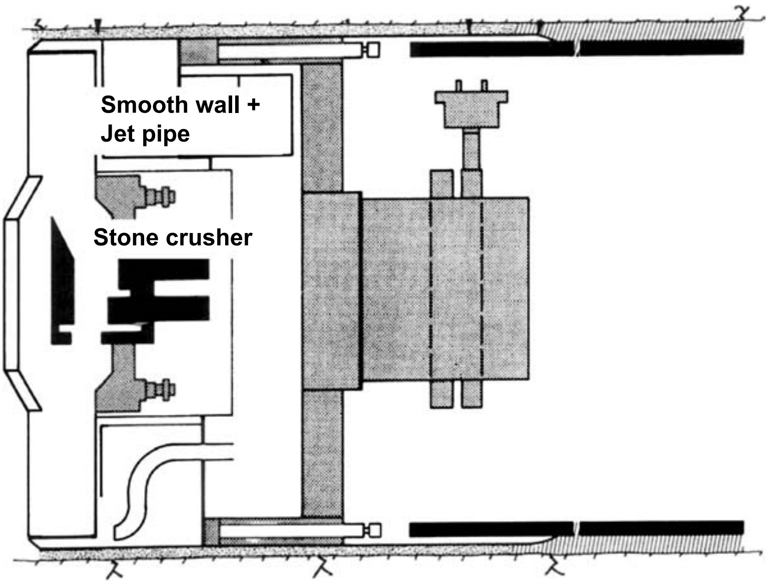

Fig. 5. Robustness-increasing measures on the machine head of the Mix shield

reinforcement by jet grouting ahead of the face was planned in areas characterised as being somewhere between soft ground and sandstone. However the contractor who was awarded the contract proposed to use a mix shield, with the possibility to tunnel either with a slurry supported face or in ‘‘dry’’ mode. The contractor also suggested excavating the tunnel from one side only.

Robustness-increasing measures were necessary for excavating through the complex geology. In order to determine which robustness-increasing measures to use, experience from other projects was considered. Anticipated problems arising from the presence of boulders in the ground and the high content of fines resulted in the adoption of the following measures (see Fig. 5):

- a stone crusher was incorporated into the middle of the boring head (to handle boulders),
- the wall of the working chamber was made as smooth as possible (to handle the high clay content), and
- a jet pipe was placed at the wall of the working chamber (to handle the high clay content).

All these measures were applied in the Mix Shield from the start of excavation. In the study reported here, these were denoted as a ‘‘low degree of robustness’’.

TBM performance data were analysed continuously during excavation to identify weaknesses in the tunnelling procedure. In practice, the geological conditions turned out to cause more problems than had been anticipated, so additional robustness-increasing measures were applied during the construction phase. For example, from the pre-contract geological investigations, it was expected that most of Zone 3 would consist of compact soil. Thus, it was planned to excavate this area in the dry mode.

In practice, however, it was decided to use a hydraulically-supported face to increase the robustness of the method.

In addition, centrifuges were provided to improve the separation of gravel from the slurry, and a wearing layer was provided on the cutters to reduce the number of changes.

Together with the measures adopted from the outset (and listed above), these additional measures allow the method to be classed as possessing a "high degree of robustness". The actual cost of taking additional measures to obtain only a low degree of robustness (i.e. the provision of the stone crusher) was approximately 2% of the tender price. To obtain a high degree of robustness, the centrifuges and wear coatings cost approximately 4% of the tender price, and stabilisation of the soil to enable the safe change of cutters cost about 4.5%.

If the excavation had proceeded without any kind of robustness-increasing measures, there is a high probability that major problems would have occurred, such as blocking of the machinehead with boulders and/or clogging of the machinehead throughout the whole length of Zone 1. The down time associated with each such problem would have been from one to several weeks, and would have led to a major delay when compared with the planned construction time. Consequently, an estimation of the total construction time without any robustness-increasing measures at all has not been made in this study.

4.3 Result of the Estimation

The total time and cost for construction of the Grauholz Tunnel have been estimated with the proposed model for [1] a low degree of robustness, [2] a high degree of robustness, and [3] robustness and measures as actually used during construction. The estimation was based on an assumption that the geological conditions were partly correlated.

In the estimations shown in Figs. 6 and 7, all types of undesirable events have been included. With the type of contract used for Grauholz, the responsibility lay more with the client than the contractor.

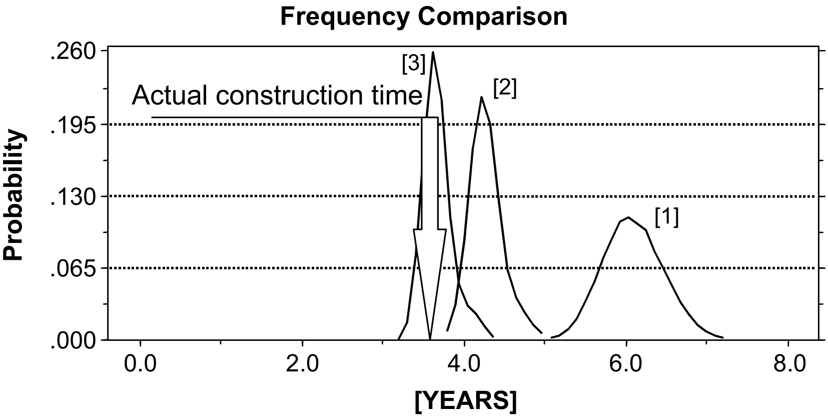

Fig. 6. Comparison of actual and estimated construction time including all exceptional time with [*1*] a low degree of robustness, [*2*] a high degree of robustness, and [*3*] robustness and measures as actually constructed

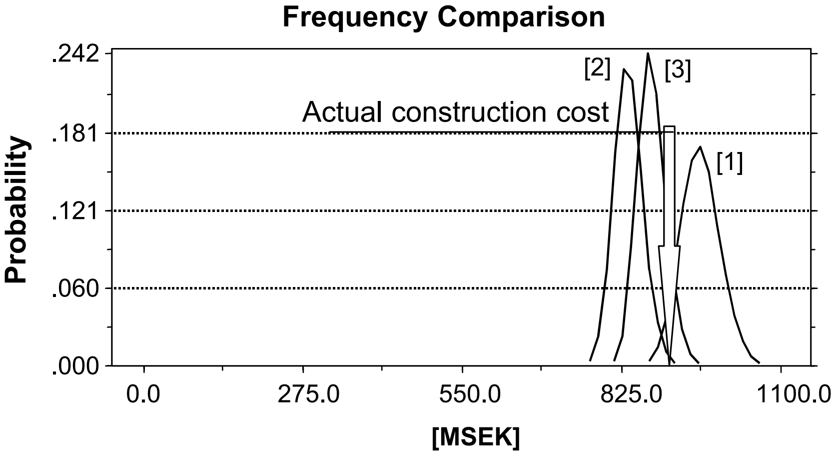

Fig. 7. Actual versus estimated total construction costs (in millions of Swedish kronor [MSEK]) including all exceptional cost with [*1*] a low degree of robustness, [*2*] a high degree of robustness, and [*3*] robustness and measures as actually constructed

Figure 6 shows the actual construction time and the estimated time for the three cases given above. For case [3], the actual high degree of robustness included the effects of using centrifuges in the separation process, a separate centre cutter for handling a high clay content in the ground, and all the others extra measures to increase the working capacity (increased amount of working hours per month), as discussed above. The estimated time was about 3.7 years and the actual time about 3.5 years. Thus, the two cases exhibit a small difference only.

With a low degree of robustness [1], the total estimated construction time was about 6.0 years, compared with about 4.3 years with a high degree of robustness [2]. In Fig. 6, the effect on total project time of the degree of robustness incorporated into the model is clear.

The total construction costs were also estimated and are given in Fig. 7. This shows the actual construction cost and estimated construction cost, including all exceptional costs.

In Fig. 7, the actual construction cost is around 900 MSEK. This exceeds the estimated cost of around 870 MSEK, as calculated with the actual high degree of robustness and the other measures used to increase the capacity. The reason for this higher cost might be that the modifications to the excavation method were introduced during the construction work, and not from the start.

Based on Fig. 7, it can also be concluded that cost estimate [2] for a high degree of robustness was lower than cost estimate [1] for a low degree of robustness. This holds despite the higher costs for installation of the extra equipment. This result is realistic, as robustness-increasing measures will reduce the effects of disturbances arising from adverse geological conditions, which in turn lead to higher production and lower excavation costs.

Thus, robustness-increasing measures may be used to increase the geological range within which the excavation method will be successful. Putting this another way, the range of geotechnical characteristics for which the method works with normal or high production efforts is extended. First and foremost, although the application of robustness-increasing measures may result in increased normal cost, it has a greater effect by reducing exceptional costs.

In summary, in the case of Grauholz tunnel, the analysis indicates that the application of measures to obtain a higher degree of robustness reduced the total construction cost more than they increased the equipment costs. Thus, the robustness increasing measures were profitable.

4.4 Factors Affecting the Result

As discussed in Section 3, there is often a correlation between the geotechnical characteristics. The degree of correlation, defined here as the distance over which the geotechnical characteristics show relatively strong correlation from one point to another, affects the distribution of total time and cost. At the outset of the project, it is difficult to know which particular distance between correlated points should be considered, and which variation is the correct one to use in the estimation, because of the limited knowledge about the geotechnical characteristics. Thus, the distance, δ_l, see Eq. (13) between correlated points has to be based on subjective estimation. The distributions of normal construction time for fully and partially correlated characteristics are shown in Fig. 8. For full correlation, the length of tunnel over which the geotechnical characteristics show relatively strong correlation from one point to another is the whole zone length; for partial correlation it is 100 m in Zones 1 and 3, and 400 m in Zone 2 (it has been assumed here that Zone 2 is more homogeneous than Zones 1 and 3). It is apparent that the correlation structure of the geology has a major impact on the distribution.

As discussed in Section 2, different decision makers in the client's and contractor's organisations have different degrees of responsibility for any increases in time and cost that result from unexpected undesirable events. The client must determine the budget for the project and the contractor the tender price. Clearly, the client has to give

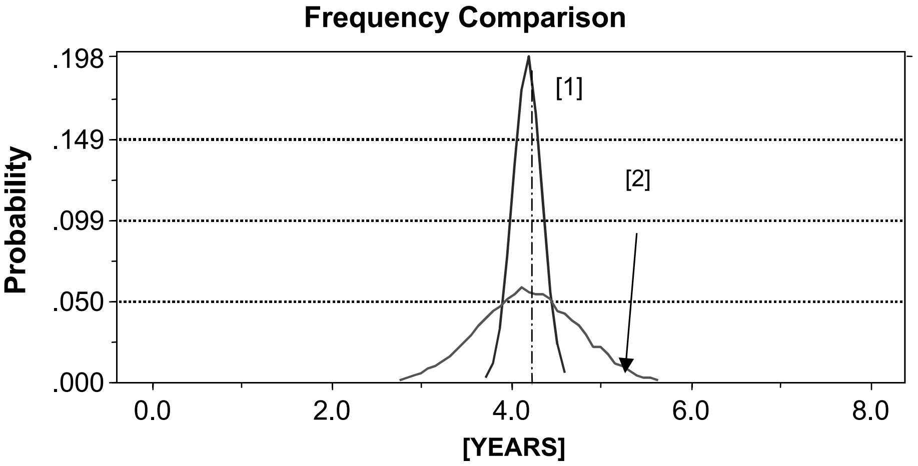

Fig. 8. Normal time with [*1*] partially and [*2*] fully-correlated geological characteristics

careful consideration to the extent of his responsibility for the possible exceptional costs that may impact on the project, in line with his role as the major stakeholder. The contract and organisation of the project chosen by him will determine the types of exceptional cost that have to be covered by the contractor, should they occur, as opposed to the costs that he will pay himself. For example, in a cost plus contract, the contractor has a minor responsibility for risk, and does not have to consider exceptional costs in his tender. In this case, the normal cost can be used as the basis for decisions about the bid price. On the other hand, where a unit price contract is used, there usually will be some contractor responsibility, so that the contractor should consider some of the possible exceptional costs. For the Grauholz tunnel project described here, a unit price contract was used, and the contractor had the responsibility for cost increases due to failure of his machines and equipment, which have been called "some exceptional costs". Finally, where the contractor has the major responsibility, for example in a lump sum contract, then all the exceptional cost, have to be considered by the contractor. Here, these are called "all exceptional costs".

Figure 9 shows the result of a Monte Carlo simulation of the total construction cost distribution considering different cost types. In this figure, the normal construction cost is shown without considering exceptional costs [1]. The same figure also shows construction cost including some exceptional costs [2], and also with all exceptional costs taken into consideration [3]. The results are based on calculations with a low degree of robustness and partly correlated geological characteristics.

At tender stage, various contractors did not find SBB's proposed tunnelling method optimal for the given conditions. Thus, alternative methods were proposed. The following three machine types were considered (Rohrer, 1994):

- *Mix shield*: able to be re-configured from slurry mode to dry excavation;
- *EPB shield*: using the soil mixture near the face to support the soil and water pressure from the ground, and a screw conveyor to transport the excavated material; and

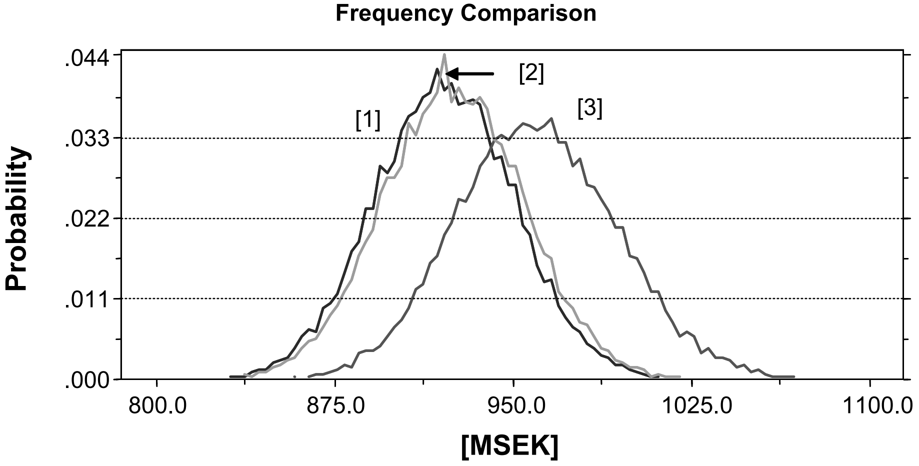

Fig. 9. Result of the simulation in millions of Swedish kronor [MSEK] for [*1*] normal cost, [*2*] total costs taking some exceptional costs into account, and [*3*] total costs taking all exceptional costs into account

- *open shield*: without the ability to support the ground and water pressure at the face; so that this shield could not be used below the groundwater table if the soil had a high conductivity.

The tunnelling method considered has a major affect on the total time and cost for a tunnelling project. Figures 10 and 11 show the results of Monte Carlo simulations of the total construction time and cost respectively for the tunnel utilising the different methods considered in this project, e.g. mix, EPB and open shield.

In the model, different robustness-increasing measures can be applied to each type of machine. When tunnelling with the mix shield, a high content of fines can cause problems with separation of the muck from the slurry. This can be avoided by using centrifuges or a band filter. To avoid clogging the machinehead, a separate center cutter can be installed, or water jets positioned around the tunnel wall. When tunnelling with

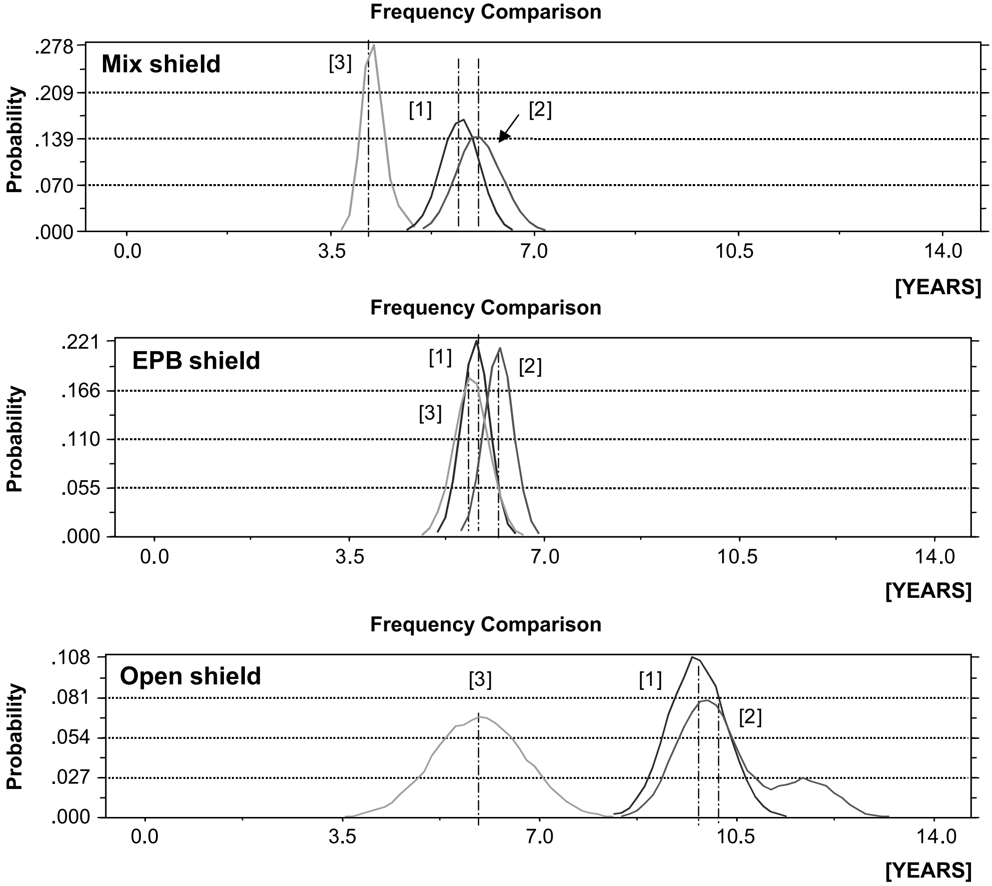

Fig. 10. Results of simulations by shield machine type, where [*1*] is the normal construction time for a low degree of robustness and partial geologic correlation without considering exceptional time; [*2*] is the total construction time for a low degree of robustness and partial geologic correlation considering all exceptional time; and [*3*] is the total construction time for a high degree of robustness and partial geologic correlation considering all exceptional time

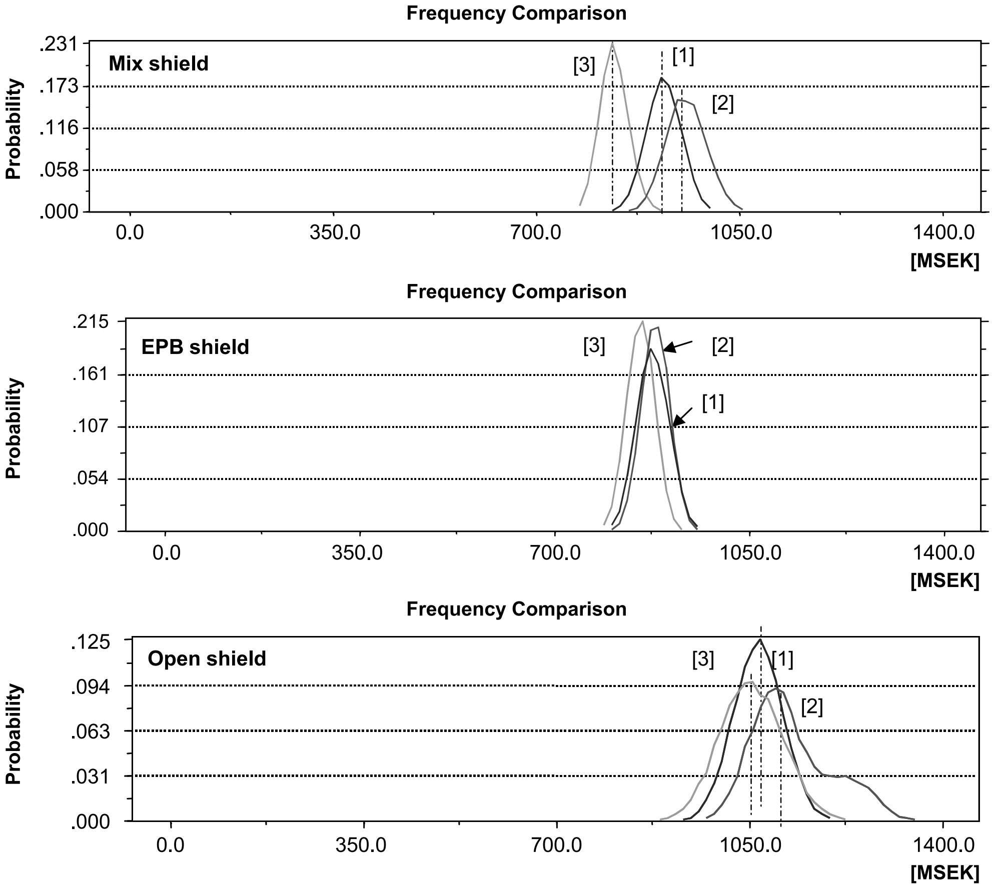

Fig. 11. Results of simulation by shield machine type in millions of Swedish kronor [MSEK], where [*1*] is the normal construction cost for a low degree of robustness and partial geologic correlation without considering exceptional cost; [*2*] is the total construction cost for a low degree of robustness and partial geologic correlation considering all exceptional costs; and [*3*] is the total construction cost for a high degree of robustness and partial geologic correlation considering all exceptional costs

an EPB shield, the soil mixture in the working chamber supports the face. Unlike the mix shield machine, it is not possible to integrate a stone crusher into the bore head. To obtain better consistency of the extruded soil, various additives such as bentonite or polymers can be used. Major problems can arise when tunnelling with an open shield machine in cohesionless soil below the water table. To increase the method's robustness in this type of soil, measures such as lowering the groundwater with wells or vacuum wells can be used, or ground freezing.

The analysis of the total construction time and cost for the different shield machines indicates that there are no major differences between the total construction costs for a Mix Shield or an EPB shield. However, when compared to an EPB shield, the Mix Shield has a considerably lower construction time if a high degree of robustness is applied. The reason for this might be that the mix shield is more suitable for excavation both in soil under water pressure and in dry sandstone, especially if the sections of tunnel with a high content of fines can be handled properly by a well designed separation plant. These conditions were present in the Grauholz tunnel project and, in the event, a mix shield was used. The reason for the higher construction time using an EPB shield is probably that the method is sensitive to boulders. This type of shield machine would probably have performed better in the simulation if it were able to crush rocks. However, this is not possible with present-day technology. For an Open Shield, both the total construction time and the cost exceed those for either a Mix Shield or an EPB shield. The reason for this might be that the Open Shield requires major drainage and support measures for excavation of large-diameter tunnels in soil under high water pressure. Thus, using this method entails very high costs. The analysis also shows that using an Open Shield at Grauholz would have involved major uncertainty about the outcome.

5. Conclusion

Various studies by, for example, Kastbjerg (1994), Andreossi (1998), and the HSE (1996) have shown that major cost and time overruns are common in infrastructure projects that include tunnelling. As such overruns cause major problems for all the parties involved in the tunnelling process, it is important that the risk factors are considered in a structured way.

Based on discussions about various risk factors and their impacts on cost and time in tunnelling projects, it has been concluded that it is important to make a distinction between *normal cost and time* and the *undesirable events* that cause *exceptional* cost and time.

In this study, variations due to ordinary risk factors have been based on an analysis of “factors causing deviations in the normal time and cost range”, such as performance-related factors like advance rate.

Undesirable events are defined as “events that cause major unplanned changes in the tunnelling process”. Such events often occur due to physical factors like geological and hydrogeological conditions. Tunnel collapse, or damage caused by unexpected changes in geological conditions, or the need for a complete change of the excavation method, are examples of undesirable events.

In this study, the term “robustness” has been used to indicate capability to deal with a range of encountered conditions. Thus, an increased robustness of the tunnelling method may reduce the occurrence of undesirable events. Robustness should therefore be considered when estimating the total time or cost for a project.

The uncertainty involved in evaluating input parameters for time and cost estimations emphasizes the advantage of using a probabilistic approach rather than a traditional deterministic calculation.

Analytical methods and decision criteria that take probability distributions into consideration are required to select an appropriate or the optimum tunnelling method. It is not always just a matter of finding the method with the lowest expected time or cost. The probability that both might exceed a certain value also has to be taken into account.

The estimation model described in this paper has been applied as a test case to the Grauholz Tunnel in Switzerland. It is concluded that the results obtained are fairly realistic. The total construction time and cost obtained from the model correspond fairly well to the actual construction time and cost.

The separate estimation of normal and exceptional time and cost contribute to the transparency of the result. It has been shown that, whilst the normal time and cost have a large influence on the overall construction time and cost, a separate estimation of the exceptional time and costs for each identifiable undesirable event can have a significant effect. This helps the different parties (client and contractor) to use the results in various contractual and organisational situations.

Due to the separate estimation of the different factors, a sensitivity analysis can also be performed, thereby revealing which factors have the greatest effect on the results.

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