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Probabilistic models for tunnel construction risk assessment

Olga Špačková [a,b,*], Eva Novotná [a], Michal Šejnoha [a], Jiří Šejnoha [a]

[a] Faculty of Civil Engineering, Czech Technical University in Prague, Czech Republic
[b] Engineering Risk Analysis Group, Faculty of Civil, Geo and Environmental Engineering, Technische Universität München, Germany

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ABSTRACT

The paper introduces different probabilistic models for prediction of tunnel construction risk. First, a simple probabilistic model for the estimation of the damage due to tunnel construction failures (e.g. cave-in collapses) is proposed. It can be used in conjunction with a deterministic estimate of the construction time/costs as a support for decision-making in tunnel construction projects. The occurrence of failures is modelled as an inhomogeneous Poisson process. The model takes into account the heterogeneity of the environment along the tunnel (changing geological conditions, changing damage potential) and it includes the influence of common factors such as human and organisational aspects. The damages caused by the failures are modelled as uncertain and they are thus represented by full probability distributions in the model.

Second, the decision-making under uncertainty in construction projects is discussed. The use of the concept of utility for considering the attitude of the stakeholder to risk is demonstrated. The simple probabilistic model and the decision-making concept are applied to a case study of construction of a 480-m-long tunnel.

Third, stochastic models for specific problems of tunnel construction, such as impacts of excavation on surface structures or probabilistic prediction of thickness of rock overburden, are introduced. The use of the models is illustrated on an example from Blanka tunnel in Prague.

1. Introduction

In compliance with ISO [8] the risk is defined as “the effect of uncertainty on objectives”. To be more specific, the risk in this paper is perceived as an expected damage due to the construction process failures and damage stands for financial losses related to a delay in construction time and/or exceeding the construction budget. Alternatively, the risk is expressed as an expected utility. The following fields are mutually interconnected while estimating risk – mechanics and economics. The former provides us with phenomena giving rise to damage, such as cave – in collapse and a vast subsidence trough yielding extensive deformations of the surface structures, and the latter arranges for the estimates of financial losses.

In current practice, the tunnel project risks are commonly analysed on a qualitative basis using different rating systems [4,1,17,6]. Such qualitative analysis is an irreplaceable basis for prioritizing the risks, for the development of risk treatment strategies and for allocating the responsibilities [24]. However, the major decisions made during planning and construction of the infrastructure should ideally be based on a consistent quantitative basis, i.e. on quantification of the risk [26].

There are several complex models for a probabilistic assessment of construction time and costs taking into account both the common variability of the construction performance and the occurrence of failures, for example Isaksson and Stille [7], Moret and Einstein [15] or Špačková and Straub [23]. These models are able to account for the high complexity of the construction process and provide a detailed quantitative analysis of construction uncertainties, but they require gathering of a significant amount of input information and, as such, their application is not always justifiable in practice.

In some cases it can be sufficient to disregard the common variability of the construction process and to analyse only the effect of construction failures. For example Sousa and Einstein [18] introduce a dynamic Bayesian networks (DBN) model for the quantification of the risk of construction failure. The model includes the uncertainty in the geological conditions but it does not consider the uncertainty in the damage caused by a failure. Eskesen et al. [4] assess the expected value of construction risk using, in principle, the same procedure as in the qualitative risk assessment. Arguably, this approach is likely to lead to an incorrect estimation of the total risk. The reason is that the identified hazards are often overlapping, they are not identified on the same level of detail and the

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* Corresponding author at: Engineering Risk Analysis Group, Faculty of Civil, Geo and Environmental Engineering, Technische Universität München, Germany.
E-mail address: olga.spackova@tum.de (O. Špačková).

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relations amongst them are not described. Therefore, a pure summation of the individual risks in the database is not possible, as they do not fulfil the condition of mutual exclusivity.

Some models analyse specific failure mechanisms. For example, Jurado et al. [12] estimate the probability of ground water related hazards using the Fault Tree Analysis (FTA). Sturk et al. [26] present assessment of the probability of environmental damages, namely of damages to trees during the tunnel construction. Šejnoha et al. [16] presented a FTA for estimating the probability of the occurrence of cave-in collapses and their consequences, especially of excessive deformations of surface structures. These models primarily focus on the probability of failure, they do not quantify the overall risk.

This paper suggests a simple probabilistic model suitable for assessing total damage related to the tunnel construction (Section 2). Application of the simple model is useful for example in early phases of the project when many different alternatives of the tunnel project are considered and one has only a little information about these alternatives. The model may also be sufficient for the assessment of risk in smaller tunnel construction projects where application of the complex models mentioned above is not justifiable. The model takes into account inhomogeneity of the geological conditions along the tunnel, the uncertainty in the prediction of damage, and allows for human and other external factors, all introducing dependencies into the construction process. Especially the latter two aspects have not been addressed by most of the available models. A simplified version of the model was previously published in Špačková [19].

Even if the damage caused by tunnel construction is correctly quantified, a common framework how to use this information for making decisions (e.g. for the selection of construction technology, for the selection of a contractor, as well as for the allocation of resources) is missing. The problem of decision-making under uncertainty in the construction projects has not been appropriately studied so far. A complex study of this topic exceeds the scope of this paper. We thus only briefly introduce the concept of utility and its use in decision-making (Section 3).

A tunnel constructed in the Czech Republic, denoted here as “TUN 3”, was selected to demonstrate the applicability of the model. A complex case study was deliberately split into application examples 1–5 to concisely illustrate theoretical approaches suggested in the specific sections.

Detailed stochastic models for the prediction of undesirable impacts of the tunnel construction on surface structures are discussed in Section 4. The following three problems are analysed: the impact of cave – in on a surface structure, the inference of jointed rock in a compact layer above the tunnel, and the effect of randomly varying depth of the rock overburden which tends to decrease along the tunnel axis. These problems had to be solved within the construction of the Blanka tunnel in Prague as is shown in application example 6.

2. Simple model of damage due to tunnel construction failures

The occurrence of failures in the course of a construction process is modelled as inhomogeneous Poisson process (Section 2.1). The estimate of the number of failures is further updated after the construction starts and the actual performance is observed.

Section 2.2 presents a procedure for the assessment of damages caused by the tunnel construction failures. It is applicable for the case, where the surroundings of the tunnel are homogeneous from the point of view of the damage potential, and the damage can therefore be considered as independent on the position, where the failure occurs. Section 2.3 applies to the tunnels which pass under different regions (e.g. partly under an agricultural land and partly under an urban area). In such a tunnel the expected damage is highly dependent on the location where the failure occurs.

2.1. Number of failures

The probability of occurrence of k failures during the construction of a tunnel can be estimated as

$$\Pr[N_F = k|\lambda, L] = \frac{(\lambda L)^k}{k!}\exp(-\lambda L), \tag{1}$$

where N_F is the number of failures, L is the length of the tunnel, and λ is the failure rate, i.e. the number of failures per a unit length of the tunnel.

The probability of occurrence of one or more failures in the tunnel then equals

$$\Pr[N_F \geqslant 1|\lambda, L] = 1 - \Pr[N_F = 0|\lambda, L] = 1 - \exp(-\lambda L). \tag{2}$$

Eqs. (1) and (2) hold under following assumptions: (1) the probability of occurrence of two or more failures in one time/space unit is small, (2) the failure rate does not change in time/space, i.e. the process is homogeneous, and that (3) the number of failures in any interval of time/space is independent of the number of failures in any other non-overlapping interval of time/space, i.e. the process is memory-less. The assumption (1) is easily fulfilled when rare events are modelled, which is also the case of modelling tunnel construction failures. However, the assumptions (2) and (3) are likely to be violated in reality. Adjustments to the homogeneous memory-less Poisson process corresponding to the Eqs. (1) and (2) are therefore proposed.

Conditions affecting the failure occurrence vary along the tunnel axis due to the changes in geological conditions. The failure rate varies accordingly, i.e. the Poisson process is inhomogeneous. For modelling purposes, it is convenient to divide the tunnel into so-called quasi-homogeneous geological zones, i.e. sections for which the failure rate is considered to be constant. The probability of occurrence of k failures then equals

$$\Pr[N_F = k|\lambda, L] = \frac{\left(\sum_{i=1}^{i=n_Z}\lambda_i L_i\right)^k}{k!}\exp\left(-\sum_{i=1}^{i=n_Z}\lambda_i L_i\right), \tag{3}$$

where L_i is the length of the ith quasi-homogenous zone, λ_i is the failure rate within this zone and n_Z is the number of quasi-homogenous geological zones in the tunnel; $\lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_{n_Z}\}$ and $L = \{L_1, L_2, \ldots, L_{n_Z}\}$. The average failure rate for the whole tunnel is:

$$\bar{\lambda} = \frac{\sum_{i=1}^{i=n_Z}\lambda_i L_i}{L}. \tag{4}$$

The construction performance and the occurrence of failures are influenced by human, organisational and other external factors. These factors affect the failure rate and introduce dependencies into the construction process (violation of the assumption 3). To give an example, the selection of a less experienced construction company or a suboptimal construction technology is likely to lead to higher failure rate. The general performance of the construction company and the appropriateness of the technology are uncertain in the planning phase, therefore, the parameters λ_i of the Poisson process are uncertain as well. After the construction starts, the performance observed in the first section of the tunnel influences the expectation about the performance (and related failure rate) also in the remaining part of the tunnel and we can thus update our predictions with these observations.

To include these dependencies into the model, we introduce a discrete random variable called “human factor” H. The human factor can be classified into three categories (states), “1: unfavourable”, “2: neutral” and “3: favourable”, and it is supposed to be

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