Tunnelling and Underground Space Technology 37 (2013) 62–78

Contents lists available at SciVerse ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Probabilistic assessment of tunnel construction performance based on data

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ARTICLE INFO

Article history:
Received 28 April 2012
Received in revised form 11 December 2012
Accepted 11 February 2013
Available online 28 April 2013

Keywords:
Construction time
Tunnel construction risk
Dynamic Bayesian Networks
Tunneling performance
Failure rate

ABSTRACT

A probabilistic model for estimating tunnel construction time is learnt with data from past tunnel projects. The model is based on the Dynamic Bayesian Network technique. The model inputs are determined through an analysis of data from three tunnels built by means of the conventional tunneling method. The data motivate the development of a novel probability distribution to describe the excavation performance. In addition, the probability of construction failure events and the delay caused by such failures are estimated using databases available in the literature. The model is applied to a case study, in which it is demonstrated how observations from the tunnel construction process can be included to continuously update the prediction of construction time.

1. Introduction

Duration and cost of construction are key factors in decision making during the planning and design phase of a tunnel project. At present, construction time and cost are commonly assessed on a deterministic basis. The deterministic approach, however, does not appropriately reflect the uncertain reality. Systematic underestimation of construction costs related to infrastructure projects has been documented, for example in Flyvbjerg et al. (2004). Major losses and delays in tunnel construction projects have been reported by insurers (e.g. IMIA, 2006). The need for analyzing the uncertainty and risks of tunnel construction has been recognized by the tunneling community (see e.g. Lombardi, 2001; Eskesen et al., 2004; Reilly, 2005; ITIG, 2006).

As shown in Isaksson and Stille (2005), the uncertainty in construction time and cost estimates results from the common variability of the construction performance and from the occurrence of extraordinary events (also denoted here as failures of the construction process) such as tunnel collapses. Risks resulting from construction failures are commonly analyzed separately using techniques such as fault tree or event tree analysis, decision trees or risk matrices (Benardos and Kaliampakos, 2004; Shahriar et al., 2008; Hong et al., 2009; Aliahmadi et al., 2011; Jurado et al., 2012). In Špačková (2012), tunnel construction failures are modeled by means of a Poisson process. Sousa and Einstein (2012) present a Dynamic Bayesian Network (DBN) model, which estimates the expected utility as a sum of the expected costs and the risk of a tunnel collapse. The full probability distribution of the construction costs, however, is not assessed.

Some models allow one to probabilistically estimate the time or costs without taking into account the occurrence of extraordinary events. They typically use Monte Carlo (MC) simulation – see e.g. Ruwanpura and Ariaratnam (2007), Chung et al. (2006), Min et al. (2008). Full probabilistic estimates of tunnel construction time or costs, taking into account both the common variability and the risk of extraordinary events, are presented in Isaksson and Stille (2005), Grasso et al. (2006) and Špačková and Straub (2012).

The probabilistic model inputs are mostly based on expert assessments. The description of geotechnical conditions is based on geological investigations, and the estimates of average advance rates and construction costs can be supported by simulations of the construction processes and by collected data (e.g. Kim and Bruland, 2009; Burbaum et al., 2005). However, little information is available on the random variability of the construction performance and on the failure rate. The available studies, e.g. those analyzing the Tunnel Boring Machine (TBM) penetration rate (Alvarez Grima et al., 2000; Sapigni et al., 2002; Chung et al., 2006), only capture a part of the uncertainty.

To the authors' knowledge, Flyvbjerg and COWI (2004) present the first study that quantifies the overall uncertainty in construction cost estimates based on an analysis of data from previous projects. However, since they assess only the cost overrun, the study is helpful for describing the present practice, but the results are not suitable for a probabilistic prediction of construction costs of future projects.

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0886-7798/$ - see front matter
http://dx.doi.org/10.1016/j.tust.2013.02.006

This paper aims to provide a framework for probabilistic prediction of tunnel construction time and presents a methodology for statistical analysis of data to determine the inputs for the probabilistic models. The data and the application example presented in this paper are limited to the conventional tunneling method, which is defined by ITA (2009) as "construction of underground openings of any shape with a cyclic construction process of: (1) excavation, by using the drill and blast methods or mechanical excavators except any full face TBM, (2) mucking and (3) placement of the primary support elements, such as steel ribs, rock bolts or sprayed concrete". Our approach might be extended to the modeling of mechanized tunneling with use of TBM.

A DBN model introduced in Špačková and Straub (2012) for the prediction of tunnel construction time is presented in Section 2. The DBN model serves as a basis for the analysis of the data presented in Section 3. This model facilitates the definition of the variables in the construction process model and their inter-dependencies. The model allows for efficient updating of the predictions based on observed geotechnical conditions and construction performance once construction has started; this facilitates the systematic, quantitative adaptation of the model estimates in real-time during the construction. The model takes into account both the common variability of construction process and the occurrence of extraordinary events. Additionally, it allows for modeling stochastic dependencies caused by common factors that systematically influence the construction process (such as human and organizational factors). The influence of stochastic dependencies on probabilistic estimates of construction time and costs has been discussed for example in Yang (2007) and Moret and Einstein (2011).

A statistical approach to determining the probability distribution of unit time (time spent on excavating a segment of the tunnel with a given unit length, inverse of the advance rate) is presented in Section 3.1. The unit costs and activity durations (advance rates) are commonly modeled using uniform, triangular or beta distribution (Min, 2003; van Dorp, 2005; Yang, 2007; Said et al., 2009). Triangular and uniform distributions are especially popular, because experts feel generally comfortable in assessing upper and lower bounds and the mean/mode of random variables. Studies analyzing data from construction projects, however, show that other probabilistic models, such as the lognormal or Weibull distribution, are often more suitable (Chou, 2011). In this paper we suggest utilizing a combined probability distribution, which allows us to better represent the construction process influenced by different effects (normal performance and small disturbances). Data on excavation performance from three tunnels constructed in the Czech Republic are used. The influence of geotechnical conditions, tunnel geometry and construction method is examined. Furthermore, the correlation of the unit time along the tunnel axis is analyzed.

Section 3.2 presents a statistical approach to estimate failure rates and assess the probability distribution of delay caused by a failure.

Finally, the probabilistic estimation of the excavation time is shown in Section 4, using an example of one of the Czech tunnels. First, a prior estimate of the excavation time, which would be done in the planning phase of the project, is shown. Second, the prior prediction is updated with the excavation time observed during construction of the tunnel.

2. Generic probabilistic model of tunnel construction process

Construction of tunnels (as well as construction of other linear infrastructure projects) is a chain of repetitive activities whose order is in most cases pre-defined. It follows that there is negligible uncertainty in the determination of the critical path. From a modeling point of view, this is a significant advantage over the modeling of the construction process for other types of construction projects (Ökmen and Öztaş, 2008).

During the excavation, the tunnel construction process is adapted to the actual conditions encountered. The selected tunnel construction method (excavation technology, support pattern) and the corresponding speed and costs of construction depend primarily on the following factors:

- Geological conditions (e.g. mechanical properties, frequency and orientation of discontinuities).
- Hydrological conditions.
- Frequency of changes of the geological and hydrological conditions - (in)homogeneity of the environment.
- Cross-section area of the tunnel.
- Inclination of the tunnel.
- Depth of the tunnel/height of overburden.
- Affected structures and systems (requirements on maximal deformations, protection of water systems and environment, operational constraints).

The real construction performance is furthermore highly dependent on the planning and design of the tunnel and on the construction management and control.

The construction process is associated with many uncertainties and risks: (1) geotechnical uncertainties, resulting from limited knowledge and natural variability of the geotechnical conditions in the vicinity of the tunnel, (2) uncertainties in construction performance, which are associated with planning, organization and management of the construction process and variability of advance rate and construction costs, (3) risk of extraordinary events, i.e. events with low probability but potentially huge consequences such as tunnel collapse, fire or legal obstructions threatening the project.

All these uncertainties and risks should be taken into account when the construction costs or time are estimated. For this purpose, a DBN model is developed. The DBN is a special type of Bayesian Network (BN), which is suitable for modeling of stochastic processes. A brief introduction to BNs is provided in Appendix A.

A generic probabilistic model of construction process is represented by the DBN shown in Fig. 1. This generic model shows the basic principles and elements of modeling of the construction process. In a specific model, the geotechnical conditions, *GC*, construction performance, *CP*, as well as extraordinary events, *EE*, should be described in more detail by sets of random variables reflecting the tunnel specifics. An example of a specific DBN is shown later in the application example (Fig. 10). The selection of the appropriate set of variables depends on local geological conditions, type of technology to be used, routines and experience of the owner, designer and contractor and on information available at the time of the estimate, i.e. on the project phase. The levels of detail in the (uncertainty) modeling of the various aspects of the process should be balanced. For example, a detailed model of geotechnical conditions is not necessarily beneficial for the time/cost prediction if it is not accompanied by a detailed model of the associated construction performance.

Each slice of the DBN in Fig. 1 represents a tunnel segment of length Δl. In the following, the segment length Δl is equal for all slices. The ith slice of the DBN thus represents a tunnel segment between position $(i-1)\Delta l$ and $i\Delta l$. All variables are modeled as constant within a segment, i.e. the model implies that the geotechnical conditions and construction performance do not change within a segment.

2.1. Geotechnical uncertainties

Here, uncertainty of geological and hydrological conditions is considered. For modeling purposes, the area of the tunnel is first