Automation in Construction 96 (2018) 378–397

Contents lists available at ScienceDirect

Automation in Construction

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

Generation and evaluation of excavation schedules for hard rock tunnels in preconstruction and construction

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ABSTRACT

Uncertain product characteristics in construction projects make it difficult for planners to develop schedules that reduce expected costs, durations, and associated risks. To overcome these challenges in hard rock tunnel projects, this research introduces a methodology that adapts stochastic programming and feedback control approaches for their excavation. Such approaches require rapid and consistent implementation using up-to-date information provided in a probabilistic manner throughout the entire excavation; therefore, the authors tailored dynamic programming and tunneling risk analysis methods for the methodology to address multiple sets of rock mass properties (RMPs), transitions among excavation methods at the excavation method level, decision-making times, and schedule adjustment policies (SAPs). In preconstruction and construction, the methodology allows construction planners of hard rock tunnels to generate a total-cost-optimal excavation schedule for each set of RMPs and evaluate the excavation costs and durations of schedules for multiple sets of RMPs in a timely and consistent manner by considering SAPs. Further research is required to take into account multiple advances of excavation methods for schedule generation and evaluation.

Database subject headings: Automated schedule generation, hard rock tunnel, uncertainties in rock mass properties, feedback control, stochastic programming, earthwork risk analysis.

1. Introduction

In construction projects, uncertain product characteristics make it difficult for planners to develop schedules that reduce expected costs, durations, and their risks. By overcoming these challenges, construction planners would obtain two main benefits from stochastic programming, which is an approach for modeling optimization problems that involve uncertainty [1]. First, the expected costs of solutions from using stochastic programming are generally smaller than the costs from using the deterministic program [2,3]. Second, stochastic programming allows for the measurement of additional costs caused by uncertainties in product characteristics, which supports planners in determining whether the further acquisition of product information is required.

In addition, if uncertainties in the product characteristics vary depending on their projects' progress and if planners could use up-to-date product information during construction, they could conduct a more accurate analysis of their decisions (e.g., the costs estimated for construction schedules). Thus, the implementation of a closed-loop (i.e., feedback) control, such as model-predictive control and feedback adaptive control, could help planners acquire more opportunities to achieve their project performance goals, such as on-time completion and within budget [4,5].

Three main characteristics of hard rock tunnel projects make it especially important to incorporate stochastic programming and feedback control into decision-making about resource-loaded excavation schedules. First, because hard rock tunnels include inherent uncertainties regarding rock mass properties (RMPs), significant differences often exist between predicted and actual RMPs [6]. Second, as the excavation of tunnels progresses, geotechnical engineers can update information about RMPs not only for the excavated sections of tunnels, but also for the unexcavated sections, where they re-predict the RMPs by employing up-to-date information on the RMPs for the excavated sections. Third, the excavation of these tunnels represents a sizable portion of such projects [7].

Despite the potential benefits associated with stochastic programming and feedback control for excavation schedules, no systematic approach allows construction planners to obtain those benefits for their hard rock tunnel projects in a consistent and timely manner. One of the main challenges concerns formulating mathematical optimization problems (e.g., linear programming, convex optimization) for multi-objective stochastic programming, which is required to consider both the excavation costs and durations resulting from excavation schedules in preconstruction and construction [8].

Thus, simulation-based optimization methods are potentially applicable for solving such problems. However, a random search of genetic algorithms (GAs), which are often used for those methods, cannot

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https://doi.org/10.1016/j.autcon.2018.09.022
Received 27 November 2017; Received in revised form 10 September 2018; Accepted 28 September 2018

guarantee whether the schedules generated by GAs consistently result in lower (or at least equal to) expected total costs, which include both excavation costs and other costs related to time at the completion of excavation (e.g., indirect costs, liquidated damages), in preconstruction and construction than those of schedules generated by deterministic programming, which is used in current practice.

In addition, finding a total-cost-optimal schedule for each of the multiple possible RMP scenarios is required to estimate additional costs caused by uncertainties in RMPs, thereby supporting planners in determining whether further geotechnical investigations are required. However, because of the difficulty in finding multiple optimal schedules developed by GAs, which is time-consuming and leads to difficulty in guaranteeing their optimality, simulation-based optimization methods also make it challenging to estimate those additional costs.

This lack of a systematic approach correlates with the fact that planners frequently encounter cost overruns and schedule delays for these types of projects [9]. For example, although the duration of the headrace tunnel of Kaligandaki "A" in Nepal had initially been estimated to take up to three and a half years, this project was actually completed with a delay of almost two years because of considerable deviations from the initial predictions about RMPs [6].

In overcoming these limitations, the research team proposed a hybrid method between stochastic and deterministic programming to achieve three research objectives associated with the benefits addressed from stochastic programming and feedback control: (1) generations of schedules with lower (or at least equal to) expected total costs than those of schedules generated by the current deterministic approach; (2) the quantification of additional costs caused by uncertainties in RMPs; and (3) the application of multiple decision-making points in time (i.e., in preconstruction and construction).

To achieve the research objectives, the hybrid method supports informed decision-making for excavation schedules by taking into account multiple schedule alternatives and a variety of possible scenarios of RMPs at multiple decision-making points in time. Specifically, the first part of the method generates multiple total-cost-optimal schedules for multiple RMP scenarios in preconstruction and construction. To generate these schedules in a consistent and time-efficient manner, the research team tailored dynamic programming (DP) to solve a two-objective optimization problem (i.e., excavation costs and durations). Using a resulting pareto frontier and the relationship between the excavation completion time (i.e., duration) and duration-dependent costs, which is often non-linear, the proposed method finds a total-cost-optimal schedule for each of the multiple RMP scenarios. The second part of the method evaluates the excavation costs and durations of the schedules for multiple possible RMP scenarios. To consistently evaluate the cost and duration of a schedule for the RMP scenario, which is different from the scenario used for schedule generation, the team extended the existing risk analysis methods for tunnel construction projects to take into account the schedule adjustment policies (SAPs) [10].

Because geostatistical simulation methods allow for the prediction of multiple possible RMP scenarios for tunnel construction projects in a statistically consistent manner (i.e., within an acceptable range of errors), this research focuses on schedule generation and evaluation [11,12]. Furthermore, in focusing on the uncertainties in the product model (e.g., RMPs), the research team did not account for any possible uncertainties in the process information (e.g., the productivity of each excavation method for the same RMP).

After describing the problems in the implementation of the hybrid approach in both current practice and the existing studies associated with the problems, this paper introduces a methodology formalized in this research. This paper also presents case studies applied to ensure that the methodology appropriately achieves the three research objectives. The authors then describe the validation procedures and results for the methodology.

Table 1
List of abbreviations frequently used in this paper.

General		Stochastic programming related	
Abbreviation	Definition	Abbreviation	Definition
RMP	Rock mass property	EV	Expected value problem
GA	Genetic algorithm	EEV	Expected result of the expected value solution
SAP	Schedule adjustment policy	RP	Recourse problem
DP	Dynamic programming	WS	Wait-and-see
DAT	Decision aids for tunneling	VSS	Value of stochastic solution
CYCLONE	Cyclic operations network	EVPI	Expected value of perfect information
PC	Phase combination	PRP	Pseudo recourse problem

2. Current practice's problems affecting the implementation of the proposed approach

This section describes the problems observed in current practice that affect the implementation of the hybrid approach proposed in this research. Before the description, the authors introduce a list of abbreviations and define the terms frequently used in this paper. Table 1 lists the abbreviations frequently used in this paper.

When geotechnical engineers predict RMPs, it is assumed that they employ one of the geo-mechanical classification systems, such as the rock mass rating (RMR) system and the Q-system, which combines a variety of geologic parameters, such as the uniaxial compressive strength of rock material, rock quality designation (RQD), the spacing of discontinuities, the condition of discontinuities, groundwater conditions, and the orientation of discontinuities [13,14]. Based on the RMPs provided, construction planners estimate the productivities (e.g., advances for unit time) and unit costs for each excavation method, and it is assumed that these values are approximated, including downtimes of equipment. The authors also define the same excavation method as the excavation method that consists of the same activities, and each activity of that method has the same types of resources. Thus, each tunneling method, such as the new Austrian tunneling method (NATM), includes a variety of excavation methods that often have different productivities and unit costs for the specific RMPs [15]. In addition, the phases in the schedule are represented by the excavation's starting locations and directions. Thus, the same phase means the phase that has the same excavation starting location and direction. In addition, each decision block represents the minimum unit of tunnel components necessary to assign one excavation method, which is assumed to have the same RMP. Thus, construction planners determine the length of each decision block based on the prediction intervals of RMPs.

To implement the proposed approach, two main requirements should be satisfied. First, the implementation requires a formal method that generates the same number of total-cost-optimal schedules as the number of RMP scenarios in a timely manner. Without the formal method, generating optimal schedules becomes quite challenging for construction planners in current practice because it requires them to look for a very large solution space, making the process extremely complicated and time-consuming. For example, if a planner (1) generates a total-cost-optimal schedule for a 4 km long tunnel, (2) decides one of 5 excavation methods for each 100 m decision block, and (3) applies an exhaustive search method [16], the planner would then need to estimate and compare the total costs of 9×10^{27} (i.e., $5^{40\ [=\ 4{,}000\mathrm{m}/100\mathrm{m}]}$) schedule alternatives under a given RMP scenario.

Therefore, to generate multiple total-cost-optimal schedules at every decision-making point in time under this challenge, the formal method should support planners in estimating the excavation cost, duration, and total cost of each schedule alternative in a consistent and