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Formal representation of cost and duration estimates for hard rock tunnel excavation

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ABSTRACT

Due to the inherent uncertainties of rock mass properties, construction planners of hard rock tunnels have difficulty achieving on-time completion within budget. Despite the potential benefits of adapting stochastic programming and feedback control approaches for decision-making for excavation schedules, the lack of formal representations of the planners' rationales required to estimate the costs and durations of excavation schedules makes the implementation of these approaches extremely challenging. To address these limitations, the authors developed an ontology that represents the estimation rationales (e.g., transition costs and durations among excavation methods, multiple sets of rock mass properties, and schedule adjustment policies). This ontology enables planners to explicitly describe more the comprehensive information required to consistently estimate the costs and durations of excavation schedules for both preconstruction and construction compared to the current practices and the existing studies. Further research that accounts for learning effects resulting from transitions among excavation methods would make cost and duration estimations for excavation schedules more realistic.

1. Introduction

Construction projects with uncertain product characteristics make it difficult for planners to achieve on-time completions within budget. Overcoming these challenges is especially important for the excavation of hard rock tunnels because significant differences often exist between the predicted and actual rock mass properties (RMPs) [1]. In addition, the excavation of these tunnels represents a sizable portion of such projects [2]. For example, the excavation costs for four different international road tunnels made up 72% of their total construction costs [3]. These characteristics force construction planners of hard rock tunnels to frequently encounter cost overruns and schedule delays [4].

To overcome these challenges, the goal of this research is to help the planners of hard rock tunnels reduce the 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). Specifically, this research takes into account the resource-loaded excavation schedules as a major decision planners need to make in preconstruction and construction.

When developing the excavation schedules, planners would obtain three main benefits of adapting stochastic programming, which is a framework for modeling optimization problems under uncertainty, and feedback control approaches [5,6]. First, these approaches help reduce the expected costs of their schedules because the expected costs solved by stochastic programming are smaller than (or at least equal to) those solved by deterministic programming [7]. Second, they could reduce the risk involved in the total costs because the expected costs of a solution estimated by the only representative values (e.g., averages) are often different from the costs by multiple possible values generated in a statistically consistent manner [8]. Third, the adaptation of a feedback control system could enhance the accuracy of excavation costs and durations estimated for excavation schedules. Uncertain RMPs in hard rock tunnels mainly stem from the fact that, because of costs or other constraints, geotechnical investigations (e.g., boreholes) are normally conducted for only a very small proportion of the total volume of ground before construction [9]. Thus, using up-to-date product information, which varies as a project progresses, allows construction planners to improve their estimation accuracy for excavation costs and durations in construction.

Despite these potential advantages, planners cannot currently adapt stochastic programming and feedback control approaches for the decision-making of excavation schedules. To adapt those approaches, planners should be able to find excavation schedules with the lowest expected total costs (i.e., cost-optimal schedules in this paper) for both

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preconstruction and construction. However, the identification of cost-optimal schedules requires these planners to carry out a large number of estimations for excavation costs, durations, and total costs of schedules for multiple possible scenarios (i.e., sets) of RMPs in a consistent manner. The current manual estimation processes thus make the implementation of stochastic programming and feedback control approaches extremely time consuming.

Consequently, the adaptation of these approaches requires automated estimation processes that take into account multiple sets of RMPs in a consistent and computationally efficient manner in preconstruction and construction. To implement these automated processes, planners are required to explicitly describe their comprehensive rationales for estimating the total costs of excavation schedules for hard rock tunnels, including multiple sets of RMPs, transition costs and durations among construction methods at the construction method level of detail, decision-making times, and schedule adjustment policies (i.e., conditions and ways to adjust the schedule when, during construction, different RMPs from those used for their schedule generation are encountered).

However, the existing representations addressed in building information modeling (BIM), geo-statistics, construction method models, construction process simulations, and earthwork risk analyses are not comprehensively formalized in a computationally efficient manner [10–15]. These limitations make it difficult for construction planners to automatically estimate the total costs of excavation schedules in a timely manner; in turn, planners cannot then adapt stochastic programming and feedback control approaches for the decision-making related to excavation schedules. As a result, in current practice, planners generate a small number of excavation schedules on an ad hoc basis and then manually evaluate the expected total costs of the schedules, considering only one set of RMPs instead of multiple possible sets.

To address the identified limitations, the authors formulated the following research question: *How can **comprehensive** estimation rationales of total costs for schedules be formally represented for hard rock tunnels in preconstruction and construction?* To answer this question, the research team first identified the planners' rationales that are required to estimate the total costs of the excavation schedules in a consistent and time-efficient manner. After reviewing the literature, an ontology was developed according to the ontology development methodology suggested by Noy and McGuinness [16]. Finally, the team validated the ontology with a case study.

2. Planners' estimation rationales required to adapt stochastic programming and feedback control approaches

To implement two-stage stochastic programming, which is one of the most widely used stochastic programming methods, planners are required to generate multiple schedules for each set of RMPs as the first stage and evaluate the excavation costs and durations of the schedules for multiple sets of RMPs as the second stage [17]. Thus, this section first describes the planners' estimation rationales for schedule generation and then illustrates these rationales for the schedule evaluation processes. To identify these rationales, the authors conducted retrospective case studies and interviewed 5 experts with more than 10 years' experience in tunnel construction projects.

To describe the rationales, the authors developed three hypothetical scenarios that a planner could encounter when estimating the excavation costs and durations of the excavation schedules. The first two are for schedule generation, and the last scenario is for schedule evaluation.

2.1. Estimation rationales required for schedule generation in preconstruction

The first scenario assumes that a planner estimates the excavation costs and durations of schedules for a hard rock tunnel, which is excavated from Phase 1 to Phase 2, in preconstruction (Fig. 1). The planner accounts for three different excavation methods (i.e., EM1, EM2, and EM3) for schedule generation and completes the excavation of Phase 2 at $STA_{(2,\ 2)}$, where $STA_{(X,\ Y)}$ is the location at Y for Phase X.

Because heavy equipment is necessary for the excavation of hard rock tunnels, the planner accounts for the costs and durations not only for the operation (i.e., the excavation itself, without consideration of transitions among excavation methods), but also for the mobilization (e.g., delivery, onsite set-up) of the equipment [2]. To estimate the excavation costs of the schedule consistently, the planner must explicitly describe the unit operation (i.e., excavation) costs for each excavation method, as well as the transition costs among excavation methods, including (de)mobilization, onsite set-up and dismantlement. Further, to estimate the excavation duration of the schedule, the planner needs to represent the operation productivities (e.g., time spent/excavation of unit length) and onsite transition times among excavation methods, including onsite set-up and dismantlement.

Because the excavation for a hard rock tunnel is a cyclic process [18], cost and duration information for operation and transition provided at the excavation method level (e.g., New Austrian Tunneling Method Type 1) makes the estimation process more computationally efficient than such information at the activity level (e.g., Installing Rock Bolts Type 1) or the event level (e.g., Tensioning Rock Bolt Type 1). Thus, because time-efficient estimation is crucial to the adaptation of stochastic programming, the planner is also required to provide the cost and duration information at the excavation method level.

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, the condition of discontinuities, and groundwater conditions [19,20]. Based on the RMP classes provided, construction planners estimate the productivities (e.g., advances for unit time) and unit costs of the excavation methods. In addition, the same excavation method means an 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 may have different productivities and unit costs for the specific classes of RMPs [21].

To adapt stochastic programming for the schedule generation process, the planner is also required to account for other multiple scenarios (i.e., sets) of RMPs, rather than the set illustrated in Fig. 1. The planner may account for multiple sets of RMPs predicted in a statistically consistent manner (e.g., geostatistical simulation methods), called reference sets of RMPs, and use those sets for both schedule generation and evaluation [14]. In addition, to find cost-optimal schedules, the planner may take into account non-reference sets, which are used for schedule generation only and consist of sets produced by interpolation (e.g., Kriging in geo-statistics) and subjective prediction.

2.2. Estimation rationales required for schedule generation in construction

To adapt a feedback control system for excavation scheduling of a hard rock tunnel, a planner is required to generate multiple schedule alternatives in construction by considering up-to-date information about the RMPs and excavation progresses. For the second scenario, a planner starts a decision-making process for the schedules at T_2 in construction and estimates the excavation cost and duration of a schedule that applies EM3 to Phase 2 as soon as possible (Fig. 2). To do so, the planner first needs to compute how long EM2 is used for the excavation of Phase 2 if the EM3 is ready at the earliest possible point in time (i.e., T_3 in Fig. 2). To consistently compute T_3 in a computationally efficient manner, the planner is required to explicitly describe the lead times among excavation methods at the excavation method level of detail and define a decision-making time for scheduling in construction.