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SIMULATION OF MULTIPLE-DRIFT TUNNEL CONSTRUCTION WITH LIMITED RESOURCES

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ABSTRACT

Construction work is often performed with limited resources. The optimal dynamic allocation of resources at simulation runtime sometimes requires that non-critical tasks be held back deliberately and not be allowed to start so that resources will be available to perform more critical activities later. This is an important issue that has escaped rigorous investigation. For certain projects it may be more expedient to model work at the activity level and not the resource level and embed the routing of resources into precedence relationships. The Hanging Lake Tunneling Project is presented as an example where the estimation of tunnel advance rates for all tunneling alternatives is performed at the activity level and where the allocation of limited resources is encapsulated in tunneling plans particular to the tunneling alternative being analyzed.

1 INTRODUCTION

In construction simulation we often advocate that modeling of cyclic operations should be performed at the process level in a manner that reflects the explicit competition for the resources required by conditional (combi) activities. Moreover, we try to model explicitly the flow of resources as they are captured and released by the tasks that need them. While this is the appropriate modeling approach for work that should be allowed to start as soon as the required resources are free, it may be very difficult to implement in cases where resources should remain idle and wait deliberately so that they may be allocated to other activities that can start later.

The problem is similar to that of limited resource allocation in CPM. Limited resources should not always be allocated to those activities that can start first. Often they need to be held back and be allocated to critical activities that start a little later and which, if delayed due to lack of resources, would delay the whole project. Committing resources to non-critical activities that happen to start earlier (simply to keep the resources busy or to start the first activities that can be started) may end up delaying the project and costing more money.

When faced with work of this kind it is advantageous to abandon conventional wisdom and explore different modeling paradigms. For example, sometimes modeling at the activity level is more straightforward and more meaningful than modeling at the process level. At the activity level the flow of resources (manpower and equipment) is embedded (hardwired) into the structure of the network (the definition of activities and their precedence relationships). Modeling at the process level treats the resources and the environment (e.g., site conditions) as prerequisites for activities and puts conditional activities (combis) into competition with each other. Making decisions at run time about what the resources should do next is not at all straightforward.

The problems that arise are not easy to explain and understand in general terms. To make matters clearer we present below an example from a tunneling project that is a good case where modeling at the activity level and bypassing the dynamic modeling at the resource level makes perfect sense. It is much easier and produces more realistic and reliable results.

2 THE HANGING LAKE TUNNELING PROJECT

The Hanging Lake Project, a twin-bore highway tunnel in Colorado, is used to illustrate the application of the above concepts. This example focuses on the part of the westbound tunnel excavated by multiple-face drill and blast tunneling methods, as shown in Figure 1. The objective of our simulation models was to estimate the distribution of the advance rate for each possible combination of construction methods and geologic conditions. Subsequently, these distributions became the main input for a dynamic decision model that determined risk-sensitive optimal construction strategies given the uncertainty in geology and construction performance.

The geologic conditions of this project were classified into three ground classes: *GC1* (best), *GC2* (medium), and

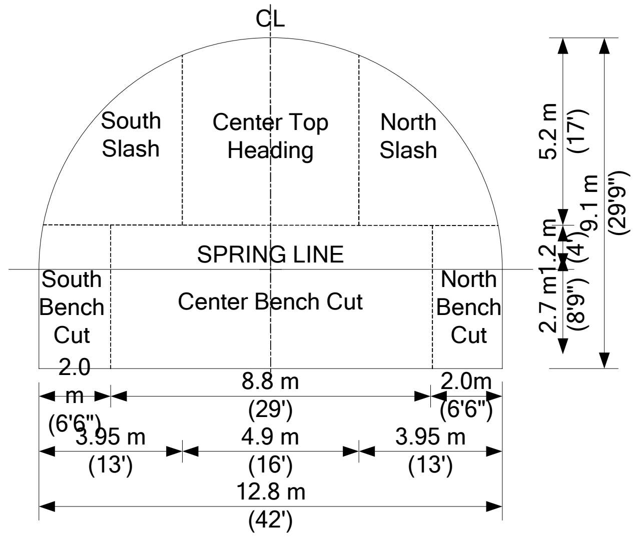


Figure 1. Cross Section of the Hanging Lake Tunnel

GC3 (worst). A detailed description of each ground class appears in (Essex et al. 1993).

For tunnel stabilization purposes, this project required staged or sequential excavation using six drifts. The faces of these drifts were not advanced to the same location in the tunnel but rather had to be staggered so that a set of minimum distances would always exist between drift faces to maintain the stability of the openings.

Three excavation methods (*EM1*, *EM2*, and *EM3*) and three primary support systems (*SS1*, *SS2*, and *SS3*) were designed corresponding to the three ground classes. For example, EM1 and SS1 are the most economical and structurally adequate excavation and support method for GC1. Table 1 shows the six drifts, the three excavation methods, their corresponding round lengths, and the minimum distances between drift faces.

Table 1. Tunnel Excavation Specifications

No	Drift	Round Length (ft)		
		EM1	*EM2*	*EM3*
1	Center top heading (CT)	12	8	4
2	North slash (NS)	16	8	4
3	South slash (SS)	16	8	4
4	Center bench cut (CB)	24	24	24
5	North bench cut (NB)	16	16	8
6	South bench cut (SB)	16	16	8

Note: Minimum distances between drift faces:

- NS must lag at least 50 ft behind CT.
- SS must lag at least 25 ft behind NS.
- CB must lag at least 100 ft behind SS.
- NB must lag at least 25 ft behind CB.
- SB must lag at least 25 ft behind NB.

3 TUNNEL ADVANCE RATES

The overall productivity of tunneling operations can be expressed by the tunnel advance rate, the length of tunnel that can be excavated and supported per unit of time. Time-dependent variable costs, a major component of the total cost of tunneling, are direct functions of the advance rate. Thus, estimating all possible tunnel advance rates is central to tunnel cost estimating.

3.1 Tunneling Alternatives

The possible combinations of different excavation and support methods and the geologic conditions to which they may be applied are called tunneling alternatives. There are nine possible tunneling alternatives in this example (i.e., three excavation and support methods matched with each of three possible ground classes). For example, alternative (*EM1*,*GC2*) represents the decision to apply *EM1* for a particular round and the actual ground class after blasting being *GC2*.

Each tunneling alternative involves a significant change in the nature of the work and thus requires different activities and precedence between them (especially when tunneling by multiple-drift methods). Thus, the advance rate for each tunneling alternative must be determined separately.

3.2 Time-Estimating Equations

Work in a tunneling project can be broken down into detailed levels such as the operation level, the activity level, and the process level by using a work breakdown structure (WBS) (Likhitruangsilp and Ioannou 2003). For example, the tunnel excavation operation can be broken down into the drill, load, and blast activities. The drill activity can be refined further into such processes as mobilize the drill rig to the tunnel face, drill blast holes, and withdraw the drill rig from the tunnel face before blasting.

The duration of tunneling work can be determined by analyzing the work at the process level. The duration of each activity is expressed by a time-estimating equation, which can be formulated by analyzing the main processes associated with that activity. The tunneling time equations used for the Hanging Lake Project were modified from those in the Tunnel Cost Model (Minott 1974) to reflect modern tunneling technologies. These time-estimating equations were used to calculate the duration of the three main tunneling operations: excavation, mucking, and support. For example, the excavation duration is determined by the duration of the drill, load, and blast activities, each of which is computed by the corresponding equation (Likhitruangsilp 2003).

3.3 Parameter Assessment

Uncertainty in the productivity of construction processes was assessed subjectively using the three-point estimate method proposed by (Perry and Greig 1975). For each parameter used in time-estimating equations, a three-point estimate (p5, M, p95) was assessed, where p5 is the 5th percentile, M the most likely value (mode), and p95 the 95th percentile for that parameter. For example, the three-point estimate for the penetration rate of a drill rig in a particular ground class was assessed to be (150, 300, 345) ft/hr. This means that the most likely drilling rate for this machine in this geologic conditions was 300 ft/hr; while there was a five percent probability that the drilling rate may be lower than 150 ft/hr and a five percent probability that the drilling rate could exceed 345 ft/hr.

The Perry and Greig method was also used to estimate the impact of other types of risk as well, such as the effect of equipment breakdowns and the effect of choosing the wrong construction method for a given geology. For example, applying an inappropriate excavation method leads to excessive rock overbreak or underbreak, and thus to additional work, delays, and extra costs, whose extent also needed to be estimated.

4 MODELING TUNNELING ACTIVITIES

The detailed estimation of tunnel advance rates requires an accurate model of tunneling activities as performed during construction. Tunneling work is cyclic in nature. Each round consists of a specific sequence of tunneling activities, such as drill, load, blast, muck, and support. The precedence logic of these activities is often determined by three major constraints: technological constraints, design details, and resource availability. The precedence logic of tunneling activities can be extremely complicated, particularly when tunneling by multiple-face methods (e.g., heading and bench, or multiple-drift), which makes estimating tunnel advance rates particularly challenging.

5 TUNNELING PLANS

To deal with these complexities in practice, contractors must develop tunneling plans that satisfy technological constraints, design details, and resource availability, and are easy to implement during construction. A developed tunneling plan is usually structured as a cyclic pattern. Each tunneling cycle consists of a specific sequence of rounds, each of which has its own precedence relationships of tunneling activities. The precedence logic of tunneling activities for the entire cycle can thus be represented as a collection of several activity networks one for each corresponding round.

Table 2 shows the tunneling cycle, rounds, and corresponding activities for alternative (EM1,GC1). Table 3 shows the tunneling patterns for the tunneling plan also for alternative (EM1,GC1).

A tunneling cycle must be designed in such a way that at the end of each cycle every tunnel heading is advanced by the same distance (called the cycle length). Thus, the tunnel advance rate for multiple-face tunneling can be approximated by dividing its cycle length by the tunneling duration for each cycle. Figure 2 shows the drilling progress achieved by each round within the 48 ft cycle of the

Table 2. Tunneling Cycle, Rounds, and Corresponding Activities for (*EM1*, *GC1*)

Drift	Round Length	Tunneling Round			
		A	*B*	*C*	*D*
Center Top (CT)	12 ft	bmsd	bmsd	bmsd	bmsd
North & South Slashes (NS & SS)	16 ft	bmsd	bmsd	bms	d
Center Bench (CB)	24 ft	m d	bm d	b	
North & South Benches (NB & SB)	16 ft	d	bmsd	bmsd	bms

Note: A tunnel cycle is 48 ft long and consists of tunneling rounds *A* – *B* – *C* – *D* in that order. Each round consists of the sequence of activities blast (b), muck (m), support (s), and drill &load (d) in that order. Thus, blasting in round *A* is performed using blast holes drilled and loaded in round *D*.

Table 3. Tunneling Patterns of Tunneling Plan for Alternative (*EM1*, *GC1*)

Tunneling Activity	Tunneling Round			
	A	*B*	*C*	*D*
Blast (b)	CT, NS, SS	All drifts	All drifts**	CT, NB, SB
Muck (m)	CT, NS, SS, CB*	All drifts	CT, NS, SS, NB, SB	CT, NB, SB
Support (s)	CT, NS, SS	CT, NS, SS, NB, SB	CT, NS, SS, NB, SB	CT, NB, SB
Drill & Load (d)	All drifts	All drifts	CT, NB, SB	CT, NS, SS

(*) Mucking CB in round A removes the results of blasting in round C from the previous cycle (**) in preparation for drilling and loading at CB at the end of round *A*. In the meantime, this muck is used as a temporary ramp for accessing the top headings.

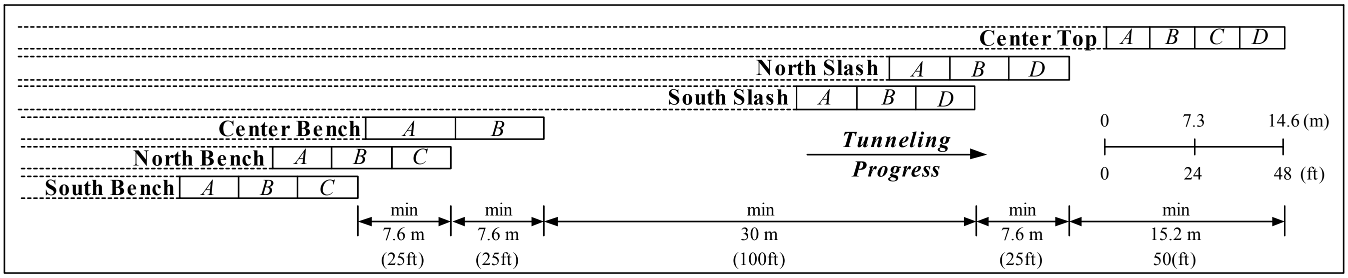


Figure 2. Drilling Progress for Tunneling Plan of Alternative (*EM1*, *GC1*)

tunneling plan for alternative (EM1,GC1).

The detailed tunneling plan for each of the nine alternatives was developed based upon tunneling specifications prescribed by tunnel design. Each plan included a typical tunneling cycle, the sequence of rounds in each cycle, and tunneling patterns that describe activities performed at different headings in a particular round.

6 ACTIVITY NETWORKS AND RESOURCE ALLOCATION

The precedence logic for each tunneling alternative was developed based on the defined tunneling plan and resource availability during construction. Figure 3 shows a precedence network of the activities performed in round *A* of the tunneling plan presented in Tables 2 and 3 (the suffix "_a" indicates round *A*).

Since the number of machines for each tunneling operation is fewer than the number of drifts, it is necessary to prioritize the utilization of these machines. For example, this network reflects the fact that only two rock-bolting rigs were available. Based on preliminary results from deterministic scheduling, one of them is assigned to work at the north and south slashes (RBNS_a and RBSS_a), whereas the other machine works at the center top (RBCT_a). Thus, although mucking at the north slash (MuckNS_a) might be finished at the same time as mucking in the south slash (MuckSS_a), rockbolt installation at this face (RBNS_a) cannot begin until the machine is available, i.e., after completing the rockbolt installation at the south slash, (RBSS_a).

These concepts are easier to understand in Figure 4. This is a time-scaled arrow network for round *C* for alternative (*EM1*, *GC1*) that uses deterministic times to investigate the effectiveness of the proposed tunneling plan. As shown in the figure, mucking in the north and south slashes are technological prerequisites for mucking the center top drift (to provide access for the equipment). Theoretically, the installation of rockbolts in both the north and south slashes could follow immediately after mucking. As this network makes evident, however, doing so would delay the start of rockbolt installation in the center top drift because there are only two rock-bolting rigs available. Thus, it is an obviously better strategy to dedicate one rock-bolting rig to the center top drift and share the other between the south and north slashes. Although this strategy delays rockbolt installation in the north slash by making it a successor to rockbolt installation in the south slash, it produces the minimum possible deterministic cycle duration (531 minutes). This strategy is clearly even more superior when uncertainty in activity duration is taken into account.

This is the fundamental essence of the issue that we would like to bring forth in this paper. For a problem such as modeling the work and the flow of all resources for all

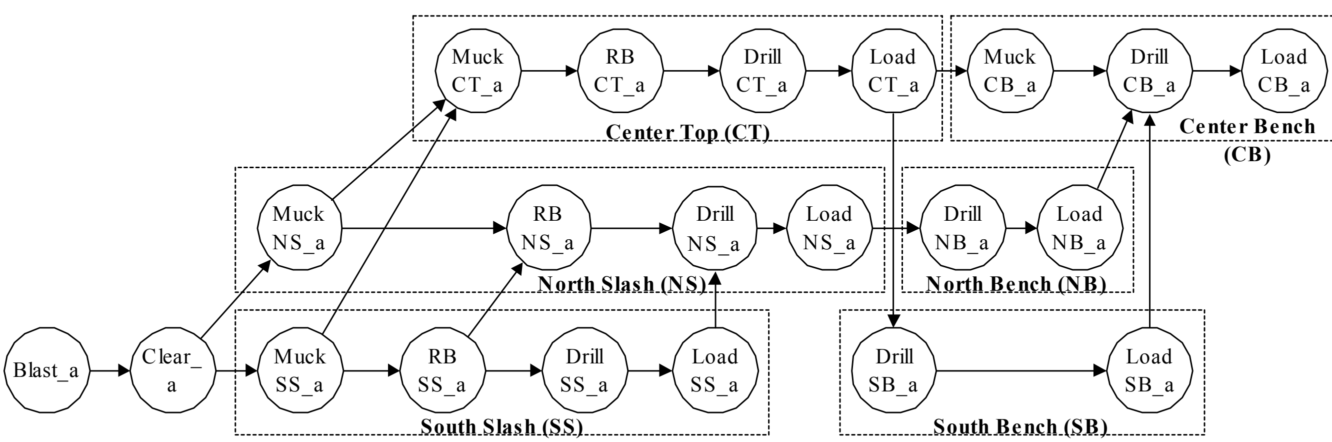


Figure 3. Precedence Network of Round *A* in Tunneling Plan for (*EM1*, *GC1*)

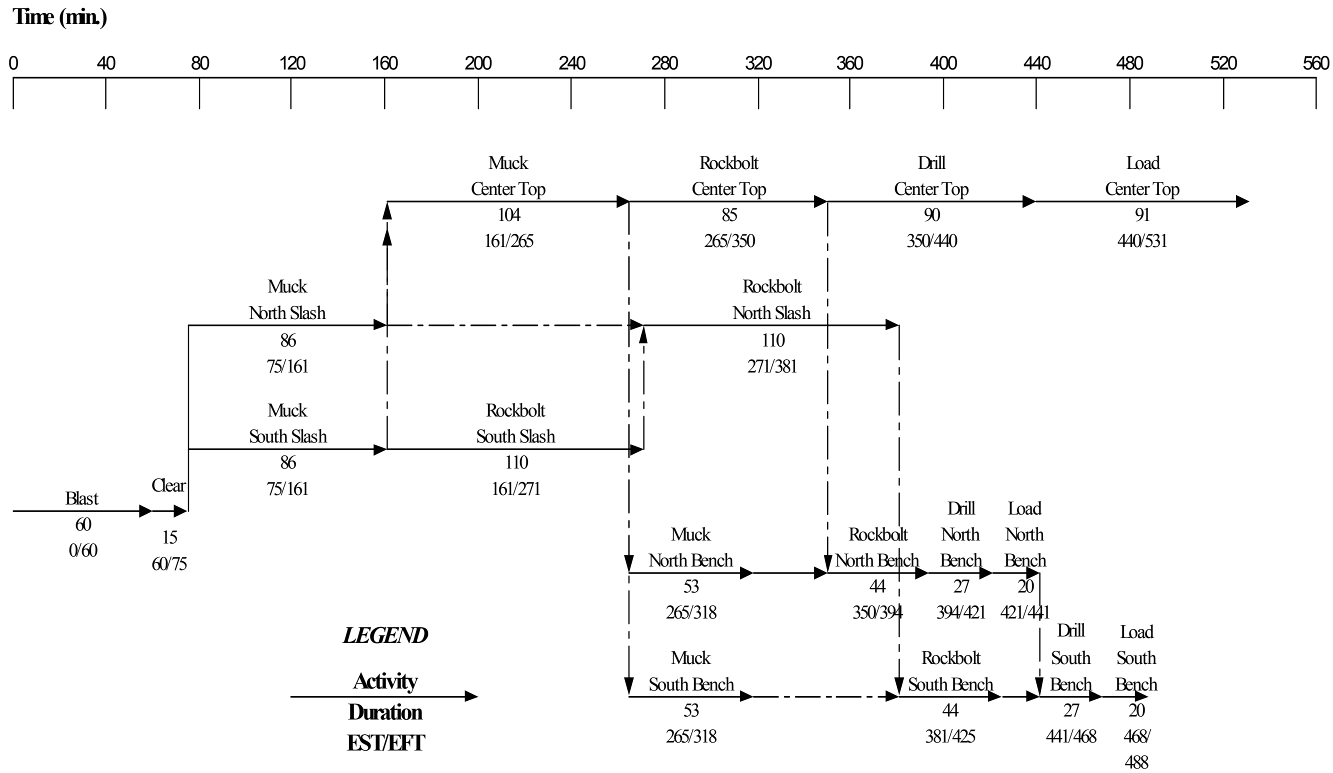


Figure 4. Time-Scaled Arrow Network for Round *C* of Tunneling Plan for Alternative (*EM1*, *GC1*)

nine possible tunneling alternatives for the Hanging Lake Project, it would be quite a challenge to develop process networks that include competition for resources among tasks and intelligent optimal dynamic resource flows at runtime. The default allocation of resources to activities on a first-come-first-served basis would obviously be inefficient because it ignores the overall criticality of activities. Thus, sometimes it may better to model the problem at the activity level, rather than the process level, and investigate strategies for resource allocation based on simplified models, such as time-scaled arrow networks.

7 TUNNEL CONSTRUCTION SIMULATION

A separate simulation model was constructed and analyzed for each of the nine tunneling alternatives. The complete network for each alternative was similar in structure to the precedence network shown in Figure 3 but was about four times larger as it included activities and precedence relationships for the work in all four rounds *A-B-C-D* within the complete cycle for each tunneling alternative.

Modeling and simulation was performed using the *ProbSched* add-in for STROBOSCOPE, a general-purpose simulation system based on activity scanning (Ioannou 1999; Ioannou and Martinez 1999, 1996a, b, c; Martinez 1996; Martinez and Ioannou 1999, 1995, 1994). The program *ProbSched* is a graphical tool for modeling probabilistic activity networks (Ioannou and Martinez 1998).

The duration of each activity in a precedence network was determined by using its corresponding time equation whose parameters were either defined deterministically or assessed subjectively by using the Perry & Greig method. The probabilistic scheduling networks for each of the nine tunneling alternatives appear in (Likhitruangsilp 2003).

The simulation results provided probability distributions for the tunnel advance rates of the nine possible tunneling alternatives in this example. Figure 5 shows the cumulative distribution functions (CDFs) for the tunnel advance rates for each of the nine alternatives as produced by simulation. These probability distributions can be approximated very well by normal distributions, the means and standard deviations of which are presented in Table 4.

Table 4. Normal Distributions for Tunnel Advance Rates

Tunneling Alternative	Tunnel Advance Rate (ft / 8-hr shift)					
	*GC*1		*GC*2		*GC*3	
	Mean	SD	Mean	SD	Mean	SD
*EM*1	7.94	0.36	3.70	0.11	1.85	0.06
*EM*2	4.04	0.13	5.42	0.16	2.50	0.08
*EM*3	2.61	0.1	2.60	0.08	4.18	0.12

8 SIMULATION RESULTS

The consequence of applying an excavation method in a particular round depends upon the actual geologic conditions revealed after blasting. As indicated in Figure 5, if the selected method is appropriate for the actual geologic conditions, this tunneling decision will lead to the highest tunnel advance rates for the geologic conditions revealed in that round. Thus, tunneling alternatives (*EM1*, *GC1*), (*EM2*, *GC2*), and (*EM3*, *GC3*) have higher advance rates than other tunneling alternatives for the same ground class.

If a contractor selects a method that is structurally inadequate for the actual ground class to be revealed, it may lead to severe damage of the surrounding rock or even tunnel collapse [i.e., (*EM1*, *GC2*), (*EM1*, *GC3*), and (*EM2*, *GC3*)]. The risks resulting from this excessive overbreak include increased mucking time and additional tunnel support. In this example, these risks were assessed subjectively and incorporated into tunnel estimating.

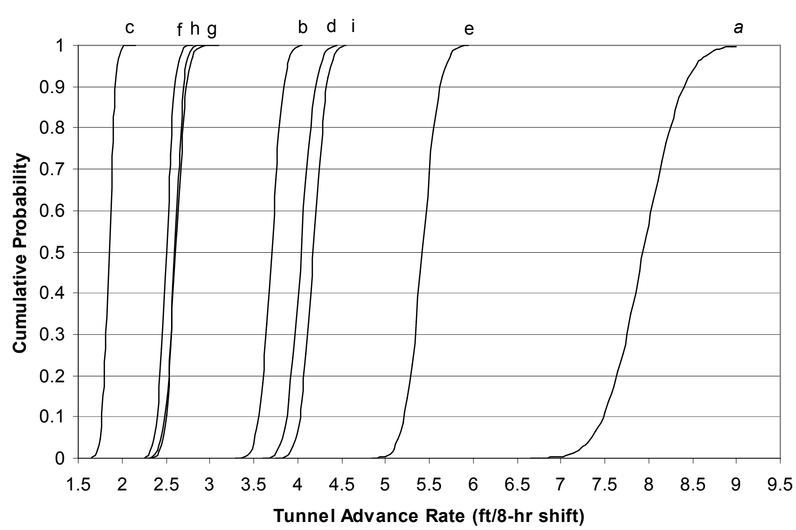
In contrast, if the selected method is overly conservative for the actual ground conditions (e.g., employs insufficient explosives), the opening might be under-excavated, which requires additional time for removing underbroken rock [i.e., (*EM2*, *GC1*), (*EM3*, *GC1*), and (*EM3*, *GC2*)]. Similarly, the risks associated with underbreaking the tunnel were also assessed subjectively and incorporated into tunnel estimating. Thus, the resulting tunnel advance rates include both direct tunnel construction time and the impact of selecting inappropriate excavation methods.

It should be pointed out that the greatest risk in tunneling is due to geologic uncertainty. Yet, the variability for each of the cumulative distribution functions for the nine advance rates in Figure 5 is relatively small. This due to the fact that each tunneling alternative is defined for particular geologic conditions as described by the corresponding ground class. Thus, the variance of each distribution in Figure 5 reflects only the effects of uncertainty in the productivity of tunneling processes (i.e., the variation in human and machine performance) that were considered while assessing time-estimating parameters. Consequently, the dispersion of these parameters is not as high as it would have been if geologic uncertainty was also a factor considered during parameter assessment.

The much stronger effect of geologic uncertainty is reflected in the overall shift from one distribution to another as a transition is made from one ground class to the next. For example, an examination of curves *a*, *e*, and *i* in Figure 5, corresponding to (*EM1*, *GC1*), (*EM2*, *GC2*), and (*EM3*, *GC3*) respectively, indicates that the advance rate distributions do not even overlap as the geology changes from best to worst, even if the most appropriate construction method is used for the corresponding ground class.

9 RISK-SENSITIVE DYNAMIC DECISION MODEL FOR TUNELING

The probability distributions of tunnel advance rates obtained from the probabilistic scheduling analysis presented in this paper were used directly in probabilistic tunnel cost estimating. The resulting probabilistic tunnel cost estimates for each of the nine tunneling alternatives and the ground class transition probabilities computed by the probabilistic geologic prediction model formed the main inputs for the risk-sensitive dynamic decision model, which optimized a contractor's tunneling decision in each tunneling stage (round) to determine optimal tunneling policies and risk-



Legend: *a* – (*EM*1,*GC*1); *b* – (*EM*1,*GC*2); *c* – (*EM*1,*GC*3); *d* – (*EM*2,*GC*1); *e* – (*EM*2,*GC*2); *f* – (*EM*2,*GC*3); *g* – (*EM*3,*GC*1); *h* – (*EM*3,*GC*2); *i* – (*EM*3,*GC*3)]

Figure 5. CDFs of Tunnel Advance Rates for Different Alternatives

adjusted costs for the project. Both results reflect available project information and the contractor's risk preference.

Figure 6 illustrates the optimal tunneling policies for the west segment of the Hanging Lake Project for a risk neutral contractor. Figure 7 illustrates the optimal tunneling policies for a risk averse contractor with an exponential utility function whose risk- aversion coefficient equals 5/$M. In these two figures each of the nine lower bars indicates the optimal excavation and support method that should be adopted at any location of the tunnel as a function of the current ground class and excavation and support method (i.e., tunneling alternative). The top bar shows the most likely ground class profile. At each location this profile shows the ground class with the largest ground class state probability. At locations where two ground classes are equally likely both ground classes are shown by using two overlapping bars.

To understand these figures and see the difference in decision making behavior based on the contractor's degree of risk-aversion, let us investigate stage 170 at location 2,028 ft of the west segment. For a risk-neutral contractor, if the current geology is in ground class *GC*1 and excavation and support method *EM*1 is being used, the optimal decision is to continue using *EM*1 for the subsequent stage (round), as shown by the top bar in Figure 6. However, for a risk-averse contractor faced with the same state, (*GC*1, *EM*1), the optimal decision is to switch to *EM*2 for the next stage, as shown by the top bar in Figure 7. That is, a risk-averse contractor would adopt a more conservative excavation method to mitigate the risks associated with using an inadequate method that might occur in the next stage. Especially in this case, where it is known that *GC*3 will be encountered in the subsequent stage (stage 171) with certainty. Therefore, the risk-averse contractor would decide to adopt a more conservative method to avoid adverse effects that might occur if *GC*3 prevails in Stage 170.

The complete analysis of the Hanging Lake Project can be found in (Likhitruangsilp 2003).

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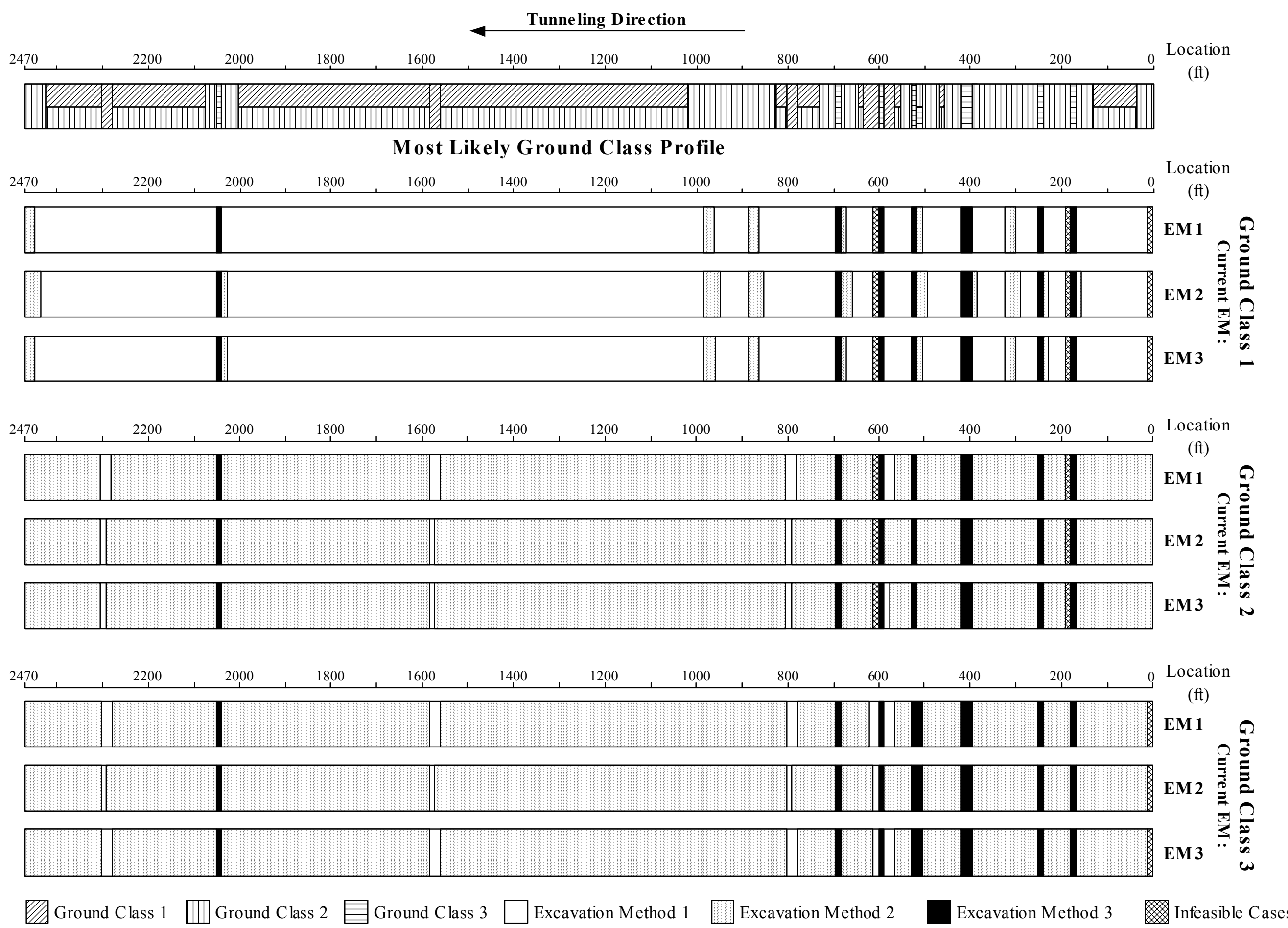

Figure 6. Optimal Tunneling Policies for the West Segment of the Hanging Lake Project for a Risk-Neutral Contractor

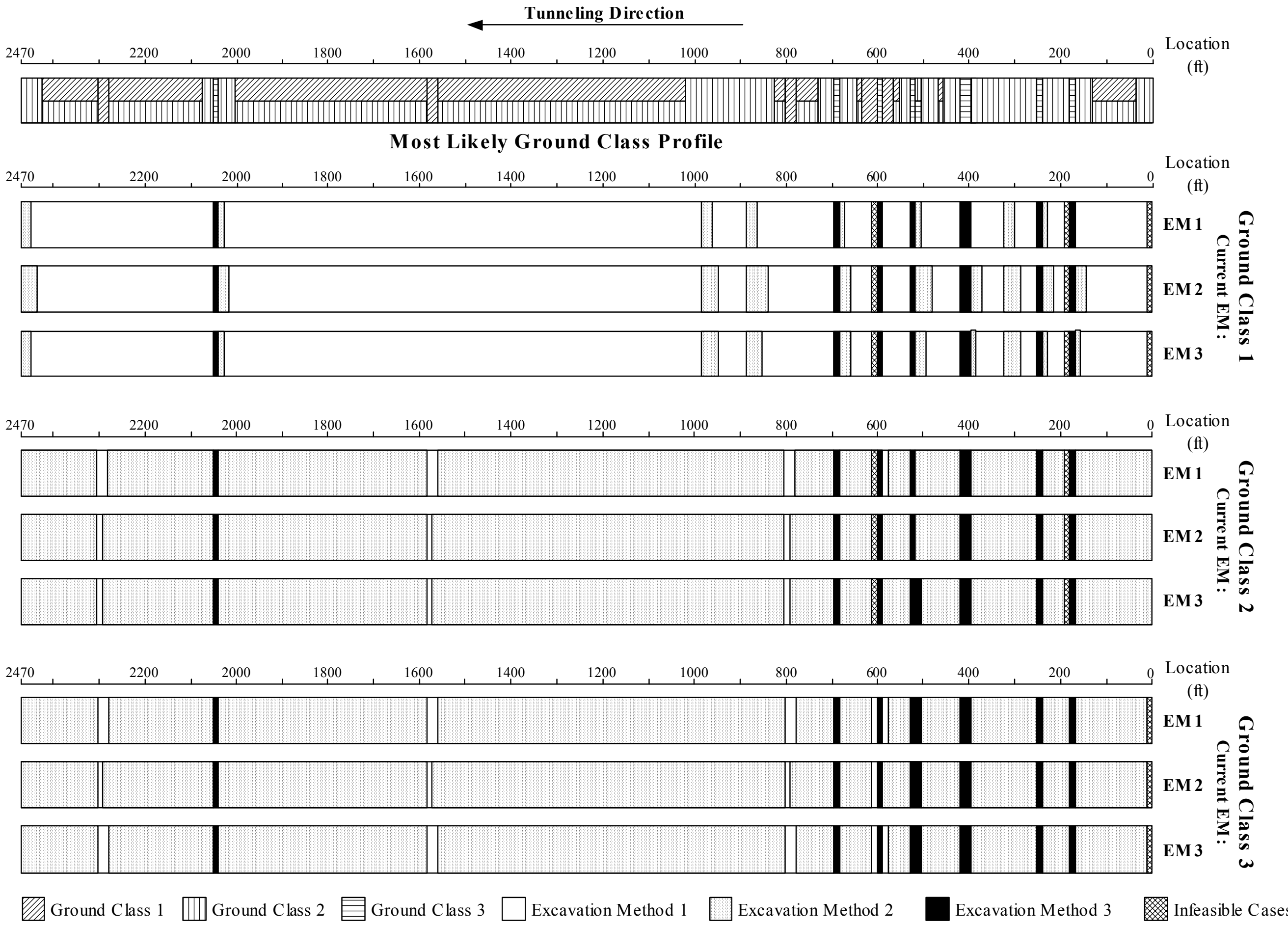

Figure 7. Optimal Tunneling Policies for the West Segment of the Hanging Lake Project for a Risk-Averse Contractor

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