DETAILED PROBABILISTIC CONSTRUCTION ESTIMATING BY MONTE CARLO SIMULATION

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ABSTRACT : The complexity of construction operations and their associated uncertainties lead to a significant amount of risk in construction estimating. Conventional deterministic estimating cannot capture these uncertainties in a systematic and quantitative manner. Thus, a probabilistic approach is necessary to assess these risks. This paper presents a detailed probabilistic estimating using Monte Carlo simulation. The probabilistic estimating of a tunneling project is presented as an example application. Tunnel advance rates are estimated using detailed probabilistic scheduling of tunneling operations. Precedence activity networks for tunneling operations are constructed as functions of the chosen excavation and support method and the revealed geologic conditions (tunneling alternatives). The duration of tunneling activities is expressed by time-estimating equations, and their associated uncertainties are assessed by subjective assessment using the Perry & Greig method. Probabilistic scheduling is analyzed by Monte Carlo simulation performed in the *ProbSched* program. The results provide probability distributions of tunnel advance rates for all possible alternatives, which can be used to determine optimal excavation and support methods for the project.

KEYWORDS : PROBABILISTIC ESTIMATING, CONSTRUCTION RISKS, MONTE CARLO SIMULATION

1. Introduction

Construction is complex work comprised of a series of interdependent operations that involve a variety of risks, which result from uncertainties associated with the work such as uncertainty in the labor's productivity. Accounting for these risks explicitly during construction estimating presents a challenge to all contractors. To be competitive and profitable, they must assess significant construction risks and incorporate them into their estimates in a systematic and quantitative manner. Because conventional deterministic estimating cannot quantify risk, a probabilistic approach is necessary to evaluate risks associated with construction operations.

This paper presents detailed probabilistic construction estimating using Monte Carlo simulation. Tunnel advance rate estimating for an actual highway tunneling project is used to illustrate the application of the proposed methodology.

2. Construction Estimating

Construction estimating is a systematic process for assessing project cost and time to allow for prudent decision making before the physical performance of the work. A complete estimate should take into account all resources that are necessary to create the facility and their impact on time and cost. Yet, this should be done at a level of detail that is useful for estimating decisions [1]. For example, in the early stage of a construction project the owner may want to know a rough estimate of the project cost for establishing the budget. Later, a contractor needs a detailed estimate for preparing the firm's bid. In general, all estimates can be determined by using one of two approaches: direct encoding or modeling (detailed estimating).

3. Direct Encoding versus Detailed Estimating

Because of limited information, the pre-design and conceptual estimates cannot achieve a high level of accuracy and are usually prepared based on directly encoded quantities and unit prices. Examples of direct encoding estimating methods are unit price estimating and parameter cost estimating. These estimating methods rely on unit prices of work items collected from previous similar projects. In contrast, contractors need and have the expertise and data to produce more accurate estimates closer to the final project cost. This is because the accuracy of a contractor's estimate significantly influences the success of his bid and profit. Thus, detailed cost estimating is the preferred approach for contractors.

In detailed estimating, an estimator typically begins with organizing all work items in the project into a number of divisions by using some form of work breakdown structure (WBS). In order to estimate costs for each division, work within that division is refined into detailed levels such as the operation level, the activity level, and the process level. Figure 1 shows a WBS designed specifically for tunneling projects. Detailed description of this WBS can be found in [2].

The total cost for each division can be determined from the costs associated with all operations that belong to that division. It is possible that different divisions are estimated by using different levels of work breakdown. This decision depends upon available information, and the complexity and uncertainty associated with the work in a particular division. The construction plans and costs for all divisions are then integrated to attain the construction plan and the total cost for the entire project.

Both direct encoding and detailed cost estimating are used in construction, especially for estimating the productivity of construction operations. Using the direct encoding approach, estimators can encode subjectively the productivity based on all available information and their experience from past similar projects. In detailed estimating, the productivity of a construction operation is analyzed at the activity or process level. A possible approach is to establish the precedence relationships of construction activities and model the work through scheduling networks. The duration of activities can be estimated by analyzing the work at the process level. The duration of the entire operation can then be determined by analyzing the activity networks using such techniques as the Critical Path Method (CPM).

Clearly, the direct encoding approach is much simpler and less time consuming than the model development needed for detailed cost estimating. However, it can provide a good estimate only if the estimating database is applicable to the project being priced; that is, the conditions of past projects (e.g., construction methods) were similar to those of the project being priced. Another shortcoming of direct encoding is its limited ability to incorporate uncertainty into estimates. This is because the estimating parameters (e.g., productivity) in the direct encoding approach are derived from the estimator's database (e.g., crew size), which generally does not maintain records of work conditions. As a result, it is quite challenging to modify these parameters to reflect uncertainty associated with work conditions in a new project. Thus, in most cases it is necessary to resort to detailed estimating to assess the risks associated with construction operations.

4. Detailed Probabilistic Estimating

Construction estimating can also be classified into deterministic or probabilistic depending on the estimating input available. The input for deterministic estimating is single values (single-point estimates), which can be average values (means), most likely values (modes), or medians. This approach is appropriate for estimating work whose uncertainty (e.g., variability) is small.

Most construction projects, however, involve significant uncertainties. For example, in tunnel construction the primary source of uncertainty is geologic uncertainty. Imperfect knowledge of geologic conditions leads to significant uncertainty in estimating tunneling time and cost. Conventional deterministic estimating cannot provide a measure of uncertainty making a probabilistic approach necessary to evaluate construction risks. Moreover, probabilistic estimating must be incorporated into detailed estimating to be able to model risks at the process level of construction operations.

5. Modeling Construction Operations

Once a construction plan for the project has been established based on available information (e.g., bidding documents), the contractor organizes all work into divisions using the owner's BOQ or his own WBS. The contractor identifies important construction operations associated with each division. The activities within each division are in turn specified. The precedence relationships of construction operations and activities are then established. The precedence logic of construction activities can be represented by scheduling networks such as precedence networks or arrow networks.

For example, the overall productivity of tunneling operations can be expressed by the tunnel advance rate, the tunnel length that can be excavated and supported per unit of time. The possible combinations of different excavation and support methods and the geologic conditions to which they may be applied are called *tunneling alternatives*. Each tunneling alternative implies a change in the nature of the work and requires different activities and precedence between activities.

The detailed estimation of tunnel advance rates requires a realistic model of tunneling activities performed during construction. Tunneling is a cyclic operation. 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. As a result, 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). This in turn can make tunnel advance rate estimating quite challenging.

To deal with these complexities in practice, contractors must develop tunneling plans that satisfy the above constraints 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 each cycle can be represented by a sequence of the activity networks (e.g., precedence networks) of its corresponding rounds. 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 the multiple-face tunneling can be approximated by dividing its cycle length by the tunneling duration for each cycle.

6. 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, as shown in Figure 1. 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 after 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 main processes associated with that activity. The tunneling time equations used in the example of this paper have been modified from those in the Tunnel Cost Model [3] to reflect modern tunneling technologies. These time-estimating equations are used to calculate the duration of 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.

7. Parameter Assessment

In order to incorporate the effects of uncertainty in the productivity of construction processes (e.g., machine breakdown) into estimating, important uncertainties associated with the processes are estimated by subjective assessment using the Perry & Greig method. Each parameter in the time-estimating equations is assessed by a three-point estimate (p_5,M,p_{95}), where p_5 is the 5th percentile, M is the most likely value (mode), and p_{95} is the 95th percentile of the parameter. For example, the drilling rate of a drill rig performing in a particular ground condition is assessed subjectively by a contractor to be (46,91,105) m/hr [i.e., (150,300,345) ft/hr]. This means that the most likely drilling rate of this machine in this particular ground condition is 91 m/hr; there is a five percent probability that the drilling rate may be lower than 46 m/hr, and there is a five percent probability that the drilling rate may exceed 105 m/hr.

The Perry & Greig method can also be applied to estimate other types of risk such as risks associated with choosing the wrong construction method. For example, in tunnel estimating applying an inappropriate excavation method may lead to excessive overbreak or underbreak problems, and the time-estimating parameters that are affected by these decisions can be assessed and incorporated into estimating by using the Perry & Greig method, similar to that presented above.

8. Probabilistic Scheduling

The probabilistic construction estimating is accomplished through probabilistic scheduling networks of the construction activities that have been analyzed using Monte Carlo simulation. Construction simulations are performed in *ProbSched*, a graphical version of the CPM add-on for the STROBOSCOPE simulation system [4].

In this paper, simulations are performed for each tunneling alternative. The necessary inputs for the *ProbSched* program include:

- A precedence network of tunneling activities in each cycle,
- Time-estimating equations for all activities, and
- Time-estimating parameters, which can be defined by deterministic values or random variables (i.e., three-point estimates).

For each replication, the random variables in the simulation model are sampled by Monte Carlo method, and the sampled values are then used as inputs for the time-estimating equations. These equations provide inputs for CPM calculations to determine the duration of the scheduling network, which in turn is used to compute the tunnel advance rate. After a large number of replications, the collection of the simulated advance rates can be represented by a probability function (e.g., a cumulative distribution function). The final results are the probability distributions of tunnel advance rates for all possible alternatives in the project, which can be used directly in probabilistic tunnel cost estimating.

9. Example Application

The Hanging Lake Tunnel Project in the state of Colorado (USA) is presented to illustrate the application of the proposed methodology. This rock tunneling project involved the construction of a pair of two-lane highway tunnels. Here we focus on the part of the westbound tunnel excavated by multiple-drift drill and blast methods.

Several rock mass classification systems were used to design this tunnel. Ultimately, the tunnel geology was classified into three ground classes: *GC*1 (best), *GC*2 (medium), and *GC*3 (worst). Detailed descriptions can be found in [5]. For rock stabilization purposes, the tunnel required staged or sequential excavation of six drifts (headings), as shown in Figure 2. The engineer also specified three excavation methods (*EM*1, *EM*2, and *EM*3) and three primary support systems (*SS*1, *SS*2, and *SS*3) in accordance with the three ground classes. For example, *EM*3 and *SS*3 represent the most conservative and the most expensive construction method for this project. It is also the only construction alternative that is structurally adequate for the worst geologic conditions anticipated in this project (i.e., *GC*3). Table 1 presents tunnel excavation specifications for the three excavation methods. The detailed specifications of *SS*3 are illustrated in Figure 2. There are nine possible *tunneling alternatives* in this example (i.e., 3 excavation and support methods × 3 possible ground classes). For example, tunneling alternative (*EM*1,*GC*3) is the decision to use *EM*1 in a particular round and the actual ground class of that round after blasting to be *GC*3 (leading to excessive overbreak).

Detailed probabilistic tunnel estimating begins with developing a tunneling plan for each alternative based on the provided tunnel design details and excavation specifications. A tunneling plan consists of a typical cycle, the sequence of rounds in each cycle, and tunneling patterns that specify construction activities that must be performed at different drifts in a particular round. Figure 3 shows the tunneling plan for alternative (*EM*1,*GC*1) in this example. As can be seen, each cycle is

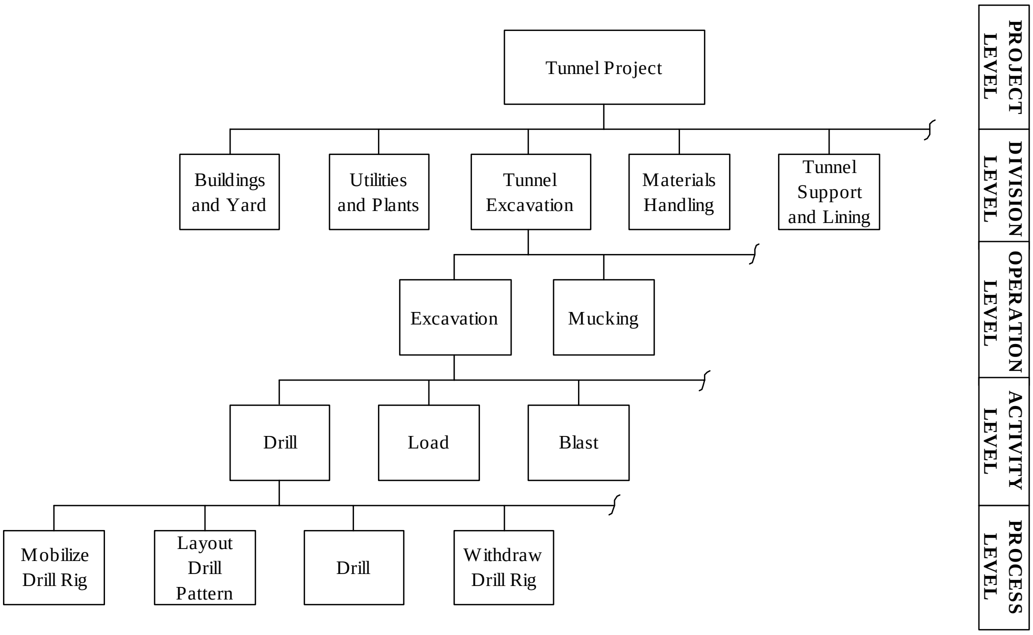

Figure 1 Work Breakdown Structure (WBS) of Tunneling Work

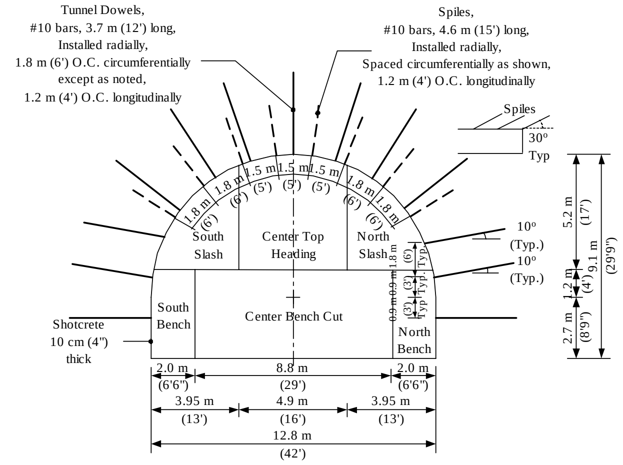

Figure 2 Tunnel Cross Section and Primary Support System 3 (*SS*3)

Table 1 Tunnel Excavation Specifications

No	Drift	Round Length		
		*EM*1	*EM*2	*EM*3
1	Center top heading (CT)	3.7 m (12 ft)	2.4 m (8 ft)	1.2 m (4 ft)
2	North slash (NS)	4.9 m (16 ft)	2.4 m (8 ft)	1.2 m (4 ft)
3	South slash (SS)	4.9 m (16 ft)	2.4 m (8 ft)	1.2 m (4 ft)
4	Center bench cut (CB)	7.3 m (24 ft)	7.3 m (24 ft)	7.3 m (24 ft)
5	North bench cut (NB)	4.9 m (16 ft)	4.9 m (16 ft)	2.4 m (8 ft)
6	South bench cut (SB)	4.9 m (16 ft)	4.9 m (16 ft)	2.4 m (8 ft)

Note: Other excavation requirements include:

- The north slash must be kept at least 15.2 m (50 ft) behind the center top.
- The south slash must be kept at least 7.6 m (25 ft) behind the north slash.
- The center bench cut must be kept at least 30 m (100 ft) behind the south slash.
- The north bench cut must be kept at least 7.6 m (25 ft) behind the center bench cut.
- The south bench cut must be kept at least 7.6 m (25 ft) behind the north bench cut.

14.6 m (48 ft) long and consists of rounds in the following order: *A* – *B* – *C* – *D*. Each round consists of the sequence of activities blast, muck, support, drill, and load in that order. Table 2 indicates tunneling activities that must be performed at different drifts for each particular round *A*, *B*, *C*, *D*.

The precedence logic of tunneling activities for each alternative is developed based on the defined tunneling plan and available construction resources (e.g., tunneling machines and work crews). Figure 4 presents a precedence network of the tunneling activities performed in round *A* of the construction plan shown in Table 2 (the suffix "_a" indicates round *A*). Because the number of tunneling machines for each operation is fewer than the number of drifts, it is necessary to prioritize the utilization of these machines. In this example, only two rock-bolting rigs are available. Based on the results from deterministic scheduling analysis, one of the machines (RB1) was assigned to work at the north and south slashes (RBNS_a and RBSS_a), whereas the other machine (RB2) worked at the center top (RBCT_a).

A separate simulation model for each tunneling alternative was constructed using the *ProbSched* program. The precedence network of a tunneling cycle for each alternative (similar to Figure 4) was defined first. The duration of each activity in the network was determined by applying the corresponding time-estimating equation whose parameters were either defined deterministically or assessed subjectively by using the Perry & Greig method. The probabilistic scheduling network for each alternative was then analyzed using Monte Carlo simulation performed by the *ProbSched* program. The main results from the simulations were probability distributions of tunnel advance rates (m/8-hr shift) for nine possible tunneling alternatives in the project, as shown in Figure 5. These simulation results can be approximated very well by normal distributions whose parameters (i.e., means and standard deviations) are presented in Table 3.

As indicated by the simulation results, the tunnel advance rate for a particular excavation method in a specific round depends upon the actual geologic conditions revealed after blasting. If the selected method is appropriate for the actual geologic conditions, this tunneling decision will lead to the highest advance rate for the revealed ground conditions in that round [i.e., (*EM*1,*GC*1), (*EM*2,*GC*2), and (*EM*3,*GC*3)]. However, if a contractor applies the method that is structurally inadequate for the prevailing ground class, it may cause severe damage of the surrounding rock or tunnel collapse [i.e., (*EM*1,*GC*2), (*EM*1,*GC*3), and (*EM*2,*GC*3)]. These wrong tunneling decisions contribute to excessive overbreak problems, which lead to increased time for mucking and installing additional tunnel support. Clearly, these adverse consequences decrease the tunnel advance rate significantly. In contrast, if the selected excavation method is overly conservative for the actual ground class (e.g., insufficient explosives), the tunnel might be underexcavated [i.e., (*EM*2,*GC*1), (*EM*3,*GC*1), and (*EM*3,*GC*2)]. These wrong tunneling decisions introduce underbreak problems, which cause additional time for removing underbroken rock and unnecessarily low progress of the work. For example, if a contractor chooses *EM*2 for excavating the tunnel in a particular round, from Table 3 the mean of tunnel advance rates for applying *EM*2 to *GC*2 (right decision) is 1.65 m/8-hr shift, whereas the means of tunnel advance rates for applying the same method to *GC*1 (underbreak) and *GC*3 (excessive overbreak) are 1.23 m/8-hr shift and 0.76 m/8-hr shift, respectively.

Since geologic conditions have already been defined as a state of each tunneling alternative (i.e., in the form of the ground class), only the effects of uncertainty in the productivity of tunneling processes (e.g., the variation of machine outputs) are considered while assessing time-estimating parameters. As a result, the dispersion of these parameters is not as high as it would have been if geologic uncertainty was also a factor considered during the parameter assessment. This leads to the relatively small variation of the simulated tunnel advance rates.

10. Conclusion

The probability distributions of tunnel advance rates obtained from the probabilistic scheduling analysis presented in this paper can be used directly in probabilistic tunnel cost estimating. The resulting probabilistic tunnel cost estimates and the ground class transition probabilities that are computed by the probabilistic geologic prediction model form main inputs for the risk-sensitive dynamic decision model, which optimizes a contractor's tunneling decision in each tunneling stage (e.g., round) to determine optimal tunneling policies and risk-adjusted costs for the project. Both results reflect available project information and the contractor's risk preference [2]. The detailed probabilistic construction estimating procedure presented in this paper can also be used in estimating other types of construction.

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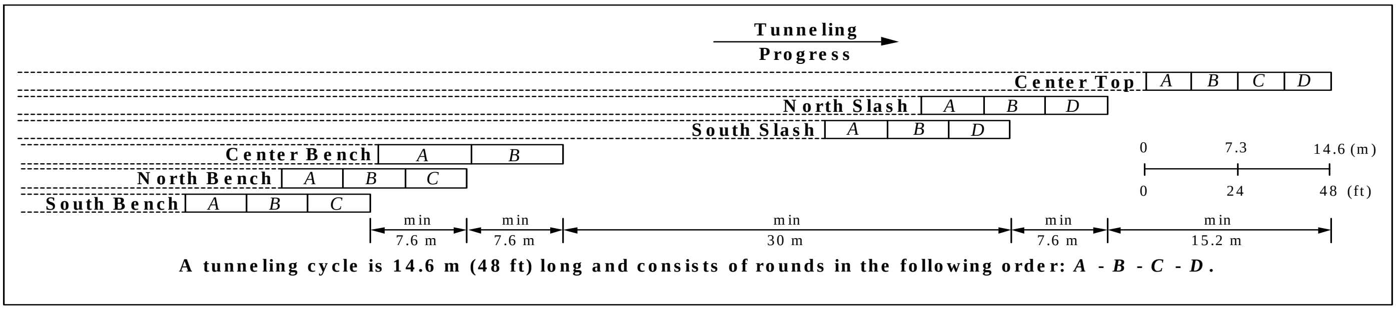
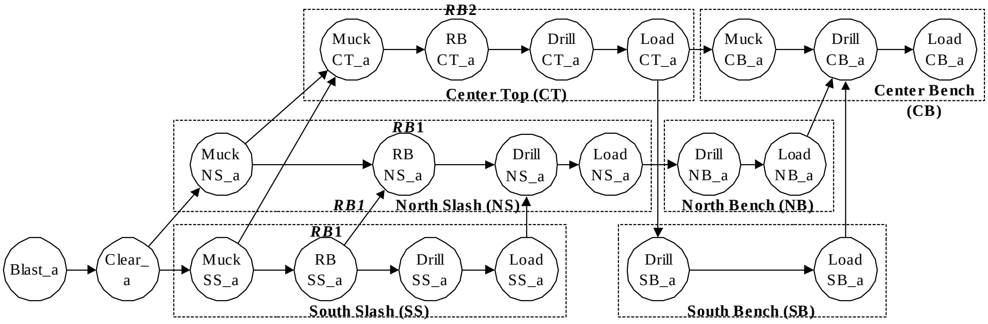


Figure 3 Tunneling Plan for Alternative (*EM*1,*GC*1)

Table 2 Tunneling Patterns of Tunneling Plan for Alternative (*EM*1,*GC*1)

Tunneling Activity	Tunneling Round			
	A	*B*	*C*	*D*
Blast	CT, NS, SS	All drifts	All drifts	CT, NB, SB
Muck	CT, NS, SS, CB	All drifts	CT, NS, SS, NB, SB	CT, NB, SB
Support	CT, NS, SS	CT, NS, SS, NB, SB	CT, NS, SS, NB, SB	CT, NB, SB
Drill & Load	All drifts	All drifts	CT, NB, SB	CT, NS, SS



Note: *RB*1 is the rock-bolting rig 1 and *RB*2 is the rock-bolting rig 2.

Figure 4 Precedence Network of Round *A* in Tunneling Plan for (*EM*1,*GC*1)

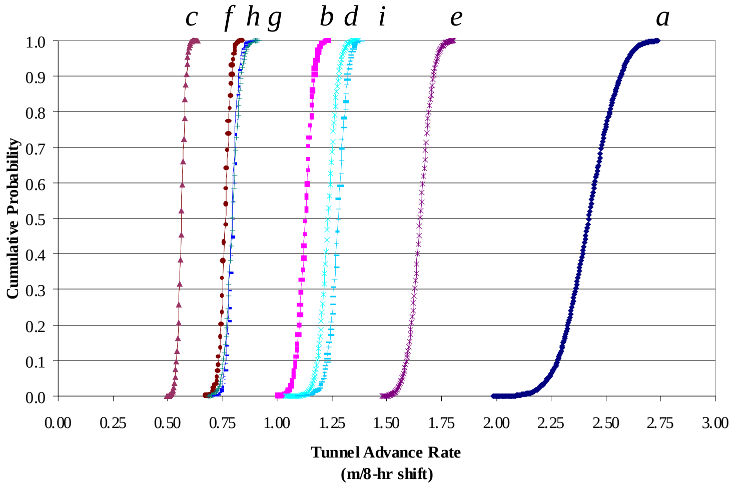


Figure 5 Cumulative Distribution Functions of Tunnel Advance Rates for Different Alternatives
[Note: *a* – (*EM*1,*GC*1); *b* – (*EM*1,*GC*2); *c* – (*EM*1,*GC*3); *d* – (*EM*2,*GC*1);
e – (*EM*2,*GC*2); *f* – (*EM*2,*GC*3); *g* – (*EM*3,*GC*1); *h* – (*EM*3,*GC*2); *i* – (*EM*3,*GC*3)]

Table 3 Parameters of Tunnel Advance Rate Normal Distributions (m/8-hr shift)

Tunneling Alternative	*GC*1		*GC*2		*GC*3	
	Mean	SD	Mean	*SD*	Mean	SD
*EM*1	2.42	0.11	1.13	0.03	0.56	0.02
*EM*2	1.23	0.04	1.65	0.05	0.76	0.02
*EM*3	0.80	0.03	0.79	0.02	1.27	0.04