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SPECIAL PURPOSE SIMULATION TEMPLATE FOR UTILITY TUNNEL CONSTRUCTION

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ABSTRACT

Utility construction projects have great opportunities for simulation applications in construction. This paper describes the special purpose tunneling simulation template developed based on the tunneling operations performed at the *City of Edmonton Public Works Department* for shielded tunnel boring machines. The tunneling operations are described, then the tunnel template and its components are illustrated. The results generated from the template using the historical data to test the template and to analyze the potential construction processes are presented. Future embellishments to the tunneling template are briefly described.

1 INTRODUCTION

Today's city centers are struggling with increasing traffic congestion, reduced surface vacancy and increased demand for infrastructure. As a result, urban developers are becoming increasingly interested in the tunneling alternative. Tunnels can be used to serve a variety of functions including subways, utility corridors and sewer lines. In general, the term "tunneling" can be used to describe a wide range of underground excavation operations. The City of Edmonton (CE) Public Works Department has carried out numerous tunneling projects over the last five decades. The CE started developing its tunneling expertise in the early part of 1950's beginning with hand tunneling. In 1965, a non-shielded tunneling boring machine (TBM) was used (also called as "spider mole"). After ten years, the CE purchased its first shielded TBM and later purchased four more. The use of TBM boosted the ability to construct TBM tunnels with excavation as large as 6.8m diameter.

The paper explains the modeling and analysis of the tunneling process for shielded *Tunnel Boring Machines* using the *Special Purpose Tunnel Template* developed with Simphony. The template is based on the special purpose simulation concepts described in AbouRizk and Hajjar (1998).

2 TUNNEL CONSTRUCTION USING TBM

Tunneling projects using shielded TBM involve the following activities:

1. excavation and support of the working shaft,
2. excavation and support of undercut, and tail tunnel,
3. excavation of the tunnel,
4. disposal of dirt from the tunnel face,
5. hoisting the dirt to the ground level,
6. lining the tunnel,
7. extending the services and rail tracks,
8. excavation and support of the removal shaft.

Except for activities (1), (2) and (8) of the above, these are repetitive tasks in a tunnel construction cycle. The purpose of the pre-planning is to ensure that minimum waste occurs during the entire construction process. The goal of eliminating the wait time is to optimize the resources and the construction process. The advancement of the tunneling operation depends on the progress of the tunneling activities between the working shaft and the tunnel face. In order to optimize the tunneling operation, all activities should be coordinated to minimize the delay occurring at either end.

Excavation on long tunnels is typically done with shielded mechanical moles. The shield provides temporary support for the front sections of the tunnel and a safe working area for the crew. There are two types of tunnel boring machines: open-face and closed-face shielded machines. Open face machines are generally employed in competent soils with reasonable stability. In conditions of runny soils such as silt or sand, a closed-face-shielded machine is used. An important property of TBMs is their excavation rate, which is dependent on the soil conditions and the TBM horsepower. Another important property is the stroke length, which determines how often the TBM will need to be re-set.

The dirt handling process involves the transportation and disposal of spoil from the tunnel face to the shaft where it is lifted to the surface. Spoil can be hauled horizontally using trains and/or belt conveyors. The selection criterion depends on the tunnel site conditions. Belt conveyers have the advantage of providing a continuous spoil removal system. However, they typically require excessive maintenance. Train haulage is energy-efficient and is compatible with most excavating and loading methods and is adaptable to almost all sizes of tunnels. Trains can also be fitted with special cars capable of transporting laborers and support liners. Depending on the tunnel diameter, a single or double-track system can be used. In most cases, a track switching system is utilized at the *undercut* to allow multiple trains to share a single track. The working shaft is utilized to remove the spoil and to transport the construction materials and personnel. The dirt can be hoisted with a skip, a clamshell bucket, or a gantry crane. Clamshells are typically used in shallow tunnels. In medium depth tunnels (10 m to 20 m), gantries or cranes are more economical and in deep tunnels (>30 m), a cage or skip is used with a head frame for hoisting the muck.

The two major types of tunnel support systems consist of either (1) rib-and-lagging or (2) concrete segments. Rib-and-lagging method has a record of high performance in a variety of ground conditions. During installation, lagging is wedged circumferentially between rib and soil. The rib-and-lagging support system acts as the primary lining system. A secondary layer made of cast-in-place concrete is placed when tunneling excavation is finished. Pre-cast concrete segment lining is the alternative to rib-and-lagging, which act as both the primary and final lining systems. Each segment is designed as a compact structural unit and thus requires the least amount of handling during erection. The full ring typically consists of four identical segments. It is partially installed inside the shield of the TBM. The ring is expanded tightly against the soil as it leaves the shield. Metal spacers are inserted in the gap created by the ring expansion to maintain its structural integrity. The gap is subsequently filled with concrete and the joints are patched with cement mortar.

In order to design the Simphony Template, the following resources and specifications were added to the initial template and tested using the historical records available at CE. The other specifications, resources and construction methods were also added as alternatives for future developments.

1. TBM close face – 2.3 meter diameter,
2. material handing – two trains with muck cars and belt conveyor at tunnel face,
3. crane at shaft,
4. liner installation: pre-cast concrete segments,
5. single tracking layout inside the tunnel and two tracks at undercut.

2.1 Repetitive Construction Processes at Tunnel Face

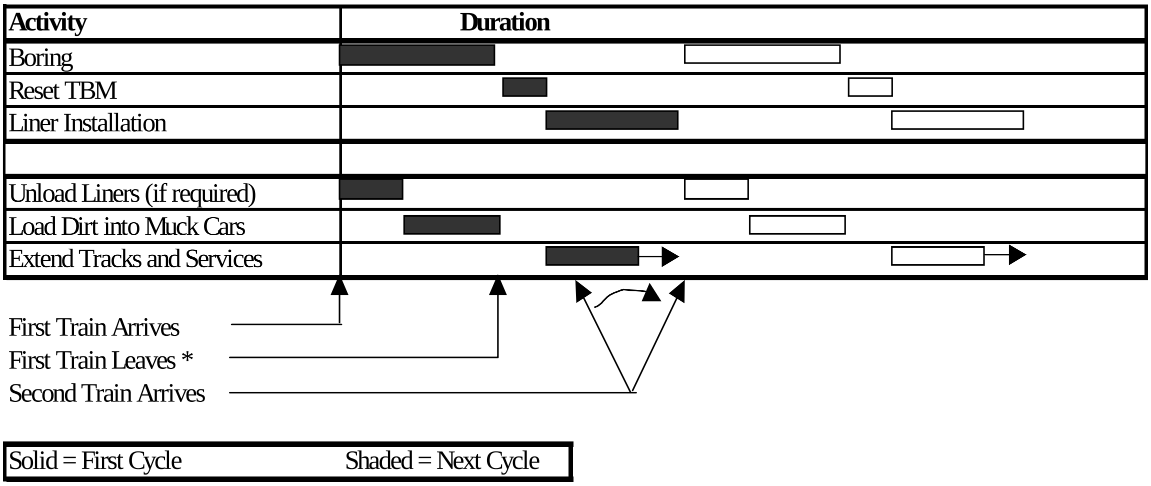
All activities at the tunnel face are repetitive. Figure 1 shows the bar chart schedule for the repetitive activities at the tunnel face. No wait time is shown in the bar chart schedule (for illustrative purposes) and it assumes that the muck cars are available to commence the next cycle. However, the whole schedule depends on the travel time of the train and the other repetitive operations at the shaft.

The second train could arrive at any time. In order to have an optimized situation; the second train must arrive at the tunnel face when lining installation is done. If the second train is late, the TBM has to wait until it arrives. Therefore, there are two waiting factors that determine the production and the tunnel advance rate; train waiting time for TBM or TBM waiting time for train.

2.2 Repetitive Construction Processes at Shaft

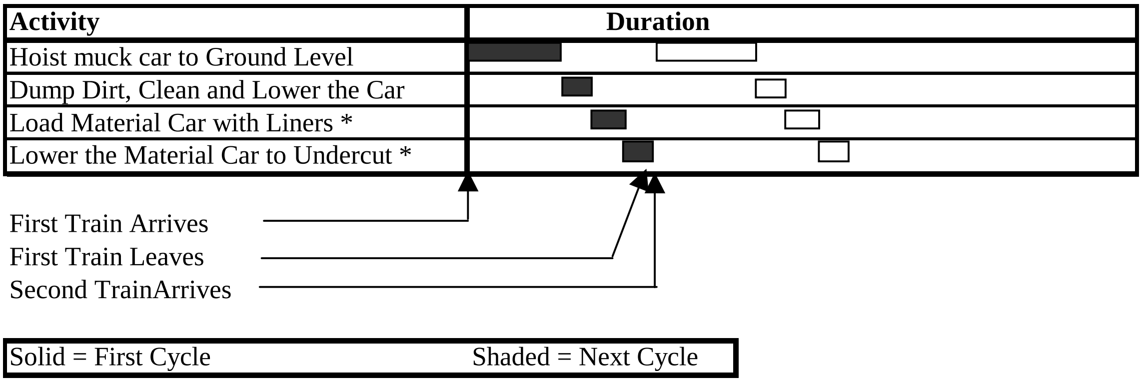
The activities at the shaft also involve repetitive operations. Figure 2 shows the bar chart schedule for the activities that occur at the shaft. The processes at the shaft depend on the travel time of the train and the operations at tunnel face plus the efficiency of the hoisting operations at shaft. It is also assumed that there is no waiting time for any of the resources when scheduling the bar chart. The second train could arrive at any time. In order to have an optimized situation; the second train must arrive at the shaft when the first train is finished loading the liners and unloading the dirt If the second train is delayed, the crane waits for the train.

There are many other basic factors that affect production. A few of those factors are TBM penetration, train time or speed, and encountering difficult soil conditions. Simulation allows for the modeling of a given system on the computer in order to allow the user to experiment with alternate scenarios and compare the results. The test analysis based on the Simphony template and the assumptions are presented in *Sections 4 and 5*.



** The leaving of the train depends on the capacity of muck cars. Refer to Section 4.1:Modelling Parameters and Processes for details.*

Figure 1: Repetitive Construction Processes at Tunnel Face



** These activities can be performed before muck cars are unloaded, if time permits.*

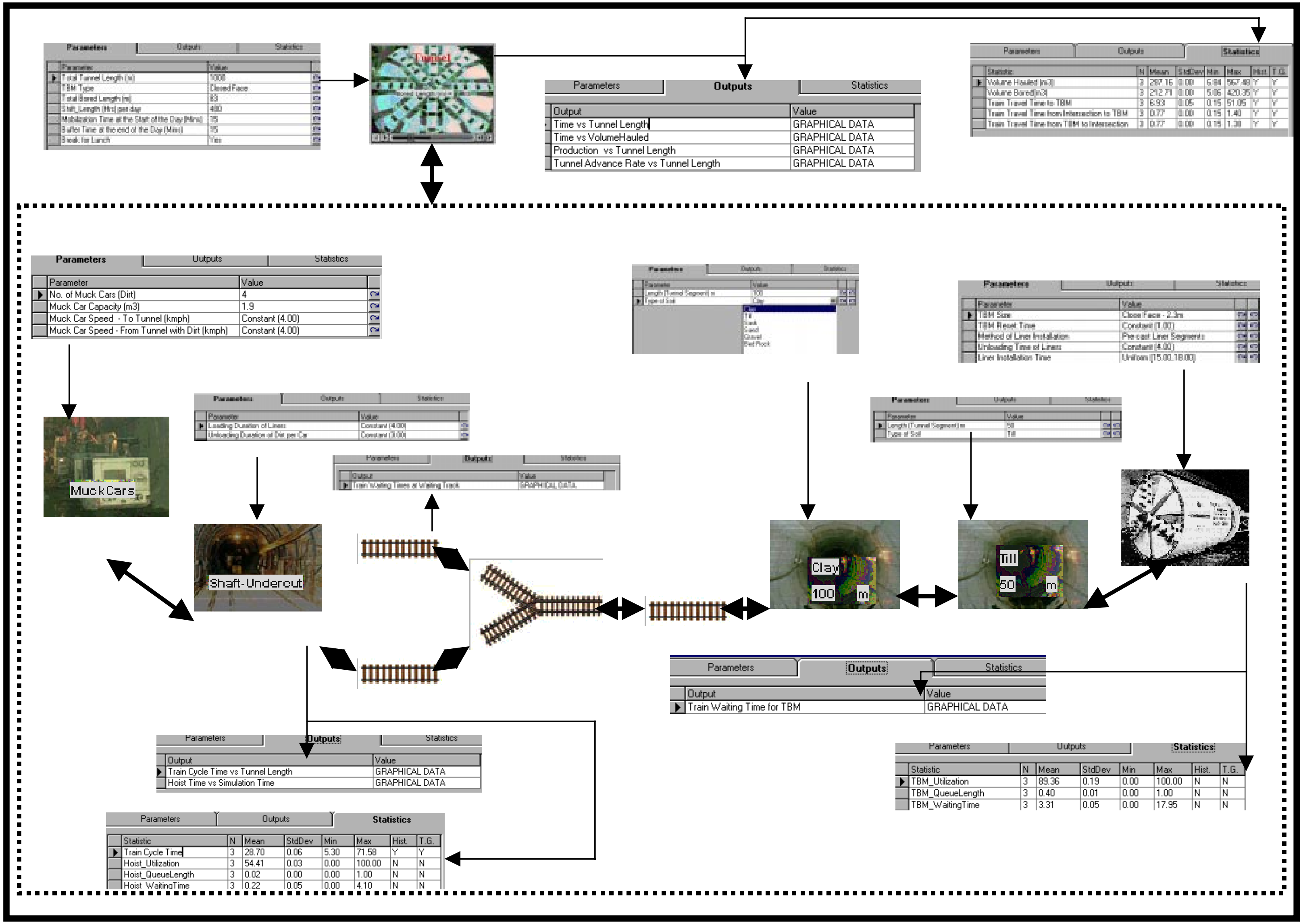
Figure 2: Repetitive Construction Processes at Shaft

3 SIMPHONY PLATFORM FOR SPECIAL PURPOSE SIMULATION.

Simphony is a simulation platform for building general and special purpose simulation models. It is a Microsoft Windows based computer system developed with the objective of providing a standard, consistent and intelligent environment for both the development as well as the utilization of the construction of Special Purpose Simulation (SPS) tools (Hajjar and AbouRizk 1999). AbouRizk and Hajjar (1998) also defined SPS as *"a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications and reporting are completed in a format native to the domain itself."*

Intended application domain, simulation theory and object oriented programming are the three key ingredients of developing a special purpose simulation tool. The successful design and implementation of a special purpose simulation depends on flexibility of the modeling environment and on user-friendliness.

In this respect Simphony fulfills the requirements to build successful special purpose simulation tools. Its object oriented application framework provides a structured approach to build any simulation template with ease, which comprises graphical, hierarchical, modular and integrated modeling techniques.



Parameter	Value
Total Tunnel Length (m)	1000
TBM Type	Closed Face
Total Bored Length (m)	83
Shift_Length (Hrs) per day	480
Mobilization Time at the Start of the Day (Mins)	15
Buffer Time at the end of the Day (Mins)	15
Break for Lunch	Yes

Output	Value
Time vs Tunnel Length	GRAPHICAL DATA
Time vs VolumeHauled	GRAPHICAL DATA
Production vs Tunnel Length	GRAPHICAL DATA
Tunnel Advance Rate vs Tunnel Length	GRAPHICAL DATA

Statistic	N	Mean	StdDev	Min	Max	Hist.	T.G.
Volume Hauled (m3)	3	287.16	0.00	6.84	567.48	Y	Y
Volume Bored(m3)	3	212.71	0.00	5.06	420.35	Y	Y
Train Travel Time to TBM	3	6.93	0.05	0.15	51.05	Y	Y
Train Travel Time from Intersection to TBM	3	0.77	0.00	0.15	1.40	Y	Y
Train Travel Time from TBM to Intersection	3	0.77	0.00	0.15	1.38	Y	Y

Parameter	Value
No. of Muck Cars (Dirt)	4
Muck Car Capacity (m3)	1.9
Muck Car Speed - To Tunnel (kmph)	Constant (4.00)
Muck Car Speed - From Tunnel with Dirt (kmph)	Constant (4.00)

Parameter	Value
Length (Tunnel Segment) m	100
Type of Soil	Clay

Parameter	Value
TBM Size	Close Face - 2.3m
TBM Reset Time	Constant (1.00)
Method of Liner Installation	Pre-cast Liner Segments
Unloading Time of Liners	Constant (4.00)
Liner Installation Time	Uniform (15.00,18.00)

Parameter	Value
Loading Duration of Liners	Constant (4.00)
Unloading Duration of Dirt per Car	Constant (3.00)

Parameter	Value
Length (Tunnel Segment) m	50
Type of Soil	Till

Output	Value
Train Waiting Times at Waiting Track	GRAPHICAL DATA

Output	Value
Train Waiting Time for TBM	GRAPHICAL DATA

Output	Value
Train Cycle Time vs Tunnel Length	GRAPHICAL DATA
Hoist Time vs Simulation Time	GRAPHICAL DATA

Statistic	N	Mean	StdDev	Min	Max	Hist.	T.G.
TBM_Utilization	3	89.36	0.19	0.00	100.00	N	N
TBM_QueueLength	3	0.40	0.01	0.00	1.00	N	N
TBM_WaitingTime	3	3.31	0.05	0.00	17.95	N	N

Statistic	N	Mean	StdDev	Min	Max	Hist.	T.G.
Train Cycle Time	3	28.70	0.06	5.30	71.58	Y	Y
Hoist_Utilization	3	54.41	0.03	0.00	100.00	N	N
Hoist_QueueLength	3	0.02	0.00	0.00	1.00	N	N
Hoist_WaitingTime	3	0.22	0.05	0.00	4.10	N	N

Figure 3: Simphony Special Purpose Tunnel Simulation Template: Inputs, Processes and Outputs

4 SPECIAL PURPOSE SIMULATION TEMPLATE FOR TUNNEL CONSTRUCTION

The Tunneling Template illustrated in Figure 3 explains in detail the modeling elements used in the template, its inputs, outputs and statistics. In this discrete event simulation model, the input parameters can be global to the system or individual to the modeling element. For example, the *TBM* element determines the operations at the tunnel face based on the shift length parameter inputted at the parent level of the model. The *Liner Installation Time* is a parameter within the *TBM* element, which can be available to the *TBM* element or any other element in the model. There is one parent "*Tunnel*" element in the model with eight child elements. The children elements are:

1. Muck Cars.
2. Shaft and Undercut.
3. Track Layout at Undercut.
4. Track Intersection between Undercut and the Breakout.
5. Waiting Track in the Undercut for Second Train.
6. Breakout Track.
7. Tunnel Section.
8. TBM Machine.

4.1 Modeling Parameters and Processes

The parent element of the model has some input parameters: the total tunnel length to be bored, TBM type (open face/ close face), total bored length, shift length per crew, mobilization time at the commencement of each shift length (or day), buffer time (the time between closing time of the shift and the end of shift) at the end of the day and the decision to stop work for lunch. At the end of the shift, the simulation model determines whether it is possible to bore another stroke length of the tunnel or install the liners after the tunnel portion has been bored within the buffer time specified. If the work is stopped for lunch, productivity is affected by the stoppage of work before lunch and re-mobilization time before construction starts after lunch.

The *muck car* element has parameters related to train and muck cars. The capacity of muck cars, the number of muck cars and the speed of the train are the input parameters. The tunnel boring operation changes depending on the total capacity of the muck cars. According to CE tunnel operations, TBM only bores one meter of tunnel before installing the pre-cast segment liners. If the total capacity of the muck cars is greater than the bank volume of one meter of dirt (larger setup), the loaded train leaves to shaft as soon as TBM finishes boring one meter of tunnel. If the total capacity of muck cars is less than the bank volume of one meter of dirt, the train leaves as soon as its cars are filled, irrespective of whether the TBM has bored one meter (smaller setup). The TBM is stopped until a new train arrives at the tunnel face. If the Train is partially filled when TBM achieves the required meter, the train waits until TBM installs the liners for the bored meter. The rest of the muck cars are filled in the next boring cycle. This material handling was an embellishment to the preliminary model designed in order to validate the model with the proposed sewer tunnel project at Mill Creek, Edmonton. The train is the main entity of the model.

The shaft-undercut element obtains the inputs for unloading time of dirt car from undercut to shaft and the loading time of liners from shaft to undercut. The loading of liners is not a continuous activity for each train. If liners are required, then this event is triggered. The crane is one of the resources of the model.

The *track at undercut*, *intersection* and *breakout Track* check various operations in the model and maneuver the traffic of the trains. If the first train is inside the tunnel and the second train has finished unloading dirt, the second train travels to the *intersection* and backs up to the *waiting track*. When the train comes out of the tunnel and travels to *undercut*, the train at the *waiting track* leaves to the tunnel face. The user is also given the option to input the length of the breakout.

The simulation model allows the user to add as many *tunnel sections* to the model depending on the soil properties. For example, if the tunnel to be bored is 170 meters long in *Clay* soil and there are 20 meters of *Bed Rock* in the tunnel to be bored starting at the 50th meter of the tunnel, the user can add three segments of *tunnel section* as in Figure 4. The type of soil and the length of the tunnel section are the input parameters. The simulation model determines the tunnel penetration rate and the swell factor of the soil based on the input.

Figure 4: Tunnel Segments for different soil types

The *TBM* element has a few more inputs: TBM size, liner installation method, TBM re-set time, unloading time of liners, and liner installation time. The simulation model determines the availability of time and the need to unload liners before the next boring cycle begins. TBM is a main resource within the model.

4.2 Modeling Outputs and Statistics

In addition to Simphony's own graphical reports and statistics, there are various designer-built graphical reports and statistics in the tunneling template. The designer-built outputs and statistics are reported to various elements of the model. Figure 3 shows all the outputs and statistics generated from the model. The *Section 5* of the paper explains in details some of the designer-built reports.

The utilization, waiting time, and queue length for each resource are generated from Simphony. The crane resource ensures an orderly and realistic representation of the loading and unloading operations. The track resource ensures that a maximum of one train is allowed to proceed at a time and the TBM resource ensures that no excavation can take place without a train.

5 ANALYSIS OF SIMULATION RESULTS

The preliminary validation of the Tunnel Simulation Template was performed using available historical data and the experience of the personnel at the City of Edmonton. Table 1 depicts the historical data obtained to test the template with the specifications of 2.3 meter diameter tunnel using LOVAT M100 TBM and two trains in good clay soil. The tunnel is supported with pre-cast segment liners.

5.1 Test # 1: Comparison of Results by Changing the Site Set-Up at Shaft

The availability of site space is a governing factor for tunnel production. If the space for shaft, undercut and tail tunnel is limited, the project manager prefers to use a smaller setup which requires smaller muck cars that are easier to be hoisted using a small crane. The alternative is to use larger capacity muck cars which are hoisted using a comparatively larger crane. The proposed Mill Creek tunnel intends to use a smaller set-up due to the same problem. The tunnel template was used to test the output results for both. Table 2 outlines the results obtained. Figure 5 and 6 illustrate the average Tunnel Advance Rate (m/hr) for both cases.

The simulation results show that the smaller setup generates a less productive tunnel advance rate. The TBM utilization is also reduced in the smaller set up. The crane utilization increased in smaller set up due to higher frequency of muck car handling.

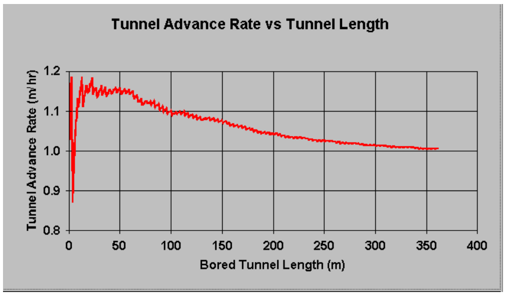


Figure 5: Tunnel Advance Rate (Smaller Setup)

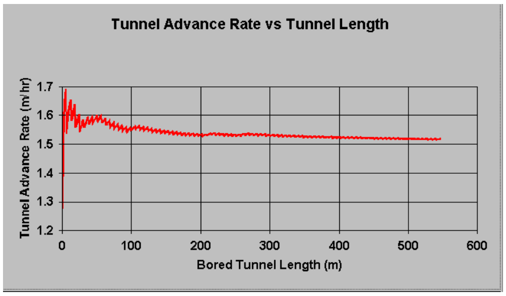


Figure 6: Tunnel Advance Rate (Larger Setup)

5.2 Test # 2: Encountering Different Soil Conditions in the Smaller Set Up

The rate of tunnel production varies depending on the soil conditions. In this modeling scenario, *Bed Rock* is encountered for 20 m when the tunnel reaches 30 meters. The soil for all the other areas is soft clay. The total tunnel length is 100 m. Figure 7 shows the tunnel advance rate for this scenario. The tunnel advance rate is considerably reduced when boring in *Bed Rock*.

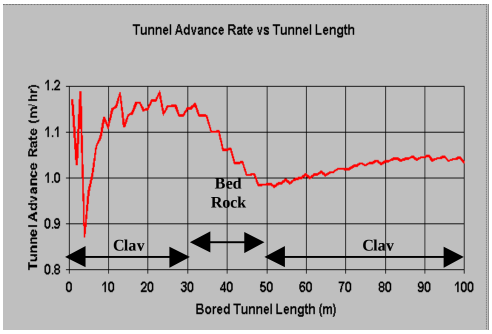


Figure 7: Tunnel Advance Rate with different soil conditions

6 FUTURE ENHANCEMENTS

This simulation template predicts the results based on the algorithms developed in the model, which are entirely based on the actual construction processes. Following are future embellishments to the model.

1. Extend the capability of the template to model the construction of a tunnel using hand-tunneling method and other sizes of tunnel boring machines for both open face and closed face.
2. Allow the users to pick compatible resources for each tunneling activity and predict the comparative results.
3. In the present model, different soil properties can be added on an arbitrary basis. The future

Table 1: Historical Input Parameters

Input Parameter	Value
Train Speed (kmph)	Uniform (3.00, 4.00)
Unloading Dirt for Muck Car (1.9 m3) - Mins	Triangular (3.00,3.50,4.00)
Unloading Dirt for Muck Car (0.75 m3) - Mins	Triangular (2.75,3.00,3.50)
No. of Muck Cars - Small Capacity	6
No. of Muck Cars - Large Capacity	4
Loading of Liners from Shaft to Undercut - Mins	Constant (4.00)
TBM Penetration Rate for Clay (m/hr)	Uniform (4.00, 4.25)
TBM Rest Time - Mins	Uniform (1.00, 3.00)
Unloading of Liners from Trains - Mins	Constant (4.00)
Liner Installation Time	Triangular (15.00,16.00,18.00)
Shift Length - Mins	480
Mobilization time at the commencement of each day - Mins	15
Buffer Time at the end of the day - Mins	15
Break for Lunch	Yes

Table 2: Statistics for Tunnel Simulation – Test # 1

	Large Muck Cars	Small Muck Cars
Tunnel Length	560	361
Days	45	45
Average Tunnel Adavance Rate (m/hr)	1.56	1.00
Average TBM Utilization	82.80%	52.30%
Average TBM Queue Length - Mins	0.14	0
Average TBM Waiting Time - Mins	1.9	0
Average Crane Utilization	39.65%	49.05%
Average Crane Queue Length - Mins	0	0.03
Average Crane Waiting Time - Mins	0	0.78

enhancement will be able to predict the possibility of meeting difficult soils based on a geotechnical analysis. The authors intend to study the probability of meeting a difficult soil using *Markovian Analysis* and embellish the template. Further this would allow an accurate predicting of the tunnel penetration rate for a composite and mixed soil strata when it bores horizontally.

4. The other possible problems during tunnel operations will also be added to the template. These include breakdown of the TBM, maintenance of equipment, surveying, adjustments for curvatures and slopes, unforeseeable events such as water seepage and structural damages etc.
5. Based on the productivity and the utilization of the resources, a cost estimation module could be added to the tunnel template to enhance the project management and project planning aspect of the model. This would help the engineers, planners and constructors to simulate the operations using multiple runs and establish the most cost-effective tunneling resources.

7 CONCLUSION

An application of computer simulation for tunnel construction has been described using the historical data and the tunneling process obtained from the City of Edmonton Public Works Department. The objective of the analysis of the simulation model was to estimate the production of the tunnel advance rate and the optimization of the resources. Further, the effect on tunnel advance rate due to the other variables has been analyzed. The results show that the tunnel advance rate is inter dependent on various factors and activities in the tunneling operations. The resources can be optimized if both cycles of tunnel face and shaft operations are analyzed and adjusted to achieve the maximum efficiency. This template will be tested again with actual data obtained from the proposed sewer tunnel for Mill Creek at Edmonton to be commencing in the Fall of 1999.

This study is another opportunity to show that simulation can be successfully used in planning a construction project. The future enhancements identified in the paper will provide a more comprehensive template for tunnel simulation. The accuracy of the tunnel simulation template will assist the consultants and the contractors to develop more realistic approaches to meet the challenges they will face as construction progresses.

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