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DESIGN, DEVELOPMENT AND APPLICATION OF SOIL TRANSITION ALGORITHMS FOR TUNNELING USING SPECIAL PURPOSE SIMULATION

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ABSTRACT

In tunnel construction, the vertical boreholes only show the soil types that are available in the borehole locations. The soil profiles between the boreholes are uncertain and assumed by practitioners for construction purposes. The productivity of the tunnel construction work is therefore affected by adverse soil conditions. The successful implementation of a special purpose tunneling simulation tool identified that the modeling of uncertainties such as soil conditions could provide better results. This paper presents new modeling algorithms to predict the transition of soils between the boreholes along the tunnel path. The use of transitional probabilities enables to predict the transition points. The various scenarios of the mixed phases of soils are considered for modeling within the special purpose tunnel simulation template. Application of the simulation for modeling algorithms to a past construction project proved that this modeling algorithms provide a logical and an accurate prediction of the tunnel advance rate.

1 INTRODUCTION

Computer simulation is a powerful tool for decision-making. It provides an appealing approach for analyzing and improving repetitive processes such as tunneling. Notwithstanding this appeal to date, application of simulation to real life construction projects has been minimal. Construction simulation also provides a great assistance to decision makers in analyzing various construction operations and alternatives. Simulation of construction operations allows analysts and construction industry personnel to experiment with different construction technologies, and estimate the possible consequences and impacts on scheduling and costs (Ruwanpura et al. 2001a). This paper presents a special purpose simulation (SPS) tool for utility tunnel construction operations that includes a new modeling technique to predict the transitions of soil types for tunneling. The uncertainty factors of the tunnel construction work have been identified through the development of a SPS tool documented in Ruwanpura et al. (2001a) for tunnel construction and successful application of this tool for project planning of tunnel construction operations. A major critical factor of tunnel construction; the prediction of soil type during tunneling has been modeled using analytical methods.

2 PREDICTION OF SOIL TRANSITIONS

The prediction of soil types along the tunnel is a challenging task due to its uncertainty and unavailability of deterministic data. The boreholes driven for a tunnel construction project only provides a handful of deterministic information at discrete locations either in the tunnel alignment itself or closer to the tunnel alignment. The borehole data determine the soil types at discrete locations, and produces deterministic estimation of the soil types and the elevations. Ruwanpura et al. (2001a) shows a simulation example of inputting the soil types arbitrarily for simulation using the deterministic borehole data in the boreholes. That method does not have the capability of extracting the soil conditions accurately and the end user could only specify the approximate values of the soil conditions based on the borehole data. Hence, the productivity and tunnel advance rate predicted by the template do not provide the conclusive outputs for accurate prediction of productivity. The approach described in this paper predicts the transition of soils along the length of the tunnel and provides an analytical method for the tunnel simulation template to calculate the boring rate (tunnel excavation rate) and other input parameters such as swell factor, composition of soils and then to determine the productivity of tunnel construction operations. Markov theory is used to create the transitional probabilities. The transitional probabilities become inputs for simulation to predict the transition points. The use of Markov probabilities for simulation comprises three stages. The end result of the first stage will affect the results of the second stage.

a) Calculation of transitional probabilities.
b) Modeling Algorithm modules based on the transition scenarios of the soils.
c) Application of the modeling algorithms within Simphony tunnel template.

3 TRANSITIONAL PROBABILITIES USING MARKOV CHAINS

A simple two-state (type A soil, type B soil) first-order Markov chains can be used to determine the occurrence of type A or type B. Figure 1 shows that the transition from type B to type A both at the top (*elevation* $_{Top}$) and bottom elevation (*elevation* $_{Bottom}$) of the tunnel between boreholes, BH1 and BH2. The transition from Soil A to Soil B can be evident only from the bottom elevation of the tunnel between boreholes, BH2 to BH3. This two-state Markov chain is defined by transitional probabilities of moving from one soil state to another state of soil. Transitional probabilities are dependant on the location of the tunnel, depth of the tunnel, start and end elevations of the soil types and the soil types in the vicinity. Equation 1 defines the transitional probability of transiting from state *b* (Soil B) on one known point (BH1) in the tunnel to state *a* (Soil A) on immediate known point (BH2) in the tunnel at tunnel *elevation* $_{Top}$.

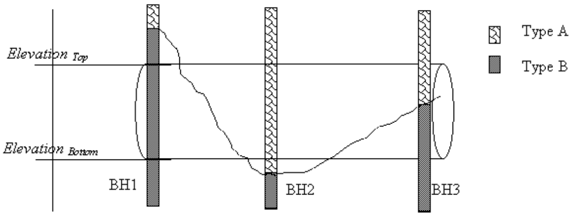


Figure 1: Transition of Soil A to Soil B Between Three Boreholes

$$P_{Top}(b/a) = \frac{N_{ba}}{n_b} \tag{1}$$

N_{ba} is the number of observed transitions generated from Soil B to Soil A at *elevation* $_{Top}$. Number of observed transitions generated from Soil B to all states including Soil A and Soil B at *elevation* $_{Top}$ is denoted by n_b. When two types of soil interact within the tunnel direction, it is only required to define four (4) transitional probabilities

$P_{Top,\,BH2}$ (A/A)	Probability of Soil A at *Location BH2* in the tunnel direction at *elevation* $_{Top}$ given that Soil A can be observed at *Location BH1* at *elevation* $_{Top.}$
$P_{Top,\,BH2}$ (A/B)	Probability of Soil B at *Location BH2* in the tunnel direction at *elevation* $_{Top}$ given that Soil A can be observed at *Location BH1* at *elevation* $_{Top.}$
$P_{Top,\,BH2}$ (B/A)	Probability of Soil A at *Location BH2* in the tunnel direction at *elevation* $_{Top}$ given that Soil B can be observed at *Location BH1* at *elevation* $_{Top.}$
$P_{Top,\,BH2}$ (B/B)	Probability of Soil B at *Location BH2* in the tunnel direction at *elevation* $_{Top}$ given that Soil B can be observed at *Location BH1* at *elevation* $_{Top.}$

The probability of observing Soil A (*state a*) in the tunnel direction at *elevation* $_{Top}$ can be calculated by Equation (6.2).

$$P_{Top}(a) = \frac{N_{Top}(a)}{T_{Top}} \tag{2}$$

Number of observed transitions in Soil A at tunnel elevation Top is denoted by $N_{Top}(a)$. T_{Top} denotes the total number of all soil types observed along the tunnel direction at elevation $_{Top}$.

4 CALCULATION OF TRANSITIONAL PROBABILITIES

According to Krumbein and Dacey (1969) and many other researches, geological observations can be structured as Markov chains in two main ways, both of which have been used in stratigrahic analysis. The first approach considers the lithology (or soil type) at discrete points that are spaced equally along a vertical profile. The points are numbered consecutively, and the use of Markov chains is based on the assumption that the lithology at point *n* depends upon the lithology at the preceding point *(n-1)*. Because the same lithology may be observed at successive points, the transition matrix that gives the probability of going from one lithology to another generally has nonzero elements on the main diagonal.- The second approach considers only the succession of lithologies, and because each transition is to a different lithology within the system, the diagonal elements are all zero (i.e. both P(A/A) and P(B/B) are zero).

Second approach that is also called as Embedded Markov chain method is totally rejected for the proposed modeling algorithm modules as the purpose of the transitional probabilities to determine the transition point between two locations. The other Markov chain calculation method is also modified in the proposed model. Further, the proposed method uses the transitional probabilities calculated along the tunnel rather than along the boreholes vertically. Almost all the examples that used the Markov chains used observations along the boreholes from top to the bottom. When calculating the transitional probabilities, the interval of which the observations are made have an impact of the values. If the interval is fixed and too short, the resulting diagonal transitional probabilities may be more biased compared to the other transitional probabilities. If the total length between the two locations is 100 meters and if there is only one transition between soil type A and B at 45 meters at the top of the tunnel elevation and if the observations are made at every 1 meter, the P(A/A) = 0.99 and the P(A/B)=0.01. However, if the fixed interval is set for 10 meters, P (A/A) = 1.0 and P (A/B) = 0.

The proposed method does not consider a fixed interval at all. Since the certainty is only with the known boreholes or additional locations along the tunnel as described in Ruwanpura et al. (2000b), the observations are made at the known borehole locations. The following are the rules for calculating the transitional probabilities. Figure 2 is used to explain the rules in modified transitional probabilities.

Figure 2 comprises the tunnel with eight boreholes. There are only two soil types in the vicinity of the tunnel. The transitions are enumerated separately in seven elevation levels. The depth level considers any gradients in the tunnel from its start to the end. The following are the elevation levels, which reflect the sample of the soil combinations in the tunnel vicinity.

a) Top of the tunnel elevation (T)
b) Bottom of the tunnel elevation (B)
c) Center of the tunnel elevation (C)
d) Mid point between Top and Center of the tunnel elevation (T^-)
e) Mid point between Center and Bottom of the tunnel elevation (B^+)
f) One point (a user determined) above the Top of the tunnel elevation (T^+)
g) One point (a user determined) below the bottom of the tunnel elevation (B^-)

The (f) and (g) requirements are user inputs. Based on the geological profile, the value for (f) and (g) could be determined. In this example, it is limited to one meter just below and above the tunnel to verify that the transitions may consider the possible occurrence of soil types closer to the tunnel's top and bottom elevations. Three transition probability

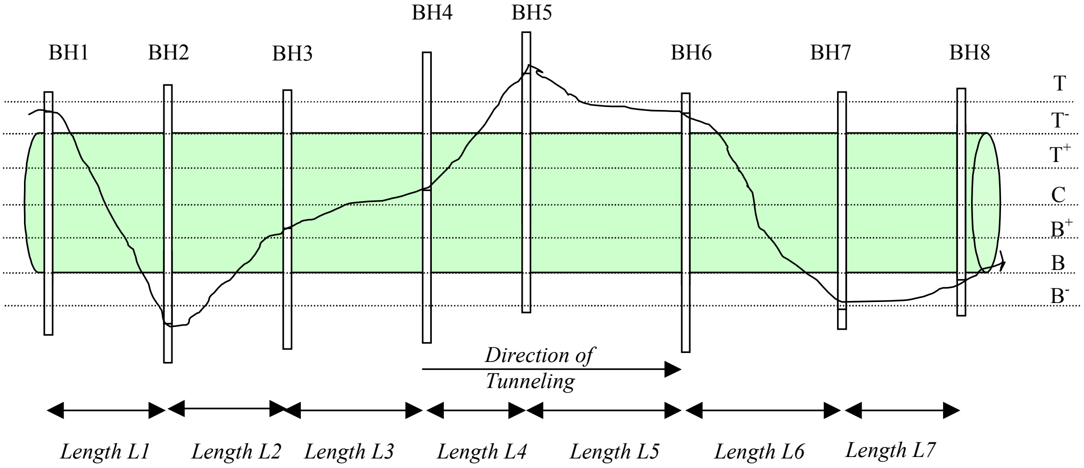


Figure 2: Transitions of Soils in the Tunnel

Table 1: Transitional Probability Matrices - Top, Center and Bottom i) Transitional Probabilities ii) Transitions

a) Top

	Soil A	**Soil B**
Soil A	0.786	0.214
Soil B	0.714	0.286

b) Center

	Soil A	**Soil B**
Soil A	0.667	0.333
Soil B	0.500	0.500

c) Bottom

	Soil A	**Soil B**
Soil A	0.400	0.600
Soil B	0.313	0.688

a) Top

	Soil A	**Soil B**
Soil A	11	3
Soil B	5	2

b) Center

	Soil A	**Soil B**
Soil A	6	3
Soil B	6	6

c) Bottom

	Soil A	**Soil B**
Soil A	2	3
Soil B	5	11

matrices are created from the transitions; Top Matrix (Table 1a), to calculate the transition point at the top elevation,Center matrix (Table 1b), to calculate the transition of soils in the middle of the tunnel, if any, and Bottom matrix (Table 1c), to calculate the transition point at the bottom elevation. Top matrix obtains the transitions at depths T^+, T and T^-, Center matrix obtains the transitions at depths T^-, C and B^+ and Bottom matrix obtains the transitions at depths B^+, B and B^-. for the tunnel depicted in Figure 2 based on Equation 1. The transitional probabilities in the matrix are stationary (or homogeneous) for the tunnel as the prediction uses these probabilities throughout the entire tunnel. It represents the probability of moving from one soil to another or remaining in the same soil type.

5 MODELING ALGORITHMS BASED ON THE TRANSITION SCENARIOS OF THE SOILS

There are several combinations of soils that make the stratigrahic of any area. Ruwanpura et al. (2001b) explains the various families of soils in Edmonton stratigraphy. The representation of those soils also has numerous variations. For example, Figure 2 shows five different combinations of soils with only two soil types in the tunnel area. The modeling algorithms for identifying the transitions of soils vary according to the following factors.

a) Number of soils in the area
b) Start and end elevations of the soils
c) Direction of the soil profiles
d) Status of the soil types (continuous or pockets)
e) Start and end elevation of the tunnel between boreholes.

The various combinations of two types of continuous layer soils, which are used to model for simulation purposes are in Figure 3.

Although some of the scenarios in Figure 3 are very similar in terms of the transitions at top and bottom, the location of the transition point could make a difference in determining the rate of boring for productivity. Algorithms to calculate the transitions points for two soils with continuous layers vary according to many factors in addition to transitional probability values. The additional factors are the direction of the transition soil profile, number of top transitions, and number of bottom transitions. The complete algorithm for transition of Soil B to Soil A both at top and bottom elevation of the tunnel (between BH1 and BH2 in Figure 1) are shown in Figure 4.

Based on the transition points, the rate of boring would change that impacts the tunnel productivity for all these scenarios. Calculation of boring rate depends on various factors. It was found during the research interviews with the tunnel personnel at the City of Edmonton that the boring rate in combined soils could have various variations depending of the type of the soil, and its inherent properties. The following are the possible calculation options identified to calculate the boring rate when a new soil is found when tunnel excavation is performed in another soil.

a) Boring rate (BR) is a combination of the composition of the soil types.
b) Minimum BR value of the two soils
c) Worse than the minimum BR value (BR_{Min}) of the two soils: This is could be most common situation according to tunnel personnel although the City of Edmonton cannot justify it with supporting data.

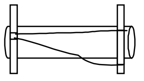
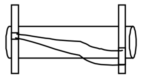
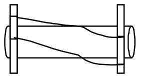
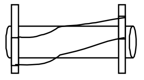
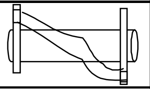
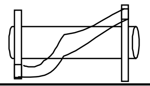
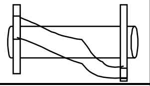
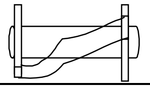
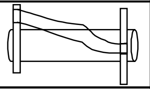
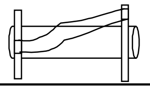
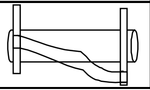
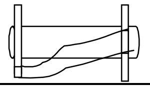
No	Scenario	Transitions	No	Scenario	Transitions
		☐ Soil A ☐ Soil B			
25		Top (None) Bottom (A to B)	26		Top (None) Bottom (A to B)
27		Top (B to A) Bottom (A to B)	28		Top (A to B) Bottom (B to A)
29		Top (A to B & B to A) Bottom (A to B & B to A)	30		Top (A to B & B to A) Bottom (A to B & B to A)
31		Top (B to A) Bottom (A to B & B to A)	32		Top (A to B) Bottom (A to B & B to A)
33		Top (A to B & B to A) Bottom (None)	34		Top (A to B & B to A) Bottom (None)
35		Top (None) Bottom (A to B & B to A)	36		Top (None) Bottom (A to B & B to A)

Figure 3: A Few Combinations of Two Continuous Soil Layer

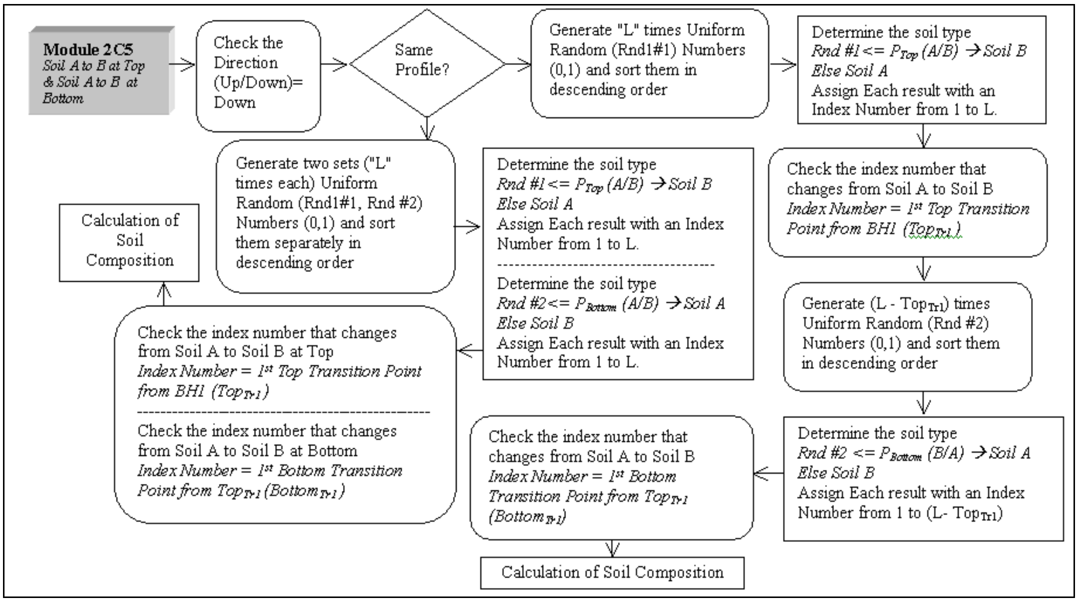


Figure 4: Transition Algorithm Module for One of the Scenarios

6 MODELING OF SOIL TRANSITIONS WITHIN SPS TUNNEL TEMPLATE

The modeling algorithms documented above are implemented within the tunnel simulation template described in Ruwanpura et al. (2001a). The Simphony simulation engine provides an easy and flexible modeling environment to implement the soil transition concepts. The one-way tunnel template has been embellished with additional modeling elements and algorithms without losing the originality of the tunnel simulation template. It is possible to adopt the original configuration of declaring soil segments without using new modeling elements. In the original one-way tunneling template of Ruwanpura et al. (2001a), there is a soil segment element, which allows the user to add the length of the soil section and select the soil type from an arbitrary list. The soil segment element was further modified to add the composition of the soil as inputs, which are referred to by other elements for decision-making during simulation.

Following five additional modeling elements were added to model the soil transition points for tunnel construction operations.

a) Markov Soil Assign
b) Soil State
c) Soil Section for two continuous soils
d) Soil Section for three continuous soils
e) Soil Section for one continuous soil and one soil pocket.
f) Soil Section for two continuous soils and one soil pocket.
g) Borehole

The purpose of the *Markov Soil Assign* modeling element is to define the various soil types that may encounter during tunneling. Properties of each soil type such as boring rate, and swell factor can be declared within this element up to five soil types, which will provide the information to the other modeling elements when requested. The boring rate when two soils interact, are the rest of the inputs in this modeling element if the boring rate is worse than low boring rates of the two soils.

Soil State modeling element is a child element within Markov Soil Assign element. The soil state element is designed to depict the matrix inputs. The present soil state, future soil state and the transitional probability (top, center and bottom) values between the two soil states and the method of calculating the boring rates are inputs of the soil state. For example, two state transitional probability matrix is formed using four soil state modeling elements (depicted later in this chapter). The present state, future state and the transitional probability values are shown on the face of the modeling element for any user to determine if a mistake has been made in inputting values.

New soil segment (two continuous soils, three continuous soils, one continuous soils with a soil pocket, two continuous soils with a soil pocket) replaces the soil segment of the original tunnel template although the inputs remain same except the type of soil being picked from an arbitrary list in the original template. Figure 5 shows the four soil modeling elements. The various scenarios explained in Section 5 are modeled within each element based on the number of soils involved in the transition.

Borehole is the other additional modeling element which holds the details of the borehole information at particular location along the tunnel alignment. The soil types and end elevations of each of the soil types in the borehole logs are the inputs. Further, the status of the soil can be defined; continuous or pocket. If the gradient of the tunnel is not the same from the tunnel start and the end, the top elevation of the tunnel that crosses the borehole is another input.

Figure 6 shows the simulation model for the boreholes and the tunnel shown in Figure 2. The total length of the tunnel is 485 metres. The calculation of boring rates was set to method 3 when both soils (Glacial Till and Bedrock) interact with each other. The results based on 20 simulation runs are shown in Table 2. The table shows the minimum, maximum, average and standard deviation of the top and bottom transitions of each soil section. Figure 7 depicts the profile of the Glacial Till (end elevation) and Bedrock (start elevation) based on the simulation results. The minimum, average, and maximum transitions points are plotted with the tunnel length and the elevations of the soil.

7 APPLICATION OF THE MODELING ALGORITHMS FOR A PAST TUNNEL CONSTRUCTION PROJECT

This section presents the analysis based on a case study to prove the above-mentioned modeling algorithms. The case study shows an actual tunnel, which was completed in 1994/5. Soil prediction algorithms explained are applied to show that the deterministic data in the borehole could only be used to obtain the results through simulation in the absence of soil characterization explained in Ruwanpura et al. (2001b). The actual productivity data for this was obtained using the daily report logs and consultation with the site supervisor and the site engineer. This particular tunnel's was excavated in Bedrock that comprises two soil types shale and sandstone. The tunnel comprised two separate construction methods. The first portion of the tunnel was 2.9 m finished diameter tunnel excavated using a M-126 Lovat TBM lined with pre-cast concrete segments. The second portion of the tunnel was

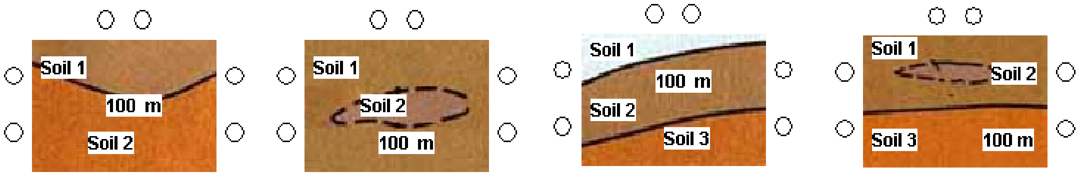


Figure 5: Soil Modeling Elements

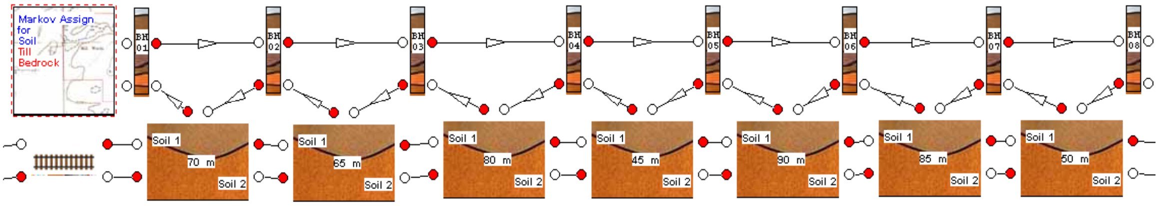


Figure 6: Simulation Layout of the Boreholes and Soil Sections Depicting Figure 2

Table 2: Results of the 20 Simulation Runs for Figure 5

Section	Length (m)	Top Transition Point				Bottom Transition Point			
		Min	Max	Avg.	SD	Min	Max	Avg.	SD
1	70	16	27	21.5	3.17	51	60	55.35	2.58
2	65					17	34	27.85	4.04
3	80								
4	45	31	43	37.1	2.81				
5	90								
6	85	20	32	26.3	4.03	63	77	69.05	3.95
7	50								

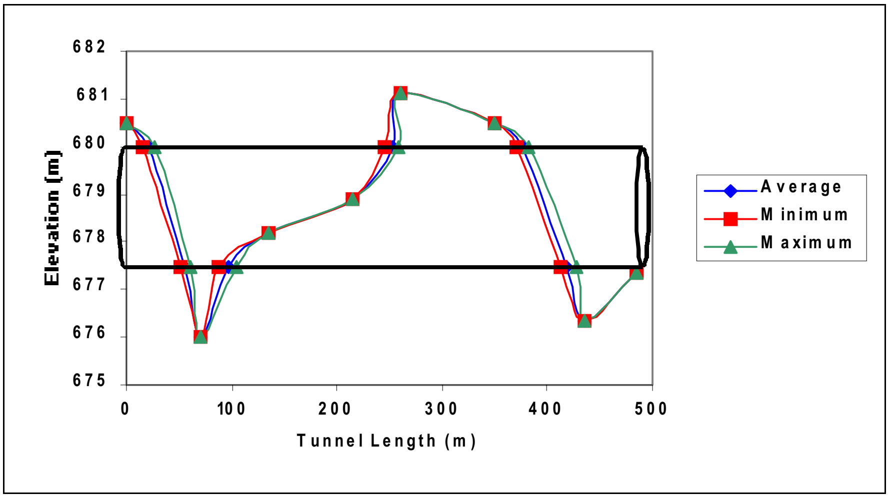


Figure 7: Profile of the Soils Based on Simulation Results

3.48 m finished diameter lined with shortcrete. The first portion has been selected for analysis as the tunnel simulation template described in Ruwanpura et al. (2001a) has been designed to simulate tunnels lined with pre-cast liner segments. Tunnel is about 20-25 meters before the ground surface and has a gradient of 0.077% from the main shaft to the removal shaft. There is about 203 meters of curve in the tunnel stating from 687th meter of the tunnel. Although there were a total of 24 boreholes in the tunnel, only 17 boreholes are in the first portion. 2 boreholes out of those 17 were very shallow and did not represent the soil types in the tunnel elevation. Tunnel is 1651 meters long and the elevation varies from 675.79 meters at the top of the start to 671.31 meters at the bottom of end. The Figure 8 shows the length between the boreholes and the estimated soil combination scenarios.

Six Models were created with 3 models using the approximate soil compositions as per method explained in Ruwanpura et al. (2001a). The best approximation is the linear interpolation of the soil compositions between the borehole and thereby using 15 separate soil modeling elements with approximate values. The other 3 models were created using the new modeling approach with different calculation methods to determine the boring rate. The results of all six models were tested against the actual tunnel productivity. Since the final productivity of model 6 (based on the assumption that the boring rate is worse than the minimum boring rate of the two soils) is very close to the actual productivity, Figure 9 is used to compare the results of the actual and model 6's tunnel advance rates. Up to about first 300 meters, the actual tunnel advance rate is far below the simulation's tunnel advance rate. The rest of the tunnel, the actual tunnel advance rate is very much close to the simulated tunnel advance rates. This comparison proves that the proper selection of inputs for boring rate could provide accurate prediction of the tunnel productivity. None of the approximate methods' tunnel advance rate was not close to the actual productivity.

Section	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Scenario	27	28	19	24	4	6	22	24	18	23	28	4	2	29	22
Length(m)	104	96	105	91	84	110	96	113	90	43	179	89	102	102	247

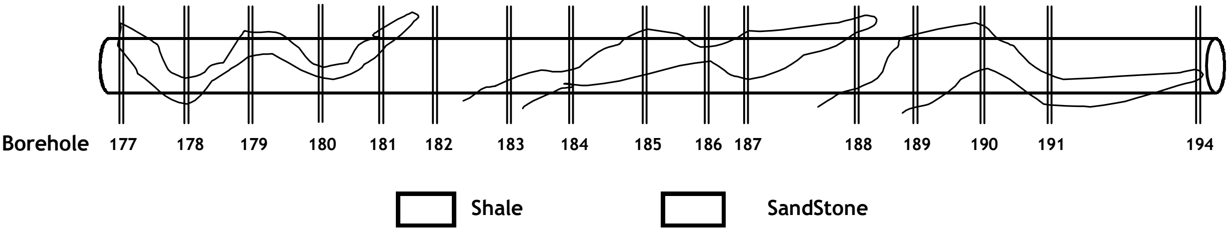


Figure 8: Profiles of the Tunnel and its Scenarios

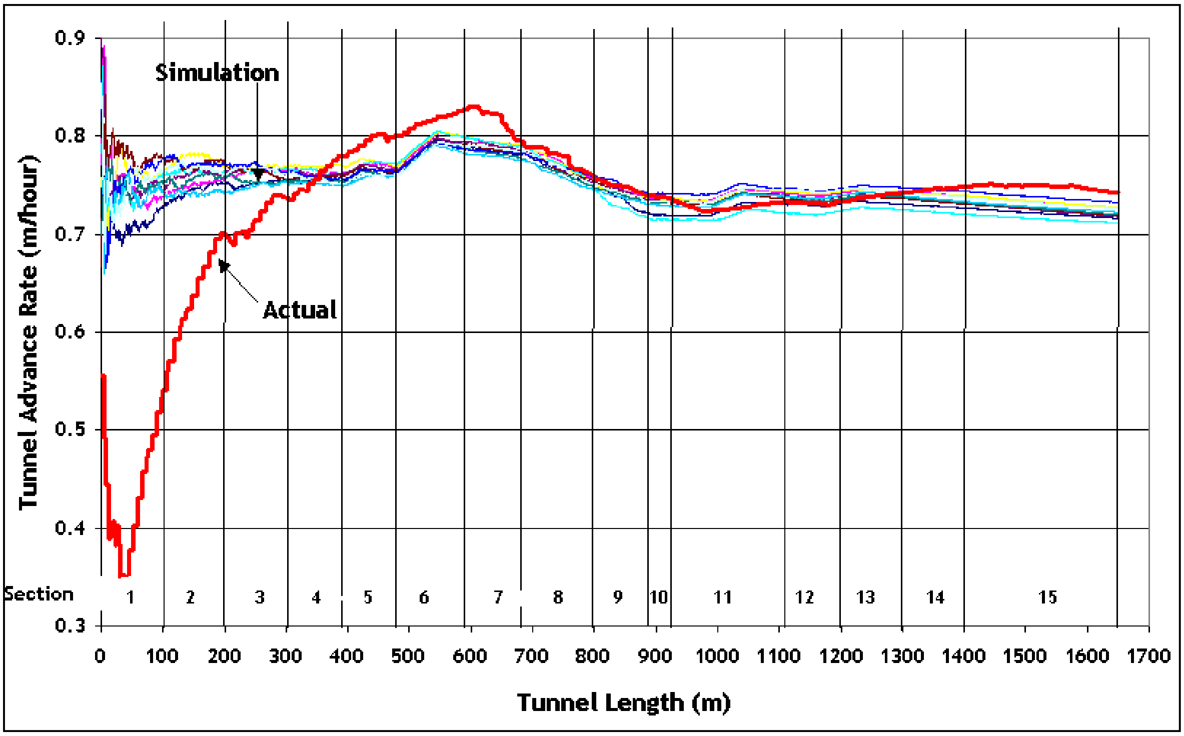


Figure 9: Tunnel Advance Rate – Actual vs. New Modeling Approach

8 CONCLUSIONS

The modeling algorithms implemented within special purpose simulation provides an analytical approach to predict the transition points along the tunnel path and thereby determining an accurate tunnel production rate rather than applying the approximate production rates based on the arbitrary/approximate composition of the soils.If the boring rate is based on the composition of the soils, the new method provides a better picture of the overall tunnel project that allows the tunnel managers to make decisions and to take remedial action (if any) before the construction commences. Since the mixed soil phases are quite common in the tunnel construction operations, the proper input of the rate of boring will provide an accurate production rate for tunneling. In the case study, the actual tunnel productivity (despite the reliability of the data) was almost predicted through simulation by applying a boring rate for mixed phases. The application and validation justifies that the new modeling algorithm not only provide a logical approach to predict the productivity based on the transition of soils, but also an accurate prediction given the fact that the end user selects the proper input data.

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AUTHOR BIOGRAPHIES

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