Tunnel Lining Methods: Selection of an efficient method

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Abstract—Selecting efficient lining method is very important for tunnel safety and serviceability. Selection of lining methods is controlled by technical and non-technical factors. Technical factors represent the project conditions such as ground condition and tunnel shape, etc. Non-technical factors are cost and time. This paper introduces a model that can be used for selecting efficient lining methods for tunnels in the preliminary stage of the project.

Keywords: Lining methods, tunnel projects, efficient methods, selection model

I. Introduction

Tunnel construction is a highly complex process. It includes considerations of various natures such as geology, geotechnique, organisation of the works, and economy. Above all, the safety of the workers and the users must be warranted as well as the serviceability of the tunnel on the long term [7]. Lining methods, which are the permanent support methods for the tunnel, play the main role for keeping tunnel from collapse and provide safe

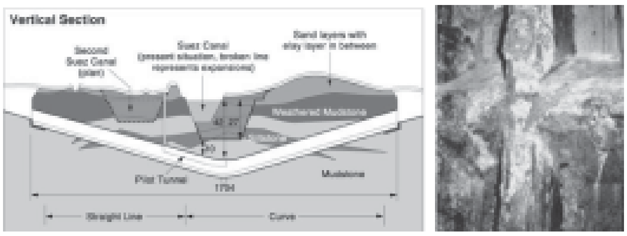

Figure 1 Ahmed Hamdi tunnel [14]

There are different lining methods for tunnels. Selecting the efficient lining method should be in the context of the whole methods used for tunnel construction to achieve a harmonised tunnel construction system. Technical and non-technical factors control the selection of the efficient tunnel lining methods. This research introduces a model service for tunnel users. Many tunnels have lining problems. Those problems are a direct consequence of poor design, bad construction, or bad selection of lining. Ahmed Hamdi tunnel in Egypt is one of those tunnels. Ahmed Hamdi tunnel is constructed in 1983 to provide a path under the Suez Canal for motor vehicles. It is 1.63 km long and has an outside diameter of 11.6 m. Leakage of salt water through the reinforced concrete lining of the tunnel was discovered very soon after construction was completed. The salty water quickly corroded the steel and degraded the concrete, leading to serious deterioration of the tunnel lining. In 1992 the tunnel was rehabilitated by a Japanese joint venture. A secondary reinforced concrete tunnel lining was then constructed inside the original one, with waterproof sheeting sandwiched in between. The secondary lining was designed to be structurally independent of the existing tunnel segments [14]. Figure 1 shows a vertical section of Ahmed Hamdi tunnel and the deterioration of its segments.
for selecting an efficient lining method based on technical and non-technical factors.

II. Technical and Non- Techchnical and Non Technical Factors

As the first step of this research, tunnel lining methods had been reviewed. Lining methods included in this research are the most common lining methods, those methods are *"Precast concrete segments"*, *"Cast steel segments (iron/steel)"*, *"Cast-in-place concrete"*, *"Pipe in tunnel"*, *"Shotcrete lining"*, *and "No final lining"*. The second step for developing a model for selecting efficient lining methods was the determination of the technical and non-technical factors (the controlling factors) that influence the selection decision [4, 11]. The technical factors are: *"Tunnel function"*, *"Tunnel cross sectional profile"*, *"Groundwater conditions"* and *"Ground conditions"*. A matrix, shown in table 1, was developed to combine the lining methods and technical factors.

Table 1 Technical controlling factors for lining methods (Lining methods matrix)

Factors				Precast concrete segments	Cast steel segments (steel/iron)	Cast-in-place concrete	Pipe in tunnel	Shotcrete lining	No Final lining
Ground conditions	Q – Value	100 - 1000							
		40 – 100							
		10 – 40							
		4 – 10							
		1 – 4							
		0.1 – 1							
		0.01 – 0.1							
		0.001 – 0.01							
	Ground is soil								
	Minimum reaction with ground mineral	Feldspars	Orthoclase						
			Plagioclase						
		Quartz	Silica						
		Clay minerals	-----						
		Micas	Muscovite						
			Biotite						
		Chlorite	-----						
		Calcite	$CaCo_3$						
		Iron Ores	Carbonates						
			Pyrite						
		Ferromagnesium minerals	Augite						
			Olivine						
Tunnel profile	Circular or Mouth profile								
	Horseshoe profile								
	Oval profile								
	Nordic profile								
	Basket Handle								
	Rectangular profile								
Tunnel function	water conveyance								
	road								
	railway								
	storage								
	defense								

Table 1 Technical controlling factors for lining methods (Lining methods matrix) (continued)

Table 1 Technical controlling factors for lining methods (Lining methods matrix) (continued)

Factors \ Lining Methods			Precast concrete segments	Cast segments (steel/iron)	Cast-in-place concrete	Pipe in tunnel	Shotcrete lining	No Final lining
Groundwater inflow / 10m tunnel length		< 10 L/min						
		10-25 L/min						
		25-125 L/min						
		> 125 L/min						
Basic tunnelling & excavation methods	Basic methods	Cut & Cover						
		NATM - Full face						
		NATM - Heading & bench						
		NATM - Multiple drift						
		NATM - Pilot enlargement method						
	Excavation methods	Excavator / Front shovel / Backhoe						
		Hand excavation						
		Drill & blasting						
		Roadheader						
		Micro-tunnelling						
		Shield machine						
		TBM machine						
Supporting methods	Rock bolts							
	Dowels							
	Steel arch							
	Shotcrete							
	Precast concrete segments							

A. Technical factors

A.1 Tunnel function

Tunnel function is an important factor in deciding what will be the tunnel lining. Tunnels for water transfer need smooth lining. Railway tunnels need strong lining under the rails to support the high load generated by the trains.

During the design of the lining matrix the aim was to determine which type of lining is more efficient for tunnel function. Tunnel functions are divided into water conveyance tunnels, road tunnels, railway tunnels, storage tunnels and defense tunnels. The tunnel functions “storage and defense” were defined by Marie [6].

A.2 Tunnel cross sectional profile

Tunnel profile affects the constructibility of a tunnel lining. The time needed to construct the final lining is different depending on tunnel profile and lining type. The objective of this factor is to determine efficient lining methods depending on tunnel profile.

A.3 Groundwater conditions

Sterling and Godard [8] stated that leakage of groundwater into the finished underground structure severely affects the quality of the space and is very difficult to correct. Groundwater sealing is a function of the water insulation system as well as of the lining system. In case of electric installations inside the tunnel, water sealing is very important. Sometimes two layers of lining are used to provide satisfactory protection against water inflow.

Groundwater flow into the tunnel is directly relational to the groundwater pressure around the tunnel. Groundwater pressure on the lining depends on groundwater table height and relative permeability of the ground. Groundwater inflow rate represents groundwater pressure and ground permeability, the amount of groundwater that the lining method will resist should be taken into consideration during selecting the lining method. Groundwater inflow per 10 m of tunnel length is divided into four ranges (see table 1). The scale is the same as that proposed by Bieniawski [2] in Geomecanics classification.

A.4 Ground conditions

Ground properties have a great influence on the selection of the tunnel lining. Selection of a lining method should be done carefully and a high degree of safety must be always in tunnel designer’s mind.

Isaksson [3] stated that defining the geological conditions can be done using different systems. The term “ground classes” is often used in Germany, Austria and Switzerland. An important factor for the definition of ground classes is the impact of the support on the tunnelling advance rate [5]. Q-system is another commonly used classification system.

The Q-system classification ranges in table 2 are used to determine the proper lining method for the tunnel. When the ground is soil, it is presented in the lining methods matrix in a separate row.

Q-value scale	Description
100 – 1000	Extremely good
40 – 100	Very good
10 – 40	Good
4 – 10	Fair
1 – 4	Poor
0.1 – 1	Very poor
0.01 – 0.1	Extremely poor
0.001 – 0.01	Exceptionally poor

The possible reaction between lining material and the surrounding ground is another important parameter that controls the selection of the lining method. Both ground mineral composition and lining material type control the possible reaction. Bell [1] and the US Army report [13] proposed the most common minerals found in the ground. Minerals in table 1 are not all mineral that can be found in the ground but they are the most common minerals in the ground.

A.5 Basic tunnelling methods, excavation methods, and supporting methods

Tunnelling system should be harmonised, which means that the selected lining method should be efficient when it is used with other construction methods of tunnelling activities. Therefore, basic tunnelling methods, excavation methods, and supporting methods are included in lining matrix (table 1) to evaluate the efficiency of lining methods against those methods [9, 10, 12].

A. Non-Technical factors

The main two non-technical factors are cost and time, they are very important factors and they can be the main factors for taking a decision of selecting the lining method.

Generally, efficiencies of methods will be evaluated with regard to the “Initial” and “Running” costs of the methods. The “Initial cost” is the amount of money needed, before the start of the method, to buy and transport the resources that will be used by the method. “Running cost” is the amount of money that will be spent during the working period of the method such as fuel and lubrication costs for machines.

The efficiency degrees of lining methods for cost and time factors are included in the matrices (tables 3 and 4). The relative efficiency degrees of the lining methods will be based on cost per 1m length of the tunnel and productivity per hour. Production rate of 75m/week is also used for lining methods.

Lining Methods / Factors	Precast concrete segments	Cast steel segments	Cast-in-place concrete	Pipe jacking	Shotcrete lining	No Final lining
Cost / 1m length of tunnel						

Table 3 Non-technical controlling factors (cost)

Lining Methods / Factors	Precast concrete segments	Cast steel segments	Cast-in-place concrete	Pipe jacking	Shotcrete lining	No Final lining
Production rate = 75m/week						

Table 4 Non-technical controlling factors (time)

III. Selecting Efficient Lining Method

The proposed model of this research is developed to help decision maker in selecting the efficient lining methods in the preliminary stage of the tunnel project. The following sections illustrate the model and how to use it.

A. Determination of the efficiency degrees (EDs) of lining methods for controlling factors

Matrices (tables 1, 3, and 4) were sent to tunnel experts working for 35 construction companies, 28 designers, and 12 clients to consult their opinions about the efficiency degree (EDs) of each lining method for each controlling factor. Tunnel experts were asked to determine the EDs of the lining methods related to the controlling factors using a scale ranging from 1 (the worst) to 4 (the best). According to the scale a lining method will have *"very good"* ED for the controlling factor when the degree is "4" on the other hand it will not have sufficient efficiency degree to work for the controlling factor when the degree is "1". "4" is the maximum efficiency degree used in the model. Four construction companies, two designers and two clients filled out and returned back the matrices. After collecting the data, average matrices were developed based on the experts' evaluations and their notes. The ED values in the average matrices are the average values of the experts' EDs.

B. Importance percentages (IPs) of the controlling factors

The IPs of the controlling factors, which will be calculated in this section represent the relative importance of each controlling factor compared to the importance of the other factors which control the selection of the lining method. The user of the model has to determine the importance degree (ID) of each controlling factor. The IDs will be used to calculate the IPs of the controlling factors.

The scale of the ID is between zero and ten where a zero value indicates that the controlling factor is not important for selecting the lining method. The most important controlling factors should be assigned the highest ID which

$$IP_i = \frac{ID_i}{\sum_{i=1}^{n} ID_i} * 100 \qquad (1)$$

Where: IP_i = importance percentage of factor "i"; ID_i = importance degree of factor "i" which is given by the user of the model; n = total number of factors

C. Calculations of the lining methods' efficiency percentages (EPs)

Calculation of the EP for any lining method has two steps. At first, the model calculates weighted efficiencies of the method for each controlling factor by multiplying the IP of the controlling factor by the ED of the method for that controlling factor. Equation (2) illustrates how to calculate the weighted efficiency of a lining method "A" for a controlling factor "i", this calculation will be repeated "n" times which is the number of controlling factors for lining method "A" (see figure 1). The second step of the calculations includes dividing the summation of the weighted efficiencies by the maximum efficiency degree to determine the EP of the lining method. Equation (3) illustrates the second step of the calculations. When the calculated EP of a lining method is zero, this means that this method could not satisfy one or more of the project's controlling factors. The model ranks the lining methods with non-zero EPs in descending order.

$$W_{Ai} = ED_{Ai} * \frac{IP_i}{100} \qquad (2)$$

$$EP_A = \frac{\sum_{i=1}^{n} W_{Ai}}{T} * 100 \qquad (3)$$

Where: "A" = a lining method; W_{Ai} = the weighted efficiency of lining method "A" for controlling factor "i"; = efficiency degree of lining method "A" for controlling factor "i"; IP_i = importance percentage of the controlling factor "i" related to the other controlling factors; T = the maximum efficiency degree which is "4"; EP_A = efficiency percentage of lining method "A"; i =

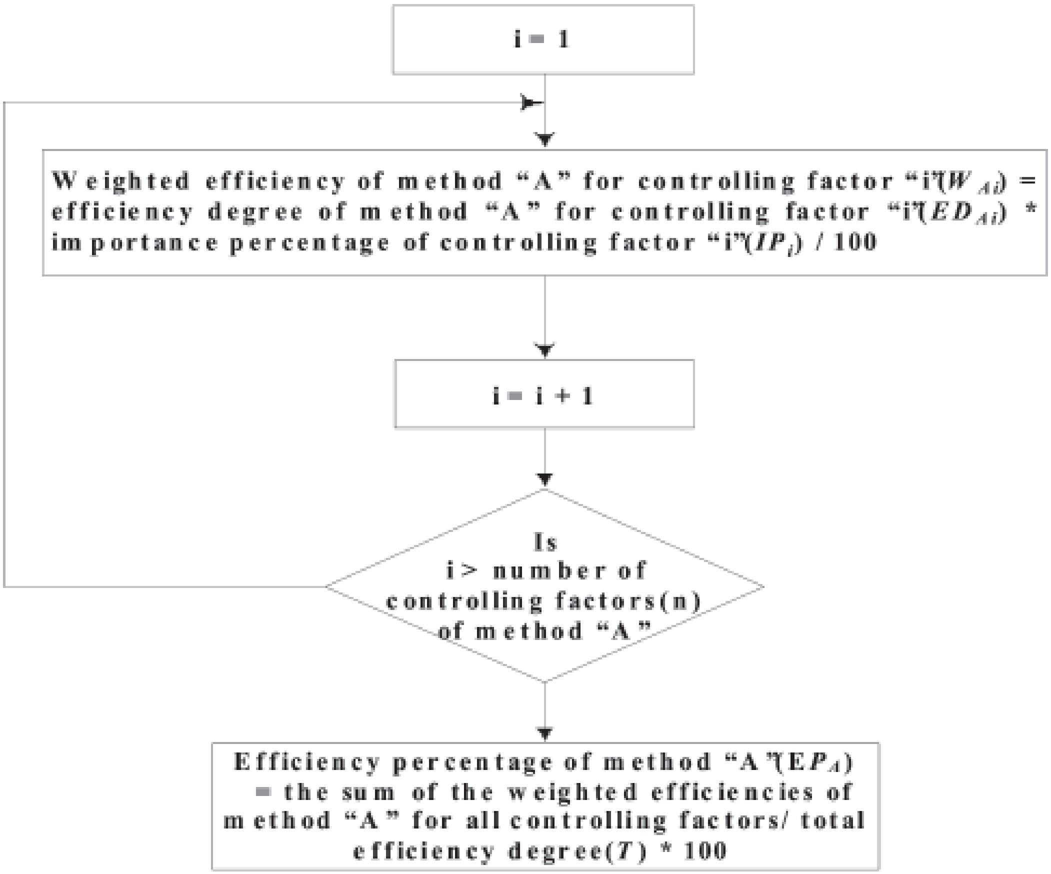

Figure 1 Calculations of lining methods' efficiency percentages

I. Application of the model

The model was applied for three projects, which are *"Wienerwald tunnel", "Tunnel project U2/2-Taborstraße", and "Gotthard base tunnel – Amsteg section lot 252"*. Application for "Wienerwald tunnel" represents the opinion of the designer, "Tunnel project U2/2-Taborstraße" represents the opinion of the client and "Gotthard base tunnel – Amsteg section lot 252" represents contractor's opinion. Table 5 shows the most efficient lining methods and their efficiency percentages as resulted from the model. For more information about the whole reports of the lining methods suggested for the three projects can be found in reference number [9].

controlling factors of lining methods; and n = number of controlling factors for lining methods.

Project	Lining method	Efficiency percentage
Wienerwald tunnel	Precast concrete segments	86.7%
Tunnel project U2/2- Taborstraße	Cast-in-place concrete	83.4%
Gotthard base tunnel – Amsteg section lot 252	Precast concrete segments	76.1%

Table 5 Lining methods as resulted from the model

V. Conclusion

The model results shows that it is a effective tool for helping the decision maker in selecting the lining methods for tunnel projects in the preliminary stage of the project. To increase the accuracy of the model more data need to be collected from tunnel experts for evaluating the EDs of the lining methods for controlling factors to develop more accurate average matrices of the EDs to be stored as database for the model.

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