A Model for Selecting Efficient Tunnelling Systems

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1. Introduction
Modern tunnelling offers a wide range of highly developed construction methods for underground excavation and final lining. Overall we must accept that an ideal method for every tunnel and every ground condition does not exist [5], but trying to find the most efficient tunnelling system at the preliminary stage of the project will help in selecting one efficient tunnelling system for a certain tunnel project, that will lead to minimizing problems during construction and finish the project within its budget and time. Sturk [9] recommended a decision process comprising two steps for selecting method of construction for underground projects. The Analytic Hierarchy Process (AHP) techniques have been used for a variety of specific applications in decision-making in underground operations. Karadogan [6] proposed the method of Fuzzy Attribute Decision Making (FADM) for the solution of an underground mining method selection and they used Saaty’s AHP method [8] for criterion pair-wise comparison. Bitarafan and Ataei [3] solved the underground mining method selection problem by using FADM with utilization of the AHP method and they also used Fuzzy Dominance Method in their analysis. Kazakidis [7] used the AHP and analyzed five different mining scenarios. Bettero and Peila [4] compared two different excavation alternatives, micro-tunnelling and trench excavation for an urban sewer construction project by using AHP. Taheri and Borujeni [10] as well as Acaroglu [1] used the AHP method to select tunnelling machine and roadheaders for tunnelling project respectively. Yavuz [13] used the AHP method for selecting the optimum support design for the main haulage road in Western Lignite Corporation (WLC) Tuncbilek in Turkey. In 2009, Alpay and Yavuz [2] presented a computer program based on the AHP and the Yager’s method to analyze the underground mining method selection problems and produce the best underground mining method swiftly for different deposit shapes and ore bodies. Summing up the activities within the last decade many methods have been developed and show a wide range of options to bridge the gap in selecting the best possible tunnelling system for a certain tunnel project.

This paper represents a model for selecting the efficient tunnelling systems during the preliminary stage of the tunnel project. The term “tunnelling system” refers to the comprehensive, harmonized methods that will be used for executing the tunnel project. An example for tunnelling systems is shown in table (1).

2. Tunnelling activities
Many activities are used to construct a tunnel. This research is concerned with the main tunnelling activities which are: excavation; initial ground support; mucking; transportation of the muck; groundwater control and final lining. In addition to selecting the efficient construction methods for the previously mentioned tunnelling activities, it is very important to select, at first,
the concept of tunnelling process. The concepts of tunnelling process are presented in this research as the "Basic tunnelling methods". Table (2a&b) shows the "Basic tunnelling methods", as well as the construction methods that can be used to execute the tunnelling activities.

Table (1) example of tunnelling systems which can be used for a tunnel project

<table>
<thead>
<tr>
<th>Tunnelling Activities</th>
<th>Basic tunnelling methods</th>
<th>Excavation</th>
<th>Mucking</th>
<th>Transportation</th>
<th>Side wall &amp; face support</th>
<th>Lining</th>
<th>Groundwater control</th>
</tr>
</thead>
<tbody>
<tr>
<td>NATM – Heading &amp; bench</td>
<td>Excavator</td>
<td>Rubber wheel loader</td>
<td>Rubber wheel truck</td>
<td>Sprayed concrete</td>
<td>Dewatering</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table (2a) Construction methods for tunnelling activities

<table>
<thead>
<tr>
<th>Construction Methods</th>
<th>Tunnelling activities</th>
<th>Basic tunnelling methods</th>
<th>Excavation</th>
<th>Support</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cut &amp; Cover</td>
<td>Hand excavation</td>
<td>Rock bolts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full face</td>
<td>Drill &amp; Blast</td>
<td>Dowels</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NATM</td>
<td>Roadheader</td>
<td>Steel arch</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiple drift</td>
<td>Micro-tunnelling</td>
<td>Sprayed concrete</td>
</tr>
<tr>
<td></td>
<td>Mechanical method</td>
<td>Shield Machine (Slurry / EPB)</td>
<td>Forepoling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shield Machine (Slurry / EPB)</td>
<td>TBM Machine (Open machine)</td>
<td>Pipe umbrella</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Doorframe slab</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Earth wedge</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Micro-tunnelling</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Precast concrete segments</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Diaphragm wall</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sheet pile</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bored pile</td>
<td></td>
</tr>
</tbody>
</table>

Table (2b) Construction methods for tunnelling activities

<table>
<thead>
<tr>
<th>Construction Methods</th>
<th>Tunnelling activities</th>
<th>Groundwater control</th>
<th>Mucking</th>
<th>Transportation</th>
<th>Lining</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dewatering</td>
<td>Rubber wheel loader</td>
<td>Rubber wheel truck</td>
<td>Precast concrete segments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slurry wall</td>
<td>Tracked loader</td>
<td>Diesel – mechanical locomotive</td>
<td>Cast steel segments (steel/iron)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compressed air</td>
<td>Rail - Locomotive type</td>
<td>Diesel - electric locomotive</td>
<td>Cast-in-place concrete</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Freezing</td>
<td></td>
<td>High voltage locomotive</td>
<td>Pipe in tunnel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chemical &amp; cement grouting</td>
<td>Conveyors</td>
<td>Sprayed concrete lining</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jet grouting</td>
<td></td>
<td>No Final lining</td>
<td></td>
</tr>
</tbody>
</table>
Table (3) Controlling factors for the tunnelling activities

<table>
<thead>
<tr>
<th>Construction methods for tunnelling activities</th>
<th>Basic tunnelling and excavation methods</th>
<th>Mucking methods</th>
<th>Transportation methods</th>
<th>Support methods</th>
<th>Lining methods</th>
<th>Groundwater control methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground conditions</td>
<td>Cost</td>
<td>Ground bearing capacity</td>
<td>Ground bearing capacity</td>
<td>Ground conditions</td>
<td>Ground conditions</td>
<td>Ground conditions</td>
</tr>
<tr>
<td>Tunnel depth</td>
<td>Time</td>
<td>Muck particle size</td>
<td>Transportation length and speed</td>
<td>Tunnel depth</td>
<td>Tunnel cross section profile</td>
<td>Tunnel depth</td>
</tr>
<tr>
<td>Tunnel cross-section</td>
<td>Technology availability</td>
<td>Tunnel span</td>
<td>Others</td>
<td>Others</td>
<td>Tunnel function</td>
<td>Others</td>
</tr>
<tr>
<td>Tunnel alignment</td>
<td>Experience</td>
<td>Tunnel slope</td>
<td>Muck particle size and water content</td>
<td>Groundwater condition</td>
<td>Tunnel position</td>
<td>Working length of the tunnel (m/day)</td>
</tr>
<tr>
<td>Health &amp; safety</td>
<td>Others</td>
<td>Others</td>
<td>Others</td>
<td>Groundwater condition</td>
<td>Health &amp; safety</td>
<td>Others</td>
</tr>
<tr>
<td>Environmental conditions</td>
<td></td>
<td>Others</td>
<td>Others</td>
<td>Environmental conditions</td>
<td>Others</td>
<td>Others</td>
</tr>
<tr>
<td>Tunnel position</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. Controlling factors
To select the efficient construction methods for executing tunnelling activities, controlling factors that represent project characteristics and conditions should be identified and determined. Controlling factors are technical and non-technical factors. Technical factors are such as ground conditions, tunnel shape, tunnel depth ...etc. Non-technical factors are such as project time and cost, technology availability and experience.

For developing the proposed model of this paper, controlling factors were initially determined based on the literature and then tunnel experts were consulted to come-up with the final list of controlling factors for each of the tunnelling activities. Table (3) shows the controlling factors for each of the tunnelling activities.

The user of the model has to determine the importance degree (ID) of each controlling factor from his/her point of view and with respect to his/her tunnel project. The IDs will be used to calculate the importance percentages (IPs) of the controlling factors, which will be used later by the model to calculate the efficiency percentages (EPs) of the construction methods. The IPs of the controlling factors represent the relative importance of each controlling factor compared to the importance of the other controlling factors which control the construction methods of the same activity, e.g. the IP of the “ground bearing capacity” controlling factor of mucking methods represents the relative importance of the “ground bearing capacity” compared to the importance of the “muck particle size” and the “tunnel span” (see table 3). 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 construction methods. The most important controlling factors should be assigned the highest ID which is ten. The higher the ID value the higher the role of the controlling factor in selecting the construction method. The model uses equation (1) to calculate the IPs of the controlling factors using the ID values which are assigned by the user.

\[
IP_i = \frac{ID_i}{\sum_{i=1}^{n} ID_i} \times 100
\]

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

4. The first phase of the model (Phase I)
The model has two phases (as shown in figure 1). In the first phase, the model calculates the efficiency percentages of different construction methods for each of the tunnelling activities, and it ranks construction methods in a descending order based on the efficiency percentages of construction methods.

4.1 Matrices of the model
Six separated matrices were developed for the “Basic tunnelling methods”, “Excavation methods”, “Mucking methods”, “Transportation methods”, “Support methods”, “Lining methods” and “Groundwater control methods”. The “Basic tunnelling methods” and excavation methods are included in the same matrix. The matrices relate construction methods and their controlling factors. More information about the matrices are presented in references [11] and [12].

Matrices were sent to tunnel experts working for 35 construction companies, 28 designers, and 12 clients. Tunnel experts of these organizations were asked to fill out the matrices by giving their evaluations for the efficiency degrees (EDs) of the construction methods related to the controlling factors using a scale ranging from 1 (the worst) to 4 (the best). According to the scale a construction method will have “very good” ED for the controlling factor when the degree is “4” and when the degree is “1”, the method will not have sufficient efficiency degree to work for the controlling factor. Four construction companies, two designers and two clients filled out and
returned back the matrices. It is important to elucidate that some responses of experts represent the opinions of a group of tunnel experts who work for the organizations not only one expert.

Determination of the most efficient "Basic tunnelling methods" and calculate their efficiency percentages

Determination of the most efficient construction methods for tunnelling activities and calculate their efficiency percentages

Combination of the most efficient methods for the "Basic tunnelling methods" and for tunnelling activities to formulate alternative tunnelling systems

Figure 1 Steps of the proposed model to determine alternative tunnelling systems

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. The values of the EDs are the database of the model which is used for calculating the EPs of construction methods.

If the model user assigns IDs for the non-technical factors "technology availability, experience or others", he/she must feed the model by the EDs of the construction methods for these factors. The model will use both of IDs and EDs of these factors to calculate their EPs.

4.2 Calculation of the Efficiency Percentages (EPs) of the construction methods
The efficiency percentage (EP) of a construction method depends on the two previously explained factors which are the "efficiency degrees (EDs) of the method for the particular controlling factors" and the "importance percentages (IPs) of the controlling factors".

Calculation of the construction method's EP 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 construction method "A" for a controlling factor "i", this calculation will be repeated "n" times which is the total number of controlling factors of construction method "A" (see figure 2). 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 construction method. Equation (3) illustrates the second step of the calculations.

4.3 Remarks about the EPs calculations
Construction methods that have EDs equal to "1" for one or more of the controlling factors will not be considered as efficient methods for the project.

The user of the model will get a separate report for every tunnelling activity. These reports give the user the ranks of the construction methods that can be used for the tunnelling activity and their EPs.
\[ W_{Ai} = ED_{Ai} \times \frac{IP_i}{100} \]  
(2)

\[ EP_A = \frac{\sum_{i=1}^{n} W_{Ai}}{T} \times 100 \]  
(3)

Caption:

\( A \) = a construction method such as “NATM-Full face”, “Sprayed concrete”, or “Dewatering” etc. (see construction methods in table 2);

\( W_{Ai} \) = the weighted efficiency of construction method \( A \) for controlling factor \( i \);

\( IP_i \) = importance percentage of the controlling factor \( i \) related to the other controlling factors;

\( ED_{Ai} \) = efficiency degree of method \( A \) for controlling factor \( i \);

\( T \) = the maximum efficiency degree which is 4;

\( EP_A \) = efficiency percentage of construction method \( A \);

\( i \) = controlling factors of method \( A \) (see table 3);

\( n \) = number of controlling factors for method \( A \)

5. The second phase of the model - Alternative tunnelling systems (Phase II)

In the second phase, the model will combine different tunnelling activities to determine the possible alternative tunnelling systems.

In each activity matrix a section is enclosed which connects the methods of the chosen tunnelling activity with the methods of other tunnelling activities [11]. Tunnel experts filled out these sections with numbers which show their opinions about the efficiency degrees of the methods in working together. Value “1” means that the two construction methods cannot work together. Value “4” is the highest efficiency degree and it means that the two methods can work together efficiently. The average values of the experts’ opinions are used by the model to calculate the efficiency percentages of the alternative tunnelling systems.

![Diagram](image)

Figure 2 Calculations of methods’ efficiency percentages

When two methods work together in one combination, the efficiency percentage of the combination will depend on efficiency percentages of the two methods which resulted from the calculations of the first phase and efficiency percentage of the two methods in working together. The efficiency percentage of the combination between methods “A” and “B” equals to the product of the efficiency percentages of “A” and “B”, which are known after the calculations of the first
phase, and the efficiency percentage “z” of the two methods working together. Equation (4) will be applied first to calculate efficiency percentage of the methods working together and then equation (5) will be used to calculate the combined efficiency percentage.

\[ R_{ij} = \frac{(D_{ij} - 1)}{3} \times 100 \]  

Caption:

- \( R_{ij} \): efficiency percentage of methods i & j to work together;
- \( D_{ij} \): efficiency degree of methods i & j working together (expert evaluation);
- \( i = 1, 2, 3, \ldots, m \) (i represents construction methods of the first tunnelling activity);
- \( j = 1, 2, 3, \ldots, n \) (j represents construction methods of the second tunnelling activity);
- \( m \): number of efficient construction methods of the first tunnelling activity which resulted from the first phase;
- \( n \): number of efficient construction methods of the second tunnelling activity which resulted from the first phase.

Equation (5) will be used to calculate efficiency percentages of the combinations of the two methods.

\[ F_{ij} = E_i \times L_j \times R_{ij} \times 100 \]  

Caption:

- \( F_{ij} \): efficiency percentage of the combination between methods i & j;
- \( E_i \): efficiency percentage of the first construction method (i);
- \( L_j \): efficiency percentage of the second construction method (j);
- \( R_{ij} \): efficiency percentage of methods “i” and “j” working together (it is calculated using equation 4).

The same concept is used to add more construction methods to formulate the alternative tunnelling systems. After adding the construction methods of all tunnelling activities the model calculates the efficiency percentages of the whole tunnelling systems and then it ranks the systems in descending order.

6. Application of the model

A computer program was developed to facilitate the use of the model. The program was written using Visual Basic 6 programming language. Data of three real projects were used to check the model validity. Projects used are the long railway tunnels “Wienerwald Tunnel (Austria)” and “Gotthard Tunnel – Amsteg section lot 252 (Switzerland)” as well as the shallow urban Metro tunnel “U2/2 Taborstraße (Austria)”. There was a difference between the support methods suggested by the model and the real case in the “Gotthard Tunnel – Amsteg section lot 252” project. For this project, the model suggests the use of the “Precast concrete segments” as the most efficient method for supporting and the “Sprayed concrete” comes in the second rank. In the real project the “Sprayed concrete” is used. Tests of the program show that the program is reliable and it is very helpful tool for the decision maker to select the efficient tunnelling system at the preliminary stage of a project. Using of the program will save time and it will narrow the selection options of the decision maker, which will facilitate taking decision. To increase the accuracy of the proposed model, it is recommended to consult the opinions of more tunnel experts and to increase the sample.
References
11. Toma, H. 2005, A computer model for selecting efficient tunnelling systems, PhD dissertation, Faculty of Civil Engineering, Vienna University of Technology, Vienna, Austria.