Selecting efficient support methods for tunnels

Construction of a tunnel consists of many activities during the construction phase of the project, supporting is one of these activities.

Hossam TOMA¹ and Hans G. JODL²

Intermediate support elements are provided to control ground movement caused by stress redistribution during tunnel drive. Certain support elements are assembled in the excavated areas of crown, side wall and additionally on the tunnel face if necessary. Typical support elements are rock bolts, reinforced sprayed concrete, girders, etc. Loose ground and weak rock within the following rounds can also be supported using methods such as pipe umbrella, forepoling, earth wedge, etc. The Selection of efficient support methods for tunnelling is very important to reduce problems during construction and maintain project cost and time within the project budget and the planned schedule. This paper introduces a model that helps decision maker in selecting tunnel support methods in the conceptual phase of the project. The model calculates efficiency percentages of support methods based on project conditions. The model provides the user with a report including support methods and their efficiency percentages ranked in descending order.

³ Assistant Professor, Department of Construction Engineering and Utilities, Faculty of Engineering, Zagazig University, Zagazig, Egypt. E-mail address: hossam.toma@gmail.com

² Professor and Head of Institute of Interdisciplinary Construction Process Management, Faculty of Civil Engineering, Vienna University of Technology, Vienna, Austria. E-mail: jodl@ibb.tuwien.ac.at

Introduction

Support of tunnel side wall and crown as well as tunnel face is very essential when the tunnel is constructed in weak ground. Lauffer (1958) proposed that the stand-up time for an unsupported span is related to the quality of the ground in which the span is excavated. In a tunnel, the unsupported span is defined as the span of the tunnel or the distance between the face and the nearest support, if this is greater than the tunnel span. When the excavated ground is hard rock the stand-up time can reach, in some cases, up to years. Weak ground which has a short stand-up time - might be less than 1 hour - needs to be supported immediately after excavation. There are several methods which can be used for tunnel side wall and crown support, these methods are rock bolts, dowels, steel arches, sprayed concrete, and precast concrete segments. Forpoling, pipe umbrella, doortframe slab, earth wedge, and sprayed concrete can also be used for supporting the tunnel face.

Selection of an efficient support method is a key factor for the success of the tunnel project. Efficient method is the method which satisfies efficiently the controlling factors which are technical and non-technical factors.

Almost all the empirical models that are used for determining support methods are related to the ground classification systems. Written rules for selecting ground support were first formulated in 1946 by Terzaghi. Deere et al (1970) presented ground support recommendations for tunnels excavated conventionally and by TBM's based on both of Terzaghi's classification and
the Rock Quality Designation index (RQD). Wickham et al. (1972) suggested also support methods for tunnels during construction based on the Rock Structure Rating (RSR) classification system. The above mentioned systems are not widely used now but they were the nucleus for the newer systems. The Geomechanics Classification or the Rock Mass Rating (RMR) system, which first published by Bieniawski in 1976, and its modifications in 1989 (Bieniawski, 1989) suggest guidelines for the selection of support in tunnels in rock for which the value of RMR has been determined. In 1974, Barton et al. proposed a Tunnelling Quality Index (Q) for the determination of rock mass characteristics and tunnel support requirements, this system was updated by Grimstad and Barton (1993) to reflect the increasing use of steel fibre reinforced sprayed concrete in underground excavation support. The guideline for geomechanical design of cyclic tunnelling (Austrian Society for Geomechanic, 2001) considers decisive geomechanical factors. All the above mentioned systems suggest support methods based only on the ground conditions ignoring other factors that may have a significant weight in choosing the support method. The introduced model takes into consideration the most important factors that may have influence on the selection of the support methods.

"Selecting efficient support method model."

The proposed model represents a quantitative calculation preselection of an efficient tunnel support method assisting decision makers in the conceptual phase of the project. The model calculates efficiency percentages (EPs) of the support methods for controlling factors which represent project's technical and non-technical conditions. Calculation of the EP for a support method depends on two factors which are the efficiency degrees (EDs) of the method for the particular controlling factors and the importance percentages (IPs) of the controlling factors.

Controlling factors: Four technical factors are used to represent the main projects' technical conditions which control the selection of support methods, these factors are ground conditions, tunnel depth, constructibility, and tunnel excavation method (Toma, 2005). Non-technical factors are cost and time. Three matrices - tables (1), (2) and (3) - were developed to combine the controlling factors and support methods. The 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 EDs of the support methods related to the controlling factors using a scale ranging from 1 (the worst) to 4 (the best). According to the scale a support 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 con-

<table>
<thead>
<tr>
<th>Factors</th>
<th>Support Methods</th>
<th>Side wall &amp; Crown support</th>
<th>Face support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground conditions</td>
<td>Rock quality (RQD values)</td>
<td>Rock bolts</td>
<td>Screws</td>
</tr>
<tr>
<td>Low</td>
<td>1 - 20</td>
<td>1</td>
<td>1</td>
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<tr>
<td>21 - 40</td>
<td>2</td>
<td>2</td>
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<tr>
<td>41 - 60</td>
<td>3</td>
<td>3</td>
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<tr>
<td>High</td>
<td>61 - 80</td>
<td>4</td>
<td>4</td>
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<tr>
<td>Over 80</td>
<td>5</td>
<td>5</td>
<td>5</td>
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<tr>
<td>Project factors</td>
<td>Failure due to weathering</td>
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<tr>
<td>Failure due to moving water</td>
<td></td>
<td></td>
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<tr>
<td>Failure due to corrosion of support</td>
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<tr>
<td>Failure due to squeezing &amp; swelling</td>
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</tbody>
</table>

Table (1): Comparing between support methods based on technical factors

<table>
<thead>
<tr>
<th>Factors</th>
<th>Cost / 1m length of tunnel</th>
<th>Side wall &amp; Crown support</th>
<th>Face support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock bolts</td>
<td>Screws</td>
<td>Steel arch</td>
<td>Segmental concrete</td>
</tr>
<tr>
<td>500 - 1000</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1000 - 5000</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Over 10000</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Table (2): Comparing between support methods based on cost

<table>
<thead>
<tr>
<th>Factors</th>
<th>Production rate = 75m/week</th>
<th>Side wall &amp; Crown support</th>
<th>Face support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock bolts</td>
<td>Screws</td>
<td>Steel arch</td>
<td>Segmental concrete</td>
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<tr>
<td>500 - 1000</td>
<td>1</td>
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<tr>
<td>1000 - 5000</td>
<td>2</td>
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<td>2</td>
</tr>
<tr>
<td>Over 10000</td>
<td>3</td>
<td>3</td>
<td>3</td>
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</tbody>
</table>

Table (3): Comparing between support methods based on time
The criteria affecting the magnitude of the controlling factor is "how much does the factor control the selection decision of support methods?" The user of the model has to answer this question when he/she determines the importance degree (ID) of each controlling factor. The IDs which will be determined by the user will be used to calculate the Importance Percentages (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 support method. 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 the selection process.

The model uses equation (1) to calculate the IPs of the controlling factors using the ID values which are assigned by the user. The user will assign the IDs of the controlling factors using the form shown in table (5).

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

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.

A controlling factor named "Others" is added to the controlling factors. This factor represents the factors that may have an influence on the selection decision of the support method, from user's point of view, and these factors are not included among the controlling factors.
The model will assign the trolling factors. If the support methods related to the factor conditions ID to this factor in the form of table factors, for example the ID for ground of the controlling factors to their the "RMR-value" factor and the failure (5).

The second step of the calculations for that controlling factor. Equation (2) illustrates how to calculate the weighed efficiency of a support method has two steps. At first, the model calculates weighted efficiencies by the maximum efficiency degree which is "4". The same calculations will be done for method "B" (see tab. 7). The EP of method "A" = 2.7/4 * 100 = 67.5%, where "4" is the maximum efficiency degree (application of equation 3). The EP of method "B" = 2.6/4 * 100 = 65%. The calculations show that method "A" has marginally higher efficiency percentage (EP) than method "B".

```
Efficiency percentage of method "A" (EPi) = the sum of the weighted efficiencies of method "A" for all controlling factors/total efficiency degree(T) * 100

Where: "A" = a support method such as "Rock bolts", "Shotcrete", or "Forepoling" etc.; = the weighted efficiency of support method "A" for controlling factor "i"; = efficiency degree of method "A" for controlling factor "i"; = importance percentage of the controlling factor "i" related to the other controlling factors; = the maximum efficiency degree which is "4"; = efficiency percentage of support method "A"; i = controlling factors of support methods; and n = number of controlling factors for support methods.
```

Example: If "A" and "B" are two support methods and they have the EDs shown in table (6) for controlling factors "X" and "Y". The maximum efficiency degree is "4" and the IPs of factors "X" and "Y" are 70% and 30% respectively. Calculation of the weighed efficiency of method "A" for controlling factor "X" is as follows (application of equation 2):

- \( ED_{AX} = 3 \) (this value is shown in tab. 6), and \( IP_x = 70\% \)
- \( W_{AX} = 3 * 0.7 = 2.1 \) (this value is the weighted efficiency of method "A" for factor "X")

The weighted efficiency of method "A" for factor "Y" will be calculated as follows:

- \( ED_{AY} = 2 \) (this value is shown in tab. 6), and \( IP_y = 30\% \)
- \( W_{AY} = 2 * 0.3 = 0.6 \) (this value is the weighted efficiency of method "A" for factor "Y")

The total weighted efficiency of method "A" = \( W_{AX} + W_{AY} = 2.1 + 0.6 = 2.7 \). The EP of method "A" = 2.7/4 * 100 = 67.5%.

```
Efficiency percentage of method "A series with non-zero EPs in descending order. The following example illustrates the calculation steps.

```
\[
W_{Ai} = ED_{Ai} \times \frac{IP_{pl}}{100}
\]

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

Where: "A" = a support method such as "Rock bolts", "Shotcrete", or "Forepoling" etc.; = the weighted efficiency of support method "A" for controlling factor "i"; = efficiency degree of support method "A" for controlling factor "i"; = importance percentage of the controlling factor "i" related to the other controlling factors; = the maximum efficiency degree which is "4"; = efficiency percentage of support method "A"; i = controlling factors of support methods; and n = number of controlling factors for support methods.
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Angaben zum Autor

Name
O.Univ.Prof. DI Dr.techn. Hans Georg JODL

Zur Person

that the difference between efficiency percentages of the "Precast concrete segments" and the "Sprayed concrete" as resulted from the model was not big at the same time the model suggests the support method in the conceptual phase of the project and further studies should be done before the final decision. The results of the model prove its validity and soundness of the program.

"Acknowledgement"

The authors would like to acknowledge Professor Herbert H. Einstein, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, USA, for his valuable contribution and opinions that helped in finishing this work. The authors thank also the staff of the projects, which used for testing the model, for their help and supplying us with the required information.

Table (7) Weighted efficiencies of methods "A" and "B"

<table>
<thead>
<tr>
<th>Factors</th>
<th>Methods</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3 * 0.7 = 2.1</td>
<td>2 * 0.7 = 1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 * 0.3 = 0.6</td>
<td>4 * 0.3 = 1.2</td>
</tr>
<tr>
<td>Total weighted efficiencies</td>
<td></td>
<td>2.1 + 0.6 = 2.7</td>
<td>1.4 + 1.2 = 2.6</td>
</tr>
</tbody>
</table>

Table (8) Comparison between the results of the model and the support methods used in the projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Methods</th>
<th>Support method used in the project</th>
<th>Support method selected by the model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wienerwald tunnel</td>
<td>Precast concrete segments</td>
<td>Precast concrete segments</td>
<td></td>
</tr>
<tr>
<td>U2/2 Taborstraße</td>
<td>Sprayed concrete</td>
<td>Sprayed concrete</td>
<td></td>
</tr>
<tr>
<td>Gotthard tunnel - Amsteg section lot 252</td>
<td>Sprayed concrete</td>
<td>Precast concrete segments</td>
<td></td>
</tr>
</tbody>
</table>

References