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Selecting efficient support methods for tunnels

Hossam Toma[1] and Hans G. Jodl[2]

1. 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

ABSTRACT

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

Key words: Tunnel construction, support methods, efficiency percentage

1. INTRODUCTION

Support of tunnel side walls 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. Forepoling, pipe umbrella, doorframe 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 TBMs 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.

2. SELECTING EFFICIENT SUPPORT METHOD MODEL

The proposed model represents a quantitative calculated pre-selection 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.

2.1 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 controlling factor. "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, the model uses these average EDs for the calculations of the support methods' EPs. The user of the model should feed it with technical data of the particular project to enable the model in determining which ED values will be used for the calculations. The form of table (4) is used to collect the project technical data which are needed for selecting the support method. When the user selects the values which represent the project conditions, the model will use the EDs which correspond to the project conditions, for the calculations.

2.2 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 support method.

The criterion 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 IPs of the controlling factors.

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

Factors / Support Methods			Side wall & Crown support					Face support				
			Rock bolts	Dowels	Steel arch	Sprayed concrete	Precast concrete segments	Forepoling	Pipe umbrella	Doorframe slab	Earth wedge	Sprayed concrete
Ground conditions	Ground is soil											
	Rock quality (RMR values)	0 - 20										
		21 - 40										
		41 - 60										
		61 – 80										
		Over 80										
	Prevent failure	Failure due to weathering										
		Failure due to moving water										
		Failure due to corrosion of support										
		Failure due to squeezing & swelling										
		Failure due to overstress										
Tunnel depth	Less than 30m											
	30 – 50m											
	50 – 100m											
	100 – 500m											
	500 – 1000m											
	Over 1000m											
Constructibility	Circular or mouth cross section											
	Oval or Horseshoe cross section											
	Other cross sections											
	Tunnel span	Less than 1.5m										
		1.5 – 4m										
		4 – 6m										
		6 – 10m										
		Over 10m										
Tunnel excavation methods	Excavator / Front shovel / Backhoe											
	Hand excavation											
	Drill & blasting											
	Roadheader											
	Micro-tunnelling machine											
	Shield machine											
	TBM (open machine)											

Table (2) Comparing between support methods based on cost

Factors / Support Methods	Side wall & Crown support					Face support				
	Rock bolts	Dowels	Steel arch	Sprayed concrete	Precast concrete segments	Forepoling	Pipe umbrella	Doorframe slab	Earth wedge	Sprayed concrete

Cost / 1m length of tunnel										

Table (3) Comparing between support methods based on time

Support Methods / Factors	Side wall & Crown support					Face support				
	Rock bolts	Dowels	Steel arch	Sprayed concrete	Precast concrete segments	Forepoling	Pipe umbrella	Doorframe slab	Earth wedge	Sprayed concrete
Production rate = 75m/week										

Table (4) Technical data of the project

Select one option for each factor *Tunnel span* □ 1.5m or less □ 2.0 – 4.0m □ 5.0 – 6.0m □ 7.0 – 10.0m □ over 10m
RMR value □ 0 - 20 □ 21 - 40 □ 41 - 60 □ 61 - 80 □ over 80 □ ground is soil
Select failure reasons (you can select more than one reason) □ failure due to weathering □ failure due to moving water □ failure due to support corrosion □ failure due to squeezing and swelling □ failure due to overstress
Tunnel depth □ 30m or less □ 31 – 50m □ 51 – 100m □ 101 – 500m □ 501 – 1000m □ over 1000m
Tunnel cross section profile □ circular or mouth profile □ oval or horseshoe □ other profiles
Tunnel excavation method □ excavator / front shovel / backhoe □ hand excavation □ drill & blasting □ roadheader □ micro-tunnelling machine □ shield machine □ TBM (open machine)

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).

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

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

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. If the user assigns an ID to this factor in the form of table (5) he/she should assign EDs for the support methods related to the factor "Others". The model will assign the IDs of the controlling factors to their sub-factors, for example the ID for ground conditions "X1" will be assigned to the "RMR-value" factor and the failure modes factors (see table (5)).

2.3 Calculations of the support methods' EPs

Calculation of the EP for any support 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 support method "A" for a controlling factor "i", this calculation will be repeated "n" times which is the number of controlling factors for support 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 support method. Equation (3) illustrates the second step of the calculations. When the calculated EP of a support method is zero, this means that this support method could not satisfy one or more of the project's controlling factors. The model ranks the support methods with non-zero EPs in descending order. The following example illustrates the calculation steps.

Table (5) Form used to assign IDs to the factors

IDs given by the user	Controlling factors	Sub-Factors will have the same ID of the parent factors	ID that will be used in the model
X1	Ground conditions	RMR value	X1
		Failure due to weathering	X1
		Failure due to moving water	X1
		Failure due to corrosion of support	X1
		Failure due to squeezing & swelling	X1
		Failure due to overstress	X1
X2	Tunnel depth	---------	X2
X3	Tunnel shape	---------	X3
X4	Tunnel span	---------	X4
X5	Tunnel excavation method		X5

X6	Cost	---------	X6
X7	Time	---------	X7
X8	Others	---------	X8
Total number of ID values			n = 13 values

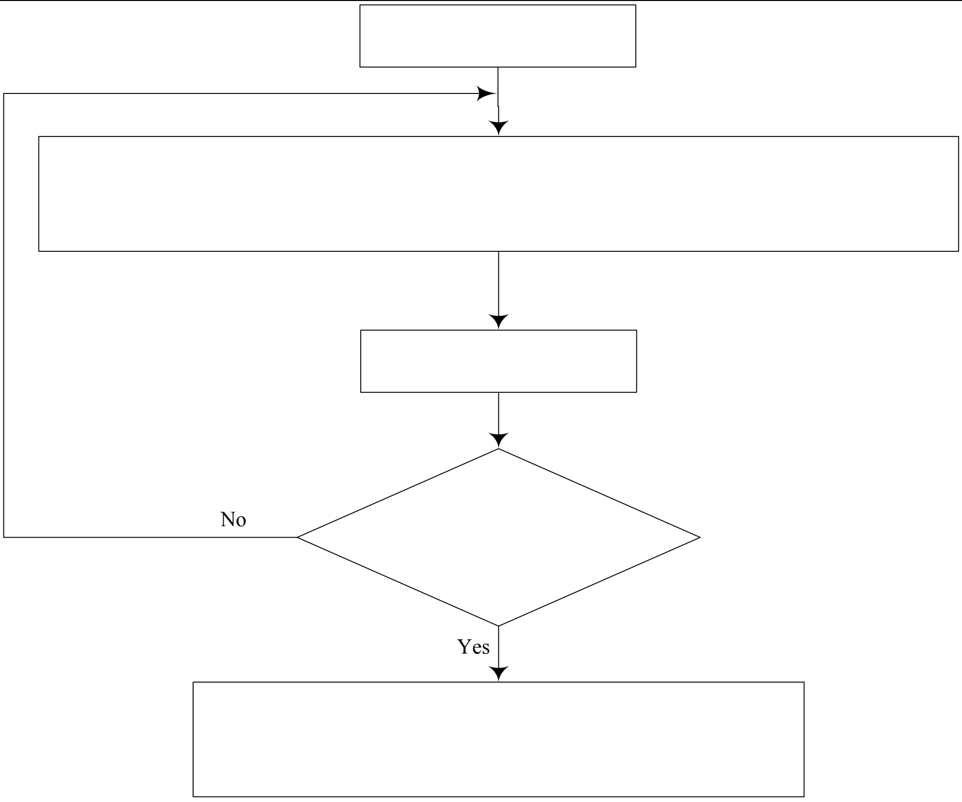

Figure 1 Calculations of support methods' efficiency percentages

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

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

Weighted effi efficiency deg importance p

Where: "A" = a support method such as *"Rock bolts"*, *"Shotcrete"*, or *"Forepoling"* etc.; W_{Ai} = the weighted efficiency of support method "A" for controlling factor "i"; ED_{Ai} = efficiency degree of support 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 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 weighted efficiency of method “A” for controlling factor “X” is as follows (application of equation 2):

Table (6) Efficiency degrees (EDs) of methods “A” and “B” for factors “X” and “Y”

Methods / Factors	A	B
X	3	2
Y	2	4

- ED_{AX} = 3 (this value is shown in table 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 table 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 same calculations will be done for method “B” (see table (7)). The EP of method “A” = $\frac{2.7}{4}$ * 100 = 67.5%, where “4” is the maximum efficiency degree (application of equation 3). The EP of method “B” = $\frac{2.6}{4}$ * 100 = 65%. The calculations show that method “A” has marginally higher efficiency percentage (EP) than method “B”.

3. APPLICATION OF THE MODEL

A computer program was developed to facilitate the use of the model. The program is written using Visual Basic 6 programming language. Data of three real projects were used to check the model validity. Projects that were used are *“Wienerwald tunnel (Austria)”, “U2/2 Taborstraße (Austria)”* and *“Gotthard tunnel – Amsteg section lot 252 (Switzerland)”*. Table (8) shows the results of the model compared with the support methods that are used really in the projects.

As shown in table (8) the support methods which have the highest EPs and they are suggested by the model for the *“Wienerwald tunnel”* project, and the *“U2/2 Taborstraße”* project are similar to the methods that are used in the project. There is a difference between the results of 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 the project and the “Sprayed concrete” comes in the second rank. In the real project the “Sprayed concrete” is used. This difference in results is not significant taking into consideration 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.

Table (7) Weighted efficiencies of methods “A” and “B”

Methods / Factors	A	B
X	3 * 0.7 = 2.1	2 * 0.7 = 1.4
Y	2 * 0.3 = 0.6	4 * 0.3 = 1.2
Total weighted efficiencies	2.1 + 0.6 = 2.7	1.4 + 1.2 = 2.6

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

Methods / Project	Support method used in the project	Support method selected by the model
Wienerwald tunnel	Precast concrete segments	Precast concrete segments
U2/2 Taborstraße	Sprayed concrete	Sprayed concrete
Gotthard tunnel – Amsteg section lot 252	Sprayed concrete	Precast concrete segments

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