DISSERTATION

A Computer Model for Selecting Efficient Tunnelling Systems

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unter der Leitung von

O.Univ.-Prof. Dipl.-Ing. Dr.techn. Hans Georg Jodl
Institut für interdisziplinäres Bauprozessmanagement,
Technische Universität Wien, Österreich

und

Prof. Dr. Herbert H. Einstein
Department of Civil and Environmental Engineering,
Massachusetts Institute of Technology, Cambridge, USA

eingereicht an der Technischen Universität Wien
Fakultät für Bauingenieurwesen

von

M.Sc. Eng. Hossam Mohamed Toma

Matr. Nr. 0127050

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Hossam Toma

Hossam Toma

Kurzfassung

Der Tunnelbau stellt eine anspruchsvolle Aufgabe im Bauwesen dar. Unterschiedliche Konzepte können für die Planung und Konstruktion vom Tunnel verwendet werden, wie z.B. die NATM und die mechanische Vortriebmethode. In der Ausbauphase eines Tunnelprojektes werden nachfolgende Tätigkeiten durchgeführt: Ausbruch, Schuttern (Laden und übergeben von Ausbruchsmaterial), Materialtransport, Stützung und Sicherung des Gebirges, Tübbinge und Grundwasserhaltung. Ein geeignetes Vortrieb- und Aufbausystem für Tunnels auszuwählen ist nicht einfach. Die Entscheidung hängt von einer Vielzahl von Parametern ab. Der Ausbruch kann durch Tunnelbagger, Bohren und Sprengen, Teilschnittmaschine oder Schildmaschine und TBM erfolgen. Welche der Ausbruch- bzw. Vortriebmethode ausgewählt wird, hängt von zahlreichen technischen und nicht technischen Faktoren ab. Technische Faktoren sind zum Beispiel Bodenbeschaffenheit, Tunneltiefe, Länge, Form und Querschnitt. Nicht technische Faktoren schließen Kosten, Zeit wie auch die allgemeinen und politischen Faktoren ein. Die Wahl der best geeigneten Ausbaumethoden für Vertrieb uns Ausbau ergibt eine Minimierung von Projektkosten, -zeit und -gefahren.

In der vorliegenden Arbeit wurde ein Computermodell entwickelt, das bei der Auswahl von einem geeigneten und effizienten Tunnelsystem im einleitenden Stadium eines Projektes helfen soll. Hierfür werden ausschlaggebende Faktoren, die die Ausbaumethoden beeinflussen können festgestellt. Für das entwickelte Modell wurden die Meinungen von Tunnelexperten über die Leistungsfähigkeit der Vortrieb- und Ausbaumethoden für unterschiedlich ausschlaggebenden Faktoren herangezogen.

Das Modell hat zwei Phasen. In der ersten Phase wird die prozentuelle Leistungsfähigkeit der Ausbaumethoden jeder einzelnen Tätigkeit, wie Ausbruch, Stützung und Tübbinge errechnet und berichtet in weiteren Folge über die Ausbaumethoden jeder Tätigkeit. In der zweiten Phase des Modells werden die Ausbaumethoden aller Tätigkeiten kombiniert, um die möglichen Alternativen der Tunnelsysteme festzustellen.

Summary

Tunnel construction is a challenging project. Different concepts can be used to construct tunnels, such as cut and cover, NATM and mechanical method. In the construction phase of a tunnel project, tunnelling activities are: excavation, mucking, transportation, initial ground support, lining, and groundwater control. Selecting a suitable construction system for tunnels is not easy. The difficulty stems from the large number of parameters that control the selection of construction methods. For example; excavation can be done by excavators, drill and blast, roadheader, and TBMs. Selecting the proper excavation method depends on technical and non-technical factors. Technical factors are, for instance, ground conditions, tunnel depth, length, shape, and cross sectional area. Non-technical factors include cost, time, and public and political factors. Selection of the most efficient construction methods results in a reduction of project cost, time and hazards.

In this research, a computer model is developed to help the decision maker in selecting an efficient tunnelling system in the preliminary stage of the project. Controlling factors that can affect the selection of construction methods were determined. The model of this research was developed based on the opinions of tunnel experts about efficiency of construction methods for different controlling factors.

The model has two phases, in the first phase, it calculates the efficiency percentages of construction methods of each tunnelling activity, such as excavation, supporting and lining, and it gives a report about construction methods of each activity. In the second phase, the model combines construction methods of all activities to determine the possible alternative tunnelling systems.

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1 Introduction

The planning and constructing of extensions to existing road and railway networks is an ongoing component of transport infrastructure development. For functional, aesthetic or environmental reasons, a large number of these extensions are planned as tunnels (Isaksson [54]).

In 1973, Walhstrom [120] defined a tunnel as a long, narrow[1], essentially linear excavated underground opening, the length of which greatly exceeds its width or height. A tunnel, as defined by Urschitz [115], is an underground structure which provides a convenient transportation through conditions posing natural difficulty or special hazard.

Colgan [22] differentiated between tunnels and drifts as follows: A tunnel is a generally horizontal passage through rock or soil with two portals one at each end, and a drift is a generally horizontal passage through rock or soil with a single portal at one end only.

Sterling and Godard [104] summarized functions and advantages of tunnels as follows:

- Tunnels play a vital environmental role by conveying clean water to and by conveying wastewater out from urban areas;
- Tunnels provide safe, environmentally sound, fast and unobtrusive urban mass transit systems;

[1] As a result of the fast development of tunnel construction methods and design tools, nowadays, tunnel diameter can be up to 15 meters.

- City traffic tunnels remove vehicles from surface streets, traffic noise is reduced, air becomes less polluted and the surface street areas may partially be used for other purposes;
- Tunnels are less vulnerable to external conditions such as effects of severe weathering than surface installations.

Tunnelling is characterized by high degrees of uncertainty, in excess of many other areas of civil engineering. Uncertainties stem from two major problems: The geological conditions are never known exactly, and, particularly for deep and long tunnels, preconstruction information may be very sparse. But even if the geologic conditions are known, there is still considerable uncertainty about the construction process (Haas and Einstein [40]).

The use of underground space is irreversible. Unlike structures above ground, which can be demolished and rebuilt differently, underground works cannot be easily demolished. This irreversible aspect of using underground space is a major consideration when developing this space (Sterling and Godard [104]).

Selecting the most efficient tunnelling system for a tunnel project minimizes construction problems and keeps the project cost and time within the planned budget and schedule.

Tunnelling system

A system is a set of independent but interrelated elements comprising a unified whole. A tunnelling system can be defined as a set of construction methods, which include a construction method for each tunnelling activity as well as a *"Basic tunnelling method"*, organized together to build a tunnel. Table 1.1 shows examples of tunnelling systems which can be used for a tunnel project.

Table 1.1 Examples of tunnelling systems which can be used for a tunnel project

System rank	Tunnelling activities / Basic methods	Excavation	Mucking	Transportation	Side wall support	Face support	Lining	Groundwater control	
1	Mechanical method	Shield machine	Shield machine	Rail (diesel - electric locomotive)	Precast concrete segments	Shield machine	Precast concrete segments	Dewatering	Construction Methods
2	NATM – Heading & bench	Excavator	Rubber wheel loader	Rubber wheel truck	Shotcrete	Shotcrete	Shotcrete	Dewatering	
3	Cut and cover	Excavator	Rubber wheel loader	Rubber wheel truck	Diaphragm walls	-	Cast – in – place concrete	Dewatering	

Basic tunnelling methods

There are different concepts for constructing tunnels, such as "Cut and cover", "New Austrian Tunnelling Method (NATM)" and "Mechanical method". Tunnels can be excavated using different excavation schemes like "Full face", "Heading and bench", "Multiple drift" and "Pilot enlargement"; the NATM concept can be applied for these schemes. The term *"Basic tunnelling methods"*, in this research, refers to tunnel construction concepts which are *"Cut and cover"*, *"NATM – full face"*, *"NATM – heading and bench"*, *"NATM – multiple drift"*, *"NATM – pilot enlargement"* and *"Mechanical method"*.

Tunnelling activity

An activity can be defined as a named process, function, or task that occurs over time and has recognizable results. Activities use up resources to produce products and services. The term *"Tunnelling activities"*, in this research, refers to the main activities used in the construction phase of a tunnel project to build the tunnel, these activities are: excavation, mucking, transportation, supporting (side wall and face support), lining and groundwater control.

Construction methods

Construction methods are the methods/equipment/tools used to complete the work of the tunnelling activities. Each one of tunnelling activities can be completed by a number of different construction methods. Examples of excavation methods are *"Drill and blast"*, *"Roadheaders"* and *"TBMs"*. Examples of support methods are *"Rock bolts"*, *"Steel arches"* and *"Shotcrete"*.

Controlling factors

The decision maker should take into consideration some factors when he/she decides which construction methods are the best for the tunnelling activities of his/her tunnel project. These factors are called the controlling factors; they are technical and non-technical factors. Technical factors represent project conditions such as tunnel depth, ground compressive strength, tunnel alignment and span. Non-technical factors include factors like cost, time and experience. The role of each controlling factor in the selection decision of the construction methods for the tunnelling activities are different from factor to factor depending on the importance of the factor which will be determined by the model user (decision maker).

Efficiency

Efficiency has been defined in other research such as [56], [63], [73], [80], [108], [110] and [111]. Efficiency in simple words as stated by Sink and Tuttle [102] is *"do things right"*.

In this research the term *"Efficiency degree (ED)"* describes how efficiently a construction method satisfies a controlling factor. In other words, the efficiency degree of a construction method for a particular controlling factor is the answer to the question: *"How well does the construction method work for the controlling factor?"* Efficiency degrees, in this research, are expressed on a scale of 1 to 4 and are based on the opinions of tunnel experts.

The term *"Efficiency percentage (EP)"* of a construction method, describes how efficiently the method satisfies its controlling factors. Calculation of the EP for a construction method, in this research, is based on the efficiency degrees of the method for the controlling factors and the importance degrees[2] of the controlling factors, example (1) explains this. The EP of a tunnelling system will be a result of the EPs of the construction methods which form the system.

Example 1

If there are two construction methods "A" and "B" and two controlling factors "X" and "Y", the importance degrees of "X" and "Y" as determined by the user are 7 and 9 respectively. Efficiency degrees of the methods "A" and "B" for the controlling factors "X" and "Y" are shown in table 1.2. The maximum efficiency degree is "4".

Table 1.2 Efficiency degrees of methods "A" and "B" for factors "X" and "Y"

Methods / Factors	A	B
X	3	2
Y	3	4

The model calculates importance percentages of "X" and "Y" from their importance degrees as follows:

[2] The user of the proposed model of this research determines the importance degrees of controlling factors on a scale from 0 to 10.

- Importance percentage of "X" = ((7) / (7 + 9)) * 100 = 43.75%
- Importance percentage of "Y" = ((9) / (7 + 9)) * 100 = 56.25%

The model will use the resulting importance percentages of the controlling factors with the efficiency degrees of table 1.2 to calculate the efficiency percentages of the methods as shown below.

- Efficiency percentage of "A" = (0.4375 * 3 + 0.5625 * 3) * 100 / 4 = 75%
- Efficiency percentage of "B" = (0.4375 * 2 + 0.5625 * 4) * 100 / 4 = 78.1%

Using an efficient construction method for each tunnelling activity leads to an efficient tunnelling system for the whole project. Efficiency percentage of a tunnelling system relies on efficiency percentages of system's components. Before determining efficient construction methods for each tunnelling activity, the most efficient *"Basic tunnelling methods"* should be determined first. Figure 1.1 shows the steps of the model proposed in this research to determine the most efficient tunnelling systems.

The proposed model in this thesis has two phases (see figure 1.1). In the first phase, it calculates efficiency percentages of the *"Basic tunnelling methods"* as well as of the construction methods of the tunnelling activities. The user of the model should determine which controlling factors represent the conditions of the tunnel project and the importance degrees of the controlling factors. The model will use the importance degrees of the controlling factors and the efficiency degrees of the construction methods for controlling factors to calculate efficiency percentages of construction methods. Example (1) illustrates the calculations of the first phase of the model. In its second phase, the model calculates efficiency percentages of alternative tunnelling systems of the project.

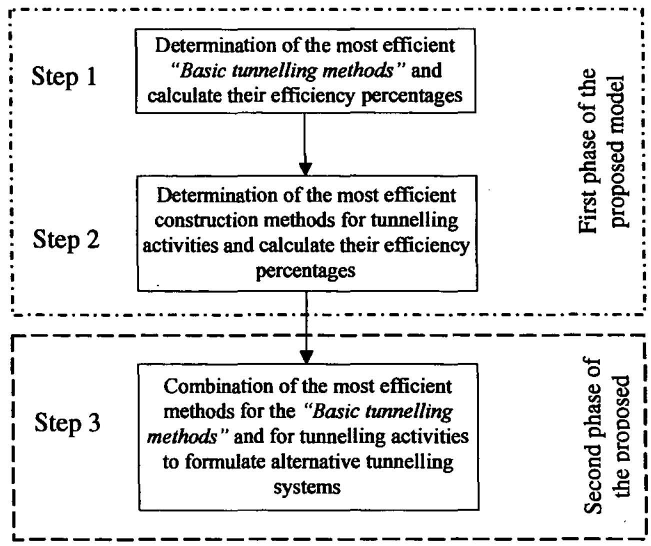


Figure 1.1 Steps of the proposed model to determine alternative tunnelling systems

1.1 Research objectives

The objective of this research is to develop a simple and flexible model that helps decision maker in selecting the most efficient tunnelling system for his tunnel project based on the technical and non-technical factors of the project.

1.2 Scope of work

Tunnel project has five phases, which are: conceptual planning, procurement, design, construction and operation and maintenance. Wassmer et al. [121] as well as Oggeri and Ova [86] defined these phases as follows:

- The conceptual planning phase is the period of a project which commences when the request is made to prepare estimates of feasibility, cost, viability and delivery options and ends when approval is given to proceed with the project into the design phase.
- The procurement phase is the stage of a project when necessary prerequisites have been defined and agreements and contracts are being established for the design, construction and operation phases.

- The design phase is the period of a project which is embodied after approval is given to proceed with the project into the construction phase, when the conceptual planning is evaluated from various aspects such as cost, viability and quality.
- The construction phase is the period of a project's development that commences with the award of the construction contracts and terminates with the commissioning of the structure.
- The operation and maintenance phase is the period after the works have been commissioned.

Alternative tunnelling systems that can be used for a tunnel project should be identified during the conceptual planning phase to start estimations of the project feasibility and cost. The efficiencies of tunnelling systems will be different due to project conditions. The proposed model in this research provides the decision maker with efficiency percentages for alternative tunnelling systems during the conceptual planning phase of his project.

1.3 Research methodology

The following steps show the methodology used in this research (see figure 1.2).

1. Determination of the main tunnelling activities that are a part of the construction phase of a tunnel.
2. Study of the available *"Basic tunnelling methods"* and of the construction methods of tunnelling activities.
3. Determination of the controlling factors for the *"Basic tunnelling methods"* and for each tunnelling activity.
4. Consulting the opinion of tunnel experts about efficiency degrees of the different construction methods for each controlling factor. These degrees will be used to calculate efficiency percentages of construction methods.

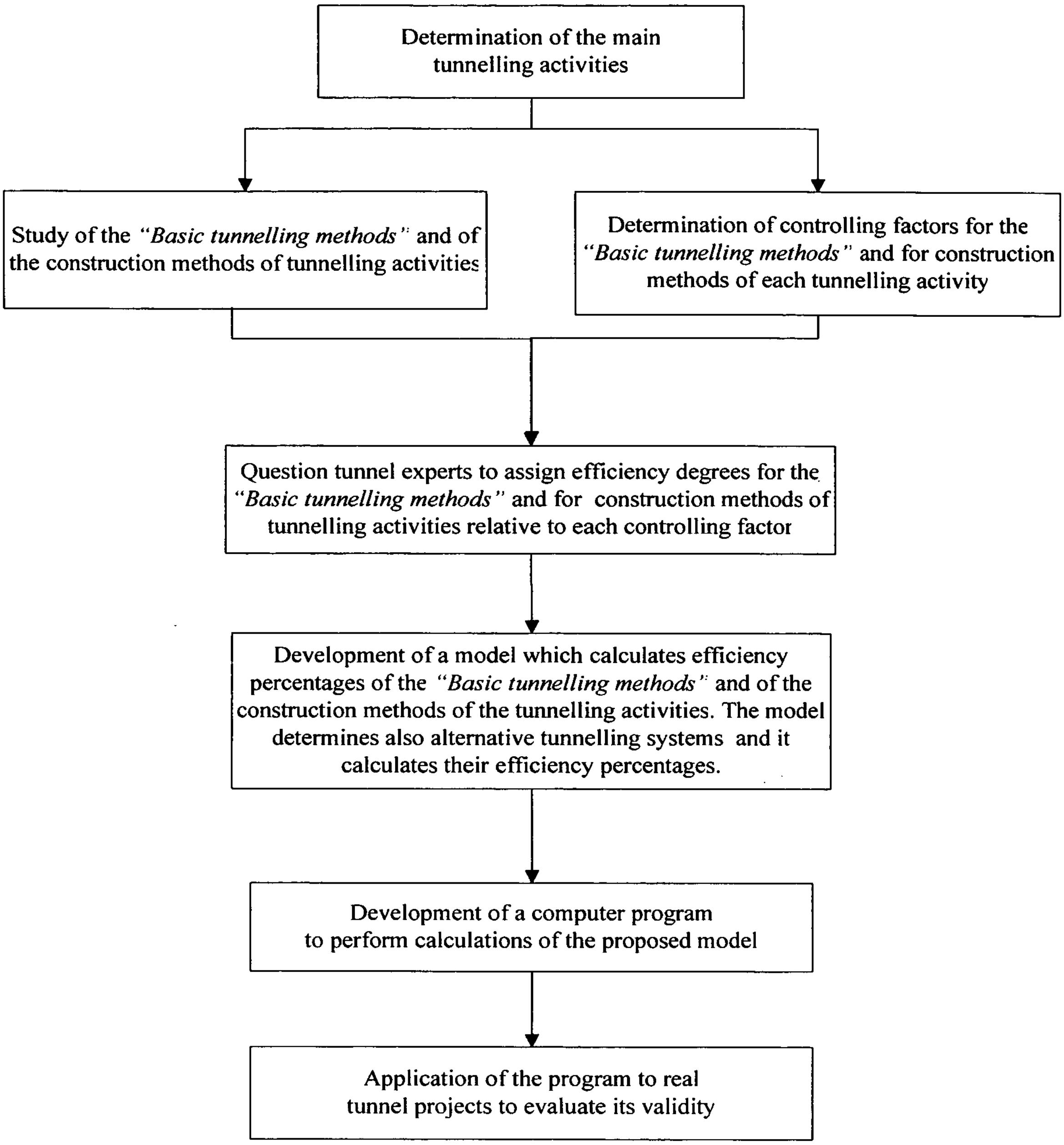


Figure 1.2 Research methodology

5. Development of a model which calculates efficiency percentages of the alternative tunnelling systems.
6. A computer program that represents the proposed model is developed to facilitate using the model.

7. Application of the model in real projects is the last step of this research to evaluate its validity and to discover its defects.

1.4 Thesis outline

Chapter two of this research discusses different tunnel construction concepts and construction methods of tunnelling activities, as well as the limits of using them. Models which are used to select construction methods are also presented in chapter two. Controlling factors which represent project conditions and influence the efficiency percentages of construction methods are presented and discussed in the third chapter of this thesis.

Chapter four represents the proposed model that calculates efficiency percentages of the alternative tunnelling systems for a tunnel project.

A computer program was developed using *"Visual Basic 6"* to perform calculations of the proposed model. Chapter five is the program's manual. The name of the program is SETS (Selecting Efficient Tunnelling System). The CD with this thesis contains the program SETS.

Data of three real projects were used to check the model validity. Chapter six shows the application of the model and the program to these projects. Projects that were used are *"Wienerwald tunnel (Austria)"*, *"U2/2 Taborstraße (Austria)"* and *"Gotthard tunnel – Amsteg section lot 252 (Switzerland)"*. The results prove the validity of the model and the program soundness. Chapter seven is a summary of this research and the conclusions. Recommendations for future work are also presented in chapter seven.

2 Tunnelling methods and models of selecting tunnelling systems

2.1 Introduction

Design of underground structures depends on the methods of construction, and often the location and geometry of the structure is adjusted to best accommodate the method chosen.

As illustrated in chapter 1, the elements of a tunnelling system are the *"Basic tunnelling method"* and the construction methods of the six tunnelling activities, which are: "Excavation", "Mucking", "Transportation", "Supporting", "Lining" and "Groundwater control". Table 2.1 shows construction methods of tunnelling activities. In this chapter, the *"Basic tunnelling methods"*, excavation methods as well as shotcrete, as a supporting and lining method, are reviewed.

2.2 Tunnel construction methods

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 (Jodl [57]).

2.2.1 The *"Basic tunnelling methods"*

The first constituent of a tunnelling system is the *"Basic tunnelling methods"* which represent the main concepts of constructing a tunnel. Six tunnel construction methods, shown in figure 2.1, are used in this research as the *"Basic tunnelling methods"*.

Table 2.1 Construction methods of tunnelling activities

Tunnelling activities								
Excavation	Mucking	Transportation	Supporting			Lining	Groundwater control	
			Side wall & crown support	Face support	Support for cut and cover			
Excavator/Backhoe /Front shovel	Rubber wheel loaders	Rubber wheel trucks	Rock bolts	Forepoling	Diaphragm walls	Precast concrete segments	Dewatering	Construction methods
Hand excavation	Tracked loaders	Rail diesel-mechanical locomotive	Dowels	Pipe umbrella	Sheet piles	Cast steel segments	Slurry wall	
Drill and blast		Rail diesel-electric locomotive	Steel arches	Doorframe slab	Bored piles	Cast-in-place concrete	Compressed air	
Roadheader		Rail high voltage locomotive	Shotcrete	Earth wedge		Pipe in tunnel	Freezing	
Micro-tunnelling Machine		Conveyors	Precast concrete segments	Shotcrete		Shotcrete	Chemical & cement grouting	
Shield machine (slurry/EPB)						No final lining	Jet grouting	
TBM (open machine)								

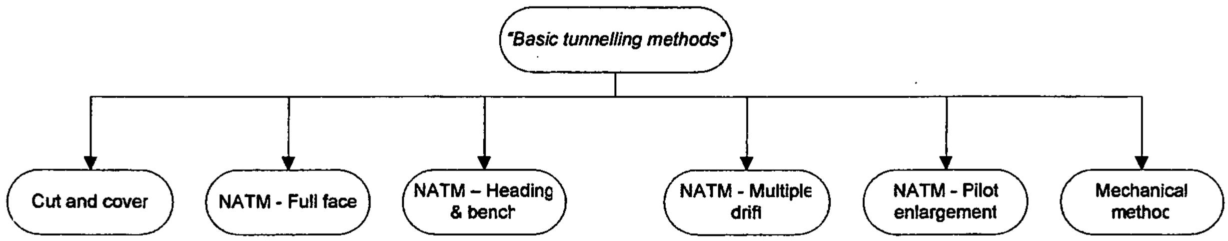
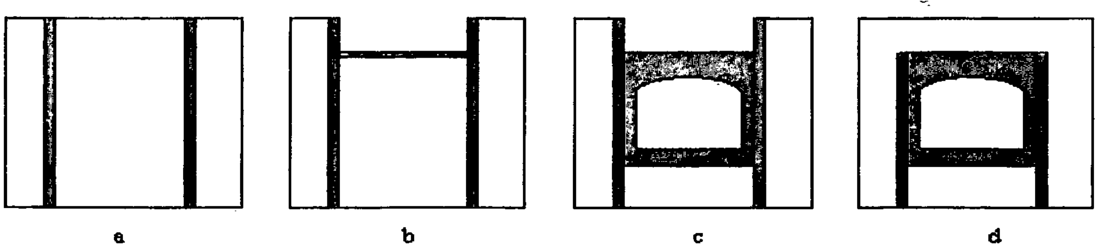


Figure 2.1 The *"Basic tunnelling methods"*

2.2.1.1 Cut and cover method

The *"Cut and cover"* method of construction has been known for a long time. McCusker [74] mentions that cut and cover tunnelling is usually thought of as trench excavation in soft sediments.

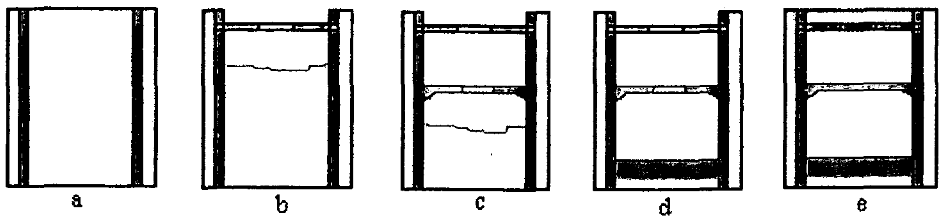
Steps of this method involve excavating an open trench to the tunnel base level. Construction of the tunnel starts from its base followed by the walls and finally the tunnel surface slab. The last step is covering the tunnel with various compacted earthen materials. In case of weak ground, diaphragm walls, sheet piles or bored piles are used to support the ground before excavation. Figure 2.2 shows the construction steps for cut and cover.



a) Construction of two diaphragm walls
b) Excavating ground from inside and construction of a struts
c) Building the tunnel
d) Covering the tunnel with soil

Figure 2.2 Construction steps of "Cut and cover"

The concept of top-down construction is another type of cut and cover method. It consists of constructing the underground structure starting from the surface slab and then (if applicable) the intermediate slabs and finally the base (see figure 2.3). This concept was used efficiently for constructing 10 underground stations of underground metro line 2 in Cairo, Egypt (Campo et al. [20]; Madkour et al. [69]).



a) Construction of two diaphragm walls b) Construction of the surface slab with a middle hole
c) Excavation from inside and construction of intermediate slab (if applicable)
d) Excavation from inside and construction of tunnel base e) Close slabs' holes and start to construct inside

Figure 2.3 Top-down concept of "Cut and cover"

Sterling and Godard [104] state that progress has been made in cut and cover construction methods, especially in the area of ground support (slurry or precast walls, grouting, and anchors), but the efficiency of these construction methods is significantly reduced by many constraints; such constraints are underground congestion due to the presence of numerous utility networks and the more and more severe environmental requirements. In addition, cut and cover methods are encountering growing resistance from local inhabitants, because of the disturbance and nuisance caused by major excavations under-taken in such congested areas.

2.2.1.2 The New Austrian Tunnelling Method (NATM)

In 1948, Prof. L. v. Rabcewicz published the basic principles of the NATM. He stated that applying a flexible supporting system to the ground face immediately after excavation prevents loosening, reduces decompression to a certain degree and helps in transforming the surrounding ground into a self-supporting arch or ring. A new equilibrium of the ground will be reached (Brandl [16], Golser [37], Jodl [58], Sauer [97]).

The flexible support system will minimize bending moments and it will facilitate the stress rearrangement process (Golser [37]). A thin layer of shotcrete, steel arches, and rock bolts, either singly or in combination can be used as a flexible support (Jodl [58], Sauer [97]).

The NATM may be defined as a method of producing underground space by using all available means to develop the maximum self-supporting capacity of the ground to provide the stability of the underground opening (Sauer [97]).

The NATM is an observational method. Therefore monitoring (in-situ-measurements) of deformation within the ground and opening as well as stress development on and in the initial lining are essential (Sauer [98], Fugeman et al. [32], Nussbaum [85]).

The pioneers of the NATM recommended that the excavation cross section of a tunnel has to be as round as possible without any corners in order to avoid stress concentrations such that the bearing capacity of the ground arch will be at its best (Poisel [90]). Leu et al. [65] summarized the typical NATM design and construction flow in figure 2.4.

The NATM is applied to soft ground as well as to rock tunnels (McCusker [74]). Soft ground can be compared to a highly viscose liquid with a limited stand-up(1)

1 The new Austrian standard for tunnelling B 2203 defines the stand-up time as the period in which the uncovered ground surface keeps stable without support.

time when excavated. This fact leads to the most important requirements of the NATM (Sauer [97] and [98]):

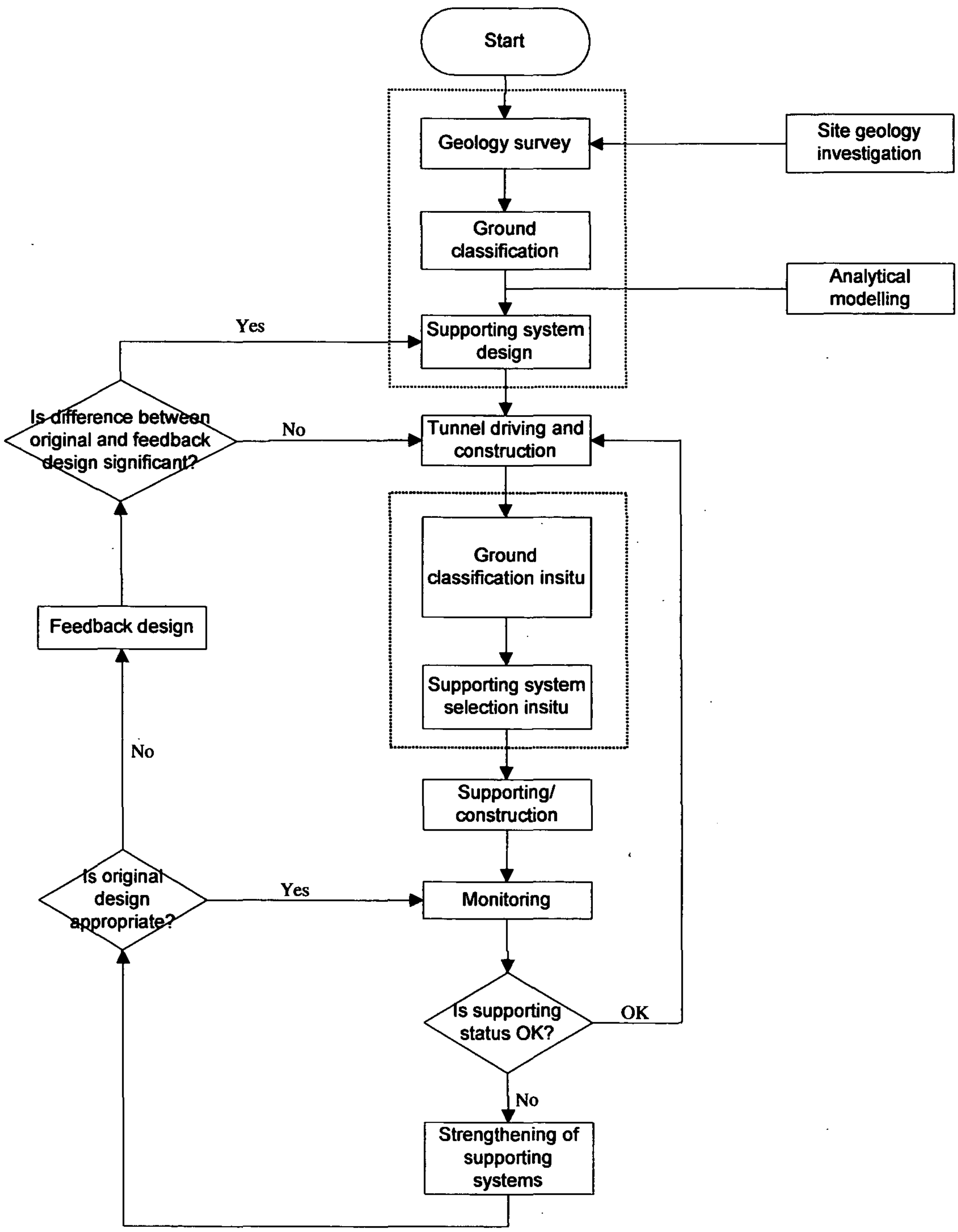


Figure 2.4 Classical flow of NATM construction (after Leu et al. [65])

- The excavated cross section should always be an ovoid shape.
- Immediate, continuous smooth support around the tunnel perimeter (and, if required, also to the face) is a significant factor to minimize initial movement in the surrounding ground. Face support can be achieved either by forepoling, by leaving a wedge of unexcavated earth to prop the face or, in extreme cases, both. A Grout Spiling Anchor (GSA) can also be used to create a canopy of solid ground under which the tunnel can be excavated.
- It is also essential to close the supporting ring as quickly as possible within one tunnel diameter from the advancing face.
- The 3-dimensional stress redistribution around the tunnel depends on geometry and time. This must be considered carefully, particularly where multiple openings are planned. It will govern the progress of tunnelling with respect to stress redistribution, soil structure interaction and curing of the shotcrete support.

The NATM in soft ground has proven to be a cost effective method for excavating short tunnels, variable cross-sections, and underground facilities such as metro stations, car parks or storage caverns (Sauer [97], [99] and [100]).

The following comparison attempts to describe significant characteristics (Jodl [58], Liebsch and Haberland [67], Sauer [96] and [100]) of the NATM:

Advantages of the NATM:

- applicable in a wide range of ground conditions
- simple and flexible adaptation to different cross sections
- high economy by optimizing necessary support measures

- economic application for short contract sections
- easy combination with TBM drives
- relatively small investment with quick amortization

Disadvantages of the NATM:

- application in groundwater only with additional measures
- rate of advance is relatively small and cannot be increased decisively
- high requirements for education, training and practice of personnel
- high requirements for the quality of construction and material
- difficult formulation and distribution of risks for client and contractor
- limited possibility of automatization

2.2.1.2.1 Full face method

Many tunnels are advanced using the *"Full face"* construction method. The concept of the *"Full face"* is excavating the entire tunnel face in one round (see figure 2.5). Hustrulid [50] stated that this method is suitable for tunnels with small cross sections. It may even be used for large tunnels (face area of 80 – 100 m^2), when ground conditions are good. Different excavation methods can be used for the *"Full face"* method.

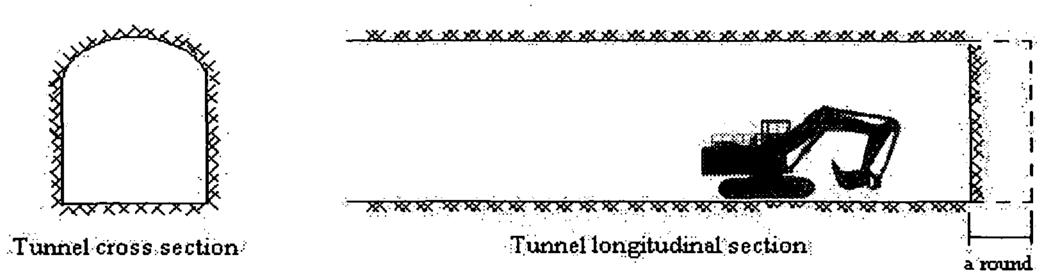


Figure 2.5 Full face method

2.2.1.2.2 "Heading and bench", "Multiple drift" and "Pilot enlargement" methods

It sometimes happens, especially in larger diameter tunnels, that it is difficult or impractical to maintain the stability of the excavation of a full size tunnel. It then becomes necessary to reduce ground loads by reducing the size of the excavation. This reduction in size may also have the benefit that excavation and support installation can be completed more quickly. Such size reduction can be achieved by excavating and supporting a top heading followed by excavation and support of the bench some distance behind (see figure 2.6). This concept is called *"Heading and bench"* method (McCusker [74]).

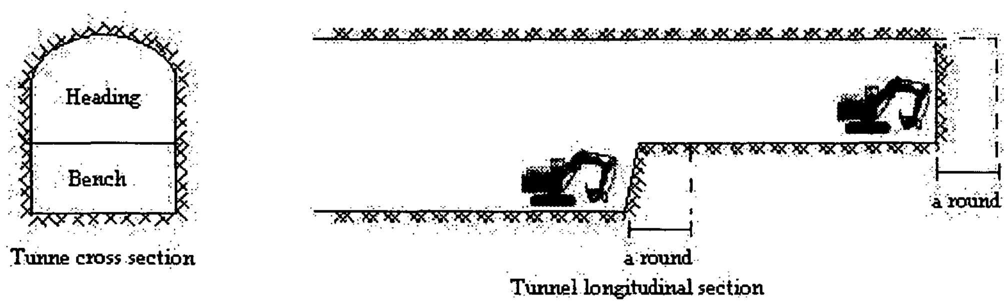


Figure 2.6 Heading and bench concept

The *"Multiple drift"* method is an extension of the *"Heading and bench"* method. In this method, the tunnel cross section is excavated in sections based on a planned schedule. There is a time lag between every two successive excavation steps to allow the crew to support the excavated part and keep the ground stable. Figure 2.7, type 3, shows an example of the *"Multiple drift"* method, where excavation of the crown comes first followed by the bench and finally the invert. Figure 2.7 illustrates examples of the different types of driving a tunnel by the *"Multiple drift"* method.

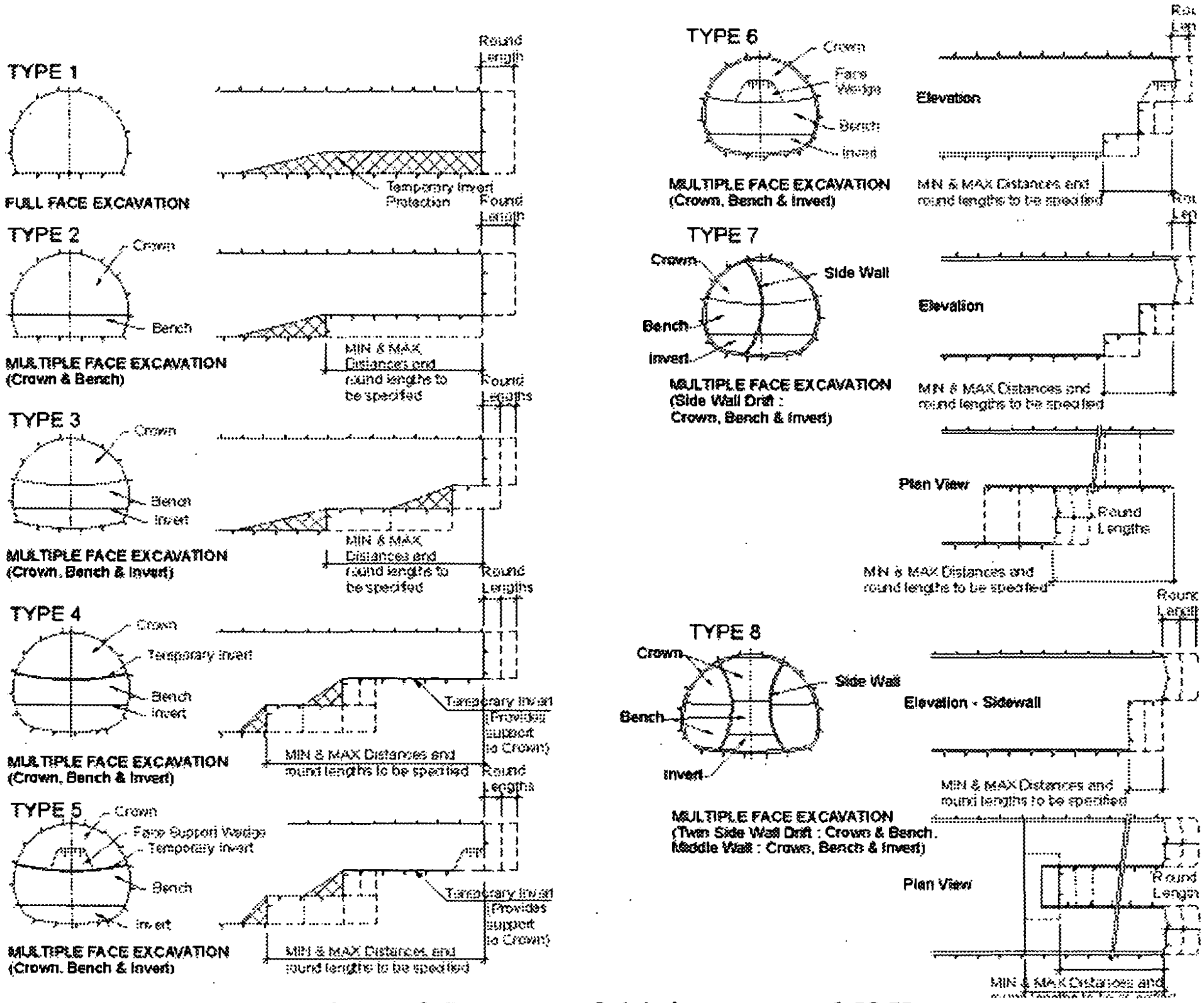


Figure 2.7 Types of driving a tunnel [95]

The *"Pilot enlargement"* is similar to the *"Multiple drift"*. It involves excavating a small part of the tunnel cross section in advance and subsequent enlargement follows until the whole cross section area of the tunnel is excavated (see figure 2.8).

2.2.1.3 Mechanical method

The number of tunnels, constructed using the mechanical method, has increased enormously during the last 15 years. *"Mechanical method"*, in this research, refers to use of *"Microtunnelling"*, *"Shield"* or *"TBMs"* for constructing the tunnel. *"Microtunnelling"*, *"Shield"* and *"TBMs"* are explained in detail in the section on excavation methods.

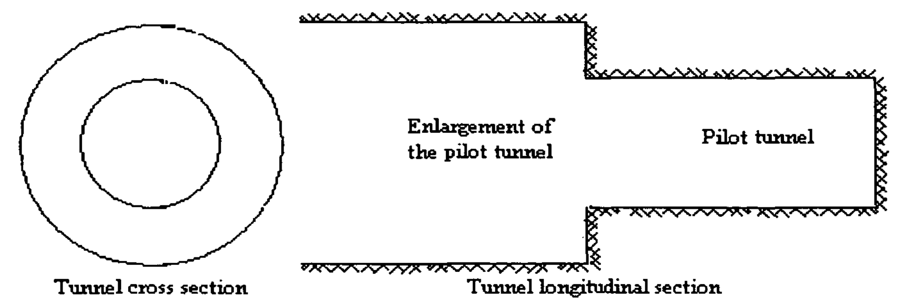


Figure 2.8 Pilot enlargement method

Many decision makers prefer mechanical methods for tunnel construction because of their high advance rate. Another advantage of the mechanical method is the high safety conditions for workers during construction. The efficiency of mechanical method is very high when the tunnel cross section is fixed and if there are no changes in the geology along the tunnel path.

The *"Mechanical method"* cannot be easily used for tunnels with changeable cross section and its efficiency decreases when tunnel cross section is not circular.

2.2.2 Excavation methods

Excavation methods reviewed in this section are: *"Excavator/Backhoe/front shovel"*, *"Hand excavation"*, *"Drill and blast"*, *"Roadheader"*, *"Microtunnelling machine"*, *"Shield machine (slurry/EPB)"* and *"TBMs"*.

2.2.2.1 Excavator and hand excavation methods

Excavator and hand excavation are used when the ground is weak. For short distance tunnels, these excavation methods are efficient.

2.2.2.2 Drill and blast method

"Drill and blasting" is usually used in hard rocks. When rock conditions are good or for tunnels of small cross sections, drill and blast is used to excavate the whole tunnel face in one round, for other conditions heading and bench is used. Benching may be done using either horizontal or vertical holes (Colgan [22], Hustrulid [50]).

Drill and blast is done in rounds. Activities of each round are: drilling blastholes, charging, blasting and ventilation, loading and transporting the blasted rock, scaling and installing rock support. 80% of the total time is spent in actual drilling operations (Hustrulid [50]).

The most important operation in the blasting procedure is creating an opening in the rock face to serve as a free surface which the initial breakage can occur towards it. One way of creating a free face is the V-cut or fan-cut which uses a number of holes drilled at an angle toward each other, usually in the lower middle of the tunnel face, to form a wedge. Detonation of these holes first will remove the material in the wedge and allow subsequent detonations to break to a free face. The blastholes will detonate in a controlled delay sequence which permits the opening to gradually increase in size. Figure 2.9 shows distribution of blastholes on a tunnel face.

Hoek and Brown [47] illustrated that the most important two factors to be considered in relation to blasting in underground excavations are:

1. The blast should break the rock efficiently and economically and should produce a well fragmented muck pile which is easy to remove, transport, store and process.

2. The rock mass left behind should be damaged as little as possible in order to reduce the need for scaling and support to a minimum.

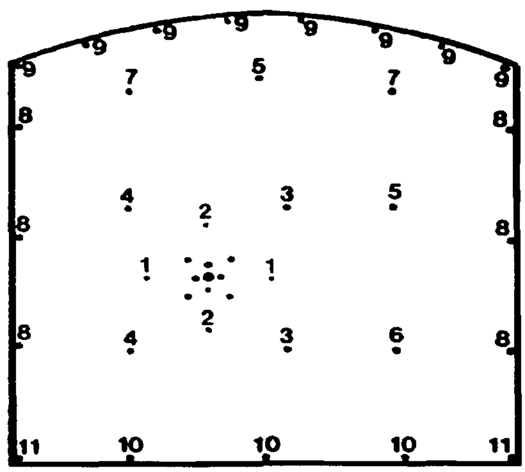


Figure 2.9 Blastholes distribution on a tunnel face (US Army report [116])

In the US Army report [116] about tunnel construction, the advantages of controlling rock damage and overbreak are given:

a) Less rock damage means greater stability and less ground support required.
b) The tunnelling operations will also be safer since less scaling is required.
c) Less overbreak makes a smoother hydraulic surface for an unlined tunnel.
d) For a lined tunnel, less overbreak means less concrete to fill the excess voids.

In the most unfavourable drill and blast case, there can be blasting overbreak amounting to 10-25% of the design cross-sectional area. This material must be removed and the space has to be refilled (Girmscheid and Schexnayder [34]).

The drill and blast method is a typical sequential production procedure, and the advance is strongly related to the length of each blast round. In some successful experiments the length of the blast rounds has been extended to 9 m. New explosives are producing less toxic fumes which reduces the need for ventilation which allows longer drives to be excavated (Broch [17]).

Broch [17] stated that the great advantage of the drill and blast method in addition to relatively low investment costs is the flexibility of the method. With the same equipment different sizes and shapes of tunnels can be made in very varying ground conditions.

Hiller [44] stated that vibration resulting from drill and blast may generate noise (sometimes called re-radiated noise) within buildings. Another related effect that occurs during drill and blast is air blast or air overpressure.

2.2.2.3 Roadheader method

Further improvements in tunnelling technology have introduced partial face tunnelling machines. Initially developed in Europe for coal mining operations, these machines (frequently referred to as *"Roadheader"*) find increasing application in the excavation of intermediate size tunnels in soft rocks (Golder and James [36]).

Roadheaders come in many sizes and shapes, equipped for a variety of different purposes. They are used to excavate tunnels by the full face or partial face method, and for excavation of small and large underground chambers (US Army report [116]). Figure 2.10 shows roadheader components.

Roadheaders are quite advantageous compared to drill and blast or TBM excavations for openings that are about 600 m in length and 20 m^2 in area, and are in soft sedimentary rock (unconfined compressive strength not to exceed 140

MPa or no more abrasive than concrete) or coal formations. They are rock mass sensitive, i.e., they would not cut a 35 MPa massive sandstone but will easily cut 140 MPa foliated shale. The roadheader can mine up to 40 to 50 percent of the available shift working time (Nelson et al. [82]). The expected excavation rate of a roadheader relative to rock strength is shown in figure 2.11.

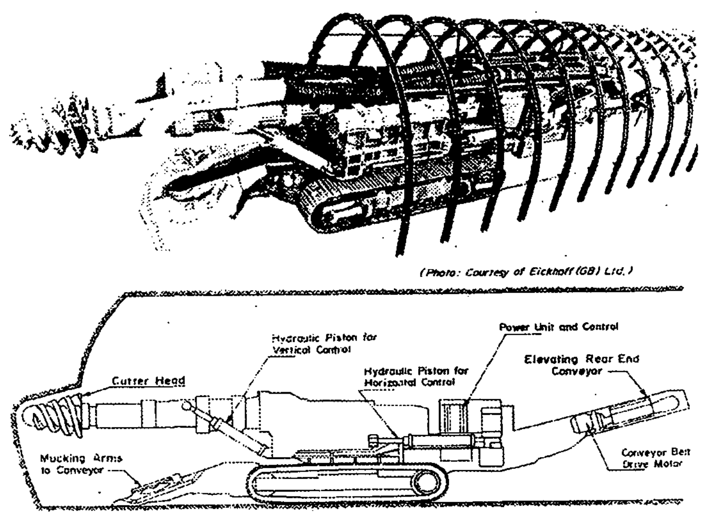


Figure 2.10 Roadheader

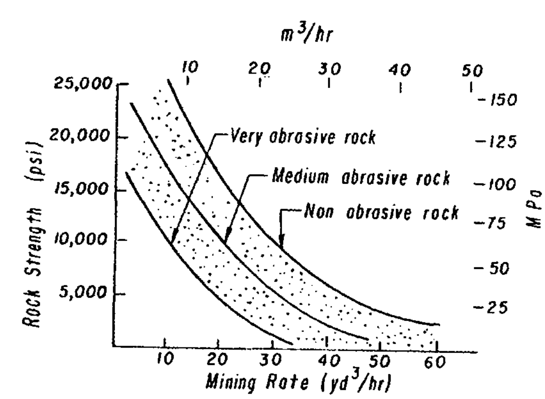


Figure 2.11 Expected excavation rate of Roadheader (Nelson et al. [82])

2.2.2.4 Tunnel Boring Machines

Tunnel Boring Machines have revolutionized tunnelling. These machines, often weighing up to 200 tons and measuring up to 15 m diameter with backup systems more than 60 meter long, bore straight through solid rock, with performances up to 75.5m/day (the best day), 428m/week (the best week), and 1719.1m/month (the best month), these rates are recorded in the "Channel tunnel" project, UK.

A tunnel boring machine is a complex piece of equipment. It includes the cutterhead, with cutting tools and muck buckets; systems to supply power, cutterhead rotation, and thrust; a bracing system for the machine during mining; equipment for ground support installation; shielding to protect workers (in case of shielded machine); and a steering system. Back-up equipment systems provide muck transport, personnel and material conveyance, ventilation, and utilities (US army report [116]).

With few exceptions, all tunnelling machines employ the use of thrust and torque to cut rock or scrape soil and to advance a heading. It is the method of reacting and delivering these forces to the cutting tools that distinguish the various machines (Nelson et al. [82]).

The preferable applications for tunnel boring machine excavations, as described by Nelson et al. [82], are projects with relatively uniform good rock mass quality, and without potential for significant groundwater inflow. In general, rock masses with RQD (Rock Quality Designation) greater than about 25 and water inflow rates less than or about 65 litre/second can be excavated efficiently with tunnel boring machine systems.

Tunnel boring machines have allowed tunnelling to achieve new records in terms of rate of drivage (Robbins [93]).

Advantages and disadvantages of tunnel boring machines as explained in the US army report [116] are:

The advantages:

- High advance rates
- Continuous operation
- Less rock damage
- Less support requirement
- Uniform muck characteristics
- High worker safety
- Potential for remote, automated operation

Disadvantages of a tunnel boring machine are the fixed circular geometry, limited flexibility in response to extremes of geologic conditions, longer mobilization time, and higher capital costs. Golder and James [36] added to the disadvantages of tunnel boring machines that this cannot be used with small radii of curvature. The tightest possible curve which can be negotiated by tunnel boring machine depends on the shape of the machine, on the diameter of the structure behind the cutting head, on possible range of adjustment on the arms and legs, and on the length of the structural frame.

Sterling and Godard [104] stated that the use of tunnel boring machines in tunnel construction has the problem that there is less opportunity to visually observe the ground conditions, obstacles or artifacts in the path of the excavation, and the ground response. This means that less is learned about the geologic environment during a project that could be of use in designing a future project.

Barton [6] stated that there are two basic types of tunnel boring machines which are illustrated in figure 2.12, a so-called open machine and a shielded machine. Figures 2.13 and 2.14 show the two types of machines. In the matrices of appendix A, shield machine refers to tunnel boring machines with a shield and TBM refers to unshielded machine (open machine), see table A.1.1, appendix "A".

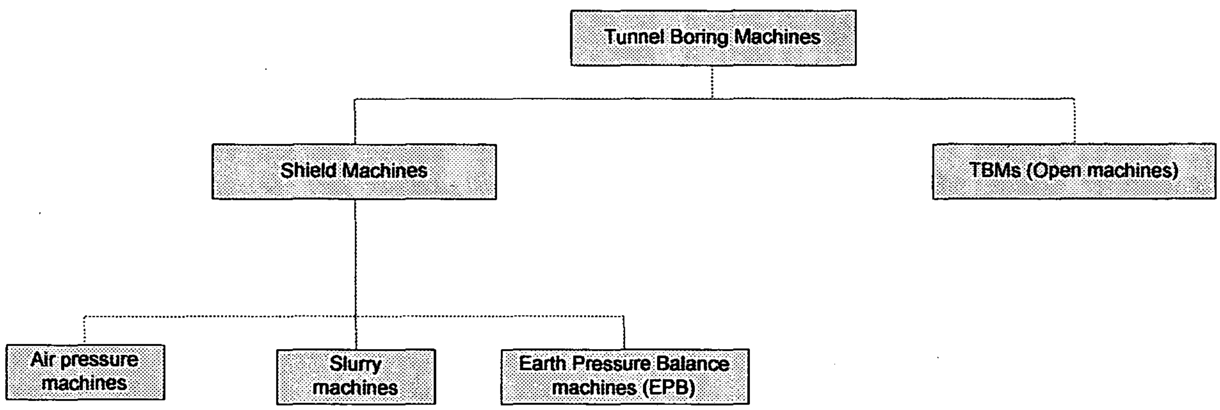


Figure 2.12 Tunnel boring machines types

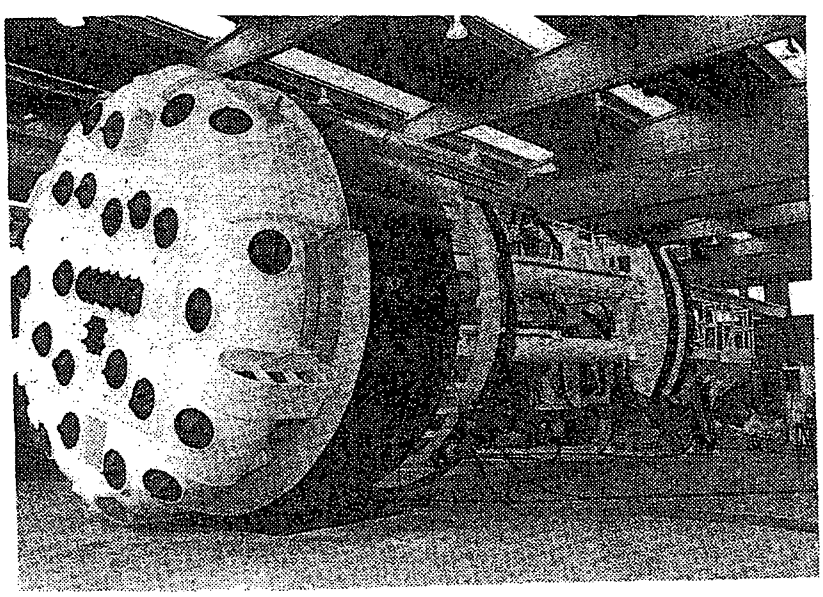


Figure 2.13 Hard rock TBM (Nelson et al. [82])

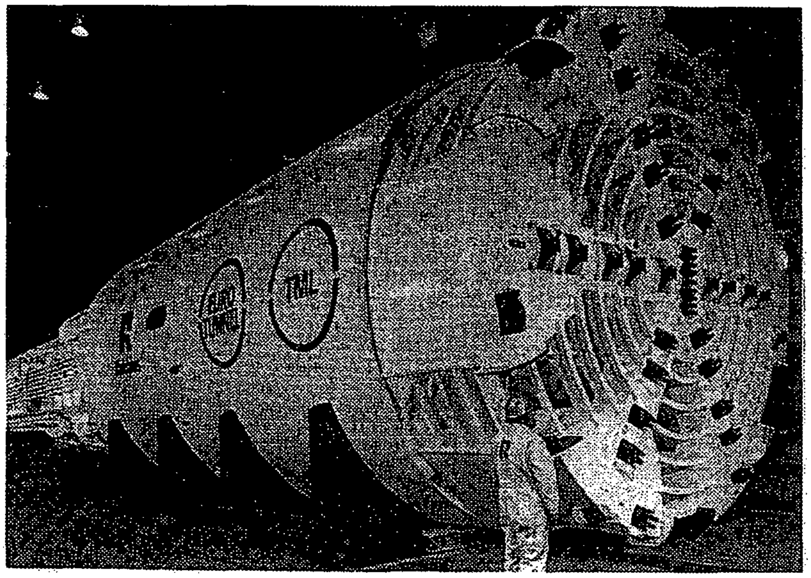


Figure 2.14 Double shield machine (Nelson et al. [82])

2.2.2.4.1 Shield Machines

Shielded tunnel boring machines are used to excavate soft ground which is unstable or has short stand-up times. Wassmer et al. [121] stated that there are two methods applicable for excavating soft ground:

a) Excavation with shield protection. In case of an unstable front face, this can be protected additionally by platforms and breasting plates. This method is often used when excavating in segments.

b) With a fully closed front shield (cutter wheel, disk). This method is used for full face excavation. The excavated material enters the shield via small openings and is then transported to the rear. When excavating in ground with high water saturation or even under the groundwater level a counter pressure must be generated to prevent liquid soil from filling the excavated hole at the face.

Types of shield machines as described by Wassmer et al. [121] are presented in this section:

Air pressure machine

The front part of the shield machine from the face to the working chamber is provided with air locks and generates a pressure strong enough to hold back inflowing liquid. Working chamber and tunnel face are supported by compressed air. This method is feasible only up to a regular water depth of approximately 35m maximum, corresponding to approximately 35 bar. Furthermore, the ground layer above the water must be thick enough to withhold air blowouts reaching the surface. This type is no longer frequently in use, therefore it is not considered in this research.

Slurry machine

In this case the unstable ground at the front is supported by a liquid mixture under increased pressure. A filter cake between the existing ground and the support liquid (i.e. using bentonite suspension) prevents the liquid from penetrating and disappearing into the ground. Depending on the subsoil permeability, density and viscosity can be varied; pressure can be regulated by controlling the speed of the delivery. The excavation is done by a turning cutting wheel. The excavated ground material and suspension liquid is mixed by hydraulic conveyance via tubes with subsequent separation of the two materials – earth and suspension.

Earth Pressure Balance (EPB) machines

Instead of a hydraulic/bentonite suspension the excavated ground is used as part of the supporting medium and forms a ground slurry. This method requires ground which is homogeneous, soft and cohesive. If the water content is too low or if small particles are absent in the grain size distribution, they must be added artificially (bentonite, polymers, foam). In this case, the environmental compatibility of the material for landfill purposes must be taken into consideration. Figure 2.15 shows the limits of using slurry and EPB shield machines.

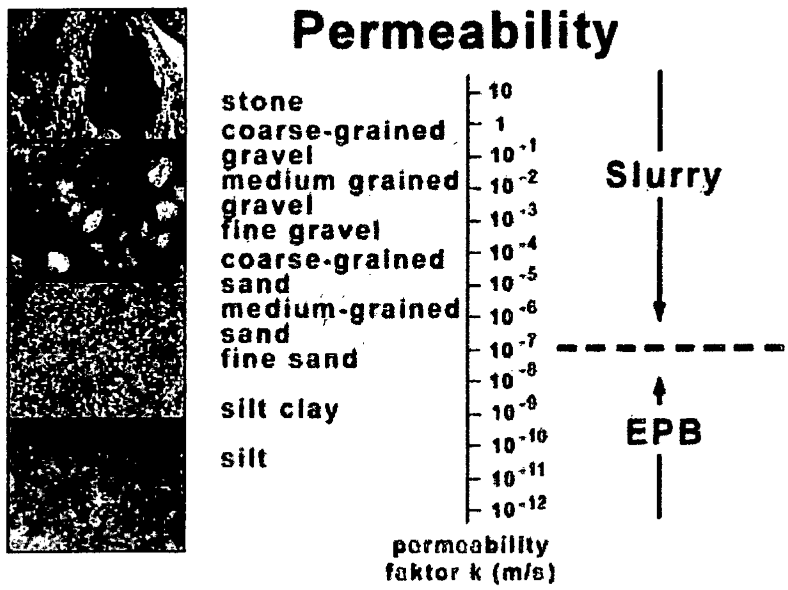


Figure 2.15a Limits of using slurry and EPB shield machine (Wassmer et al. [121])

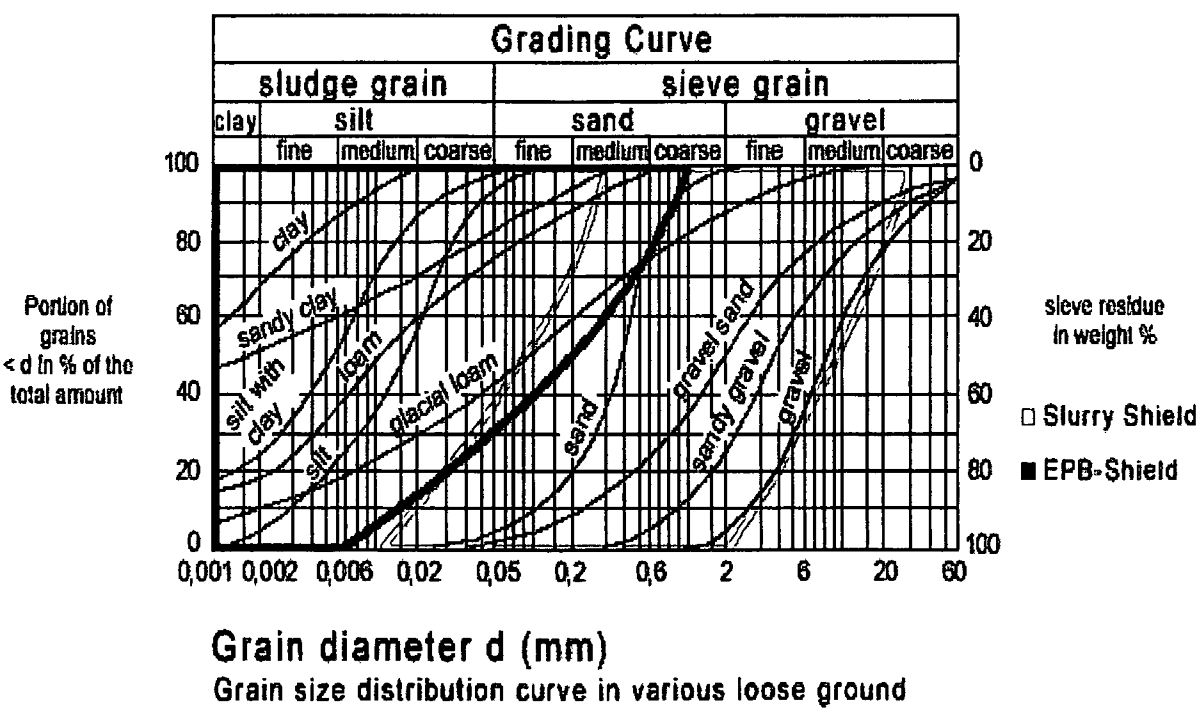


Figure 2.15b Limits of using slurry and EPB shield machine (Wassmer et al. [121])

2.2.2.4.2 Micro-tunnelling machines

The general concept of pipejacking is installing a pipe system without disturbing the surface (Hegab and Salem [42]). Micro-tunnelling, according to Atalah and Hadala [4] is defined as a remotely controlled and guided pipejacking technique that provides continuous support to the excavation face without personnel entry into the tunnel.

Usually micro-tunnelling includes pipes with diameters up to 900 mm, which is the minimum acceptable diameter for man-entry pipe, but according to technical development there is no size limit. In Europe, machines of diameters more than 900 mm are often called pipejacking machines (Hegab and Salem [42]).

In this research, the term *"Micro-tunnelling"* refers to a remote-controlled shield machine that has diameter up to 900 mm (non-man entry diameter).

Micro-tunnelling productivity depends on a number of factors such as soil type, operator experience, and machine diameter (Nido [84]).

Klein [60] stated that micro-tunnelling methods may have economic advantages in terms of lower construction costs. But Micro-tunnelling may come to a virtual standstill when unanticipated bedrock or boulders were encountered and the equipment could not advance through the obstacle.

A significant factor for carrying out long distance tunnelling using micro-tunnelling machine is the reduction and control of the frictional resistance which depends on the soil to be excavated, the level of the groundwater, the quality of the machine steering and the consistent lubrication of the pipe conduit (Adams [1]).

Suhm and Killmann [107] grouped micro-tunnelling machines under two distinct operating modes, which are generally referred to as slurry and earth pressure balance (EPB) systems. At present in Europe and America the slurry system predominates, having a market share in excess of 90%. In contrast, in Asia, the EPB system takes approximately 30-40% of the market for micro-tunnelling systems. This greater use of EPB systems in Asia is a result of the prevailing ground conditions of homogeneous, soft silts and clays.

2.2.3 *"Shotcrete"* as a supporting and lining method

The replacement of timbering by steel sets, rock anchors and shotcrete represents one of the greatest achievements in the history of tunnelling (Kovári [61] and [62]).

Hoek and Brown [47] defined shotcrete as pneumatically applied mortar and concrete (generally known as "Gunite", "Shotcrete", or "Spread concrete").

Kovári [61] stated that the development of shotcrete technology started with the invention of the 'cement-gun' by the American taxidermist C.E. Akeley. Shotcrete was called 'gunite' and later 'torcret' and since 1921 also 'shotcrete'.

The Austrian engineer Rabcewicz [91] wrote in 1964 in retrospect: *"The first successful application of surface stabilization by means of shotcrete for tunnels in unstable ground as an integral part of the driving process, instead of using timber or steel, was for the Lodano-Mosogno tunnel of the Maggia Hydroelectric Scheme, in Switzerland, 1951 – 1955"*.

Melbye and Garshol [77] stated that there are two basic types of shotcrete. Dry-mix shotcrete, as the name implies, is mixing dry components (cement and gravel) and the water is added at the nozzle. Wet-mix shotcrete is mixed as a low slump concrete which is then pumped to the nozzle. In the case of the dry-mix, accelerator can be added to the mix but, in the case of the wet-mix process, it must be added at the nozzle. A comparison between dry-mix and wet-mix shotcrete is given in table 2.2.

Table 2.2 Comparison between dry-mix and wet-mix shotcrete

Wet-mix	Dry-mix
• Lower rebound when spraying. • Lower dusting. • Control of water/cement ratio. • Quality control in the preparation of the materials is easier because the manufacture of materials is nearly identical to concrete. • Quality of in-place shotcrete is not so sensitive to the performance of the nozzle man since he does not adjust water flow. • Nozzle man directly controls the impact velocity of the particles and thus compaction by regulating air flow at the nozzle. • Higher production rates.	• More adaptable to varying ground conditions, particularly where water is involved. • Dry-mix equipment is typically less expensive and a larger inventory of used equipment is available. • Dry-mix machines are typically smaller and are thus more adaptable to tunnels with limited space. • Easier to clean. • Lower maintenance costs.

Hoek and Brown [47] stated that shotcrete can be used in tunnel lining but the brittle behaviour of concrete is one of the problems associated with the use of sprayed concrete lining in tunnels. In order to overcome this problem, the use of wire mesh reinforcement is common and an increasing amount of attention is being given to steel fibre or glass fibre reinforcement of shotcrete. A further problem with the use of shotcrete is associated with the irregular excavation profile which is usual in a drill and blast tunnelling operation. Due to the jointed nature of the rock mass and to careless blasting practices, substantial overbreak is common in hard rock tunnelling and, while this situation can be improved by the use of correct blasting techniques, it is not possible to avoid it completely. Therefore, they do not recommend the use of shotcrete as the sole means of excavation support in situations in which the tunnel profile deviates by more than a few percent from the design profile.

Melbye and Garshol [77] stated that shotcrete has many advantages, where it is flexible, rapid in construction and economical.

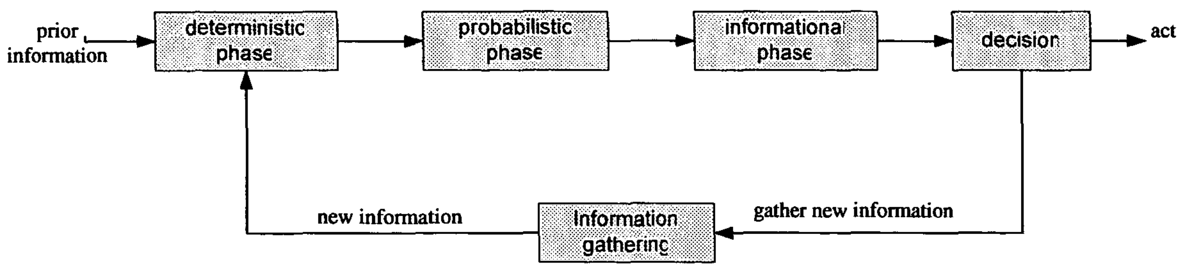
2.3 Models of selecting tunnelling systems

2.3.1 Decision-making process

Underground projects often include decision situations in which a very complex series of events and interaction between several technical systems must be considered. Decision making for underground projects is difficult because the soil and rock mass are associated with large uncertainties (Sturk et al. [106]).

Raiffa [92] introduced a decision analysis cycle, shown in figure 2.16, consisting of deterministic, probabilistic and information phases, which can be used in analysing problems and taking decisions.

Sturk et al. [106] recommended the decision process, shown in figure 2.17, for underground construction. The first step of taking the decision is to identify alternatives which could be in the case of tunnel construction using drill and blast or tunnel boring machine for the excavation of the tunnel.



<u>Deterministic Phase</u>

1. Define problem and limits of investigation
2. Alternative courses of action
3. Outcomes of each alternative
4. Select decision and state variables
5. Relate outcomes and variables
6. Method of comparing relative values of each outcome
7. Time preference
8. Dominated alternatives eliminated
9. Sensitivity of outcome to variables

<u>Probabilistic Phase</u>

1. Express uncertainty in variables by means of probabilities
2. Probabilistic model
3. Establish relative value of probabilistic outcomes
4. Probabilistic sensitivity analysis

<u>Information Phase</u>

1. Value of perfect information
2. Evaluate various information collection schemes

Figure 2.16 Decision analysis cycle (Raiffa [92], Einstein [29])

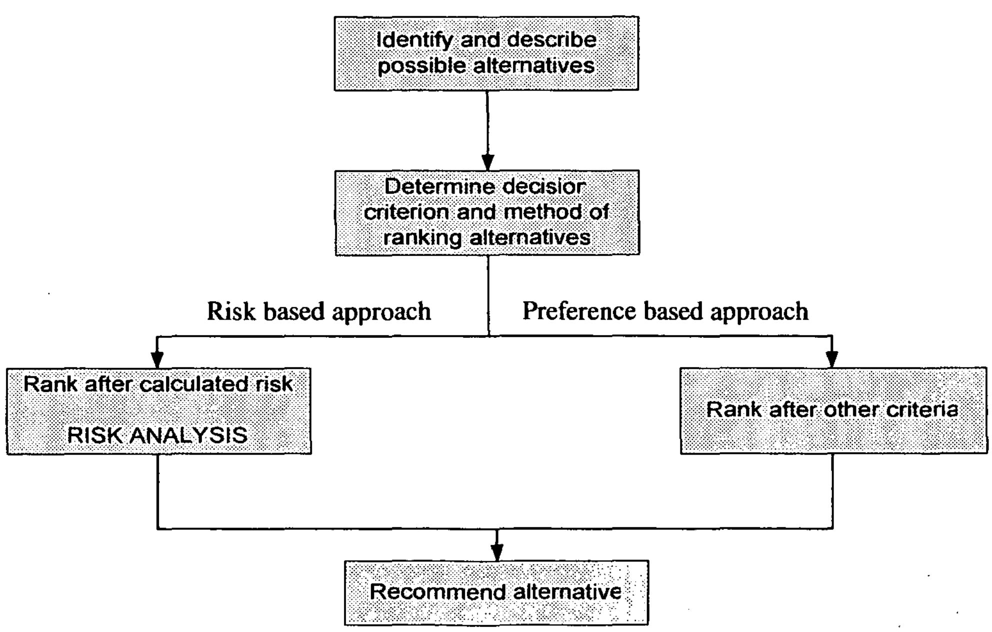


Figure 2.17 Recommended decision process for underground construction

The second step of the decision process is determining a decision criterion and a method of ranking alternatives. In order to make a decision one needs a system to estimate the value of and rank the different decision alternatives and one needs decision criteria. The decision criteria are based on the values allotted to different possible outcomes of a certain decision. Following the second step, the decision maker can choose one of two ways to continue the decision process. These two ways are "risk based approach" or "preference based approach".

"Risk based approach" is the situation in which it is possible to describe the alternatives in terms of probabilities (p) and utilities (u), where utilities may be expressed as a unitary measure (for example, money). In such situations the *principle of expected value* is used. The expected utility, E(u), is defined as:

$$E(u) = p_1 * u_1 + p_2 * u_2 + \ldots\ldots\ldots\ldots + p_n * u_n$$

"Preference based approach" is used when it is difficult to assign a common measure to different properties related to a certain event. Examples of such properties are environmental aspects, aesthetics and damage costs. In these cases the expected utility criterion cannot be used. Instead, one has to rely on methods in which alternatives are ranked based on different (subjective) preferences.

When choosing an alternative based on subjective preferences, one might try to do a direct ranking based on an evaluation of the possible composite outcomes. From a practical engineering point of view, however, it might be easier to compare the different alternatives with respect to one parameter at a time. Problems arise if one alternative is better than the others, not in all respects but just in a few. In this case, some sort of weighting must be assigned to different parameters. A good method of doing this is the Analytic Hierarchy Process, AHP. Figure 2.18 shows an example of the AHP as described by Sturk et al. [106]. Multi-attribute utility analysis can be also used for preference approach.

The decision process ends with some sort of basis for decision or recommendation to the decision maker.

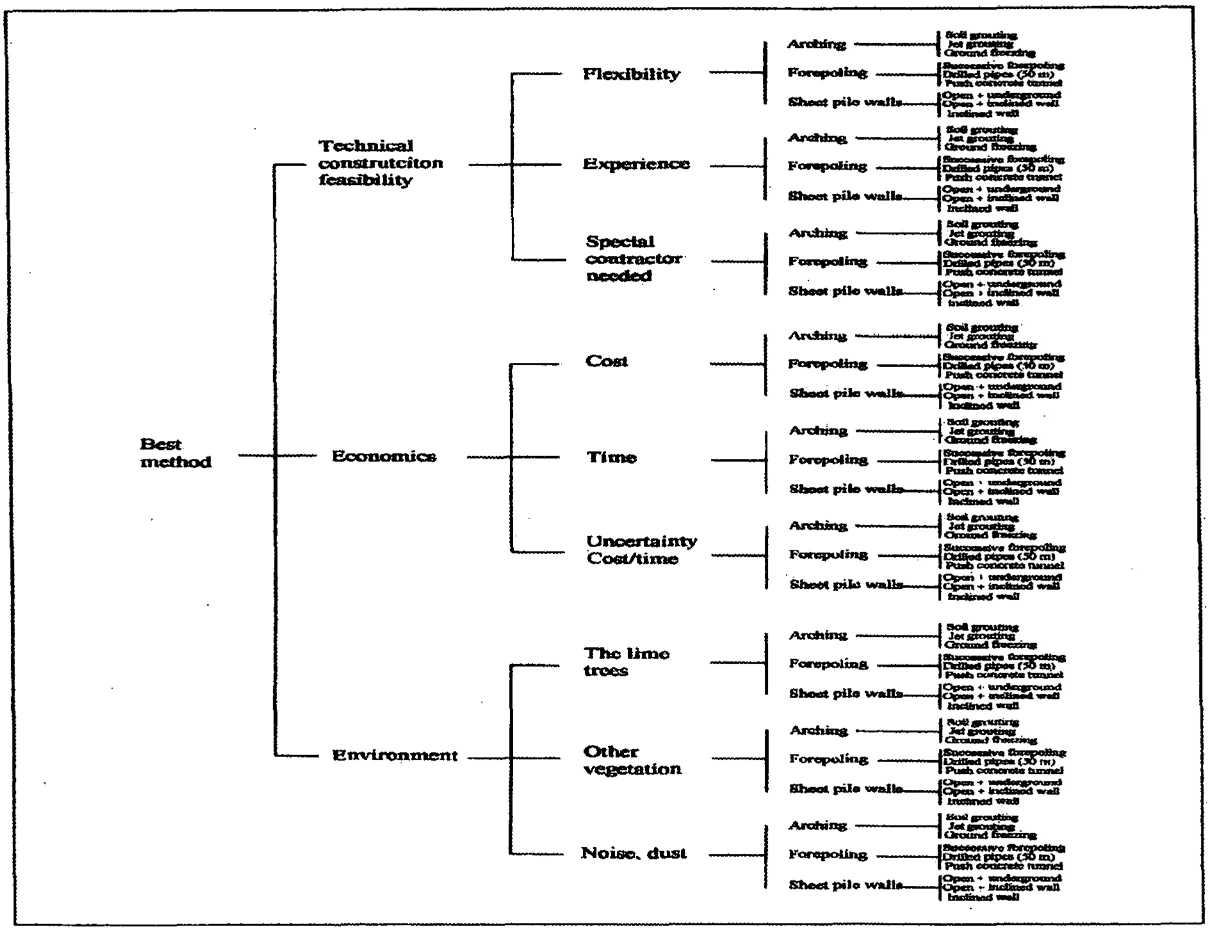


Figure 2.18 An example of the AHP (Sturk et al. [106])

2.3.2 Models for tunnel construction

The Decision Aids for Tunnelling (DAT) were developed to estimate cost and time of constructing a tunnel or other underground facility. The most important feature of the DAT and of the associated computer code, SIMSUPER, is the possibility to consider uncertainties. The resulting time-cost distributions, e.g. in form of scattergrams, form the basis for decision making. It is also possible to decide if additional information gathering (exploration) is worth the expenditure. Alternative alignments can be compared not only on the basis of individual time-cost pairs but also on the basis of their time-cost uncertainties. In addition to predicting construction time and cost, the DAT can also determine the resources required and produced, again including their uncertainties (Indermitte and Einstein [52]).

The DAT consist of two major components: the geology module and the construction module (Einstein et al. [28]; Halabe [41]). The two modules of DAT were described by Haas and Einstein [40] as follows: The geology module produces probabilistic geologic/geotechnical profiles that indicate the probabilities of particular geologic conditions occurring at a particular tunnel location; they are usually obtained through a combination of objective information and subjective estimates by experts. One usually starts by subdividing the tunnel geology into so-called zones that correspond to geologic units. This is followed by estimating the geologic/geotechnical parameters. Subsequently, the DAT uses this information to generate a possible profile for each parameter. The profiles for all parameters are then combined in ground class profiles where each combination of parameter states defines a particular ground class (see figure 2.19).

	Area 1							Area 2
	Zone 1		Zone 2					Zone 3
Param 1	Gneiss		Schist		Granite		Gneiss	Schist
Param 2	Not Faulted	Faulted	Not Faulted	Faulted		Not Faulted		Not Faulted
Ground Class	Gneiss / Not Faulted	Gneiss / Faulted	Schist / Not Faulted	Schist / Faulted	Granite / Faulted	Granite / Not Faulted	Gneiss / Not Faulted	Schist / Not Faulted

Figure 2.19 Tunnel hierarchy: area, zones, parameters and ground classes (Indermitte and Einstein [52])

The construction module simulates the construction process through each of the ground class profiles. This involves relating geologic/geotechnical conditions (ground classes) to construction classes or "tunnelling methods" which define tunnel cross sections and initial and permanent support, as well as the excavation method best suited for a particular ground class. Each method is associated with construction cost and time, which are usually given in the form of cost and advance-rate distributions expressing cost and time uncertainties for each tunnelling method. In the DAT, probabilistic input and thus also construction cost or time for a particular ground class are usually defined by a triangular probability density function (Figure 2.20).

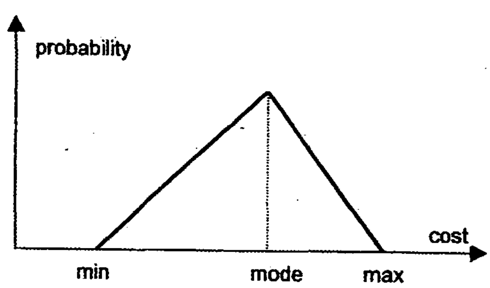


Figure 2.20 Triangular probability density functions (pdf) (Haas and Einstein [40])

The construction of a tunnel is simulated by advancing round by round through one of the geologic profiles. Each simulation results in a different cost-time pair for constructing the tunnel. The entire geologic and construction uncertainty for a tunnel is thus represented by a number of cost-time pairs, which can be shown in a so-called cost-time scattergram.

Typically the DAT has been applied at an early stage in the project life, almost exclusively before construction actually started (Einstein at al. [27]; [28]). The DAT have also been expanded to include updating during construction. Also, they have been applied in numerous practical cases and in research (Sinfield and Einstein [101]).

Several models have been developed in the past to predict the performance of TBMs (Nelson et al. [81]). Most of these models are concerned solely with the prediction of the penetration rate. The *penetration rate* is defined as the rate of progress during actual operation of the TBM.

Tarkoy [112] presented a model to predict the penetration rate of TBMs, which uses the total hardness as a predictor parameter. The total hardness is estimated by using the Schmidt hammer rebound value and the rock abrasion hardness. A major disadvantage of Tarkoy's model is that it considers neither the rock mass characteristics nor the machine characteristics, which are very important in the overall performance of TBMs.

McFeat-Smithe and Tarkoy [75] presented different relations to predict the penetration rate for different types of TBMs in different geological conditions. This model is not generally valid and it has to be recalculated for each new project.

Graham [38] introduced a model in which the penetration rate of TBM is computed as a function of the normal force per cutter, the RPM, and the unconfined compressive strength of the tunnelled rock. The model considers neither the discontinuities nor the cutter properties. In addition, there is no data on the range of validity.

Roxborough and Phillips [94] developed an implicit formula, to calculate the penetration rate of TBMs, which can be solved numerically. The model includes the diameter, thrust per cutter, the unconfined compressive strength and the disc edge angle. In this model, rock mass defects such as discontinuities are not considered. The structure of Roxborough and Phillips's model is quite similar to that of the Graham model with the difference that with the cutter edge angle is considered. The validity range of this model is well described.

Ozdemir et al. [87] developed a model for TBM performance that allows one to compute the normal force and the rolling force of a cutter, given a disc diameter, cutter radius, penetration of disc, spacing of the disc grooves, unconfined compressive strength, shear strength and the cutter edge angle. The rock types on which the model is based are mainly igneous and metamorphic. No discontinuity properties are included in the model.

Farmer and Glossop [31] presented a model to calculate the penetration rate of TBMs in which the penetration rate is computed by using the average cutter force and the tensile strength of the rock. The model is based on eight different case histories. This seems to be its major limitation regarding the wide variety of TBMs available. Rock mass defects (i.e. discontinuities) and cutter properties are not considered in the model.

Boyd [15] presented a model to calculate penetration rate of TBMs that uses a totally different approach. The rock mass is assumed to have a specific energy (in KWh/m^3) that is needed for disintegration. If the cross-sectional area of the tunnel and the installed cutter-head power are known, the penetration rate can be calculated by dividing the power of the machine by the specific energy and the cross-sectional area. This method has been mainly used to determine the performance of roadheaders.

McFeat-Smith and Fowel [76] derived some relations that predict the specific energy of a rock, and they built a model to calculate the penetration rate of TBMs based on the specific energy of the rock. Their approach presents some problems, since the installed cutter-head power is not necessarily the power that will be delivered to the rock face, and the specific energy is not dependent only on the properties of the rock. The specific energy depends largely on chip size, and therefore on the prevailing cutting process, which itself is determined partially by the machine characteristics and not solely by the rock mass characteristics. Therefore, the method can be applied only if both the TBM characteristics and the rock properties are known.

Hughes [49] presented a model that is similar to the Graham model described above. The force per cutter, unconfined compressive strength, and RPM are considered in the model. It also includes the number of cutters per kerf (groove) and the radius of the discs. However, the model does not consider the rock mass defects (discontinuities).

Bruland et al. [18] presented an updated version of the model presented by Lislerud [68], which was developed by the same Norwegian research group to predict the performance of TBMs. The first version of the model was published in 1976 by Johannessen et al. [59] (in Norwegian). The changes in Bruland's model are minimal. As pointed out by Verhoef [118], this method is perhaps the best model for the prediction of TBM performance, since it is the only one that includes most of the relevant influencing factors. The intact rock properties are included in the form of Drilling Rate Index (DRI). Discontinuity direction and spacing, as well as machine characteristics such as thrust per cutter, cutter size and RPM are considered. The model was developed using multivariate regression, and it uses charts to obtain the important parameters. To obtain the

DRI, the brittleness test and the Siever's miniature drill test are performed. The test procedures are described in a paper by Johannessen et al. [59] that also contains DRI values from more that 1300 sample locations, of which about 85% are from Norway.

Innaurato et al. [53] introduced an updated version of the method presented by Cassinelli et al. [21] to predict the penetration rate of TBMs. The method includes the Rock Structure Rating (RSR) of Wickham et al. [122]. The major change of the updated method is the incorporation of the unconfined compressive strength of the rock. It must be noted that the RSR was originally developed for the determination of the appropriate steel rib tunnel wall support, and that it includes parameters such as rock type, geological structure, joint spacing, dip direction, joint condition, and the water inflow. In the RSR method, the strength of the intact rock is only partially accounted for by the rock type and classification by hardness. This is perhaps one of the reasons why the unconfined compressive strength is included in Innaurato's model. The method is based upon 112 homogeneous sections; however, no information is provided on the number of bored tunnels.

Sundin and Wänstedt [109] developed a model that uses boreability and a penetration index to predict the TBM performance. It includes the rock mass discontinuities, the thrust per cutter and the rotational speed of the cutter-head. It should be noted that the model was tested for three cases in Sweden, mainly in metamorphic and igneous rocks.

Grima et al. [39] used the neuro-fuzzy concept and the Artificial Neural Network principle to derive a model to calculate both the penetration rate (PR) and the advance rate (AR) of TBMs. They defined the PR as the speed at which a TBM advances through a given rock, assuming full usage of the machine (thrust against the face and rotating cutter-head). The advance rate is defined as the product of the PR and the utilization.

The modelling strategy used for the PR model is illustrated in figure 2.21. The model inputs are five parameters which used to predict the PR value. These parameters as shown in table 2.3.

To validate the model and check its generalization capability Grima et al. [39] used ten different checking sets (validation sets). The derived final penetration rate model not only has the lowest error in the training set, but also yielded good results for the checking set. This indicates a good generalization capability of the neuro-fuzzy model.

Figure 2.22 depicts the modelling strategy employed to build the advance rate model on a monthly basis of a tunnel in rock made by TBM (Grima et al. [39])

Table 2.3 Parameters for PR modelling

Parameter	Remarks
Core Fracture Frequency (CFF)	The only discontinuity parameter; parameters such as roughness, orientation and weathering state are not available
Rock strength (UCS)	The only strength parameter in the data set.
Revolution per minutes (RPM)	An increase of cutter rotation rate should lead to a proportional increase of the penetration rate. The recorded RPM is the maximum RPM, which depends on the diameter of the tunnel and the quality of the steel.
Thrust per cutter	In order to compare the performance of TBMs, the thrust per cutter is used in literature and it is a parameter to take into consideration.
Cutter diameter	Larger-diameter cutters allow for more thrust to be applied.

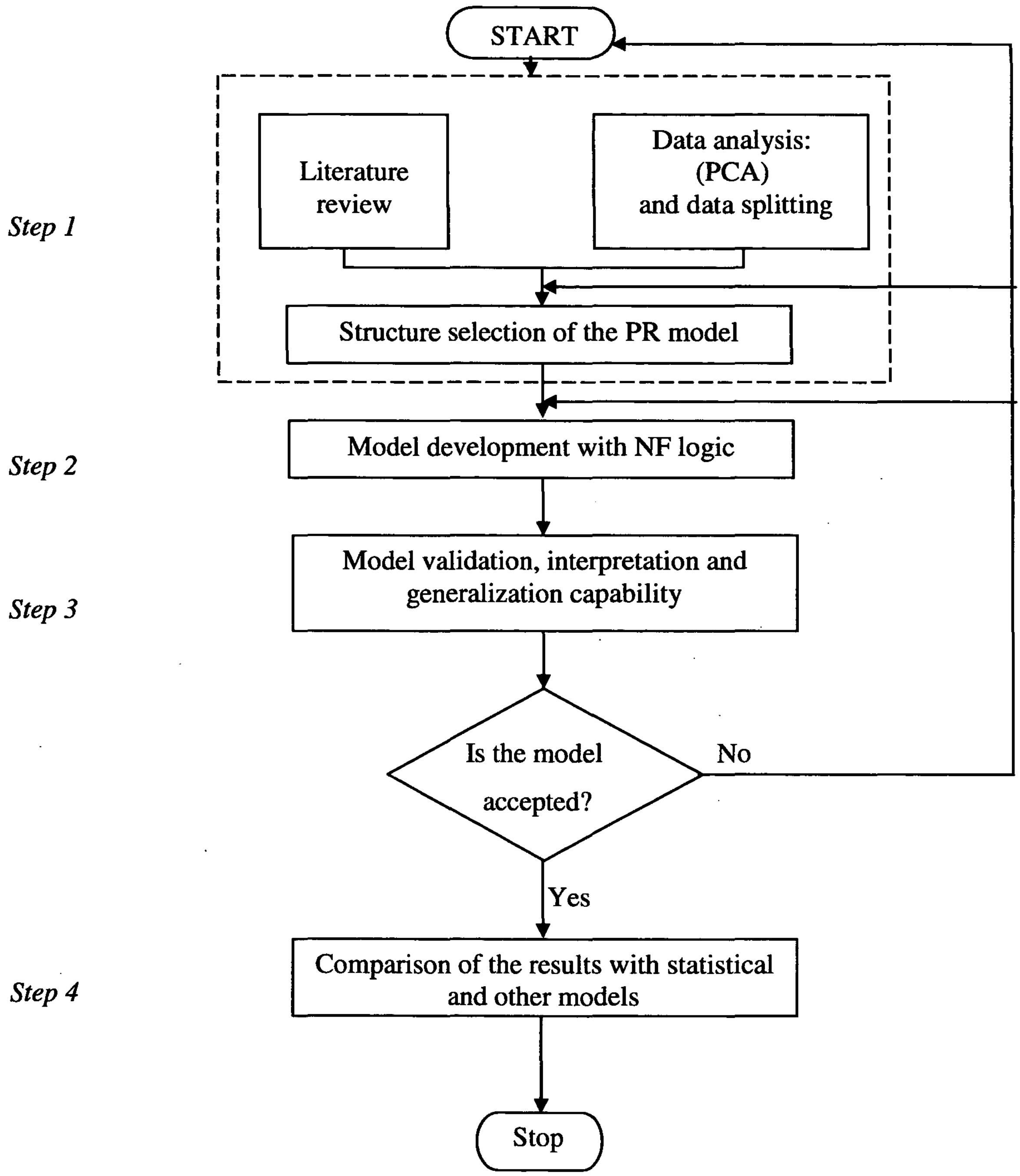


Figure 2.21 Modelling strategy used for the PR model (Grima et al. [39])

The input factors to the ANN model that calculate the advance rate (AR) are shown in figure 2.23.

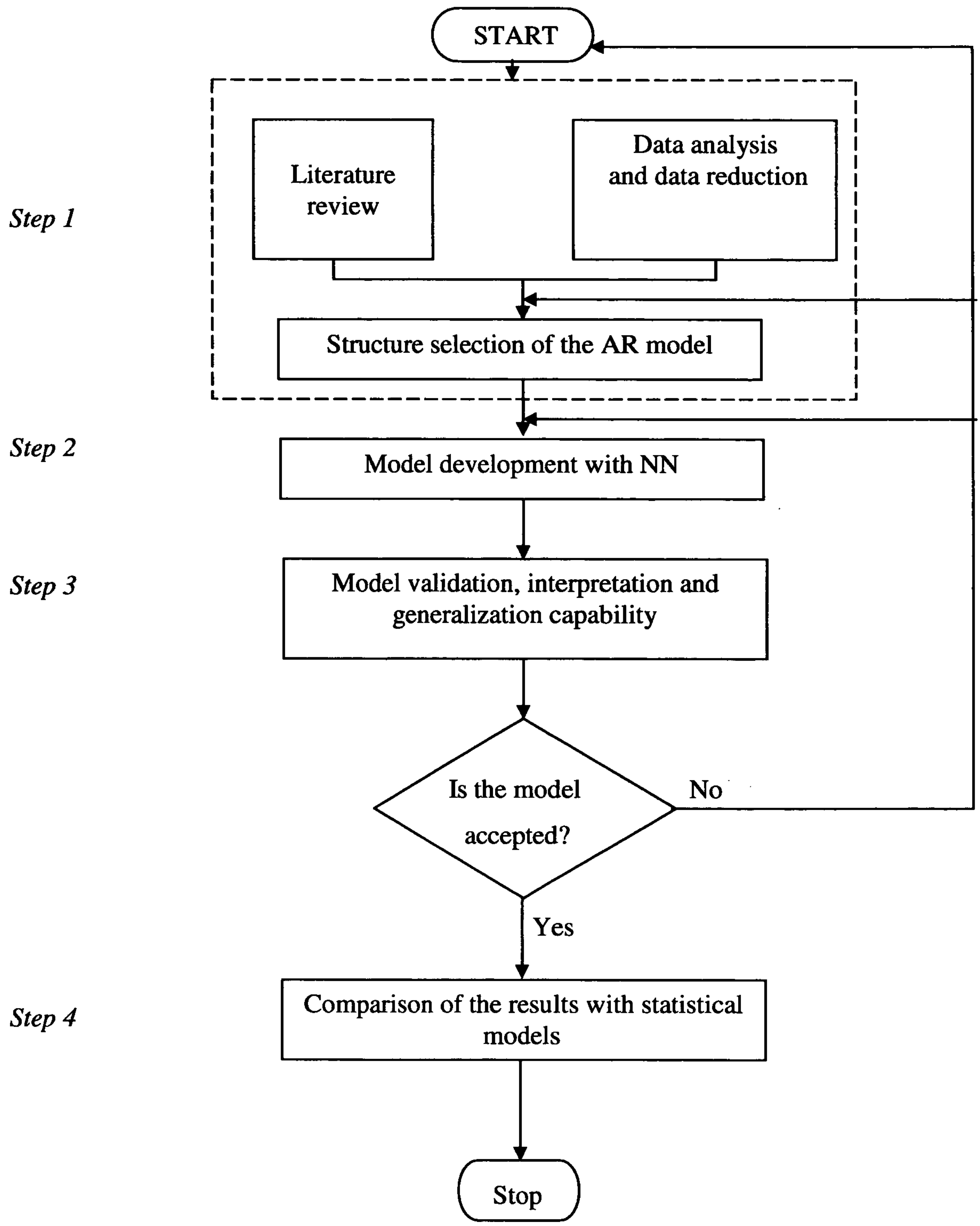


Figure 2.22 Modelling strategy used for the AR model (Grima et al. [39])

Touran [114] states that estimating the cost and duration of tunnelling projects poses a major challenge because of the uncertainties involved. He suggested that probabilistic procedures provide a logical approach to this problem. He developed an analytical model to calculate the advance rate of TBM and the required time to complete the project. Touran's model is based on progress in the completed portion of the tunnel. The model may be used on relatively long tunnels with durations extending over several months where the tunnelling has already begun and sufficient data have been collected. For formulation of his model, he used actual data from the Outfall Tunnel of the Boston Harbor Cleanup Project. He stated that, his model may not be effective in other projects.

Most of the reviewed models are designed to calculate TBM advance rates. Except of the DAT these models cannot be used to select efficient tunnelling system. The DAT concentrate on time and cost as controlling factors for deciding which method is suitable for the tunnel.

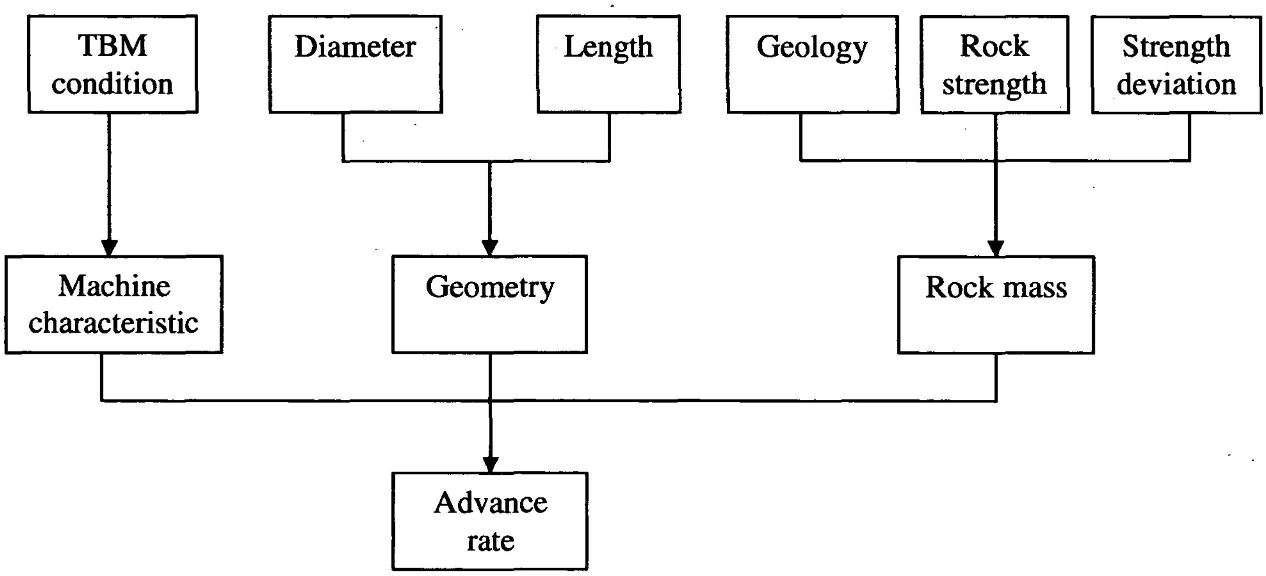


Figure 2.23 Main factors influencing the advance rate (Grima et al. [39])

3 Decision controlling factors for selection of tunnelling methods

3.1 Introduction

Decision controlling factors represent project conditions which play an important role in determining efficiency percentages of the construction methods of tunnelling activities and consequently the efficiency percentages of the alternative tunnelling systems.

Each tunnelling activity has a number of technical and non-technical controlling factors which control the selection of construction methods for each activity. Factors like ground conditions, tunnel depth and tunnel cross sectional area and profile are technical controlling factors. Non-technical factors include factors like time and cost. Table 3.1 shows the technical and non-technical controlling factors for tunnelling activities. Determination of the controlling factors is one of the steps of this research.

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. The matrices were developed to collect the opinions of tunnel experts about efficiency degrees of construction methods for the controlling factors (see appendix "A"). The first part of the matrices in appendix "A" represents technical factors while the second part represents non-technical factors. This chapter shows how the matrices were developed, also a detailed explanation of the controlling factors and their scale for the *"Basic tunnelling methods"* as well as tunnelling activities are introduced.

Table 3.1 Controlling factors for the tunnelling activities

Construction methods for tunnelling activities											
Basic tunnelling and excavation methods		Mucking methods		Transportation methods		Support methods		Lining methods		Groundwater control methods	
Technical factors	Non-technical factors	Technical factors	Non-technical factors	Technical factors	Non-technical factors	Technical factors	Non-technical factors	Technical factors	Non-technical factors	Technical factors	Non-technical factors
Ground conditions	Cost	Ground bearing capacity	Cost	Ground bearing capacity	Cost	Ground conditions	Cost	Ground conditions	Cost	Ground conditions	Cost
Tunnel depth	Time	Muck particle size	Time	Transportation length and speed	Time	Tunnel depth	Time	Tunnel cross section profile	Time	Groundwater conditions	Time
Tunnel cross-section	Technology availability	Tunnel span	Others	Tunnel span	Others	Constructibility	Others	Tunnel function	Others	Tunnel depth	Others
Tunnel alignment	Experience			Tunnel slope				Groundwater condition		Tunnel position	
Health & safety	Others			Muck particle size and water content						Working length of the tunnel (m/day)	
Environmental conditions				Health & safety						Health & safety	
Tunnel position										Environmental conditions	

Controlling factors (rows)

3.1.1 A general note about matrices of appendix "A"

To develop a harmonized tunnelling system, methods of different activities should be able to work efficiently together. Matrices connect construction methods of different activities together, where each matrix, in tables A.1.1, A.1.2, A.1.3, A.1.4, A.1.5 and A.1.6 (appendix "A"), includes a section which connects construction methods of two or three different activities, for example in table A.1.1 excavation methods are connected to the *"Basic tunnelling methods"*, table 3.2 shows the connections between excavation and the basic tunnelling methods. Table 3.2 is a part of table A.1.1, and it is an example to show how the matrices connect methods of different activities. Cells of table 3.2 will be filled with efficiency degrees which represent the efficiency of the *"Basic tunnelling methods"* when they work with the excavation methods.

Table 3.2 Connecting excavation and the *"Basic tunnelling methods"*

Basic tunnelling methods / Excavation methods	Cut & cover	New Austrian Tunnelling Method (NATM)				Mechanical method
		Full face	Heading & bench	Multiple drift	Pilot enlargement	
Excavator/Backhoe/Front shovel						
Hand excavation						
Drill & blast						
Roadheader						

3.2 The *"Basic tunnelling methods"* and excavation methods matrix

The objective of this matrix (table 3.3) is to collect the opinions of tunnel experts about the efficiency degrees of the *"Basic tunnelling methods"* and of the excavation methods, from a technical point of view, with regard to the controlling factors which are presented in table 3.4.

Table 3.3 Controlling factors for the basic tunnelling & excavation methods (basic tunnelling & excavation methods matrix)

Factors \ Methods			Basic tunnelling methods						Excavation Methods						
				NATM											
			Cut & Cover	Full face	Heading & bench	Multiple drift	Pilot enlargement	Mechanical method	Excavator / Backhoe / Front shovel	Hand excavation	Drill & Blast	Roadheader	Micro-tunnelling	Shield Machine (Slurry / EPB)	TBM Machine (Open machine)
Ground Conditions	Compressive Strength	Less than 0.4 MPa													
		0.4 - 1.25 MPa													
		1.25 – 5.00 MPa													
		5.00 – 12.5 MPa													
		12.50 – 50 MPa													
		50 – 100 MPa													
		100 – 200 MPa													
		Over 200 MPa													
	GWT $\leq$ 0.5D & GWT $\leq$ 7m														
	GWT = D & GWT $\leq$ 14m														
	14m < GWT $\leq$ 30m														
	GWT > 30m														
	Existence of gases														
Tunnel depth	Tunnel invert $\leq$ 30 m														
	Tunnel invert > 30 m														
Tunnel Cross Section	Variable cross section														
	Circular or mouth cross section														
	Oval or Horseshoe section														
	Other cross sections														
	Area	Less than 2 m^2													
		2 – 10 m^2													
		10 – 30 m^2													
		30 – 100 m^2													
		Over 100 m^2													

Table 3.3 Controlling factors for the basic tunnelling & excavation methods (basic tunnelling & excavation methods matrix) (continued)

Factors \ Methods		Basic tunnelling methods						Excavation Methods						
			NATM											
		Cut & Cover	Full face	Heading & bench	Multiple drift	Pilot enlargement	Mechanical method	Excavator / Backhoe / Front shovel	Hand excavation	Drill & Blast	Roadheader	Micro-tunnelling	Shield Machine (Slurry / EPB)	TBM Machine (Open machine)
Tunnel Alignment	Horizontal curve radius < 40m													
	40m < Horizontal curve radius < 150m													
	Horizontal curve radius > 150m													
	Vertical slope < 3%													
	Vertical slope > 3%													
Health & Safety	Good health environment													
	Few accidents													
Environmental Conditions & Tunnel Position	Low noise for public													
	Low vibration & effect on buildings													
	Good for archaeological areas													
	Low effect on traffic													
	Low dust particles in air													
	Low landscape effect													
	Limited site area for start up													
	Tunnel near sewer, gas, water pipes													
Excavation Method	Excavator / Backhoe / Front shovel													
	Hand excavation													
	Drill & Blast													
	Roadheader													

Table 3.4 The basic tunnelling and excavation methods and their controlling factors

Basic tunnelling methods	***Controlling factors***
• Cut & cover	
• NATM - Full face	
• NATM - Heading and bench	
• NATM - Multiple drift	• Ground conditions
• NATM - Pilot enlargement	• Tunnel depth
• Mechanical method	• Tunnel cross section
	• Tunnel alignment
Excavation methods	• Health and safety
• Excavator/Backhoe/Front shovel	• Environmental conditions
• Hand excavation	• Tunnel position
• Drill & blast	
• Roadheader	
• Micro-tunnelling	
• Shield machine (slurry/EPB)	
• TBM (open machine)	

3.2.1 Ground conditions

Ground conditions control the selection of the *"Basic tunnelling methods"* as well as of the excavation methods where methods that can be used for hard rock are different from those for soil. The *"Ground conditions"* factor is used to describe the ease/difficulty of excavation but not to describe how they relate to support requirements. In the support matrix, which will be explained later, ground conditions have another scale.

Nichols and Day [83] differentiated between soil and rock as *"Soil is loose surface material. Rock is the hard crust of the earth, which underlies and often projects through the soil cover"*. They stated also that there is no clear distinction between soil and rock. Geologically all soils are considered to be rock formations. The soil mechanics-design manual [79] classifies soil and rock based on strength values as shown in tables 3.5 and 3.6.

Table 3.5 Unconfined compressive strength of soil [79]

Soil	Unconfined compressive strength (MPa)
Very soft	< 0.025
Soft	0.025 – 0.05
Medium	0.05 – 0.1
Stiff	0.1 – 0.2
Very stiff	0.2 – 0.4
Hard	> 0.4

Table 3.6 Hardness classification of intact rock [79]

Rock	Uniaxial compression strength (MPa)
Extremely hard	> 200
Very hard	200 – 100
Hard	100 – 50
Soft	50 – 25
Very soft	25 – 1

Rock is divided into soft rock and hard rock. Rock classifications of Terzaghi [113], Lauffer [64], and Bieniawski [13] help in the differentiation of rock quality. The Institution of Civil Engineers ICE [103] has defined soft ground as *"It is any type of ground requiring support as soon as possible after excavation in order to maintain stability of the excavation"*. Hard rock is the rock that can stand without support for long time. Stand-up time for good rock can be many years.

Rock properties that influence the cutability of rock during tunnelling are mentioned in the following references [5], [10], [23], [43], [45], [51], [65], [70], [72], [89], and [115]. These properties are *"Rock type"*, *"Amount of weathering"*, *"Faults"*, *"Joints and discontinuities"*, *"Rock hardness"*, *"Rock abrasiveness"* and *"Rock strength"*. Strength of rock is an indication for rock type, amount of weathering and rock hardness.

Both rock strength and number of joints, faults and discontinuities of rock are two important factors for selecting excavation method. Hencher [43] stated that if the tunnelling method relies on the presence of fractures to allow the rock to be excavated, the wrong identification of fracture spacing at the site investigation stage can have severe consequences. Therefore, in the basic tunnelling and excavation methods matrix, rock strength is used as a factor to determine efficiency percentages of the *"Basic tunnelling methods"* and the excavation methods.

Bell [10] mentions several scales of unconfined compressive strength of intact rock. Three scales are given in table 3.7, which describe rock based on unconfined compressive strength. Another scale proposed by Marie [72] is shown in table 3.8.

The scale suggested by Anon [3] is used here for the *"Basic tunnelling methods"* and for the excavation methods because of its wider scale. It can distinguish easily between methods. Two other ranges were added to the scale to cover the case when ground is soil. The ranges "compressive strength less than 0.4 MPa" and "0.4 – 1.25MPa" cover the soil cases. The complete scale is presented in table 3.9 (see also the whole matrix in table 3.3).

Table 3.7 Description of unconfined compressive strength (Bell [10])

Geological Society (Anon [3])		IAEG		ISRM	
Strength (MPa)	Description	Strength (MPa)	Description	Strength (MPa)	Description
Less than 1.25	Very weak	1.5 – 15	Weak	Under 6	Very low
1.25 – 5.00	Weak	15 – 50	Moderately strong	6 – 20	Low
5.00 – 12.50	Moderately weak	50 – 120	Strong	20 – 60	Moderate
12.50 – 50	Moderately strong	120 – 230	Very strong	60 – 200	High
50 – 100	Strong	Over 230	Extremely strong	Over 200	Very high
100 – 200	Very strong				
Over 200	Extremely strong				

Table 3.8 Unconfined compressive strength, rock ranges (Marie [72])

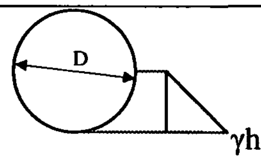
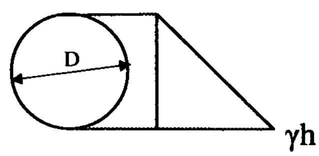
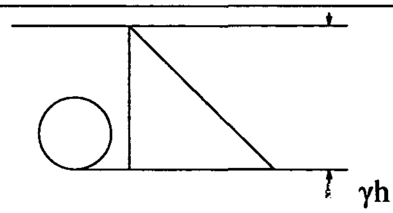
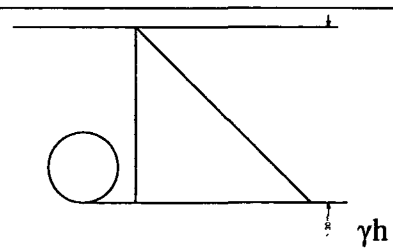
Class	Descriptor	Unconfined stress range (psi)	Unconfined stress range (MPa)
R0	Extremely soft	20 – 100	0.2 – 0.7
R1	Very low strength	100 – 1000	0.7 – 7
R2	Low strength	1000 – 4000	7 – 28
R3	Moderate strength	4000 – 8000	28 – 55
R4	Medium high strength	8000 – 16000	55 – 110
R5	High strength	16000 – 32000	110 – 220
R6	Very high strength	> 32000	> 220

Table 3.9 Ground compressive strength scale of the basic tunnelling methods and excavation matrix

Ground compressive strength (MPa)	Description
Less than 0.4	Extremely weak
0.4 – 1.25	Very weak
1.25 – 5.00	Weak
5.00 – 12.50	Moderately weak
12.50 – 50	Moderately strong
50 – 100	Strong
100 – 200	Very strong
Over 200	Extremely strong

The groundwater table level is included in the basic tunnelling methods and excavation methods matrix (table 3.3) because groundwater pressure can result in many problems during construction. Sterling and Godard [104] demonstrated that groundwater pressures affect the stability of excavation faces. The scale which is used for the basic tunnelling methods and for the excavation methods is derived from the groundwater control methods matrix, which will be explained later in this chapter. The scale consists of 4 ranges (see table 3.10). The first range is groundwater table level (GWT), measured from tunnel invert level to the GWT elevation, is ≤ 0.5 D where "D" is tunnel diameter/height and it is less than or equal to 7m. The second range is GWT is equal to tunnel diameter/height and it is less or equal to 14m. It is expected for the first and second ranges that water pressure will be not high (approximately 0.07 MPa and 0.14 MPa respectively). The third range is GWT is between 14m and 30m and the fourth range is GWT is over 30m.

Table 3.10 Scale of groundwater table level

Scale of groundwater table level	Description
GWT $\leq$ 0.5 D & GWT $\leq$ 7m	
GWT = D & GWT $\leq$ 14m	
14m < GWT $\leq$ 30m	
GWT > 30m	

Existence of underground gases is an important factor to be considered. Underground gases may be explosive and/or toxic. Hence, gas can affect the selection decision of the basic tunnelling and excavation methods. In the *"Basic tunnelling methods"* and excavation methods matrix, the ground gases factor is included to determine efficiency degrees of construction methods when there are gases in the ground (see table 3.3). When there are no harmful ground gases, it is assumed that all the basic tunnelling and excavation methods are efficient.

3.2.2 Tunnel depth

It is important to differentiate between shallow and deep tunnels. Wagner [119] divided tunnels into three categories, deep, shallow (medium) deep and shallow tunnels. When the overburden exceeds 200 meters and could have as much as to 2000 meters and more it will be deep tunnel *(Overburden > 200m, tunnel is deep)*. Shallow (medium) deep tunnel will be between overburden exceeds 2 tunnel diameter up to less than 200 meters *(2 tunnel diameter < overburden < 200m, tunnel is shallow (medium) deep)*. If overburden ranges from half of a tunnel diameter up to 2 tunnel diameter, tunnel will be shallow tunnel *(0.5 tunnel diameter < overburden < 2 tunnel diameter, tunnel is shallow)*. Wagner also stated that if the overburden is less than half of a tunnel diameter, tunnels, in this case, are usually built by using cut and cover method.

Morawetz [78] defined shallow tunnels as the tunnels with inverts maximum up to 15m below ground. If the tunnel invert is at more than 15m the tunnel will be deep tunnel. For the basic tunnelling methods and excavation methods matrix, it is easier to deal with a fixed number than with Wagner's classification system.

30m depth is used in the basic tunnelling methods and excavation methods matrix (table 3.3) to differentiate between shallow and deep tunnels.

3.2.3 Tunnel cross section

There are three variables related to the tunnel cross-section which are "cross-section is fixed or changeable along the tunnel path", "cross-section profile" and "cross-section area". All excavation methods can be used with fixed or circular cross sections. When tunnel cross section is not circular or the area is variable along the tunnel some excavation methods will not be efficient.

Girmscheid and Schexnayder [34] stated that Tunnel Boring Machines require a predetermined (fixed) tunnel diameter. Such a circular profile can be excavated with a high degree of accuracy by the TBMs. However, with drill and blast methods the tunnel cross section can be created to any required shape and, most importantly, the tunnel shape can be changed along the length of the drive. The diameter of a circular cross section can be increased or decreased as required, or a circular section can be changed to a horseshoe form when necessary.

The US Army report [116] mentioned that the largest roadheaders can cut a face larger than $60m^2$ from one position. Nelson et al. [82] stated that roadheaders can be used with non-circular cross sections as small as $20m^2$ in area. To use impact hammer, opening size should not be less than $30m^2$.

Workers cannot work in very small cross sections. The minimum diameter for the tunnel to enable workers to work efficiently is 1.8m.

The tunnel cross section scale which is used for the basic tunnelling methods and excavation methods matrix (table 3.3) is shown in table 3.11.

3.2.4 Tunnel alignment

Horizontal and vertical alignments of the tunnel influence the selection of the basic tunnelling and excavation method. Some machines cannot work with small horizontal radii.

Table 3.11 Tunnel cross section scale

Cross section scale	Description
Variable cross section	Tunnel cross section is fixed or variable
Circular or mouth cross section	This part of the scale feeds the model with tunnel cross section profile
Oval or horseshoe cross section	
Other cross sections	
Less than $2m^2$	This part of the scale feeds the model with tunnel cross section area
$2 - 10m^2$	
$10 - 30\ m^2$	
$30 - 100m^2$	
Over $100m^2$	

The US Army report [116] suggested that the horizontal radii to be between 40m to 80m to enable open TBM to work. For shielded TBM, horizontal radii should be in the range 150m to 400m. Tighter curves should be avoided or planned in conjunction with a shaft to facilitate equipment positioning.

Nelson et al. [82] ranked the horizontal curves radii for TBM as follows; 100m-125m for unshielded TBMs and 225m-300m for shielded TBMs.

The classification system stated on the US Army report [116] for horizontal curve radii which is suitable for TBM work was the base for the scale which is used in the basic tunnelling methods and excavation methods matrix (table 3.3) because it is more recent than the Nelson et al. classification system and it depends on new invented machines (see table 3.12).

The US Army report [116] also mentions that the efficiency of TBMs will be higher when tunnel vertical slope is less than 3% because mucking and groundwater control will be easier. In the *"Basic tunnelling methods"* and excavation methods matrix, efficiency of the construction methods will be evaluated for tunnel vertical slope < 3% and over 3% (see table 3.12).

Table 3.12 Tunnel alignment scale

Horizontal curve scale	Vertical curve scale
Horizontal curve radius < 40m	Vertical slope < 3%
40m < Horizontal curve radius < 150m	Vertical slope > 3%
Horizontal curve radius > 150m	

3.2.5 Health and safety

This factor evaluates the efficiency of construction methods with regard to the safety of the workers (few accidents to the workers). It also evaluates the ample environment for workers health. This factor ranks the basic tunnelling and excavation methods based on the potential degree of harm of each method to workers health.

3.2.6 Environmental conditions

This factor is concerned with six items (see table 3.3). These items are:

- Noise effects on general public and workers
- Vibration and effect on surrounding buildings
- Damage to archaeological areas
- Traffic flow

- Amount of the dust released during work
- Damage to landscape

Hiller [44] stated that excavation is one of the principal sources of construction vibration. There are differences in the amount of noise, vibration and dust resulting from each of the basic tunnelling and excavation methods.

It is important to select the method which creates low noise levels for workers as well as for the general public. When a tunnel passes near some old buildings, vibrations resulting from excavation must be calculated and taken into account. Selecting the method of excavation which results in minimum amount of dust is important for workers and public people health.

In big and crowded cities, traffic is a key factor in selecting the *"Basic tunnelling methods"* and methods of excavation. Cut and cover will have disadvantage effects on traffic flow as well as landscape.

Shallow soil layers, especially in older urban areas, may be rich in archaeological remnants. These sites and artefacts would normally not be discovered without an excavation. For example, the excavation for a car park in front of a Paris cathedral exposed city walls from the Middle Ages and excavation for the Mexico City metro exposed the foundations of ancient structures (Sterling and Godard [104]).

Morawetz [78] stated that one of the advantages of using cut and cover in constructing the Vienna underground metro is that, cut and cover allowed archaeologists and art historians to further explore the Vienna underground to obtain valuable information on the city's historic past. Sterling and Godard

[104] stated that using TBM does not allow one to see and discover the ground. Efficiency of the TBM is low for the archaeological factor.

3.2.7 Tunnel position

This factor is represented in the matrix (table 3.3) with two elements within Environmental factor and it includes the two items mentioned below:

- Limited site area for start up
- Tunnel near sewer, gas or water pipes

In old and crowded cities the site area for start up the project can limit the use of some excavation methods. Shield machines need a large site for mobilization and start up.

In case of the tunnel passing near water, sewer, or gas pipes, it is important to select excavation methods which cause the least disturbance in the ground. If the excavation method causes significant disturbance, pipes may break, for instance. As a consequence water from broken pipes may flow into the tunnel. Breaking of sewer pipes can result in the release of methane gas.

3.3 Mucking methods matrix *(table 3.13)*

The mucking methods matrix contains three technical factors, which are "ground bearing capacity", "muck particle size" and "tunnel span", as a base for selecting efficient mucking equipment.

3.3.1 Ground bearing capacity (mucking methods matrix)

Tracked equipment is more efficient than rubber wheel equipment in soft ground. When the ground bearing capacity is low, sometimes it is not possible for rubber wheel equipment to work. In the mucking matrix (table 3.13), ground bearing capacities are divided into four ranges which are:

- Less than 0.05 MPa
- 0.05 MPa – 0.10 MPa
- 0.10 MPa – 0.20 MPa
- Over 0.20 MPa

Table 3.13 Controlling factors for mucking methods (Mucking methods matrix)

Factors \ Mucking Methods		Rubber wheel loader	Tracked loader
Ground bearing capacity	Less than 0.05 MPa		
	0.05 – 0.10 MPa		
	0.10 – 0.20 MPa		
	Over 0.20 MPa		
Muck particle size	Very big particles (particle size > 45cm)		
	Big particles (7cm < particle size < 45cm)		
	Medium particles (2cm < particle size < 7cm)		
	Small particles (particle size < 2cm)		
Tunnel span	Less than 2m		
	2m – 4m		
	4m – 8m		
	Over 8m		
Excavation methods	Excavator / Front shovel / Backhoe		
	Hand excavation		
	Drill & blasting		

3.3.2 Muck particle size

Muck particle size is also an important factor for choosing the mucking material equipment. Large particles need powerful mucking machines. Efficiencies of the mucking machines are different according to the muck particle size and the machine's power. The scale used for particle size in the mucking matrix consists of four ranges which are listed below:

- Very big particles (particle size > 45cm)
- Big particles (7cm < particle size < 45cm)
- Medium particles (2cm < particle size < 7cm)
- Small particles (particle size < 2cm)

3.3.3 Tunnel span

Tracked equipment are heavy and they need large area to work compared to rubber wheel equipment. Tracked equipment need more space than rubber wheel equipment to maneuver. Efficiencies of the mucking equipment will be evaluated with regard to tunnel span. The scale used in the mucking methods matrix (table 3.13) for tunnel span is:

- Less than 2m
- 2m – 4m
- 4m – 8m
- Over 8m

3.4 Transportation methods matrix *(table 3.14)*

The objective of the transportation matrix is to select the most efficient method of transportation based on six factors which are:

- Ground bearing capacity

Table 3.14 Controlling factors for material transportation methods (Transportation methods matrix)

Factors \ Transportation Methods				Rubber wheel truck	Rail - Locomotive type			Conveyors
					Diesel – mechanical locomotive	Diesel - electric locomotive	High voltage locomotive	
Ground bearing capacity	Less than 0.05 MPa							
	0.05 – 0.10 MPa							
	0.10 – 0.20 MPa							
	Over 0.20 MPa							
Transportation length and required transportation speed	Required Transportation speed	High speed	Transportation distance: Less than 0.5 km					
			0.5 km – 1 km					
			1km – 3km					
			Over 3km					
		Medium speed	Less than 0.5 km					
			0.5 km – 1 km					
			1km – 3km					
			Over 3km					
		Low speed	Less than 0.5 km					
			0.5 km – 1 km					
			1km – 3km					
			Over 3km					
Tunnel vertical slope	Less than 3%							
	3% - 10%							
	10% - 20%							
	20% - 25%							
	Over 25%							
Tunnel span	Less than 2m							
	2m – 4m							
	4m – 8m							
	Over 8m							

Table 3.14 Controlling factors for material transportation methods (Transportation methods matrix) (continued)

Factors \ Transportation Methods			Rubber wheel truck	Rail - Locomotive type			Conveyors
				Diesel – mechanical locomotive	Diesel - electric locomotive	High voltage locomotive	
Muck particle size & water content	Particle size	Less than 45cm					
		More than 45cm					
	Water content	Almost dry muck					
		High water content					
Health & safety	Good health environment						
Excavation methods	Excavator / Front shovel / Backhoe						
	Hand excavation						
	Drill & blasting						
	Roadheader						
	Micro-tunnelling						
	Shield machine						
	TBM machine						

- Tunnel span
- Transportation length and speed
- Tunnel vertical inclination
- Muck particle size and water content
- Health and safety

3.4.1 Ground bearing capacity (transportation methods matrix)

If ground bearing capacity is low, wheel trucks will be less efficient and rail or conveyors will be preferred. The same scale as in the mucking matrix is used here (see table 3.14).

3.4.2 Tunnel span (transportation methods matrix)

Selecting the suitable transportation method for a particular tunnel span is vital in the determination of tunnel advance rate. Interference between concrete transportation and placement on the one hand and tunnel excavation and mucking on the other hand is likely to slow tunnel advance.

Small spans pose restrictions on large equipment. The size of the equipment should be suitable to the tunnel span. The tunnel span should also be enough for wheel equipment to maneuver and return. The tunnel span scale is the same as that used in the mucking methods matrix (see table 3.14).

3.4.3 Transportation length and speed

Rail equipment and conveyors are faster than wheel equipment. The speed of the equipment, in relation with transportation length, is a factor in choosing suitable and efficient equipment. The US Army report [116] proposed that wheel equipment be used for short distances and rail equipment be used for long distances.

Transportation lengths used here are as follow:

- Less than 0.5km
- 0.5km – 1km
- 1km – 3km
- More than 3km.

Transportation speed is related to the transportation lengths. Three speed ranges are used (see table 3.14);

- High speed
- Medium speed
- Low speed

3.4.4 Tunnel slope

With rail transport in the tunnel, a grade of 2 percent is normal and 3 percent is usually considered the maximum grade. Higher grades – up to more than 12 percent – can be used with cable hoisting gear or similar equipment. Rubber – tired equipment can conveniently negotiate a 10-percent grade, but up to 25 percent is possible. For conveyor belts, a grade of 17 percent is a good maximum, though 20 percent can be accommodated with muck that does not roll down the belt easily (US Army report [116]). Five ranges of vertical slope percentages are used in the transportation matrix which are:

- Less than 3%
- 3% - 10%
- 10% - 20%
- 20% - 25%
- Over 25%

3.4.5 Muck particle size and water content

The maximum particle size of the muck limits the usage of some transportation methods. Belt conveyors cannot be used if the maximum particle size of the muck is bigger than the belt width. The US Army report [116] proposed that to use belts, the maximum particle size should be in the range of 0.3 – 0.45m. Muck particle size presented in transportation matrix is; less or more than 45cm.

If the water content of the muck is high, the efficiency of conveyors will be low. Muck water content is included in the transportation methods matrix to check if the muck has high water content or it is dry (see table 3.14).

3.4.6 Health and safety

Diesel equipment result in emissions which are not good for workers' health and safety (World tunnelling [30]). Some transportation methods can result in dust particles in the air. These particles are harmful for workers lungs. Selecting the transportation method with a minimum of air pollution is important and it is the objective of this factor in the transportation methods matrix.

3.5 Support methods matrix *(table 3.15)*

Support methods are used to support ground and stabilize the tunnel until the installation of the permanent support (lining). Factors that control the selection of the supporting methods are:

- Ground conditions
- Tunnel depth
- Constructibility

The support methods matrix includes support methods for side-wall, crown, and face support in regular mined tunnels and support methods for cut and cover.

Table 3.15 Controlling factors for support methods (Support methods matrix)

Factors \ Support Methods			Side wall & Crown support					Face support					Cut & cover		
			Rock bolts	Dowels	Steel arch	Shotcrete	Precast concrete segments	Forepoling	Pipe umbrella	Doorframe slab	Earth wedge	Shotcrete	Diaphragm wall	Sheet pile	Bored pile
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														

Table 3.15 Controlling factors for support methods (Support methods matrix) (continued)

Support Methods / Factors			Side wall & Crown support					Face support					Cut & cover		
			Rock bolts	Dowels	Steel arch	Shotcrete	Precast concrete segments	Forepoling	Pipe umbrella	Doorframe slab	Earth wedge	Shotcrete	Diaphragm wall	Sheet pile	Bored pile
Basic tunnelling & excavation methods	Basic methods	Cut & Cover													
		NATM - Full face													
		NATM - Head & 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													
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													

3.5.1 Ground conditions (support methods matrix)

"Geological engineers and project engineers on site were consulted and they revealed that rock type, RQD, groundwater, discontinuity conditions, faults and weak zones, distance from driving face, distance from bench face, support time and support methods seemed to be significant parameters for support stability based upon their observation and experiences" (Leu, Chen, and Chang [65]).

Classification systems have been developed to estimate rock quality taking into account the parameters determined by Leu, Chen, and Chang [65]. Detailed explanations of the classification systems are in references [5], [9], [10], [11], [12], [13], [14], [23], [26], [47], [48], [64], [88], [113], [116], [117] and [123].

"Rock mass classification schemes have been developing for over 100 years since Ritter (1879) attempted to formalize an empirical approach to tunnel design, in particular for determining support requirements" (Hoek, Kaiser, and Bawden [46]).

The main rock classification systems that were published to assist in the design of underground excavations are summarized in table 3.16.

Table 3.16 Major rock classification systems (Barton [7])

Name of classification	Originator
Rock loads	Terzaghi [113]
Stand-up time	Lauffer [64]
RQD	Deere [24,25,26]
RSR concrete	Wickham et al. [123]
Geomechanics (RMR)	Bienawski [11,12,13,14]
Q-system	Barton et al.[9],Barton [5,8]

The rock classification, which is used in the support methods matrix, depends on RMR system. RMR gives only five categories to the rock types. Support methods matrix contains 13 support methods, using RMR system, which is shown in table 3.17, means that there are 65 cells need to be filled with the efficiency degrees, on the other hand using Q system, which has 9 categories to the rock type, means that there are 117 cells need to be filled with efficiency degrees, to make it easier for tunnel experts RMR was selected for support methods matrix.

In the support methods matrix (table 3.15), the rock classification consists of five classes shown in table 3.17. If the ground is soil, it is represented in the support methods matrix in a separate row.

Table 3.17 Rock classification used in the support matrix

RMR value	Rock quality
0 – 20	Very poor rock
21 – 40	Poor rock
41 – 60	Fair rock
61 – 80	Good rook
Over 80	Very good rock

The US Army report [116] states that selecting rock support based on empirical systems such as the RMR or Q-system sometimes leads to selection of inadequate ground support because they do not cover some failure reasons which are shown below. These failure reasons are included in the support methods matrix.

- failure due to weathering
- failure caused by moving water

- failure due to corrosion of ground support components
- failure due to squeezing and swelling conditions
- failure due to overstress in massive rock

3.5.2 Tunnel depth (support methods matrix)

In case of deep tunnels, the overburden will be high and the stresses in the rock mass will be high. The greater the depth of the tunnel the greater the vertical stress. Hoek and Brown [47] plotted the relationship between the vertical stress and depth below surface. It is a linear relationship (see figure 3.1).

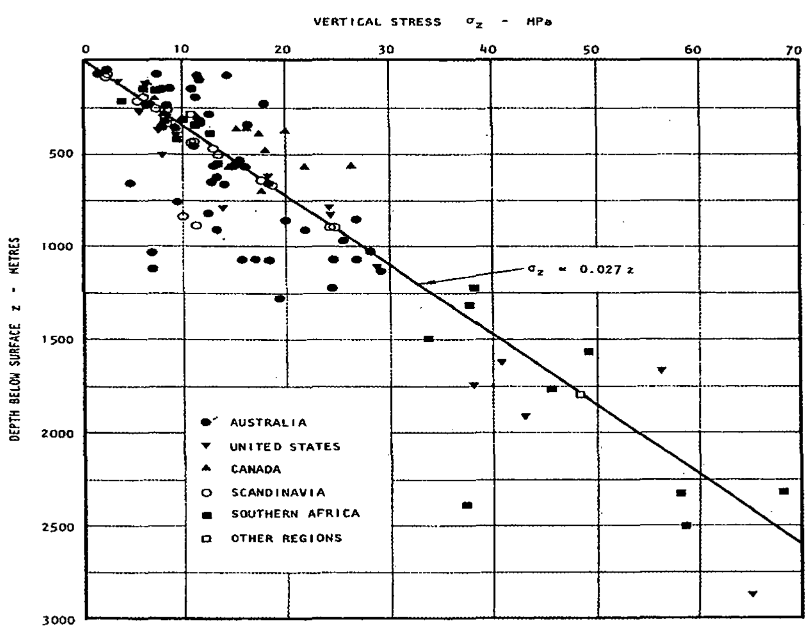


Figure 3.1 Vertical stress related to depth (Hoek and Brown [47])

Bell [10] announced that, in tunnels driven at great depths, rock may suddenly break from the sides of the excavation, a phenomenon known as rock bursting. Most rock bursts occur at depths in excess of 600m. The stronger the rock the more likely it is to burst. The most explosive failures occur in rocks which have unconfined compressive strengths > 140 MPa and values of Young's modulus greater than 34500 MPa.

In the support matrix (table 3.15) tunnel depth is divided into six ranges which are:

- Less than 30m
- 30 – 50
- 50 – 100
- 100 – 500
- 500 – 1000
- More than 1000m

For tunnels with depth less than 30m, cut and cover can be used for constructing the tunnels with a support method which could be a diaphragm wall, sheet piles or bored piles.

3.5.3 Constructibility

This factor measures the degree of constructibility of each support methods related to the size and shape of the tunnel. Increasing the tunnel size and depth will result in serious problems for face stability as stated by Hoek [45]. Selecting a support method that is suitable for tunnel size is important.

Some support methods cannot be used with small tunnel sizes. For large tunnel size, support methods are different in their efficiency. In support methods matrix (table 3.15) the size of the tunnel is covered by the following ranges for the tunnel span:

- Less than 1.5m
- 1.5m – 4m

- 4m – 6m
- 6m – 10m
- Over 10m

In support methods matrix, tunnel shape is divided into:

- Circular or mouth profile
- Oval or horseshoe profile
- Other cross sections

3.6 Lining methods matrix *(table 3.18)*

Factors control lining methods are discussed in this section. These factors include: *"Tunnel function"*, *"Tunnel cross sectional profile"*, *"Groundwater conditions"* and *"Ground conditions"*.

Construction methods like *"Precast concrete segments"* and *"Shotcrete"* will have efficiency degrees different from their efficiency degrees in the support methods matrix because the controlling factors here are different.

3.6.1 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 (see table 3.18). The tunnel functions "storage and defense" were defined by Marie [72].

Table 3.18 Controlling factors for lining methods (Lining methods matrix)

Factors			Lining Methods	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								

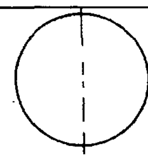
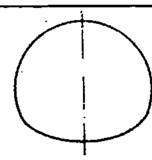
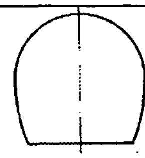
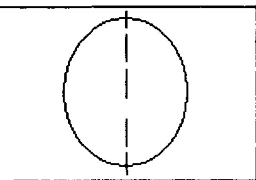
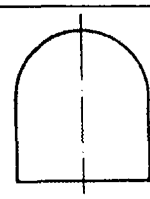
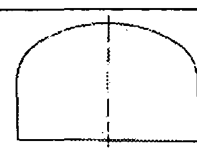
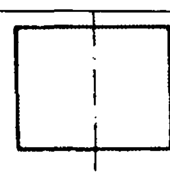
Table 3.18 Controlling factors for lining methods (Lining methods matrix) (continued)

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							

3.6.2 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. Tunnel profiles that are frequently used are represented here (see table 3.19).

Table 3.19 Tunnel profiles

Profiles name	Description
Circular or mouth profile	 circular  mouth
Horseshoe profile	
Oval profile	
Nordic profile	
Basket handle profile	
Rectangular profile	

3.6.3 Groundwater conditions

Sterling and Godard [104] 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 3.18):

- Less than 10L/min
- 10L/min – 25L/min
- 25L/min – 125L/min
- Over 125L/min

The scale is the same as that proposed by Bieniawski [12] in Geomecanics classification.

3.6.4 Ground conditions (lining methods matrix)

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

Isaksson [54] 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 (Maidl [71]). Q-system is another commonly used classification system.

The Q-system classification ranges in table 3.20 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. The Q-system is used in the lining methods matrix because it has clear classification for the rock in numbers.

Table 3.20 Q-system scale

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 [10] and the US Army report [116] proposed the most common minerals found in the ground. Table 3.21 represents the minerals that used in the lining methods matrix (see also table 3.18), minerals in table 3.21 are not all mineral that can be found in the ground but they are the most common minerals in the ground.

Table 3.21 Common minerals in rocks

Mineral group	Chemical composition
Feldspars	Orthoclase feldspar, Plagioclase feldspar
Quartz	Silica
Clay minerals	-
Micas	Muscovite mica Biotite mica
Chlorite	-
Calcite	CaCo3
Iron Ores	Carbonates Pyrite
Ferromagnesium Minerals	Augite Olivine

3.7 Groundwater control methods matrix (*table 3.22*)

The presence of groundwater can cause significant problems during tunnelling as a result of strength reduction due to either physical deterioration of the ground or the reduction of the stress due to pore water pressure (Hoek [45]). Selecting the most suitable method for groundwater control is the objective of the groundwater control methods matrix which includes the following factors:

- Ground conditions
- Groundwater conditions
- Tunnel depth

Table 3.22 Controlling factors for groundwater control methods (Groundwater control methods matrix)

Factors		Groundwater control methods → Dewatering	Slurry wall	Compressed air	Freezing	Chemical & cement grouting	Jet grouting
Ground conditions	GM (gravel – sand – silt mixtures)						
	GC (gravel – sand – clay mixtures)						
	SM (silty sands)						
	SC (clayey sands)						
	ML (inorganic silts)						
	CL (inorganic clays)						
	OL (organic silts)						
	OH (organic clays)						
	GWT ≤ 0.5D & GWT≤ 7m						
	GWT = D & GWT≤ 14m						
	14m < GWT ≤ 30m						
	GWT > 30m						
Groundwater inflow / 10m tunnel length	< 10 L/min						
	10-25 L/min						
	25-125 L/min						
	> 125 L/min						
Tunnel depth	Less than 15m						
	15m – 30m						
	30m – 50m						
	Over than 50m						
Tunnel position	Under urban areas						
	Under water bodies						

Table 3.22 Controlling factors for groundwater control methods (Groundwater control methods matrix) (continued)

Factors \ Groundwater control methods			Dewatering	Slurry wall	Compressed air	Freezing	Chemical & cement grouting	Jet grouting
Working length Of the tunnel (m/day)	Less than 4m							
	4m – 8m							
	8m – 15m							
	15m – 25m							
	Over 25m							
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						
Health & safety	Good heath environment							
	Few accidents							
Environmental conditions	Minimum bad effect on buildings							
	Less contamination of groundwater							
	Minimum effect on groundwater regime							

- Tunnel position
- Working length of the tunnel
- Health and safety
- Environmental conditions

3.7.1 Ground conditions (groundwater control methods matrix)

This factor includes two parameters which are *"Ground material"* and *"Groundwater table level"*. Golder and James [36] reported that in 1945 Glossop and Skempton [35] published two curves to show the relation between groundwater control methods *"Dewatering and grouting"* and ground particle size distribution. The two curves, in figure 3.2, are the bases of the ground material classification used in the groundwater control methods matrix. The classification used in the matrix (table 3.22) is also based on the Unified soil classification system.

The groundwater table levels presented in this matrix are the same as for the basic tunnelling and the excavation methods matrix (see tables 3.10 and 3.22).

3.7.2 Groundwater conditions (groundwater control methods matrix)

The amount of groundwater that needs to be controlled during construction depends on the groundwater table level and ground permeability. Liebsch [66] stated that if the excess pressure, in case of using air pressure method to control groundwater in the tunnel, is too high or the soil too permeable this leads to a blow-out.

The groundwater conditions that were used in the lining methods matrix are also used in the groundwater control methods matrix. Table 3.23 shows the groundwater flow scale.

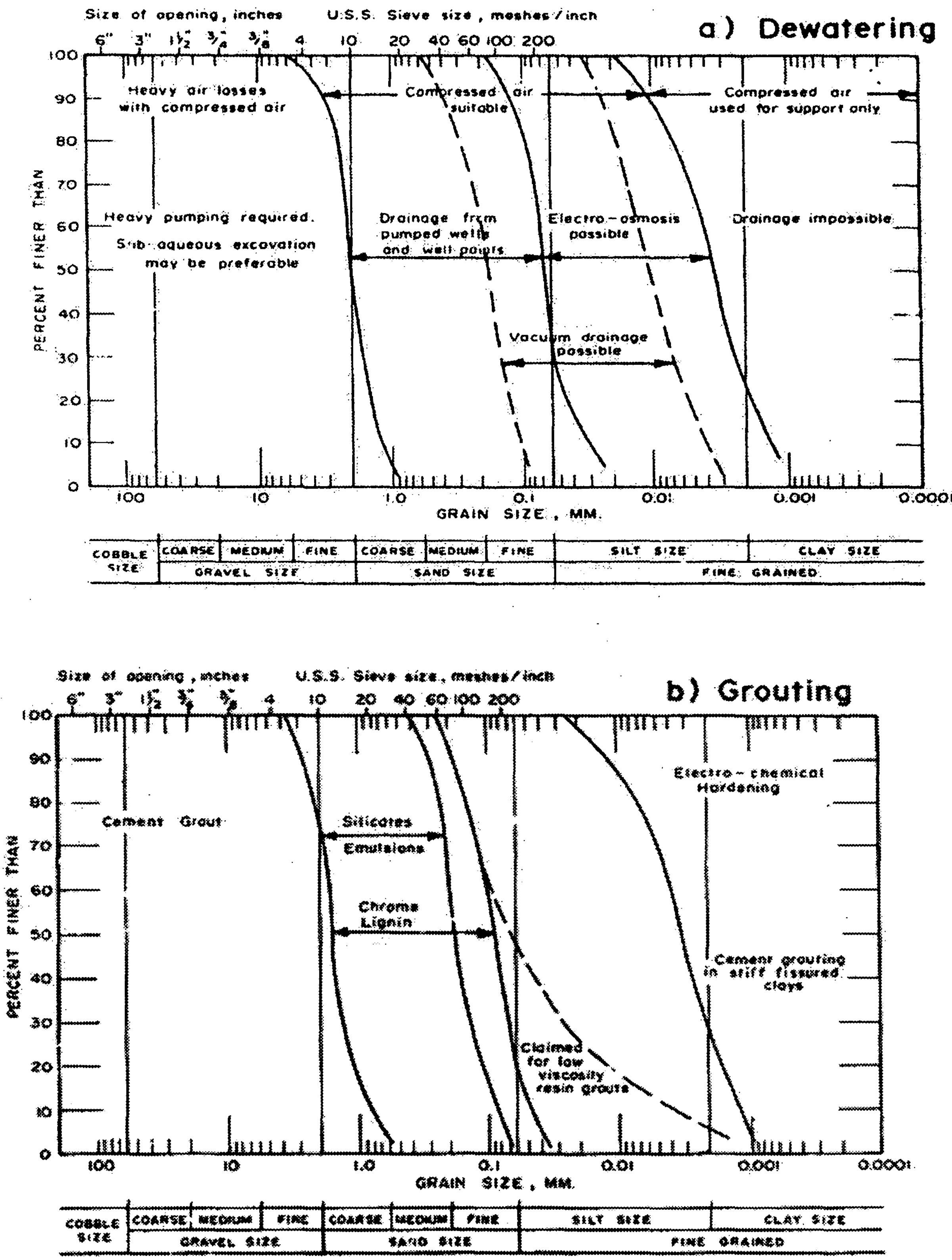


Figure 3.2 Particle size distribution and dewatering and grouting [35 and 36]

Table 3.23 Scale of groundwater flow

	The scale
Groundwater inflow / 10m of tunnel length	< 10 l/min
	10-25 l/min
	25-125 l/min
	> 125 l/min

3.7.3 Tunnel depth (groundwater control methods matrix)

The depth of the tunnel plays a role in selecting the method of groundwater control. The US Army report [116] stated that dewatering usually cannot control deep groundwater, however grouting or freezing can be tried.

Tunnel depth scale used in groundwater matrix (see table 3.22) is as follows:

- Less than 15m
- 15m – 30m
- 30m – 50m
- Over than 50m

3.7.4 Tunnel position (groundwater control methods matrix)

Sometimes tunnel position leads to select the groundwater control method. Using pumps for dewatering is not preferred in case of tunnels under water bodies. Pontoons that will carry these pumps will be obstacle for navigation.

The scale which is used in groundwater control matrix checks two positions of the tunnel which are:

- Tunnel under urban areas

- Tunnels under water bodies

3.7.5 Working length of the tunnel

The required length of the tunnel that needs to be kept dry is a factor in selecting the groundwater control method. Isaksson and Lindblad [55] as well as Sturk [105] stated that the means of advance rates, from projects using conventional methods, are ranging between 26 m/month to 200m/month. The advance rates means, in TBM projects stated by Gehring and Kogler [33] and Aebersold [2], are ranging between 2m/day to 33m/day. The length that needs to be kept dry is related to the advance rate. Efficiencies of the groundwater control methods are evaluated with regard to the required tunnel length that should be kept dry daily. The lengths that used as a scale in the groundwater control methods matrix (table 3.22) cover the faster advance rates because it is more critical. This scale (m/day) is:

- Less than 4m
- 4m – 8m
- 8m – 15m
- 15m – 25m
- Over 25m

3.7.6 Health and safety (groundwater control methods matrix)

Liebsch [66] stated that the compressed air method for groundwater control has disadvantages in that it has a greater risk for the personnel such as compressed-air diseases, greater risk of fire and blow-out.

The groundwater control method matrix intends to relate the efficiency degrees of groundwater control methods for two parameters, shown in table 3.24, related to health and safety factor.

Table 3.24 Health and safety factor scale

Health and safety factor	Scale
	Good health environment
	Low accidents

3.7.7 Environmental conditions (groundwater control methods matrix)

The "Environmental conditions" factor concerns with the quality of groundwater and its regime. It concerns also with the effect on the buildings near to the tunnel project. Using the "Grouting" as a groundwater control method can affect the quality of the groundwater, where using chemicals in grouting may influence the groundwater. These chemicals may be carried by groundwater to near wells that are used for agriculture.

Lessens the settlement of buildings and little impact on groundwater regime are two advantages of compressed air method as proposed by Liebsch [66]. But if compressed air pressure is high it can result in damages in the surrounding buildings.

Dewatering using pumps leads to lowering groundwater level and settlement may happen to the existing buildings. Dewatering system will also lower the groundwater level in the near wells that may affect the environment and habitants' activities.

Selecting groundwater control method with less effect on the buildings and environment is the target of this factor. The scale of this factor is shown below (see also table 3.22):

- Minimum bad effect on buildings

- Less contamination of groundwater
- Minimum effect on groundwater regime

3.8 Non-technical factors *(cost and time)*

The main two non-technical factors included in the matrices are cost and time. When developing the non-technical factors matrices, it was taken into consideration that the cost and time of construction methods depend on the technical factors of the project. Cost and time are very important factors and they can be the main factors for taking a decision during selecting the method of construction.

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 following sections describe the non-technical factors for the *"Basic tunnelling methods"* and methods of the tunnelling activities.

3.8.1 The *"Basic tunnelling"* and excavation methods

Cost is divided into running and initial cost for the *"Basic tunnelling"* and excavation methods (see table 3.25).

Time is also divided into rate of advance per week and mobilization time (see table 3.26). There are many factors that determine the advance rate/week;

75m/week was selected as an average advance rate/week to be used in table 3.26.

Both of the running cost and rate of advance/week depend on some technical factors like ground compressive strength and tunnel span. The running cost and rate of advance/week of the methods will be evaluated for the "ground compressive strength" (see tables 3.25 and 3.26).

The "Mechanical method" is considered worthwhile when tunnel length is more than 3km, because the initial cost of the "Mechanical method" is high and using it for tunnel lengths less than 3km makes it not worthwhile. The influence of the tunnel length on the efficiency degree of the *"Basic tunnelling methods"* and excavation methods from the running cost point of view is included in table 3.25.

3.8.2 Mucking methods

For mucking methods the cost factor is divided into *"Running cost"* and *"Initial cost"*. The time factor measures the productivity rate of the mucking methods (see tables 3.27 and 3.28). The "size of the machine", "bucket capacity" and "cycle time" are some factors that control the productivity rate of the machine. $20m^3$/hour is selected as an average production rate for table 3.28.

3.8.3 Transportation methods

Transport distance has an effect on the running cost and it is therefore included in the matrix. Initial cost is also included (see table 3.29).

Time factor is divided into two sub-factors which are *"Transportation time < 5min/km"* and *"Minimum preparation time"* (see table 3.30).

Table 3.25 Comparing between the basic tunnelling methods and excavation methods based on cost

Factors \ Methods			Basic tunnelling methods						Excavation Methods						
				NATM											
			Cut & Cover	Full face	Heading and bench	Multiple drifts	Pilot enlargement	Mechanical method	Excavator / Backhoe / Front shovel	Hand excavation	Drill & Blast	Roadheader	Micro-tunnelling	Shield Machine (Slurry / EPB)	TBM Machine (Open machine)
Running Cost / 1m of tunnel length	Ground Strength	Less than 0.4 MPa													
		0.4 - 1.25 MPa													
		1.25 – 5.00 MPa													
		5.00 – 12.5 MPa													
		12.50 – 50 MPa													
		50 – 100 MPa													
		100 – 200 MPa													
		Over 200 MPa													
	Tunnel length less than 3km														
	Tunnel length more than 3km														
Initial Cost															

Table 3.26 Comparing between the basic tunnelling methods and excavation methods based on time

Factors \ Methods			Basic tunnelling methods						Excavation Methods						
				NATM											
			Cut & Cover	Full face	Heading and bench	Multiple drift	Pilot enlargement	Mechanical method	Excavator / Backhoe / Front shovel	Hand excavation	Drill & Blast	Roadheader	Micro-tunnelling	Shield Machine (Slurry / EPB)	TBM Machine (Open machine)
Advance rate = 75m / week	Ground Strength	Less than 0.4 MPa													
		0.4 - 1.25 MPa													
		1.25 – 5.00 MPa													
		5.00 – 12.5 MPa													
		12.50 – 50 MPa													
		50 – 100 MPa													
		100 – 200 MPa													
		Over 200 MPa													
Minimum preparation & mobilization Time															

Table 3.27 Comparing between mucking methods based on cost

Mucking Methods / Factors	Rubber wheel loader	Tracked loader
Running cost		
Initial cost		

Table 3.28 Comparing between mucking methods based on time

Mucking Methods / Factors	Rubber wheel loader	Tracked loader
Production rate = $20m^3$ / hour		

Table 3.29 Comparing between transportation methods based on cost

Transportation Methods / Factors			Rubber wheel truck	Rail - Locomotive type			Conveyors
				Diesel-mechanical locomotive	Diesel-electric locomotive	High voltage locomotive	
Runneing Cost	Transportation distance	Less than 0.5 km					
		0.5 km – 1 km					
		1km – 3km					
		Over 3km					
Initial Cost							

Table 3.30 Comparing between transportation methods based on time

Transportation Methods / Factors	Rubber wheel truck	Rail - Locomotive type			Conveyors
		Diesel-mechanical locomotive	Diesel-electric locomotive	High voltage locomotive	
Transportation time < 5min/km					
Minimum preparation & Mobilization Time					

3.8.4 Support methods

The cost factor in the support matrix measures the efficiency degree of support methods that will give less cost per 1m length of the tunnel compared to each other (table 3.31). For the time factor, support methods that have higher productivity will get higher efficiency degrees (table 3.32). Production rate of 75m/week is used in table 3.32.

3.8.5 Lining methods

The efficiency degrees of lining methods for cost and time factors are included in the matrices (tables 3.33 and 3.34). 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.

3.8.6 Groundwater control methods

The time factor for groundwater control methods measures efficiency degree of the methods with regard to the minimum preparations and mobilization time required for each method compared to the other methods (table 3.35). Cost factor has two sub-factors, which are *"Running cost"* and *"Initial cost"*. *"Running cost"* is related to rate of groundwater flow (table 3.36); efficiencies of groundwater control methods will be evaluated based on how to control water with different rate of flow along with lower cost.

Table 3.31 Comparing between support methods based on cost

Support Methods / Factors	Side wall & Crown support					Face support					For cut & cover		
	Rock bolts	Dowels	Steel arch	Shotcrete	Precast concrete segments	Forepoling	Pipe umbrella	Doorframe slab	Earth wedge	Shotcrete	Diaphragm wall	Sheet pile	Bored pile
Cost / 1m length of tunnel													

Table 3.32 Comparing between support methods based on time

Support Methods / Factors	Side wall & Crown support					Face support					For cut & cover		
	Rock bolts	Dowels	Steel arch	Shotcrete	Precast concrete segments	Forepoling	Pipe umbrella	Doorframe slab	Earth wedge	Shotcrete	Diaphragm wall	Sheet pile	Bored pile
Production rate = 75m/week													

Table 3.33 Comparing between lining methods based on cost

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 3.34 Comparing between lining methods based on time

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 3.35 Comparing between groundwater control methods based on time

Groundwater control methods / Factors	Dewatering	Slurry wall	Compressed air	Freezing	Chemical & cement grouting	Jet grouting
Minimum preparation & mobilization time						

Table 3.36 Comparing between groundwater control methods based on cost

Groundwater control methods / Factors			Dewatering	Slurry wall	Compressed air	Freezing	Chemical & cement grouting	Jet grouting
Running Cost / hour	Groundwater inflow / 10m tunnel length	< 10 L/min						
		10-25 L/min						
		25-125 L/min						
		> 125 L/min						
Initial Cost								

4 Proposed model for determining the efficient tunnelling systems

4.1 Introduction

This chapter represents a proposed model which was developed, first (phase I) to calculate and rank efficiency percentages of construction methods for both of the *"Basic tunnelling methods"* and the tunnelling activities, and then (phase II) to determine the alternative tunnelling systems for tunnel project.

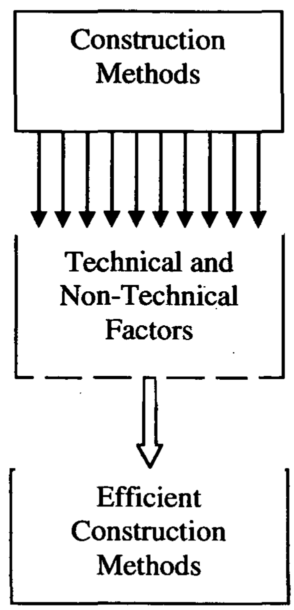


Figure 4.1 The main idea of the proposed model

The matrices which were described in chapter 3 are the basis of the proposed model. Figure 4.1 shows the main idea of the model where the first box represents construction methods of a tunnelling activity which will be checked for their controlling factors in the second box. When a method has an accumulated efficiency percentage for all controlling factors higher than zero, the method passes through the second box (controlling factors) and it will be collected in the third box amongst the efficient construction methods for that activity. This process is applied separated for each construction method of the

Phase I of the model
Calculation of efficiency percentages of construction methods for the basic tunnelling methods and for tunnelling activities

Phase II of the model
Finding out alternative tunnelling systems

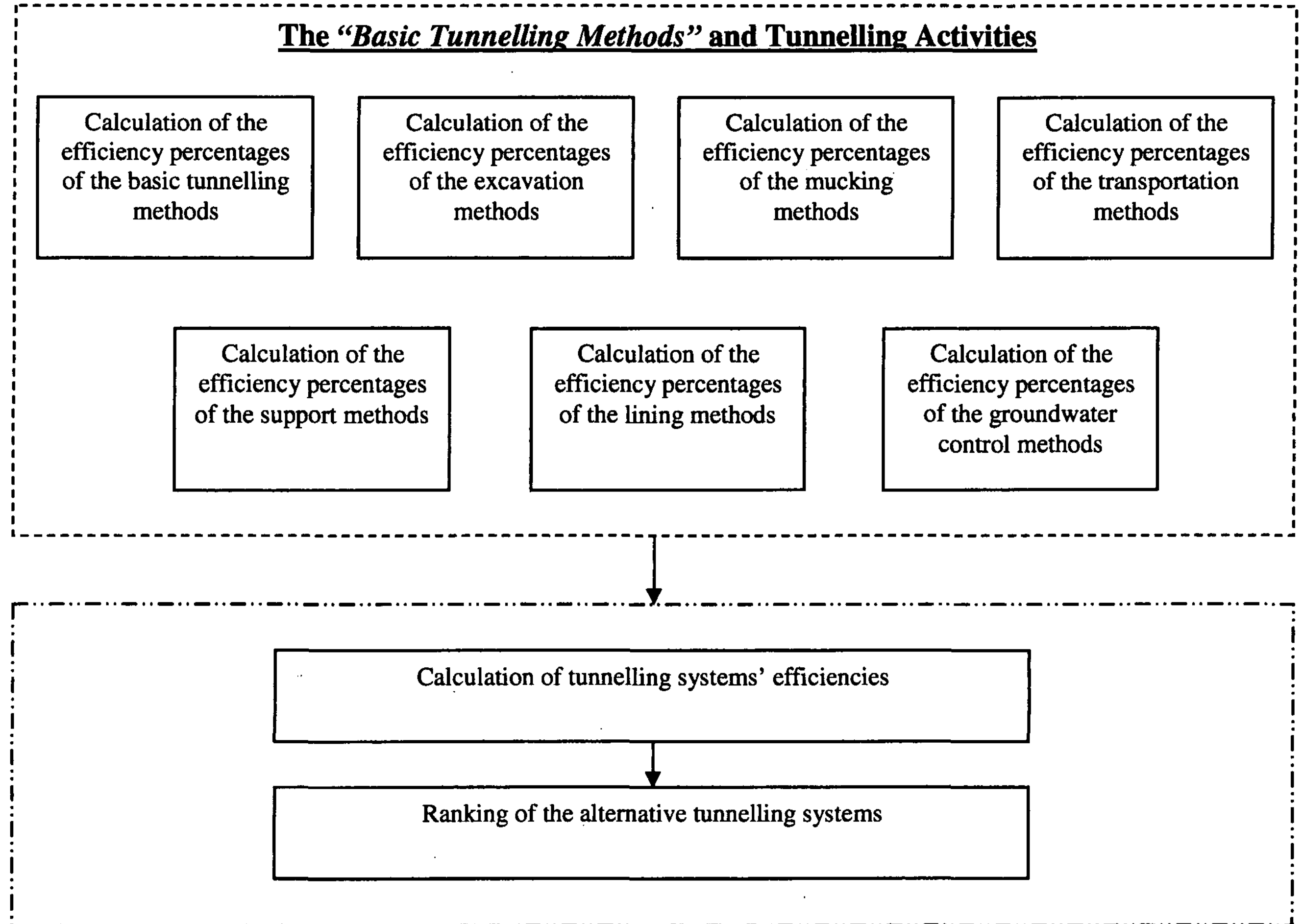


Figure 4.2 Model calculation phases

"Basic tunnelling methods" and the tunnelling activities in the first phase of the model (see figure 4.2; there are no connections between the methods of the different activities in Phase "I" of the model).

In the second phase, the model searches for the possible matches between methods of different activities to obtain harmonized alternative tunnelling systems, where methods of the system can work efficiently together. The model is designed to be simple and flexible in getting data from the user. Output of the model is also easy and clear.

4.2 Calculation of the efficiency percentages of the construction methods (Phase I)

In this phase, the model deals with the *"Basic tunnelling methods"* and each tunnelling activity as a separate case therefore, calculation procedures which will be described in this section will be applied independently for construction methods of each tunnelling activity without any link to the construction methods of the other tunnelling activities. The calculation steps of "Phase I" are shown in figure 4.3.

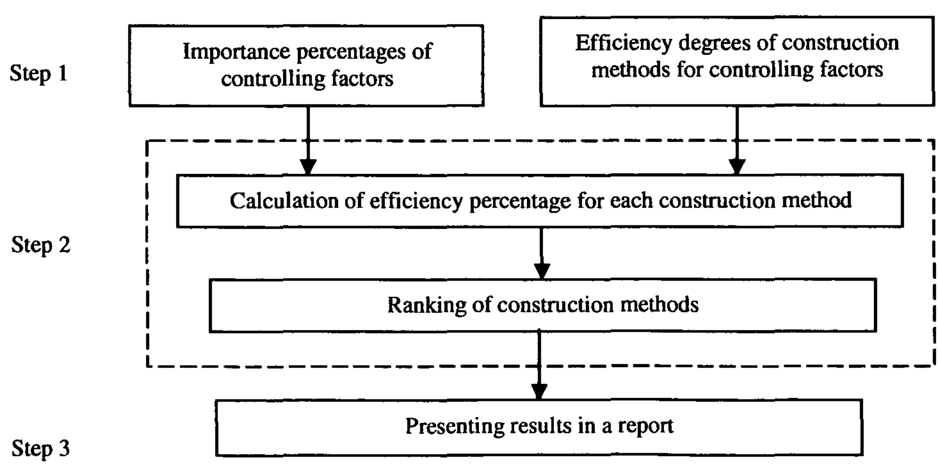


Figure 4.3 Calculation steps for construction methods efficiencies

The efficiency percentage (EP) of a construction 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"* (see step1 of figure 4.3), these two factors will be explained in sections 4.2.1 and 4.2.2 respectively.

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 4.1 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 number of controlling factors of construction method "A" (see figure 4.4). 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 4.2 illustrates the second step of the calculations. Example 1 shows an application of the calculation steps.

$$W_{Ai} = ED_{Ai} * \frac{IP_i}{100} \qquad (4.1)$$

$$EP_A = \frac{\sum_{i=1}^{n} W_{Ai}}{T} * 100 \qquad (4.2)$$

Where:

"A" = a construction method such as *"NATM-Full face"*, *"Shotcrete"*, or *"Dewatering"* etc. (see construction methods which are mentioned in tables of appendix "A")

W_{Ai} = the weighted efficiency of construction method "A" for controlling factor "i"

ED_{Ai} = efficiency degree of 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" (it will be explained in section 4.2.1)

EP_A = efficiency percentage of construction method "A"

i = controlling factors of method "A" (see table 3.1)

n = number of controlling factors for method "A"

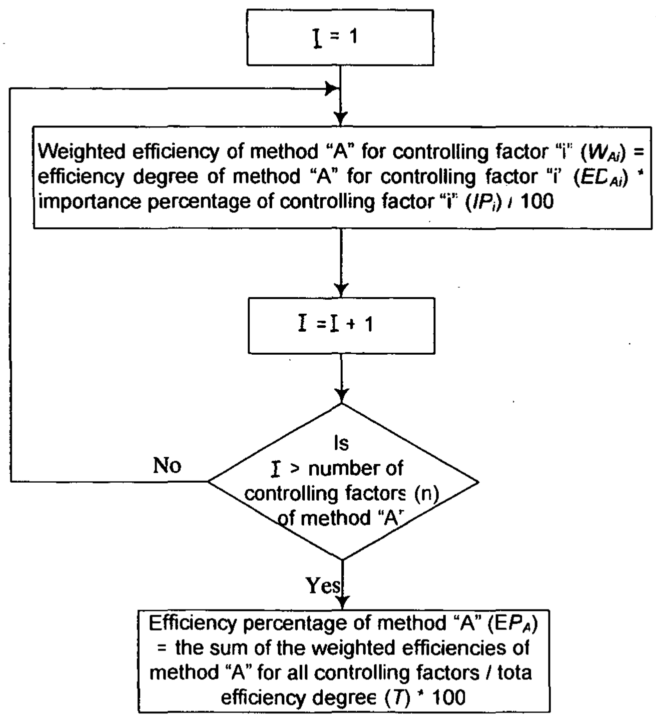


Figure 4.4 Calculations of methods' efficiency percentages

Example 1

If "A" and "B" are two construction methods and they have the EDs shown in table 4.1 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.

Table 4.1 Efficiency degrees (EDs) of methods "A" and "B" for factors "X" and "Y"

Methods / Factors	A	B
X	3	2
Y	2	4

Calculation of the weighted efficiency of method "A" for controlling factor "X" is as follows (application of equation 4.1):

- $ED_{AX} = 3$ (this value is shown in table 4.1), 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 4.1), 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 4.2).

The EP of method "A" = $\frac{2.7}{4} * 100 = 67.5\%$, where "4" is the maximum efficiency degree (application of equation 4.2).

Table 4.2 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

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".

4.2.1 Efficiency degrees (EDs) of construction methods

The matrices that were derived in chapter 3 were sent to tunnel experts working for construction companies, clients and designers all over the world. Interviews with some experts also took place (see table 4.3).

Tunnel experts of these organizations were asked to fill out the matrices by giving their evaluations of the EDs of the construction methods for the controlling factors using the scales shown in tables 4.4, 4.5 and 4.6. The scales range from 1 (the worst) to 4 (the best). According to the scale in table 4.4, 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. "4" is the maximum efficiency degree used in the model as shown in tables 4.4, 4.5 and 4.6.

Table 4.3 Evaluation of organizations' responses for the matrices

Matrices were sent to:	35 construction companies, 28 designers and 12 clients
Matrices were filled out and returned back by:	4 construction companies, 2 designers and 2 clients
Percentage of response:	11.43% of construction companies, 7.14% of designers and 16.67% of clients

Table 4.4 Scale indications for technical factors

Scale degree	Description of the scale
4	Construction method has a very good efficiency degree for the controlling factor
3	Construction method has a good efficiency degree for the controlling factor
2	Construction method has a sufficient efficiency degree for the controlling factor
1	Construction method has an insufficient efficiency degree for the controlling factor

Table 4.5 Scale indications for cost factors

Scale degree	Description of the scale
4	Construction method is very good economically(1)
3	Construction method is good economically
2	Construction method is sufficient economically
1	Construction method is not sufficient economically

[1] The term "economically" means that the method has a low capital cost or running costs compared to the other methods.

Table 4.6 Scale indications for time factors

Scale degree	Description of the scale
4	Construction method needs very short time (high advancement rate)
3	Construction method needs short time (good advancement rate)
2	Construction method needs long time (low advancement rate)
1	Construction method needs very long time (very low advancement rate)

The experts from four construction companies, two designers and two clients representing different countries filled out the matrices and returned them (see table 4.3). The ED values of matrices that came back from some companies represent the opinion of a group of experts in these companies.

After collecting the data, average matrices were developed based on the experts' evaluations and their notes (see tables of appendix A). The ED values in the matrices of appendix "A" are the average value of the experts' EDs. As an example, the ED of the *"Conveyors"* from a health and safety point of view is "3.13" (see table A.1.3, appendix "A"), this value is the average of the experts' EDs which are shown in table 4.7.

Table 4.7 Efficiency degrees (EDs) given by the experts for the *"Conveyors"* for the "health and safety" controlling factor

Expert	A	B	C	D	E	F	G	H
Efficiency degree (ED)	2	4	4	3	2	3	4	3

The average ED of the *"Conveyors"* for health and safety controlling factor = (2 + 4 + 4 + 3 + 2 + 3 + 4 + 3) / 8 = 3.13

The above mentioned calculations were applied for all methods to determine their average EDs for all controlling factors. There are some exceptions: When all experts except only one gave the same ED value for a construction method for a controlling factor, no average was calculated in this case and the ED assigned by the majority of experts was used in the average matrices while the exceptional evaluation was neglected.

The ED values of the "NATM-Full face" construction method for the "ground compressive strength" controlling factor depend not only on the strength value but also on tunnel cross sectional-area. Experts evaluated the "NATM-Full face" method based on the cases shown in table 4.8. After collecting the experts' evaluations, the average values of the EDs were calculated and the results are show in figure 4.5 (see also table A.1.1 of appendix "A").

Table 4.8 Form used to collect tunnel experts' evaluation of "Full face" method

Factors	Method	The ED values of "NATM-Full face"
Tunnel cross sectional-area ≤ $2m^2$	Ground compressive strength ≤ 0.4MPa	
	Ground compressive strength (0.4 – 1.25MPa)	
	Ground compressive strength (1.25 – 5.00MPa)	
Tunnel cross sectional-area ($2.5m^2$ – $10m^2$)	Ground compressive strength ≤ 0.4MPa	
	Ground compressive strength (0.4 – 1.25MPa)	
	Ground compressive strength (1.25 – 5.00MPa)	
Tunnel cross sectional-area > $10m^2$	Ground compressive strength ≤ 0.4MPa	
	Ground compressive strength (0.4 – 1.25MPa)	
	Ground compressive strength (1.25 – 5.00MPa)	

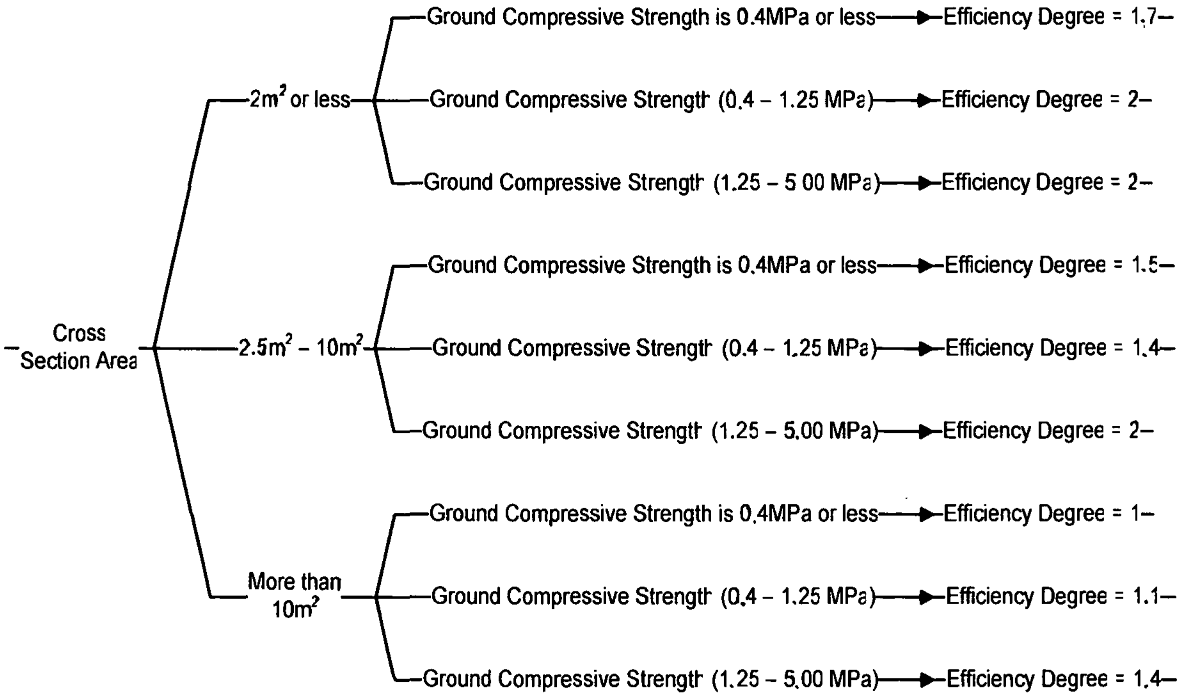


Figure 4.5 Efficiency degrees of the "NATM-Full Face" method of construction for different ground compressive strengths and tunnel cross section areas

"Hand excavation" is another case where the efficiency of the method with regard to the cost depends simultaneously on two factors which are tunnel length and the level of labour cost in the country of the project. The form in table 4.9 was designed to collect the experts' evaluations of "Hand excavation" for tunnel length and labour cost. The average EDs of experts' evaluations are shown in figure 4.6 (see also table A.2.1 of appendix "A").

In table A.1.5 of appendix "A", the "Pipe in tunnel" lining method has two EDs for the controlling factor "Tunnel shape – circular or mouth profiles". The EDs are "4" and "1.85". This means that the "Pipe in tunnel" method has ED equal to "4" when tunnel profile is circular and when the profile is mouth profile the ED will be "1.85" (these values are the average values of experts' evaluations).

Table 4.9 Form used to collect tunnel experts' evaluation of "Hand excavation" method

Factors	Method	The ED values of "Hand excavation"
Low labour cost	Tunnel length ≤ 3 kilometres	
	Tunnel length > 3 kilometres	
High labour cost	Tunnel length ≤ 3 kilometres	
	Tunnel length > 3 kilometres	

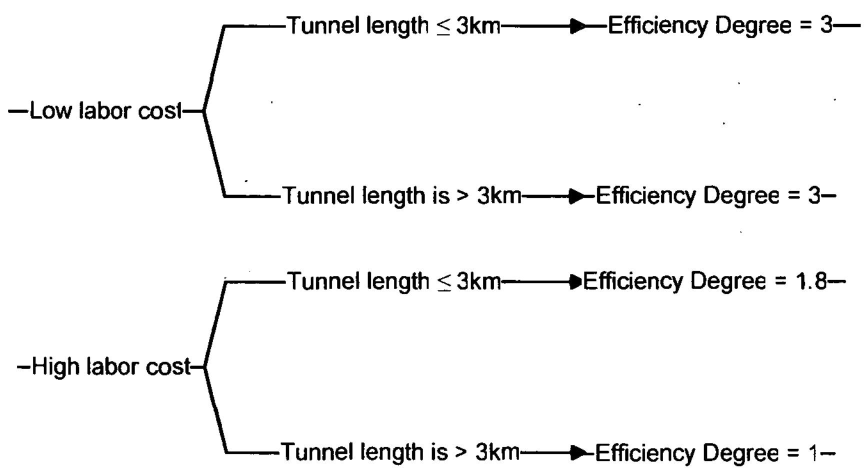


Figure 4.6 Efficiency degree of "Hand Excavation" related to tunnel length & labour cost

Three controlling factors are included in the model as non-technical factors but they are not shown in the matrices of appendix "A" because they are related directly to the user of the model. These factors, which are *"Technology availability"*, *"Experience"* and *"Others"*, cover the factors which are not included in the matrices. When the user of the model thinks that these factors have an influence on the selection decision of the construction methods, he/she should determine the ED values of the methods for these factors. The following table 4.10 is used to collect the EDs from the user. The factor "Others" in table 4.10 covers the conditions of the project which the user of the model sees them as important factors for the selection decision of construction methods and they are not covered by the controlling factors, such as political conditions.

Table 4.10a ED values of the *"Basic tunnelling"* and excavation methods

Methods / Factors	Basic tunnelling methods						Excavation Methods						
		NATM											
	Cut & Cover	Full face	Heading and bench	Multiple drift	Pilot enlargement	Mechanical method	Excavator / Backhoe / Front shovel	Hand excavation	Drill & Blast	Roadheader	Micro-tunnelling	Shield Machine (Slurry / EPB)	TBM Machine (Open machine)
Technology availability													
Experience													
Others													

Table 4.10b ED values of mucking methods

Mucking methods / Factors	Rubber wheel loader	Tracked loader
Others		

Table 4.10c ED values of transportation methods

Transportation methods / Factors	Rubber wheel truck	Rail - Locomotive type			Conveyors
		Diesel – mechanical locomotive	Diesel – electric locomotive	High voltage locomotive	
Others					

Table 4.10d ED values of support methods

Support methods / Factors	Side wall & Crown support					Face support					Cut & cover		
	Rock bolts	Dowels	Steel arch	Shotcrete	Precast concrete segments	Forepoling	Pipe umbrella	Doorframe slab	Earth wedge	Shotcrete	Diaphragm wall	Sheet pile	Bored pile
Others													

Table 4.10e ED values of lining methods

methods / Factors	Precast concrete segments	Cast segments (steel/iron)	Cast-in-place concrete	Pipe in tunnel	Shotcrete lining	No Final lining
Others						

Table 4.10f ED values of groundwater control methods

methods / Factors	Dewatering	Slurry wall	Compressed air	Freezing	Chemical & cement grouting	Jet grouting
Others						

The previous explanations show how the ED values of appendix "A" were calculated. The model will use only the EDs which are related to the conditions of the project. 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 forms of table 4.11 are used to collect the project technical data for the *"Basic tunnelling methods"* and the tunnelling activities from the user.

When the user selects the values which represent the project conditions, the model will use the EDs from the tables of appendix "A", which correspond to the project conditions, for calculations.

Table 4.11a General project data

Project name	
Client	
Tunnel height	
Groundwater level	
Tunnel invert level	
Select only one of these □ ground is rock □ ground is soil	
Select only one of these □ labour cost is high □ labour cost is low	

Table 4.11b Technical data of the *"Basic tunnelling"* and excavation methods

Select one option for each factor *Ground compressive strength* □ 0.4Mpa or less □ 0.50 – 1.25MPa □ 1.50 – 5.00MPa □ 5.50 – 12.5MPa □ 13.0 – 50.0MPa □ 50.5 – 100MPa □ 101 – 200MPa □ over 200MPa
Ground gases □ there are harmful gases □ no harmful gases
Tunnel cross sectional area □ $2m^2$ or less □ $2.5 - 10m^2$ □ $11 - 30m^2$ □ $31 - 100m^2$ □ over $100m^2$
Regularity of cross section □ fixed cross section □ variable cross section
Tunnel cross section profile □ circular or mouth □ oval or horseshoe □ other profiles
Tunnel length □ 3km or less □ more than 3km
Tunnel depth □ 30m or less □ more than 30m
Tunnel horizontal alignment □ horizontal curve radius < 40m □ 40m < horizontal curve radius < 150m □ horizontal curve radius > 150m
Tunnel vertical alignment □ vertical slope ≤ 3% □ vertical slope > 3%
Construction site area □ big site area □ limited site area
Tunnel position □ no utilities in the tunnel path □ there are utilities in the tunnel path

Table 4.11c Technical data of transportation methods

Select one option for each factor *Ground bearing capacity* □ 0.05MPa or less □ 0.05 – 0.10MPa □ 0.10 – 0.20MPa □ over 0.20MPa
Tunnel span □ 2m or less □ 3 – 4m □ 5 – 8m □ over 8m
Tunnel vertical slope □ 3% or less □ 4% - 10% □ 11% - 20% □ 21% - 25% □ over 25%
Transportation distance □ 0.5km or less □ 0.6 – 1.0km □ 1.5 – 3km □ over 3km
Transportation speed □ high □ medium □ low
Water content □ almost dry muck □ high water content
Particle size □ 45cm or less □ more than 45cm

Table 4.11d Technical data of mucking methods

Select one option for each factor
Ground bearing capacity □ 0.05MPa or less □ 0.05 – 0.10MPa □ 0.10 – 0.20MPa □ over 0.20MPa
Muck particle size □ very big (particle size > 45cm) □ big (7cm < particle size < 45cm) □ medium (2cm < particle size < 7cm) □ small (particle size < 2cm)
Tunnel span □ 2m or less □ 2.5 – 4m □ 4.5 – 8m □ over 8m

Table 4.11f Technical data of lining methods

Select one option for each factor
Q-value □ 101 – 1000 □ 41 – 100 □ 11 - 40 □ 5 - 10 □ 2 - 4 □ 0.2 - 1 □ 0.02 – 0.1 □ 0.001 – 0.01 □ ground is soil
Groundwater flow □ 10 l/min or less □ 11 – 25 l/min □ 26 – 125 l/min □ over 125 l/min
Select one or more of the following minerals □ orthoclase □ plagioclase □ quartz □ clay minerals □ mica (muscovite) □ mica (biotite) □ chlorite □ calcite □ carbonates □ pyrite □ augite □ olivine
Tunnel function □ water conveyance □ road □ railway □ storage □ defense
Tunnel cross section profile □ circular □ circular with flatted invert □ horseshoe □ oval □ nordic □ basket handle □ rectangular

Table 4.11e Technical data of support methods

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

Table 4.11g Technical data of groundwater control methods

Select one option for each factor
Groundwater flow □ 10 l/min or less □ 11 – 25 l/min □ 26 – 125 l/min □ over 125 l/min
Working length/day (m/day) □ 4m or less □ 5 – 8m □ 9 – 15m □ 16 – 25m □ over 25m
Tunnel depth □ 15m or less □ 16 – 30m □ 31 – 50m □ over 50m
Ground conditions □ GM (gravel – sand – silt mixtures) □ GC (gravel – sand – clay mixtures) □ SM (silty sand) □ SC (clayey sand) □ ML (inorganic silts) □ CL (inorganic clays) □ OL (organic silts) □ OH (organic clays) □ ground is rock
Tunnel position □ under urban area □ under water bodies

Table 4.11 shows differences in the scales used for the same controlling factors of different tunnelling activities, for example the scale used for tunnel slope in table 4.11b is different from the scale used for tunnel slope in table 4.11c. Scales of the controlling factors, as explained in chapter 3, were selected to make clear differentiation between efficiencies of construction methods. Scale ranges which make this differentiation depend on the methods of construction that can be used for the tunnelling activities, and because these construction methods are different from a tunnelling activity to another activity, the scales of controlling factors are also different. For example in table 4.11b the vertical slope 3% is sufficient to make differentiation between efficiencies of excavation methods but it is not enough to make the differentiation between efficiencies of the transportation methods because of that the scale used for transportation methods is wider. As explained before, the model deals with tunnelling activities independently in the first phase, the differences in the scales of controlling factors make the results of calculations for each tunnelling activity more accurate.

4.2.2 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 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 3.1).

The criterion affecting the magnitude of the controlling factor is "how much does the factor control the selection decision of tunnel construction 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.

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 4.3 to calculate the IPs of the controlling factors using the ID values which are assigned by the user.

$$IP_i = \frac{ID_i}{\sum_{i=1}^{n} ID_i} * 100 \qquad (4.3)$$

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

The user will assign the IDs of controlling factors for the *"Basic tunnelling methods"* as well as tunnelling activities using the forms shown in tables 4.12, 4.13, 4.14, 4.15, 4.16 and 4.17.

Some controlling factors have sub-factors. For example "ground conditions", in table 4.12, has three sub-factors which are "ground compressive strength", "groundwater level" and "existence of harmful gases". The model will assign the IDs of the controlling factors to their sub-factors. As shown in table 4.12, the user will assign the IDs for 18 factors (see the first column of table 4.12, the assigned values by the user are "X1 – X18") but some of these ID values will be repeated for the sub-factors (see the last column in table 4.12), the assigned values by the user to the "Ground conditions" factor (X1) will be assigned by the model to the sub-factors "ground compressive strength", "groundwater level" and "existence of harmful gases", each sub-factor will have an ID equal to (X1), therefore, the total number of values in the last column of table 4.12 is 27 values.

Table 4.12 Controlling factors and their sub-factors for the *"Basic tunnelling"* and excavation methods

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	Ground compressive strength	X1
		Groundwater level	X1
		Existence of harmful gases	X1
X2	Tunnel depth	---------	X2
X3	Tunnel cross section	Cross section is fixed or variable	X3
		Cross section profile	X3
		Cross section area	X3
X4	Tunnel alignment	Horizontal alignment	X4
		Vertical alignment	X4
X5	Health and safety	Good health environment	X5
		Few accidents	X5
X6	Low noise for workers & public	---------	X6
X7	Low vibration & effect on buildings	---------	X7
X8	Good for archaeological areas	---------	X8
X9	Low effect on traffic	---------	X9
X10	Low dust particles in air	---------	X10
X11	Low landscape effect	---------	X11
X12	Limited site area for start up	---------	X12
X13	Utilities in tunnel path	---------	X13
X14	Cost	Initial cost	X14
		Running cost relative to ground strength	X14
		Running cost relative to tunnel length	X14
X15	Time	Preparation time	X15
		Working time	X15
X16	Technology availability	---------	X16
X17	Experience	---------	X17
X18	Others	---------	X18
Total number of ID values			n = 27 values

Table 4.13 Controlling factors and their sub-factors for mucking methods

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 bearing capacity	---------	X1
X2	Muck particle size	---------	X2
X3	Tunnel span	---------	X3
X4	Cost	Running cost	X4
		Initial cost	X4
X5	Time	---------	X5
X6	Others	---------	X6
Total number of ID values			n = 7 values

Table 4.14 Controlling factors and their sub-factors for transportation methods

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 bearing capacity	---------	X1
X2	Transportation speed	---------	X2
X3	Tunnel vertical slope	---------	X3
X4	Tunnel span	---------	X4
X5	Muck particle size	---------	X5
X6	Muck water content	---------	X6
X7	Health and safety	---------	X7
X8	Cost	Running cost related to transportation distance	X8
		Initial cost	X8
X9	Time	Transportation time	X9
		Preparation time	X9
X10	Others	---------	X10
Total number of ID values			n = 12 values

Table 4.15 Controlling factors and their sub-factors for support methods

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	Cost	---------	X5
X6	Time	---------	X6
X7	Others	---------	X7
Total number of ID values			n = 12 values

Table 4.16 Controlling factors and their sub-factors for lining methods

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	Q – Value	---------	X1
X2	Reaction with ground minerals	---------	X2
X3	Tunnel shape	---------	X3
X4	Tunnel function	---------	X4
X5	Rate of groundwater flow	---------	X5
X6	Cost	---------	X6
X7	Time	---------	X7
X8	Others	---------	X8
Total number of ID values			n = 8 values

Table 4.17 Controlling factors and their sub-factors of groundwater control methods

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	Type of ground	X1
		Groundwater level	X1
X2	Rate of groundwater flow	---------	X2
X3	Tunnel depth	---------	X3
X4	Tunnel position	---------	X4
X5	Rate of tunnel advancement	---------	X5
X6	Health and safety	Good health environment	X6
		Few accidents	X6
X7	Effect on buildings	---------	X7
X8	Groundwater contamination	---------	X8
X9	Effect on groundwater regime	---------	X9
X10	Cost	Running cost	X10
		Initial cost	X10
X11	Time	---------	X11
X12	Others	---------	X12
Total number of ID values			n = 15 values

The total number of values in the last columns of tables 4.12, 4.13, 4.14, 4.15, 4.16 and 4.17 (zero values are not counted) will be the "n" in equation 4.3. For example, if "X1" in table 4.17 is zero (the value of "X1" is determined by the user), this means that "ground conditions" factor is not important, the model assigns a zero values as IDs for the sub-factors of the "ground conditions" factor, the two sub-factors of this factor will not be counted (because they will have ID values equal to zero) and the total number of values in the last column of table 4.17 will be 13 instead of 15 (assuming that the other factors have non-zero IDs).

Table 4.15 shows the controlling factors of support methods. If "X1" is not zero ("X1" is determined by the model user), the model will assign the value of "X1" to the sub-factors which are "RMR – value" and "failure reasons", i.e. the ID of the "RMR-value" will be "X1" and each failure reason selected by the model user will have ID equal to "X1". The value of "n" will depend on how many failure reasons the user will select for his project, i.e. when he/she selects all mentioned failure reasons, "n" will equal to "12" and if he/she selects only two failure reasons, "n" will be "9" in this case.

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, as explained before in table 4.10. The model will use both of IDs and EDs of these factors which will be determined by the user to calculate their EPs.

If the user does not feed the model with project technical data which are related to a controlling factor, the ID of this factor will be neglected during the calculations of the IPs. For example, if the user gave an ID value for the "tunnel depth" controlling factor in table 4.12 and he/she does not feed the model with a value of the tunnel depth, the ID of the "tunnel depth" will be ignored during calculations of the IPs of the controlling factors in table 4.12.

Example 2: calculation of the IPs

This example and example 3 show how a decision maker selects the most efficient mucking method for his tunnel project. This example and examples 3 show how the model calculates the EPs of the mucking methods and gives recommendations to the decision maker about the ranking of mucking methods according to their efficiency percentages. Example 2 explains how to calculate the IPs of the mucking methods which will be used in example 3 to calculate the EPs of the mucking methods.

Table 4.18 shows the IDs that were assigned by the decision maker (the user of the model) for the controlling factors of the mucking methods (see the first column of table 4.18). The model will assign the IDs of the controlling factors, which were determined by the model user, to their sub-factors (see the last column of table 4.18). In this example, there are only two sub-factors which belong to the controlling factor "cost", therefore the ID of the "cost" factor will be used two times in the calculations, the other ID values of controlling factors will be used only once in calculations because they do not have sub-factors.

Table 4.18 The IDs of the mucking methods controlling 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
4	Ground bearing capacity	---------	4
7	Muck particle size	---------	7
8	Tunnel span	---------	8
10	Cost	Running cost	10
		Initial cost	10
10	Time	---------	10
0	Others	---------	0
Total number of ID values			n = 6 values

The last column in table 4.18 shows that the value of "n" is 6 where the ID of the factor "Others" is zero and it will not be counted among the other values.

To calculate IPs of the controlling factors using their IDs, equation 4.3 will be used as follows:

1- $\sum_{i=1}^{6} ID_i = (4 + 7 + 8 + 10 + 10 + 10) = 49$

2- $IP_{ground\ bearing\ capacity} = (4 / 49) * 100 = 8.16\%$

3- $IP_{muck\ particle\ size} = (7 / 49) * 100 = 14.29\%$

4- $IP_{tunnel\ span} = (8 / 49) * 100 = 16.33\%$

5- $IP_{cost} = (10 / 49) * 100 = 20.41\%$

6- $IP_{time} = (10 / 49) * 100 = 20.41\%$

Example 3: calculation of mucking methods' EPs

The decision maker should feed the model with the technical data about his project to continue calculations and determine the EPs of mucking methods. The technical data will determine which EDs of tables A.1.2, A.2.2 and A.3.2, appendix "A", will be used for the calculations. The decision maker determined the following technical data about his project which are related to the mucking methods:

- ground bearing capacity is over 0.2MPa
- muck particle size is medium
- tunnel span is 6m

According to the technical data of the project, the EDs which are shown in table 4.19 will be used for the calculations. Table 4.19 is divided into 3 sections, the first section is the technical factors, the EDs of these factors are taken from table A.1.2, the EDs of the cost factor, the second section of table 4.19, are taken from table A.2.2 and the EDs of time factor in the third section of table 4.19 are taken from table A.3.2 (see appendix "A").

Using the IP values of the controlling factors which were calculated in example 2 and EDs which are shown in table 4.19 the weighted efficiencies of mucking methods can be calculated by equation 4.1. Table 4.20 shows the calculations of the weighted efficiencies for mucking methods.

Table 4.19 Efficiency degrees of mucking methods for the controlling factors

Controlling factors	Mucking methods' EDs	
	Rubber wheel loader	Tracked loader
Ground bearing capacity is over 0.20 MPa	4	3
Particle size is medium	4	2.5
Tunnel span is between 4m – 8m	3.75	3
Running cost	3	2.67
Initial cost	3.67	2.33
Time	3.67	3.67

Table 4.20 Weighted efficiencies of mucking methods

Controlling factors	Weighted efficiencies of mucking methods	
	Rubber wheel loader	Tracked loader
Ground bearing capacity is over 0.20 MPa	4 * 0.0816 = 0.3264	3 * 0.0816 = 0.2448
Particle size is medium	4 * 0.1429 = 0.5716	2.5 * 0.1429 = 0.35725
Tunnel span is between 4m – 8m	3.75 * 0.1633 = 0.6124	3 * 0.1633 = 0.4899
Running cost	3 * 0.2041 = 0.6123	2.67 * 0.2041 = 0.545
Initial cost	3.67 * 0.2041 = 0.749	2.33 * 0.2041 = 0.4756
Time	3.67 * 0.2041 = 0.749	3.67 * 0.2041 = 0.749
Total weighted efficiencies	3.6207	2.862

By applying equation 4.2 knowing that the maximum efficiency degree is "4", EPs of mucking methods can be calculated as follows:

$EP_{rubber\ wheel\ loader} = (3.6207 / 4) * 100 = 90.5\%$

$EP_{tracked\ loader} = (2.862 / 4) * 100 = 71.5\%$

The model calculations show that "*Rubber wheel loader*" is more efficient than "*Tracked loader*" based on project data in examples 2 and 3.

4.2.3 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. For example if the tunnel depth is more than 30m, the "Cut and cover" method has an ED equal to "1" (see table A.1.1, appendix "A"), which will be considered as a non-efficient method for this 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 (see figure 4.7 and appendix "B-1"). These detailed reports enhance the model because sometimes the user needs a report about only one activity not the whole tunnelling system.

4.3 Alternative tunnelling systems (Phase II)

As shown in figure 4.7, the model produces 8 separate reports after the calculations of the first phase (calculation of EPs of construction methods); these reports show the efficiency percentages and the ranks of construction methods. In the second phase, the model will combine different tunnelling activities to determine the possible alternative tunnelling systems. Table 4.21 shows the layout of the alternative tunnelling systems where each row represents a tunnelling system.

The "Basic tunnelling methods" Methods	EPs
Mechanical method	84.3%
NATM-Heading & bench	82.4%
NATM-Multiple drift	77.2%
NATM-Full face	73.8%
NATM-Pilot enlargement	71.4%
Cut and cover	Excluded

Excavation methods: Methods	EPs
Excavator	90.8%
Shield machine	84.3%
Roadheader	73%
Hand excavation	Excluded
Drill and blast	Excluded
Micro-tunnelling	Excluded
TBM	Excluded

Mucking methods: Methods	EPs
Rubber W loader	92.7%
Tracked loader	67.3%

Transportation methods: Methods	EPs
Conveyors	85%
Rail D-E	84.4%
Rubber W truck	82.7%
Rail D-N	82.6%
Rail truck HV	78.2%

Side wall support methods: Methods	EPs
Shotcrete	83.4%
Steel arch	76.7%
Precast conc seg	76%
Dowels	75.5%
Rock bolts	71.9%
Diaphragm wall	Excluded
Sheet pile	Excluded
Bored piles	Excluded

Face support methods: Methods	EPs
Shotcrete	83.8%
Earth wedge	71.3%
Forepoling	70.9%
Pipe umbrella	Excluded
Doorframe	Excluded

Lining methods: Methods	EPs
Precast conc seg	86.7%
Cast in place conc	81.6%
Cast seg. (steel/iron)	76.9%
Shotcrete	72.7%
Pipe in tunnel	71.9%
No final lining	Excluded

Groundwater control methods: Methods	EPs
Dewatering	89.7%
Slurry wall	78.7%
Compressed air	78%
Chemical grouting	77.5%
Jet grouting	77.5%
Freezing	72.4%

Figure 4.7 Sample reports of Efficiency Percentages (EPs) of different construction methods

Table 4.21 Layout of the alternative tunnelling systems

Basic tunnelling methods	Excavation methods	Mucking methods	Transportation methods	Side wall support methods	Face support methods	Lining methods	Groundwater control methods
1.1	2.1	3.1	4.1	5.1	6.1	7.1	8.1
1.2	2.2	3.2	4.2	5.2	6.2	7.2	8.2
1.3	2.3	3.3	4.3	5.3	6.3	7.3	8.3
1.4	2.4	3.4	4.4	5.4	6.4	7.4	8.4
1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5
1.6	2.6	3.6	4.6	5.6	6.6	7.6	8.6

Calculations of the second phase will find the construction methods which can fill in the cells of table 4.21 to obtain the alternative tunnelling systems (numbers in table 4.21 are cells names which correspond to the columns and rows of the cells).

In each activity matrix of appendix "A" there is a section which connects the methods of the tunnelling activity with the methods of other tunnelling activities. In appendix "A" - table A.1.1, excavation methods are connected to the *"Basic tunnelling methods"*, and table A.1.2 shows the connection between excavation methods and mucking methods (excavation methods which can perform the mucking by itself, like TBMs, are not included). Transportation methods are connected to excavation methods in table A.1.3. The support matrix in table A.1.4 of appendix "A" shows the connection between support methods and both of excavation and the *"Basic tunnelling methods"*. Lining methods are connected to the *"Basic tunnelling methods"*, excavation methods and support methods (see table A.1.5 of appendix "A"). The *"Basic tunnelling methods"* and excavation methods as well as groundwater control methods are connected in table A.1.6 of appendix "A". The connections among tunnelling activities are shown in figure 4.8.

Tunnel experts filled out these sections, which connect methods of different activities together, with numbers which show their opinions about the efficiency degrees of the methods in working together. The scale is the same which is shown in table 4.4. "1" means that the two construction methods cannot work together, "4" is the highest efficiency degree and it means that the two methods can work together efficiently. Numbers in tables of appendix "A" are the average values of the experts' evaluations.

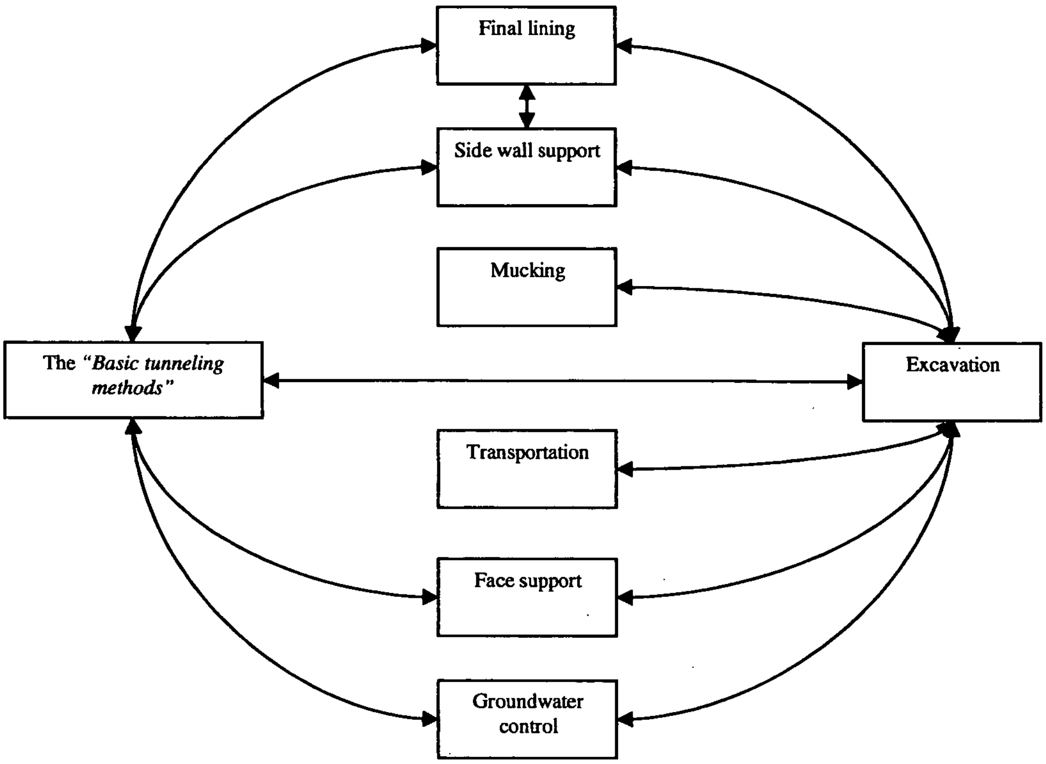


Figure 4.8 Connections among tunnelling activities

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 (see figure 4.9). The efficiency percentage of the combination between methods "A" and "B" of figure 4.9 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.

Calculations of the second phase will follow on according to the steps shown below:

1- The model will search for the possible matches between the efficient[(2)] methods of the *"Basic tunnelling methods"* and excavation methods which resulted from the first phase calculations. This step will enable the model to determine the *"Basic tunnelling methods"* and excavation methods which will fill in the first and second columns of table 4.21.

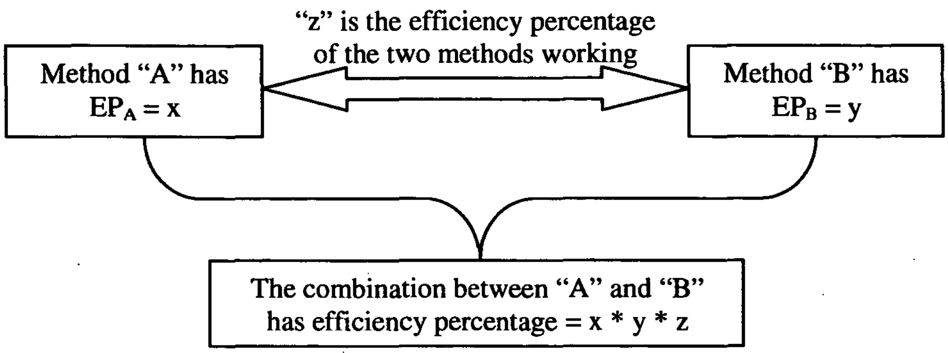


Figure 4.9 How to calculate efficiency percentage of a combination of two methods

2- When excavation method in cell (2.1), which resulted from the previous step, can work with more than one mucking methods which resulted from the first phase, the model will select the mucking method which can work with this excavation method with the best efficiency percentage to put it in cell (3.1). Calculations of this step will be repeated for all excavation methods in the second column of table 4.21 to find mucking methods that will be in the third column.

3- The calculations of step 2 will be applied to transportation methods to find methods which can work efficiently with the excavation methods. From this step, transportation methods in the fourth column of table 4.21 will be determined.

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[2] Efficient methods are the methods resulting from the calculations of the first phase of the model and have EPs higher than zero.

4- Because side wall support methods, lining methods, excavation methods and the *"Basic tunnelling methods"* are all connected together as shown in figure 4.8, the model will find in this step side wall support and lining methods which give the best efficiency percentage when they work together with the *"Basic tunnelling methods"* and excavation methods of each row of table 4.21, i.e. the side wall support method in cell (5.1) and the lining method in cell (7.1) will be selected to give the highest efficiency percentage when they work with the *"Basic tunnelling method"* in cell (1.1) and the excavation method in cell (2.1). The calculations will be repeated to determine the side wall support and lining methods for the other excavation methods and *"Basic tunnelling methods"* in table 4.21. After this step, the methods in columns 1, 2, 3, 4, 5 and 7 of table 4.21 were determined and to complete the tunnelling systems, the face support methods (column 6 of table 4.21) and groundwater control methods (column 8 of table 4.21) should be determined.

5- Face support methods are connected to both of the *"Basic tunnelling methods"* and excavation methods as shown in figure 4.8. The model will select the face support method which gives the highest efficiency percentage when it works together with the *"Basic tunnelling methods"* and excavation methods of each row in table 4.21.

6- The calculations of step 5 will be repeated to find the groundwater control methods which will give the highest efficiency percentages when they work with the *"Basic tunnelling methods"* and excavation methods.

4.3.1 Matching of the *"Basic tunnelling methods"* and excavation methods

In this stage, the model searches for the possible combinations between the *"Basic* *tunnelling methods"* and excavation methods. Only efficient methods which resulted from the calculations of the first phase will be considered for the calculations of this section. The efficiency percentage of each combination depends on the efficiency percentages of the *"Basic tunnelling method"* and excavation method as well as efficiency percentage of the two methods working together. Equation 4.4 will be applied first to calculate efficiency percentage of the methods working together and then equation 4.5 will be used to calculate the combined efficiency percentage.

$$R_{i\,j} = \frac{(D_{i\,j} - 1)}{3} * 100 \qquad (4.4)$$

Where:

i = 1, 2, 3, ..., m (i represents the *"Basic tunnelling methods"*)

j = 1, 2, 3, ..., n (j represents the excavation methods)

m = number of efficient construction methods of the *"Basic tunnelling methods"* which resulted from the first phase

n = number of the efficient excavation methods which resulted from the first phase

D_{ij} = efficiency degree of methods i & j working together (expert evaluation, see table A.1.1 of appendix "A")

R_{ij} = efficiency percentage of methods i & j to work together.

Equation 4.5 will be used to calculate efficiency percentages of the combinations of the *"Basic tunnelling methods"* and excavation methods.

$$F_{i\,j} = E_i * L_j * R_{i\,j} * 100 \qquad (4.5)$$

Where:

$F_{i\,j}$ = efficiency percentage of the combination between methods i & j

E_i = efficiency percentage of the *"Basic tunnelling method"* (i)

L_j = efficiency percentage of the excavation method (j)

$R_{i\,j}$ = efficiency percentage of methods "i" and "j" working together (it is calculated using equation 4.4)

The model ranks the possible combinations between the *"Basic tunnelling methods"* and excavation methods in descending order based on efficiency percentages of the combinations. The combinations between the *"Basic tunnelling methods"* and excavation methods can be called the *"Basic combinations"*.

The example, in Figure 4.10, shows the efficient methods of the *"Basic tunnelling methods"* and excavation methods which resulted from the calculations of the first phase. The efficiency percentage of each method is also shown in figure 4.10. The model will calculate the efficiency percentages of each combination, i.e. it will calculate the efficiency percentages of the following combinations:

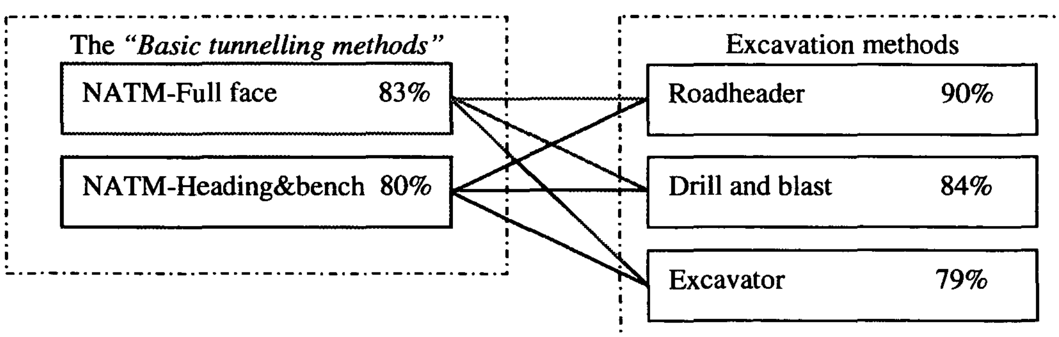


Figure 4.10 Combinations between the *"Basic tunnelling methods"* and excavation methods

- "NATM – Full face" and "Roadheader"

- "NATM – Full face" and "Drill and blast"
- "NATM – Full face" and "Excavator"
- "NATM – Heading & bench" and "Roadheader"
- "NATM – Heading & bench" and "Drill and blast"
- "NATM – Heading & bench" and "Excavator"

To calculate efficiency percentages of the combinations shown in figure 4.10, we should find the efficiency degrees of the methods working together from table A.1.1 of appendix "A", table 4.22 shows these efficiency degrees.

Table 4.22 Efficiency degrees of the *"Basic tunnelling methods"* and excavation methods working together (from table A.1.1, appendix "A")

Excavation methods / Basic methods	Excavator	Drill and blast	Roadheader
NATM – Full face	4	3.83	3.33
NATM – Heading & bench	3.67	3.2	2.67

Equation 4.4 will be used to derive efficiency percentages from efficiency degrees in table 4.22.

$$R_{NATM-Full\ face/Excavator} = \frac{(4-1)}{3} * 100 = 100\%$$

$$R_{NATM-Heading\ \&\ bench/Excavator} = \frac{(3.67-1)}{3} * 100 = 89\%$$

$$R_{NATM-Full\ face/Drill\ and\ blast} = \frac{(3.83-1)}{3} * 100 = 94.33\%$$

$$R_{NATM-Heading\ \&\ bench/Drill\ and\ blast} = \frac{(3.2-1)}{3} * 100 = 73.33\%$$

$$R_{NATM-Full\ face/Roadheader} = \frac{(3.33-1)}{3} * 100 = 77.67\%$$

$$R_{NATM - Heading \& bench/Roadheader} = \frac{(2.67-1)}{3} * 100 = 55.67\%$$

Equation 4.5 will be used to calculate efficiency percentages of the possible combinations of figure 4.10.

Efficiency percentage of the "NATM – Full face" = 83% (see figure 4.10)
Efficiency percentage of "Roadheader" = 90% (see figure 4.10)
Efficiency percentage of "NATM – Full face" to work with "Roadheader" = 77.67%
Efficiency percentage of the combination between "NATM – Full face" and "Roadheader" = 0.83 * 0.9 * 0.7767 * 100 = 58.02% (table 4.23 shows the whole calculations)

Table 4.23 Efficiency percentages of the combinations

Combinations	Efficiency percentage of the combination
"NATM – Full face" + "drill & blast"	0.83 * 0.84 * 0.9433 * 100 = 65.77%
"NATM – Full face" + "excavator"	0.83 * 0.79 * 1 * 100 = 65.57%
"NATM – Full face" + "roadheader"	0.83 * 0.9 * 0.7767 * 100 = 58.02%
"NATM – Heading & bench" + "excavator"	0.8 * 0.79 * 0.89 * 100 = 56.2%
"NATM – Heading & bench" + "drill and blast"	0.8 * 0.84 * 0.7333 * 100 = 49.3%
"NATM – Heading & bench" + "roadheader"	0.8 * 0.9 * 0.5567 * 100 = 40.1%

Table 4.23 shows that the combination "NATM-Full face + drill and blast" has the highest efficiency percentage.

4.3.2 Adding mucking and transportation methods to the *"Basic tunnelling methods"* and excavation methods

As shown in figure 4.8, mucking and transportation methods are connected to excavation methods. For each one of the *"Basic combinations"* which were formed in section 4.3.1, the model will find mucking and transportation methods that will give the highest efficiency percentages when they work with excavation methods of the combinations. Searching for mucking and transportation methods will be done by the model in two distinct steps.

The model uses equations 4.6 and 4.7 to find efficiency percentages of the combinations between excavation methods and both of mucking and transportation methods separately.

$$R_{ij} = \frac{(D_{ij} - 1)}{3} * 100 \qquad (4.6)$$

Where:

i = 1, 2, 3, ..., m (i represents the mucking or transportation methods)

j = 1, 2, 3, ..., n (j represents the excavation methods)

m = number of efficient mucking or transportation methods which resulted from the first phase

n = number of the efficient excavation methods which resulted from the first phase

D_{ij} = efficiency degree of methods i & j to work together (expert evaluation, see tables A.1.2, A.1.3 of appendix "A")

R_{ij} = efficiency percentage of methods i & j working together.

Equation 4.7 will be used to calculate efficiency percentages of the combinations between excavation methods and both of mucking and transportation methods.

$$F_{ij} = E_i * L_j * R_{ij} * 100 \qquad (4.7)$$

Where:

F_{ij} = efficiency percentage of the combination of methods i & j

E_i = efficiency percentage of mucking or transportation method (i)

L_j = efficiency percentage of excavation method (j)

$R_{i\,j}$ = efficiency percentage of methods "i" and "j" to work together (it is calculated using equation 4.6)

The first combination of the *"Basic combinations"* in table 4.23 is "NATM – Full face + drill & blast". If the "Drill and blast" can work with the two mucking machines "Rubber wheel loader" and "Tracked loader", the problem is which one will be selected to work with the "Drill and blast"? The model will calculate the efficiency percentages of the two combinations between the "Drill and blast" and both of "Rubber wheel loader" and "Tracked loader". The mucking method which gives higher combination efficiency percentage will be selected to work with "Drill and blast".

The model will select the transportation methods which give the highest efficiency percentages when they work with the excavation methods of the *"Basic combinations"*. The model repeats the procedures explained in the previous paragraph to determine the transportation methods.

If the *"Roadheader"*, *"Micro-tunnelling machine"*, *"Shield machine"* or *"TBM"* will be used for the excavation activity they do not need a mucking method because the machine itself can perform excavation and mucking simultaneously.

The efficiency percentages of the mucking methods for the project, which is shown in figure 4.10, are presented in table 4.24. The calculations of the model will be used now to determine the most efficient mucking methods for the excavation methods of table 4.23.

Table 4.24 Efficiency percentage of mucking methods (resulting from the first phase of the model)

Mucking methods / EPs	Rubber wheel loader	Tracked loader
Efficiency percentage	90%	84%

The excavation methods in table 4.23 are "Roadheader", "Drill and blast" and "Excavator". "Roadheader" will not need a mucking method, therefore the possible combinations are:

- Drill and blast + rubber wheel loader
- Drill and blast + tracked loader
- Excavator + rubber wheel loader
- Excavator + tracked loader

The efficiency degrees of these methods working together (shown in table 4.25) will be taken from table A.1.2.

Table 4.25 Efficiency degrees of excavation and mucking methods to work together

Excavation methods / Mucking methods	Excavator	Drill and blast
Rubber wheel loader	4	4
Tracked loader	3	3

Equation 4.6 will be used to derive efficiency percentages of excavation and mucking methods working together as follows:

$$R_{Excavator/Rubber\ wheel\ loader} = \frac{(4-1)}{3} * 100 = 100\%$$

$$R_{Excavator/Tracked\ loader} = \frac{(3-1)}{3} * 100 = 66.67\%$$

$$R_{Drill\ and\ blast/Rubber\ wheel\ loader} = \frac{(4-1)}{3} * 100 = 100\%$$

$$R_{Drill\ and\ blast/Tracked\ loader} = \frac{(3-1)}{3} * 100 = 66.67\%$$

Efficiency percentages of the combinations can be calculated using equation 4.7 as follows:

$$F_{Excavator/Rubber\ wheel\ loader} = E_{Rubber\ wheel\ loader} * L_{Excavator} * R_{Excavator/Rubber\ wheel\ loader} * 100$$
$$= 0.90 * 0.79 * 1 * 100 = 71.1\%$$

$$F_{Excavator/Tracked\ loader} = E_{Tracked\ loader} * L_{Excavator} * R_{Excavator/Tracked\ loader} * 100$$
$$= 0.84 * 0.79 * 0.6667 * 100 = 44.24\%$$

$$F_{Drill\ and\ blast/Rubber\ wheel\ loader} = E_{Rubber\ wheel\ loader} * L_{Drill\ and\ blast} * R_{Drill\ and\ blast/Rubber\ wheel\ loader} * 100$$
$$= 0.90 * 0.84 * 1 * 100 = 75.6\%$$

$$F_{Drill\ and\ blast/Tracked\ loader} = E_{Tracked\ loader} * L_{Drill\ and\ blast} * R_{Drill\ and\ blast/Tracked\ loader} * 100$$
$$= 0.84 * 0.84 * 0.6667 * 100 = 47.04\%$$

The efficiency percentage of the combination excavator and rubber wheel loader is higher than the efficiency percentage of the combination excavator and tracked loader consequently the tracked loader will not be considered to work with the "Excavator". The rubber wheel loader is also better than tracked loader to work with drill and blast. Table 4.26 shows the combinations between mucking methods and the methods of table 4.23.

The same procedures which were used to find mucking methods will be used to find transportation methods. After adding mucking and transportation methods to the *"Basic combinations"*, the model has formed a partial section of the tunnelling system which consists of four activities which are the *"Basic tunnelling methods"*, excavation, mucking and transportation.

Table 4.26 Combination between methods of three activities

Partial tunnelling system	Basic tunnelling methods	Excavation methods	Mucking methods
1	NATM – Full face	Drill and blast	Rubber wheel loader
2	NATM – Full face	Excavator	Rubber wheel loader
3	NATM – Full face	Roadheader	Roadheader
4	NATM – Heading & bench	Excavator	Rubber wheel loader
5	NATM – Heading & bench	Drill and blast	Rubber wheel loader
6	NATM – Heading & bench	Roadheader	Roadheader

4.3.3 Adding support and lining methods to the *"Basic combinations"*

Support methods are grouped under two types which are "side wall and crown support" and "face support". Side wall support methods and lining methods are connected to each other, because some methods can be used for both of them at the same time such as "Shotcrete", and they are connected at the same time to both of the *"Basic tunnelling methods"* and excavation methods. The model will search for the side wall support and lining methods that can work efficiently with the *"Basic combinations"*. In case of *"Cut and cover"*, support and lining methods are not connected together therefore the model will search for the support and lining methods for cut and cover in two different steps.

4.3.3.1 Adding support methods for *"Cut & cover"* and excavation methods

When the *"Basic combinations"* include "Cut and cover" plus an excavation method, the model will search for support method that will give the highest efficiency percentage for this *"Basic combination"*. Support methods for the *"Cut and cover"* are also connected to the excavation methods.

In this step, the model searches for the support method that can give the highest efficiency percentage working with cut and cover and the excavation method at the same time. The model uses equation 4.8 to calculate efficiency percentages of support methods for the *"Cut and cover"* and excavation methods.

$$E_{ij} = A_k * B_i * C_j * F_{ki} * F_{kj} * F_{ij} * 100 \qquad (4.8)$$

Where:

E_{ij} = efficiency percentages of the combinations between support methods (j) and *"Cut & cover"* (k) as well as excavation methods (i)

A_k = efficiency percentage of *"Cut & cover"* (k)

B_i = efficiency percentage of excavation method (i)

C_j = efficiency percentage of support method (j)

F_{ki} = efficiency percentage of excavation methods (i) working with *"Cut & cover"* (k)

F_{kj} = efficiency percentage of support method (j) working with *"Cut & cover"* (k)

F_{ij} = efficiency percentage of excavation method (i) and support method (j) working together

j = support methods

i = excavation methods

k = Cut and cover method

The model will derive the values of F_{ki}, F_{kj} and F_{ij} from efficiency degrees of the methods working together which are in table A.1.4 of appendix "A"; this is done using equation 4.6.

The support method that gives the highest efficiency percentage *"E_{ij}"* will be taken by the model as the best support method for the combination excavation methods and *"Cut and Cover"*, and other methods will not be considered.

4.3.3.2 Adding lining methods for *"Cut & Cover"* and excavation methods

The same calculations that were used to add support methods to the "Cut and cover" and excavation methods will be applied for lining methods. Equation 4.6 will be employed to calculate the efficiency percentages of the lining methods working with the "Cut and cover" and excavation methods using efficiency degrees in table A.1.5 of appendix "A". Equation 4.8 will be used also to calculate efficiency percentages of the combinations of the lining methods with the "Cut and cover" and excavation methods. Lining methods which produce the highest efficiency percentages of the combinations with "Cut and cover" and excavation methods will be used and the other methods will not be considered.

4.3.3.3 Adding side wall support and lining methods for the *"Basic combinations"*

This section explains how the model adds side wall and lining methods at the same time to the *"Basic combinations"* so as to form alternative tunnelling systems. Basic combinations which have cut and cover is not considered here because they are special cases which was explained in sections 4.3.3.1 and 4.3.3.2.

"Precast concrete segments" and *"Shotcrete"* construction methods have two different efficiency percentages resulting from calculations of the first phase. The first efficiency percentage is when they are used as a support methods and the second efficiency percentage is when they are used as lining methods. Model

calculations are based on the small efficiency percentages for *"Precast concrete segments"* and *"Shotcrete"*, which resulting from support and lining calculations, to give the model more reliability. For instance, if efficiency percentage of the *"Precast concrete segments"* that resulted from the support calculations is 78% and its efficiency percentage that resulted from lining calculations is 82%, the model will consider efficiency percentage of the *"Precast concrete segments"* as 78% for all calculations at this stage.

Equation 4.9 is used to determine efficiency percentages of the combinations between side wall support and lining methods with the *"Basic combinations"*.

$$E_{ijk} = A_i * B_i * C_j * D_k * F_{A_iB_i} * F_{A_iC_j} * F_{A_iD_k} * F_{B_iC_j} * F_{B_iD_k} * F_{C_jD_k} * 100 \qquad (4.9)$$

Where:

E_{ijk} = efficiency percentage of the combinations among the *"Basic tunnelling methods"*, excavation methods, side wall support methods and lining methods

A_i = efficiency percentage of the *"Basic tunnelling method"* which is a constituent of the *"Basic combination"* (i)

B_i = efficiency percentage of excavation method which is a constituent of the *"Basic combination"* (i)

C_j = efficiency percentage of side wall support method (j)

D_k = efficiency percentage of lining method (k)

$F_{A_iB_i}$ = efficiency percentage of the *"Basic tunnelling method"* and excavation method working together

$F_{A_iC_j}$ = efficiency percentage of the *"Basic tunnelling method"* and support method working together

$F_{A_iD_k}$ = efficiency percentage of the *"Basic tunnelling method"* and lining method working together

$F_{B_iC_j}$ = efficiency percentage of excavation method and support method working together

$F_{B_iD_k}$ = efficiency percentage of excavation method and lining method working together

$F_{C_jD_k}$ = efficiency percentage of support method and lining method working together

i = basic combinations

j = side wall support methods

k = number of lining methods

Efficiency percentages of the methods working together in equation 4.9 are calculated with equation 4.6 using efficiency degrees of each two methods to work together from the matrices of appendix "A".

Side wall support and lining methods that will give the highest efficiency percentage of the combinations will be used and the other methods will not be considered.

4.3.3.4 Adding face support methods to the *"Basic combinations"*

Face support methods are connected to the *"Basic tunnelling methods"* and excavation methods. The model searches for the face support method that will give the highest efficiency percentage when it works with the *"Basic combinations"* using equation 4.10.

$$E_{ik} = A_i * B_i * D_k * F_{A_i B_i} * F_{A_i D_k} * F_{B_i D_k} * 100 \tag{4.10}$$

Where:

E_{ik} = efficiency percentages of the combinations between the *"Basic combinations"* (i) and face support method (k)

A_i = efficiency percentage of the *"Basic tunnelling method"* which is a constituents of the *"Basic combination"* (i)

B_i = efficiency percentage of excavation method which is a constituent of the *"Basic combination"* (i)

D_k = efficiency percentage of face support methods "k"

$F_{A_i B_i}$ = efficiency percentage of the *"Basic tunnelling method"* and excavation method working together

$F_{A_i D_k}$ = efficiency percentage of the *"Basic tunnelling method"* and face support method working together

$F_{B_i D_k}$ = efficiency percentage of excavation method and face support method working together

i = basic combinations

k = face support methods

Efficiency percentages of the methods working together will be calculated using equation 4.6 by means of efficiency degrees of the methods working together that are shown in the matrices of appendix "A".

Good rock does not need a face support. When the RMR value is in the range (60 – 80) or over 80, the model gives information to the user that there is no need for face support.

"Micro-tunnelling machine", *"Shield machine"* or *"TBM"* can perform excavation and support the face simultaneously; therefore there is no face support method used with these machines.

4.3.4 Adding groundwater control methods to the *"Basic combinations"*

The last component of the tunnelling system is groundwater control methods. Groundwater control methods are connected to the *"Basic tunnelling methods"* and excavation methods. The model applies the procedures of finding face support methods to find groundwater control methods.

For *"Shield machine"* and *"Micro-tunnelling"* use of groundwater control methods is optional because the model considers that the shield will give protection against water during excavation. Searching for a groundwater control method, in this case, is to give the user information about which method is efficient to work with these machines when it is needed.

4.3.5 Calculation of the efficiency percentages of the alternative tunnelling systems

After finding methods for the different tunnelling systems, the model calculates efficiency percentages of the different tunnelling systems to arrange the systems in a descending order. To calculate efficiency percentages of the different tunnelling systems, the model multiplies efficiency percentages of the methods which are the system components and it multiplies them also with efficiency percentages of the methods in working together. The model creates a comprehensive report which tells the user which systems are more or less efficient for his project.

5 Computer program to select efficient tunnelling system (SETS)

5.1 Introduction

A computer program was developed to apply the proposed model that was explained in chapter 4. This computer program helps decision taker to select the most efficient tunnelling system for his project. The program name is SETS and it is an abbreviation of the words **S**electing **E**fficient **T**unnelling **S**ystem. The program is designed to be easy for use and give its results in clear reports.

5.2 General information about SETS

The program was developed using an object oriented programming language which is Microsoft Visual Basic 6. The program works under windows system and it can benefit of other windows applications, for instance, the program can have a link with Microsoft word. Size of the program is 2.08 MB and it has 45 files. Configuration of the computer that used to build the program is Pentium 4 with processor of 1.8GH. SETS can work with computers with lower configuration. The program takes 1 or 2 seconds for making calculations[(1)].

5.3 Getting started

User of the program should create a new folder on his hard disk, "C" drive, and give it the name "SETS". Then, he makes a copy and paste of the program files on the CD to this folder. The name of the executable file "SETS", there is also a shortcut for the executable file which the user can put it on his computer disk top for easy launce of the program.

[1] Speed of the program to make calculations differs from one computer to another depending on the configuration of the computer.

5.4 Program logic

The program follows the same steps of the model that described in chapter 4. Figure 5.1 shows a general flow chart of the program. The program starts with a screen shows name of the program and its version. There are some tunnelling methods' photos in the first screen. Opening screen will hide automatically and a screen of general project data will be activated. Figure 5.2 shows the opening screen and figure 5.3 shows the general data screen.

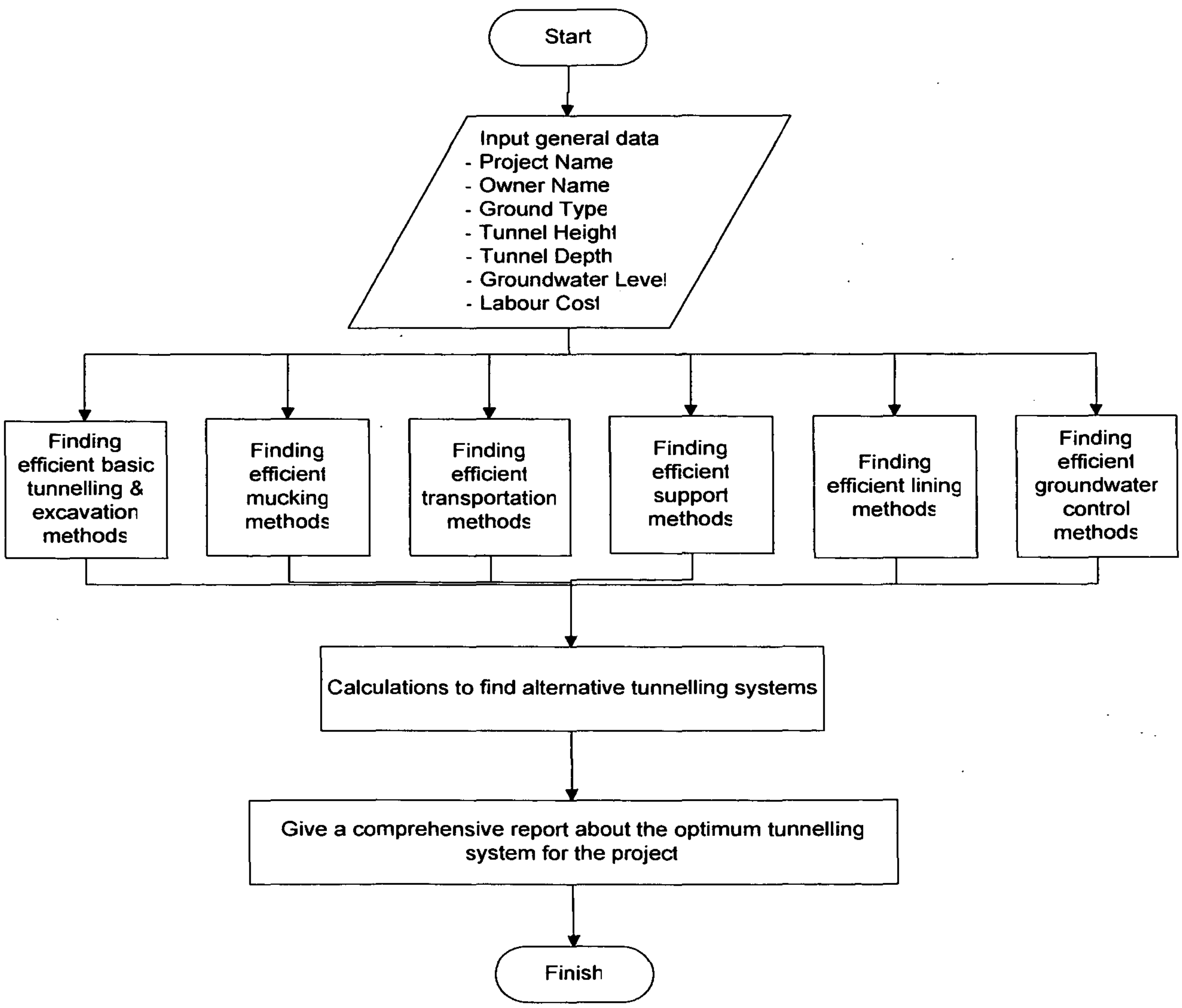


Figure 5.1 General flow chart of program SETS

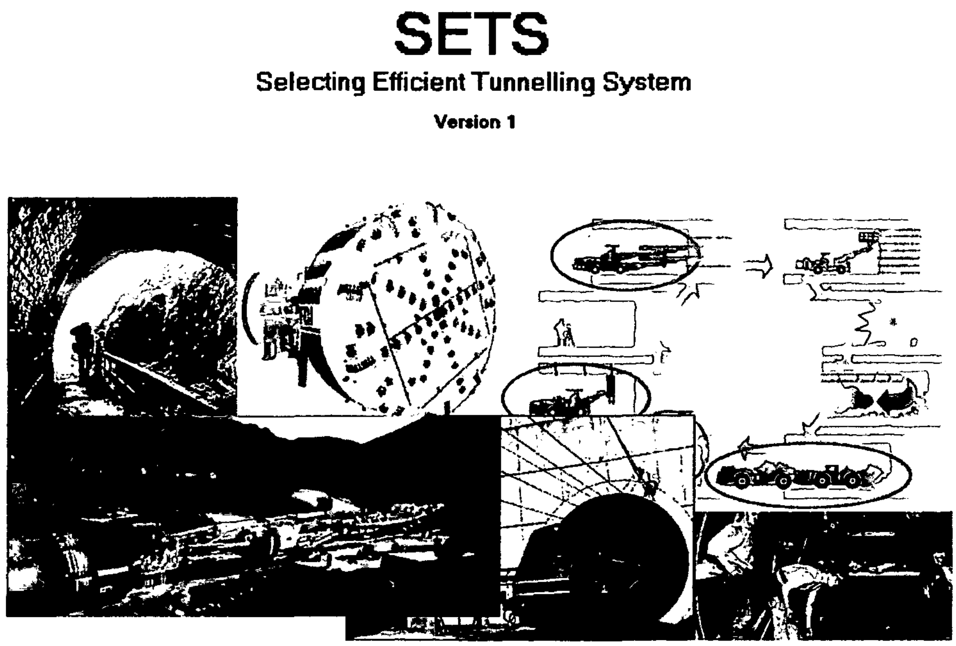


Figure 5.2 The opening screen

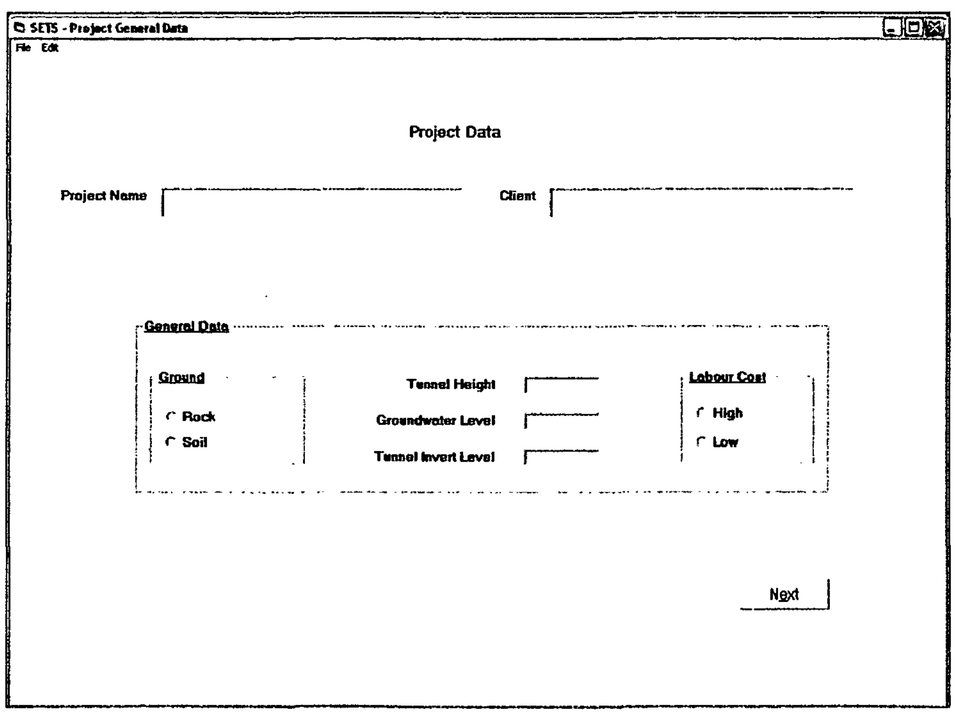


Figure 5.3 General data screen

In the general data screen, the user of the model will feed the program with project name, client name, tunnel height, groundwater level, tunnel invert level, and labour cost (high or low). SETS program accepts project name and client name up to 50 characters. User of the model determines ground conditions, if it is rock or soil by selecting the button. For labour cost the user will select high or low by clicking on the radio button of his choice.

The general project data screen has menu at the top. In this menu there are two options. The first is file and the second is edit. Clicking file will open a list which has another option that is end. Clicking end will terminate the program. Figure 5.4 shows the submenu of file.

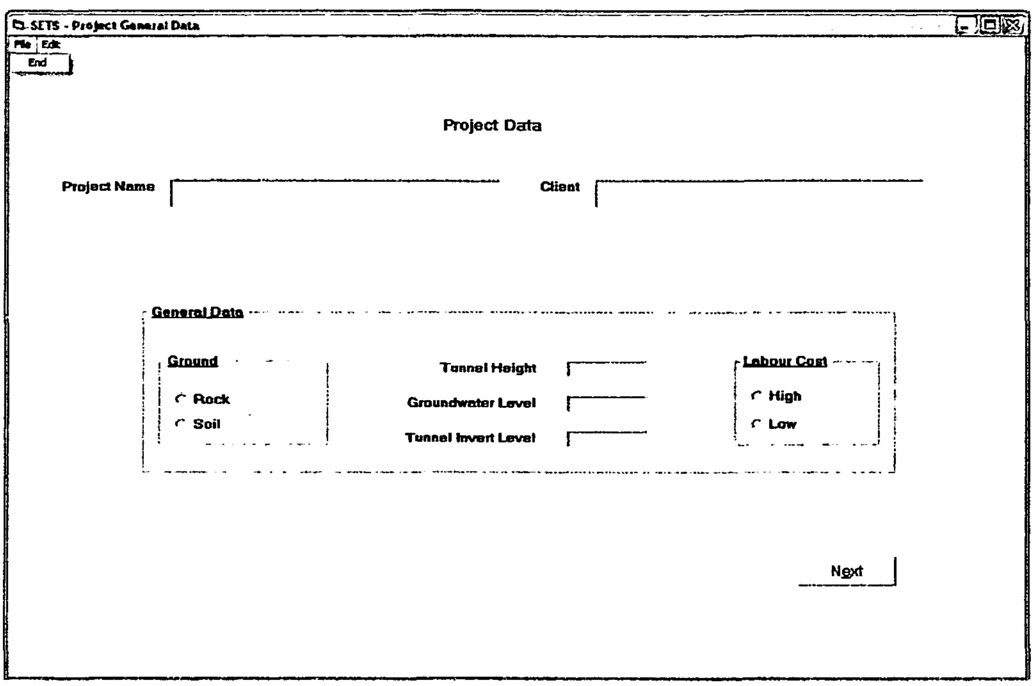


Figure 5.4 Submenu of file option in project general data screen

The other option in the menu is edit. This option enables the user to edit data of different screens. Clicking edit will open a list containing names of different screens (see figure 5.5) and clicking any of them will hide project general data screen and the required screen will be opened. The user can utilize shortcuts for transferring to another screen. Table 5.1 shows shortcuts. Edit option is existed in all program screens and it does the same function as described earlier. The name of the activated screen will be grey in submenu of edit in different screens.

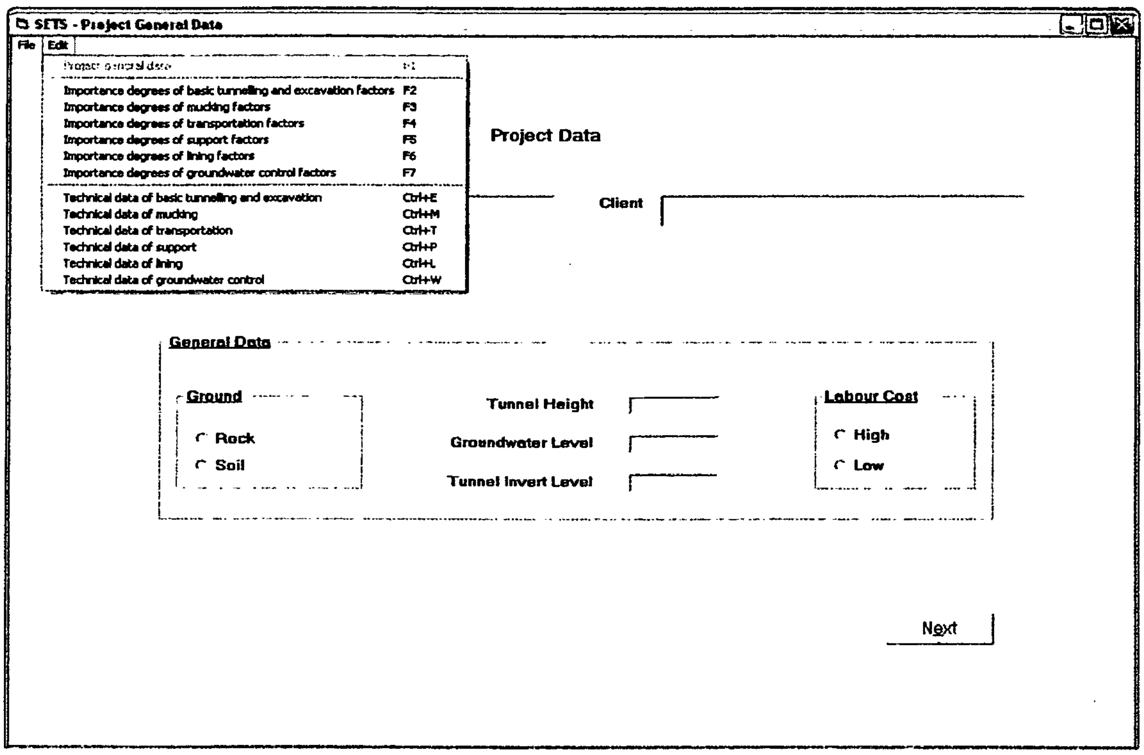


Figure 5.5 Submenu of edit option in project general data screen

Table 5.1 Shortcuts of edit submenu

Screen name	Shortcut
Project general data	F1
Importance degrees of basic tunnelling and excavation factors	F2
Importance degrees of mucking factors	F3
Importance degrees of transport factors	F4
Importance degrees of support factors	F5
Importance degrees of lining factors	F6

Table 5.1 Shortcuts of edit submenu (continue)

Importance degrees of groundwater control factors	F7
Technical data of basic tunnelling and excavation	Ctrl + E
Technical data of mucking	Ctrl + M
Technical data of transportation	Ctrl + T
Technical data of support	Ctrl + P
Technical data of lining	Ctrl + L
Technical data of groundwater control	Ctrl + W

The button *"Next"* in the project general data screen enables the user to go to next screen, which is the *"Tunnelling activities and methods"*. Shortcut of this button is *"Alt + E"*.

Before moving from project general data screen to any other screen, SETS program will check values that were given to tunnel height, groundwater level, and tunnel invert level. Tunnel height should be a positive number. Groundwater level and tunnel invert level should be numbers. When user feeds the program with something not a number or if the value of tunnel height is negative value, the program will not go to any other screen and it gives the user information message to inform him about the accepted values. Colour of the wrong value will be turned to red (see figure 5.6a and b). Clicking *"ok"* in the message will delete the wrong value and zero will be assigned to this field in black colour. After checking the values fed by the user, the program will assign these values to some variables, which will be used in later stages of calculations.

Not feeding the program with values in project general data screen results in wrong calculations in next steps.

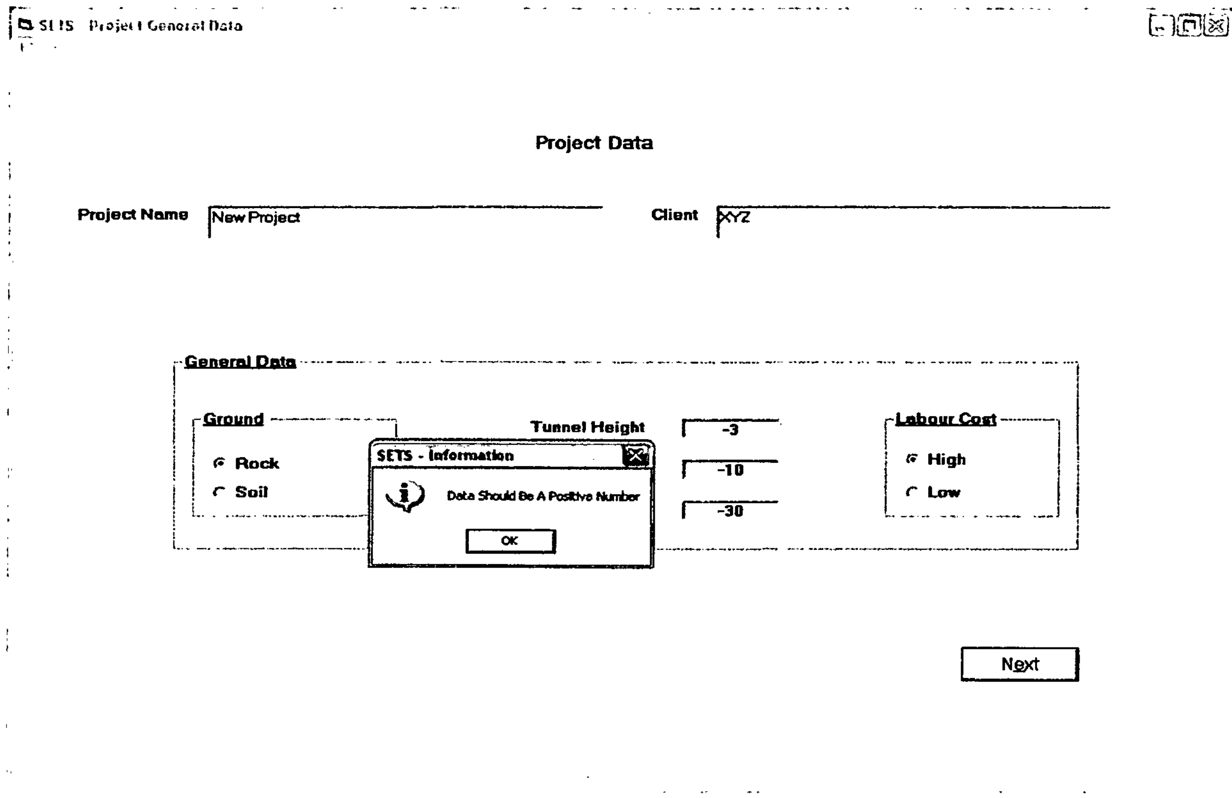


Figure 5.6a Information message for wrong value

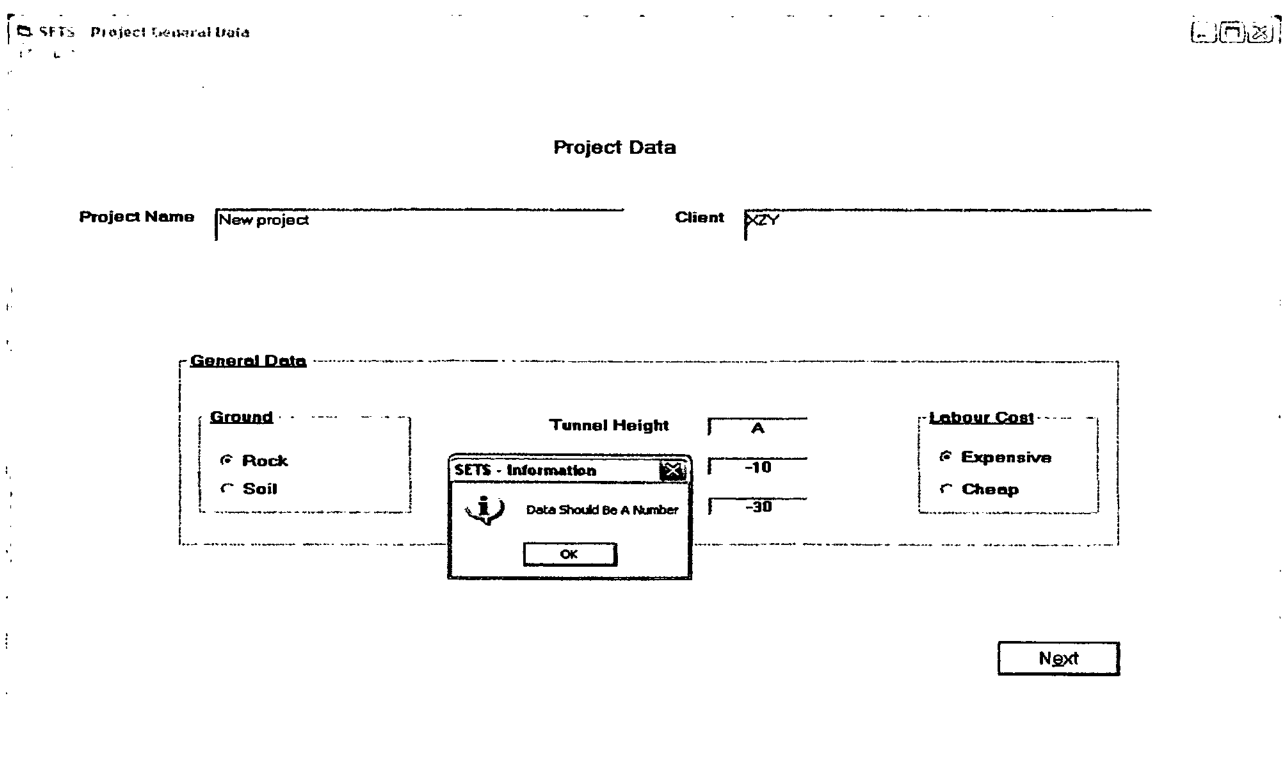


Figure 5.6b Information message for wrong value

"Tunnelling Activities and Methods" screen that shown in figure 5.7 has six buttons. Each button has a name of a tunnelling activity. Down of each button, names of construction methods that are possible for the activity are written, to give the user information about construction methods for each tunnelling activity that the program is dealing with. Clicking each button will display a screen that enables the user to feed the program with importance degrees of controlling factors of that activity. Table 5.2 shows buttons name and screen names that will be displayed when clicking the button.

Table 5.2 Buttons for screen names (tunnelling activities and methods screen)

Button name	The name of displayed screen
Basic tunnelling and excavation	Importance degrees (Basic tunnelling & Excavation Activities)
Mucking	Importance degrees (Mucking Activity)
Transportation	Importance degrees (Transportation Activity)
Support	Importance degrees (Support Activity)
Lining	Importance degrees (Lining Activity)
Groundwater control	Importance degrees (Groundwater Control Activity)

Figure 5.8 shows submenu of the edit option in the *"Tunnelling activities and methods"* screen. The submenu looks similar like the submenu of edit option in project general data screen. By clicking any of submenu options or using shortcuts the user can hide the *"Tunnelling activities and methods"* screen and the screen that he has chosen will by displayed. Shortcuts of submenu of edit option are the same as shown in table 5.1.

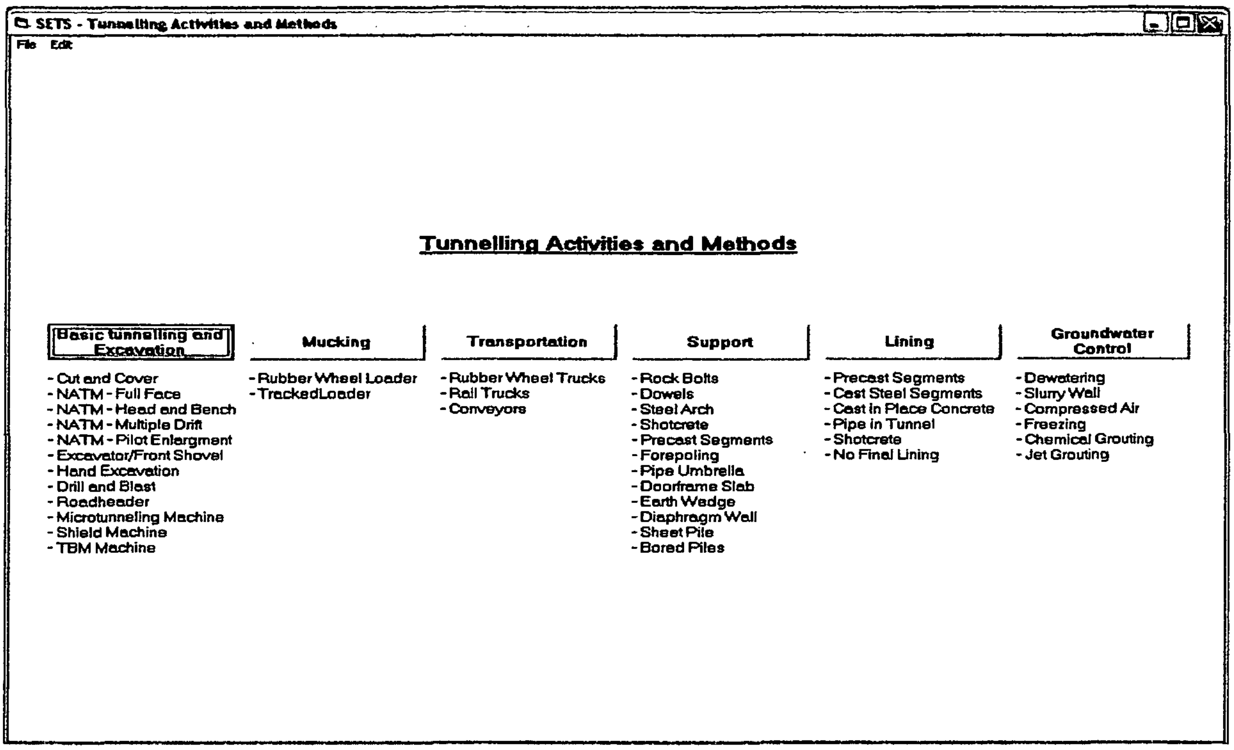


Figure 5.7 Tunnelling activities and methods screen

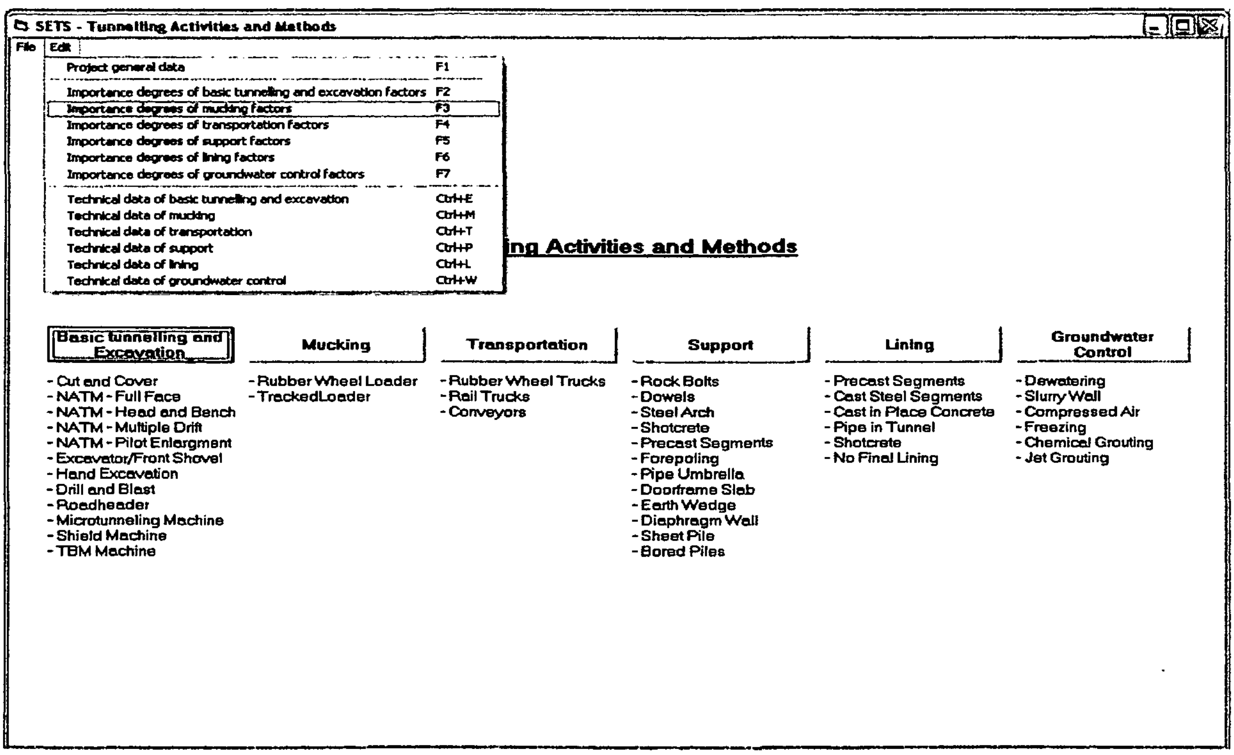


Figure 5.8 Submenu of edit option in tunnelling activities and methods screen

5.4.1 "Basic tunnelling methods" and excavation activity

The program starts to calculate efficiencies of construction methods that can work for basic tunnelling methods and excavation activity. Clicking the button of basic tunnelling and excavation in the screen *"Tunnelling activities and methods"* will display the screen of *"Importance degrees (Basic tunnelling methods & Excavation Activities)"*. In this screen, the user can assign importance degrees for controlling factors of basic tunnelling and excavation activity. Figure 5.9 shows the flow chart that describes calculations of the program for the screen *"Importance degrees (Basic tunnelling methods & Excavation Activities)"*. Figure 5.10 presents the screen of *"Importance degrees (Basic tunnelling & Excavation Activities)"*. When screen starts, the button *"Efficiency degrees"* will be disabled and the cursor will be in the field of importance degree for ground conditions and all fields have a zero value.

The user enters values for importance degrees, in the fields, in the range of 0 to 10. He can change from one field to another using tab button. When the cursor moves to new field the value in this field will be deleted and it will be ready to receive a new value from the user.

If one or more of the factors, *"Technology availability"*, *"Experience"*, and *"Others"* has a value more than zero the button *"Efficiency degrees"* will be enabled. Clicking the *"Efficiency degrees"* button will hide the screen *"Importance degrees (Basic tunnelling & Excavation Activities)"* and the screen *"Efficiency degrees of basic tunnelling and excavation methods"* will show up.

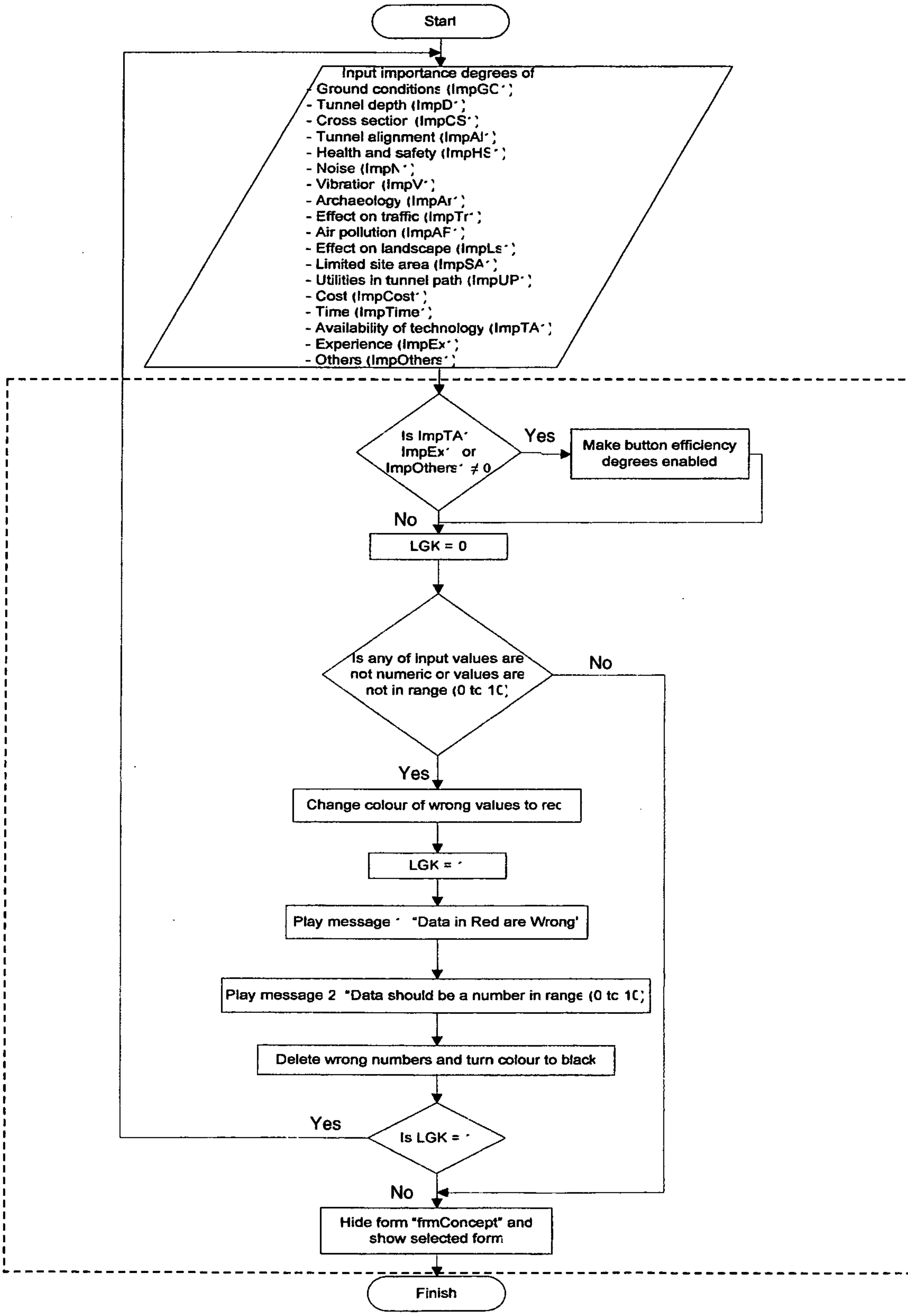


Figure 5.9 Flow chart shows calculations for activities basic tunnelling and excavation

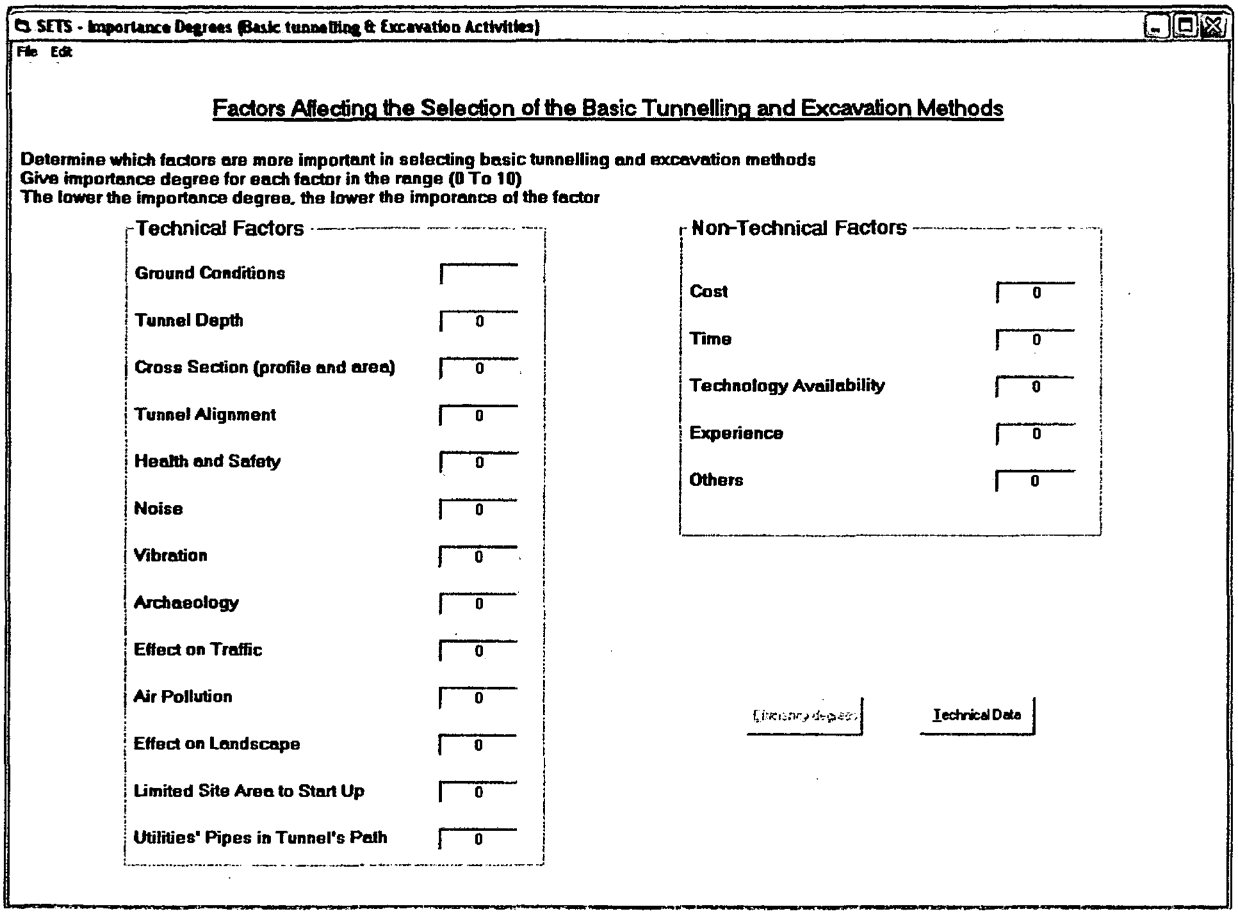


Figure 5.10 Screen of *"Importance degrees (Basic tunnelling & Excavation Activities)"*

At the top of the screen there are instructions for the user to assign the importance degrees for controlling factors.

The screen *"Importance degrees (Basic tunnelling & Excavation Activities)"* has a menu with two options *"File"* and *"Edit"*. Submenus for the two options are the same as that of the screen *"Project general data"*. Clicking any option of edit submenu will hide the activated screen and show another screen. Clicking the two buttons in the screen *"Importance degrees (Basic tunnelling & Excavation Activities)"* will hide the working screen, as well. Procedures in the doted box, in the flow chart (figure 5.9), will be done when the user try to move from this screen to any other screen.

The program assigns a zero value at the beginning for the variable LGK (see figure 5.9), and then importance degrees will be checked by the program. If values are not numeric or they are out of the range (0 to 10), the program will change the colour of wrong values to red and value of variable LGK will be 1. Two messages will be displayed in this case to inform the user about what is wrong. Clicking "ok" of the second message will delete the wrong values and put instead of them zero in black colours. The program will not move forward until correct values are assigned to importance degrees. The program will move forward when the value of LGK variable is zero.

Figure 5.11 shows the screen after filling out fields with values of importance degrees. The button *"Efficiency degrees"* is enabled because the importance degree of the controlling factor *"Others"* is not zero. Shortcuts of the buttons *"Efficiency degrees"* and *"Technical Data"* are *"Alt + E"* and *"Alt + T"* respectively. It can be seen that importance degree for controlling factor *"Air pollution"* is "K". Importance degrees, of controlling factors *"Utilities in tunnel path"* and *"Cost"*, are "-2" and "12", respectively. These values are not accepted by the program.

Clicking the button *"Efficiency degrees"* results in changing the colour of these fields to red and a message will be displayed as shown in figure 5.11.

Figure 5.12 shows the second message. The screen will look like figure 5.13 when the button "ok" of the second message is clicked. It can be seen that the red value is changed to zero in black colour.

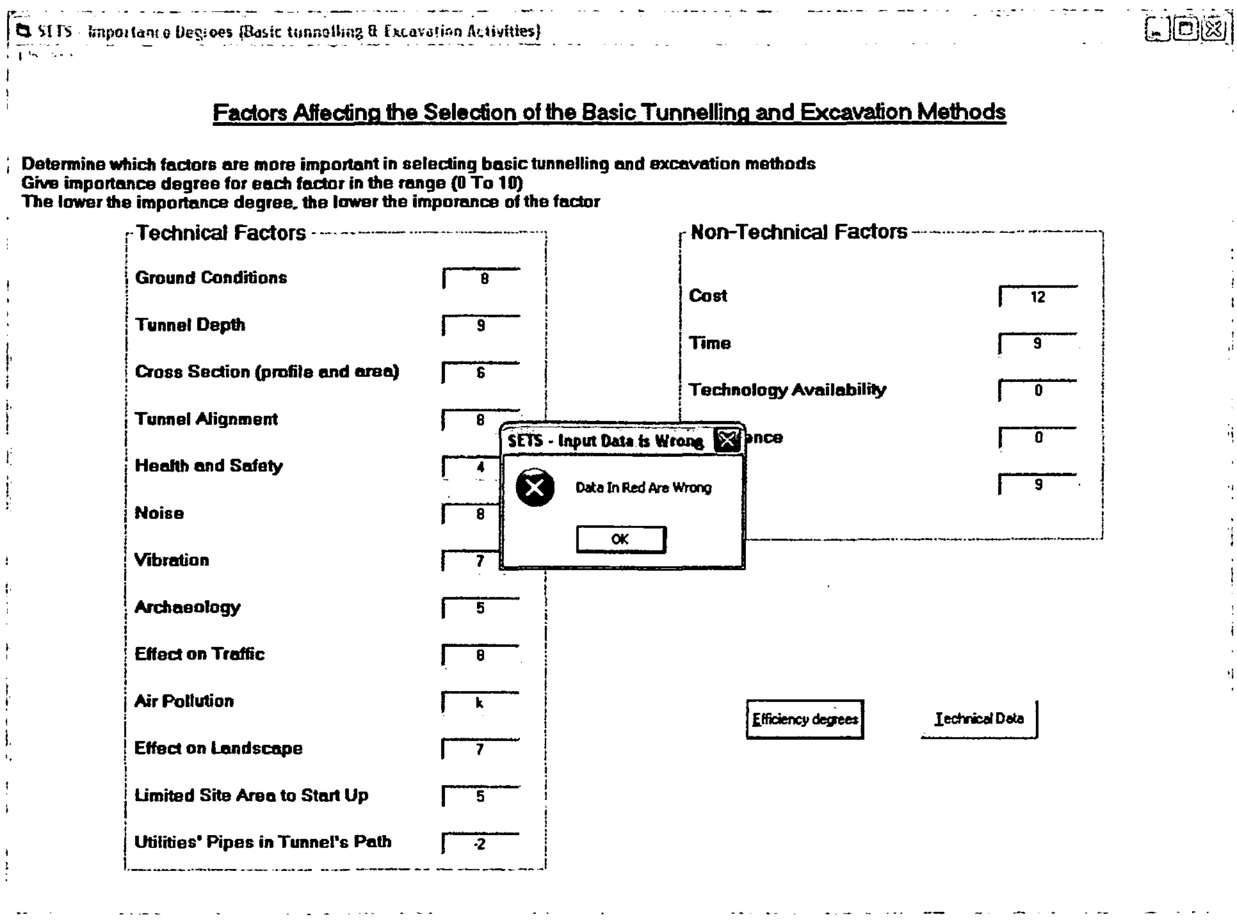


Figure 5.11 First message displayed for wrong data

Non-zero values for controlling factors *"Technology Availability"*, *"Experience"*, or *"Others"* allow to the user to feed the program with efficiency degrees of construction methods for these controlling factors. In screen *"Efficiency degrees of basic tunnelling and excavation methods"* the user can feed the program with efficiency degrees of construction methods. Screen *"efficiency degrees of basic tunnelling and excavation methods"* has three groups of construction methods for the three controlling factors. The user should assign efficiency degrees for construction methods under the title of the controlling factor that he gave it an importance degree higher than zero.

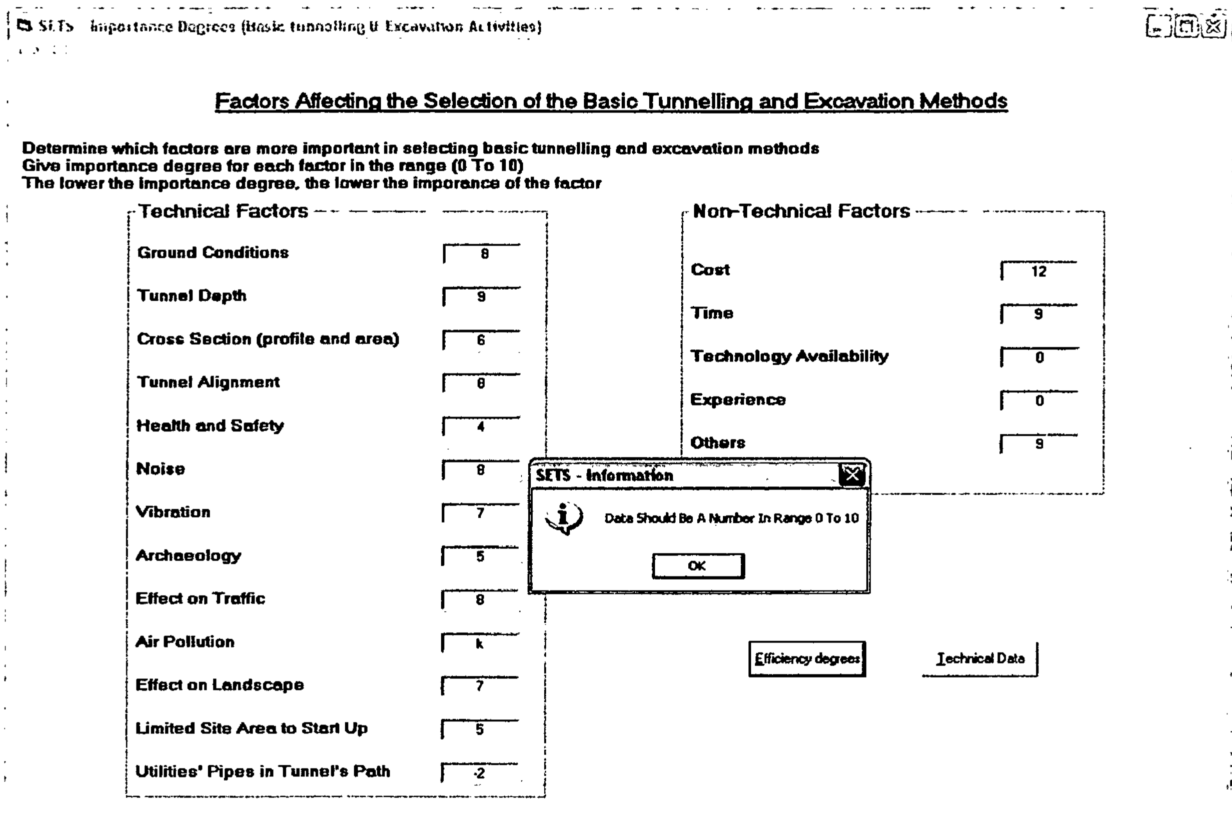


Figure 5.12 Second message displayed for wrong data

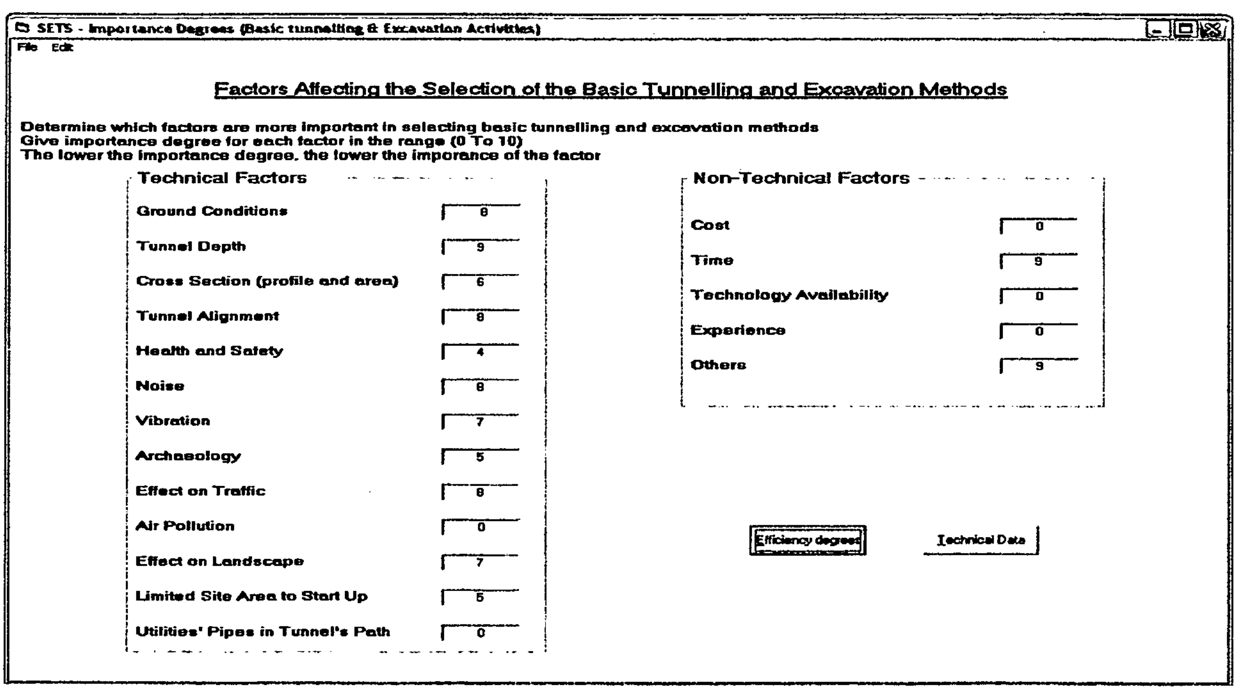


Figure 5.13 Look of the screen after second message

When screen *"Efficiency degrees of basic tunnelling & excavation methods"* starts, the user will find that all fields have efficiency degrees equal to "4", except the first field where the cursor is flashing. Figure 5.14 presents screen *"Efficiency degrees of basic tunnelling & excavation methods"*. At the top of the screen, there is information to the user about how he can deal with this screen. At the end of the screen, there is an explanation to the efficiency degrees values. The user moves from field to another using tab button or by clicking the field that he wants to move to it. If the user did not give an importance degree for a controlling factor and he gives efficiency degrees for construction methods of that factor, the program will ignore these values.

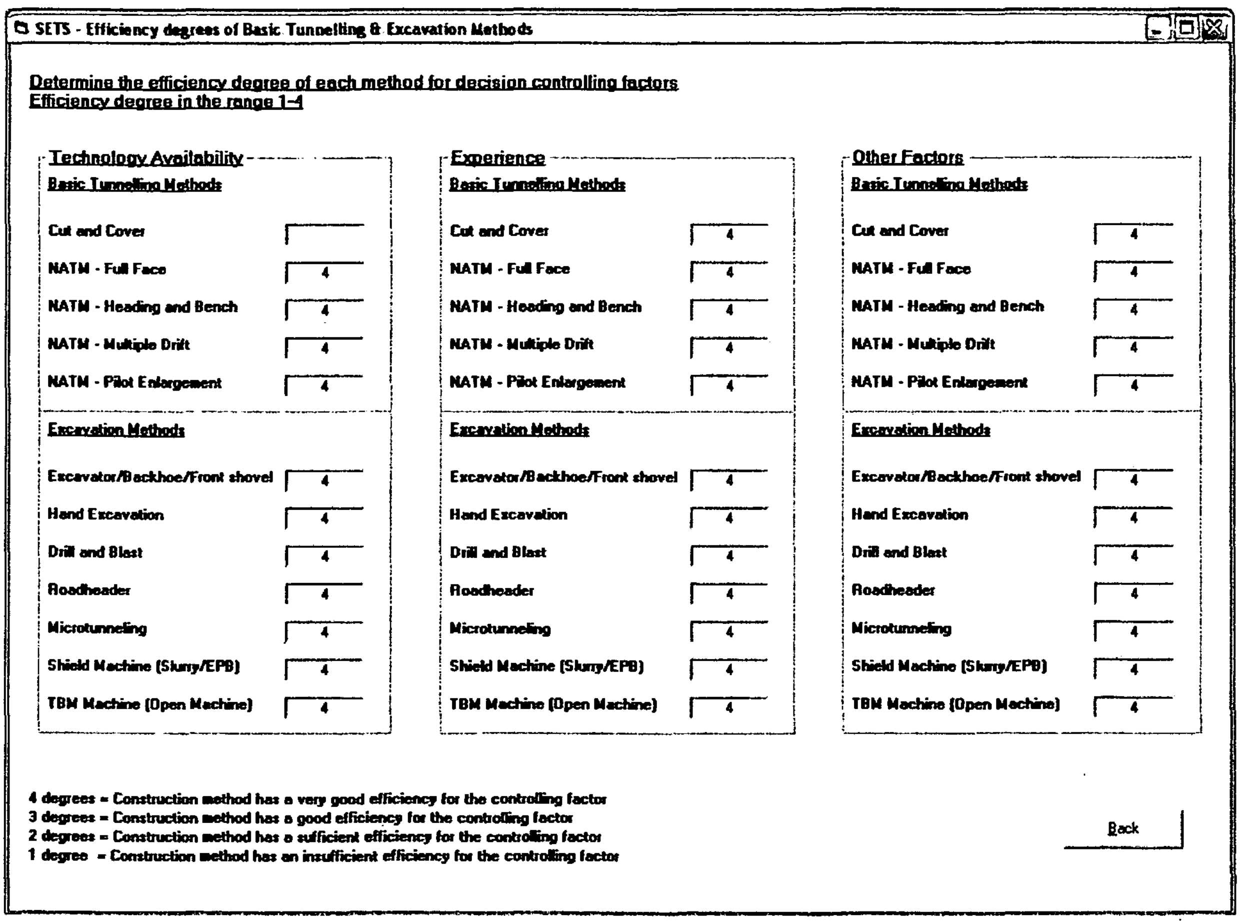


Figure 5.14 Screen: *"Efficiency degrees of basic tunnelling & excavation methods"*

After finishing of feeding the program with data, the user clicks the button *"Back"* or uses the shortcut *"Alt + B"* to return back to screen *"Importance degrees (Basic tunnelling & Excavation Activities)"*. In screen *"Importance degrees (Basic tunnelling & Excavation Activities)"* (figure 5.13) the user clicks the button *"Technical Data"* to move to screen *"Project Technical Data (Basic tunnelling methods & Excavation)"* that shown in Figure 5.15a&b.

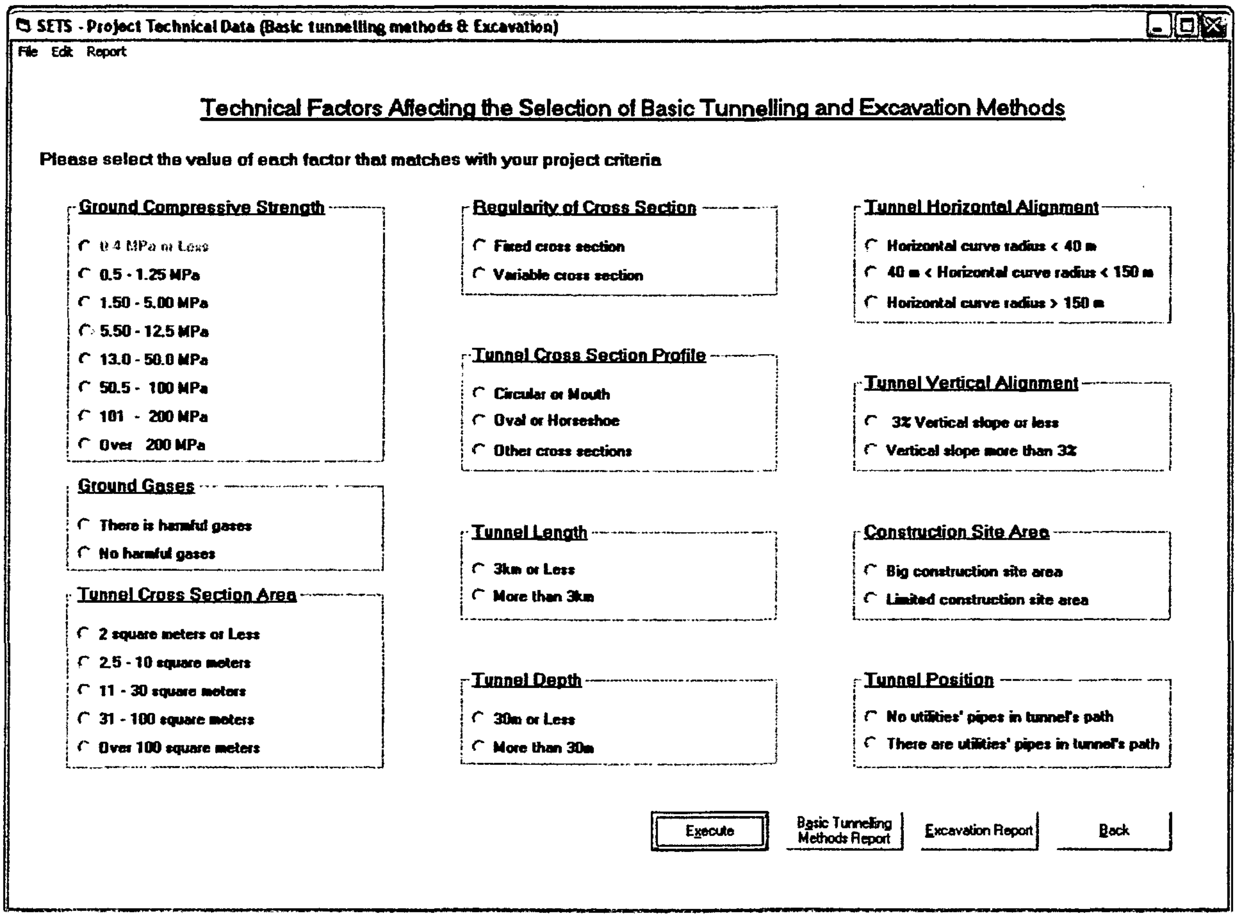


Figure 5.15a Screen: *"Project Technical Data (Basic tunnelling methods & Excavation)"*

"Project Technical Data (Basic tunnelling methods & Excavation)" screen (figure 5.15) has 11 groups of technical data. The user selects the radio button of each group that represents technical data of his project using mouse.

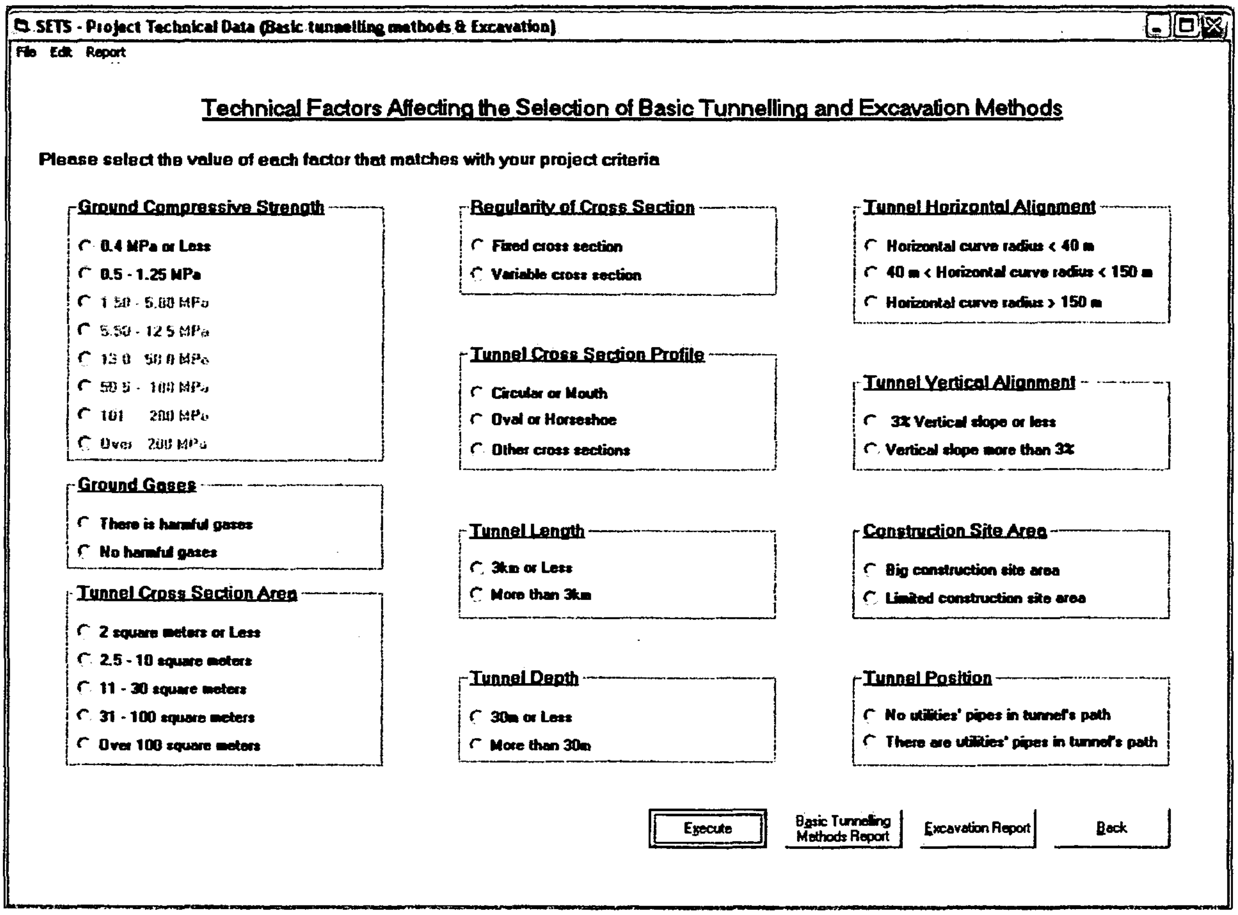


Figure 5.15b Screen: *"Project Technical Data (Basic tunnelling methods & Excavation)"*

When the user selects ground condition is rock, in screen *"Project general data"*, the first option in *"Ground compressive strength"* group will be disabled as shown in figure 5.15a. In case that the user selects ground conditions as soil, only the first two options in group of "Ground compressive strength" can be chosen and the others are disabled as shown in figure 5.15b.

Submenu of option *"Report"* enables the user to see any report of tunnelling activities. *"Comprehensive Report"* option will be disabled until *"Execute"* button of all activities are clicked (see figure 5.16).

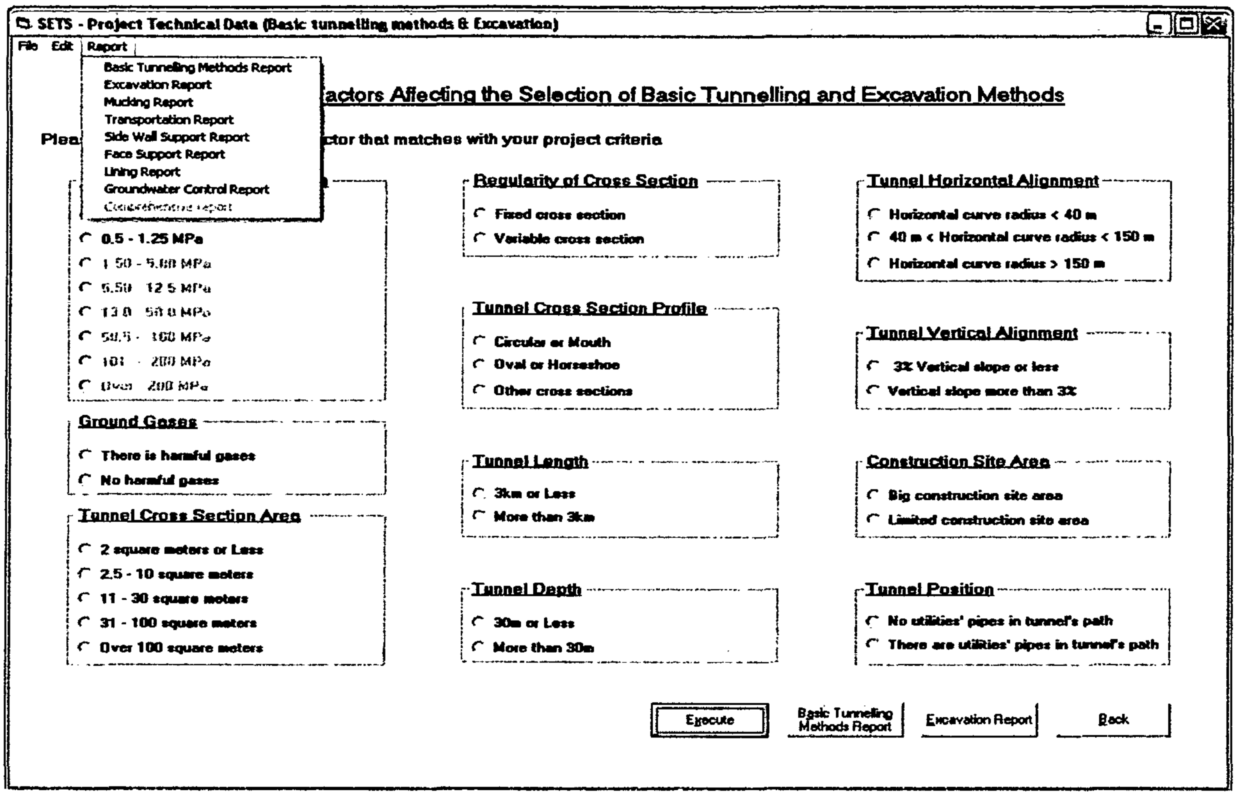


Figure 5.16 Submenu of option *"Report"*

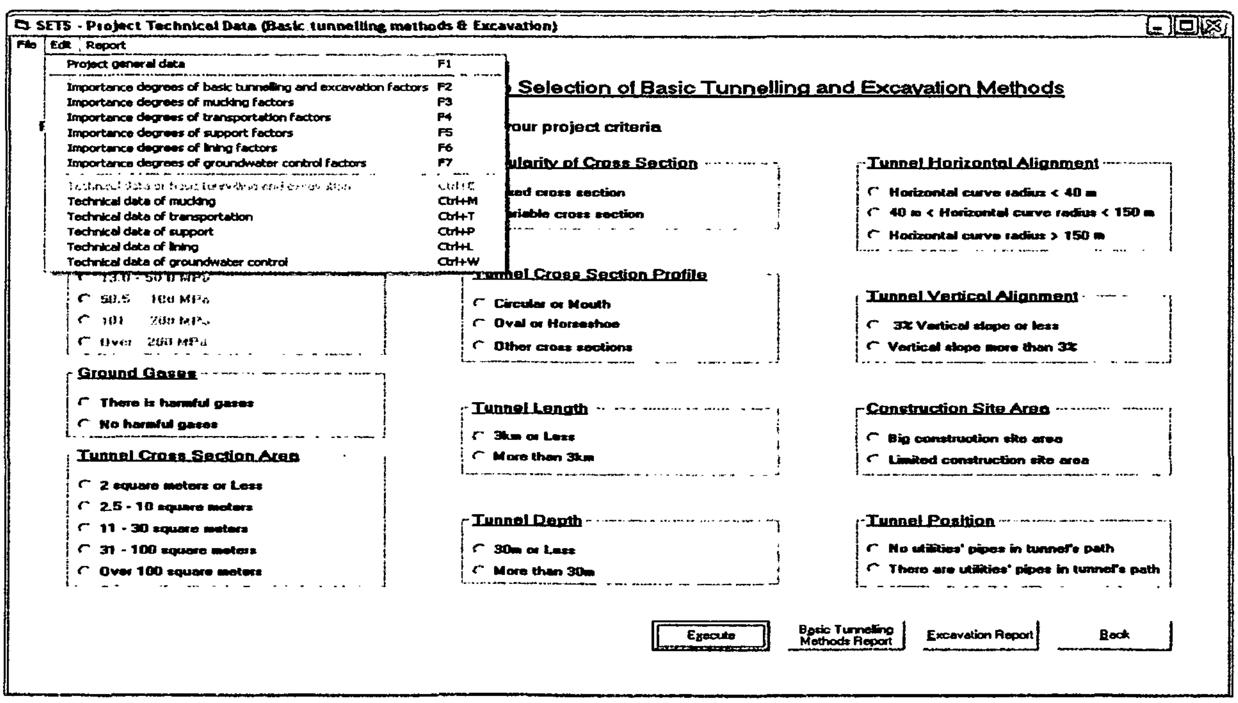


Figure 5.17 Submenu of option *"Edit"*

Edit submenu that shown in figure 5.17 has the same options like edit submenus of previous screens, but the option of this screen will be in grey and it is disabled.

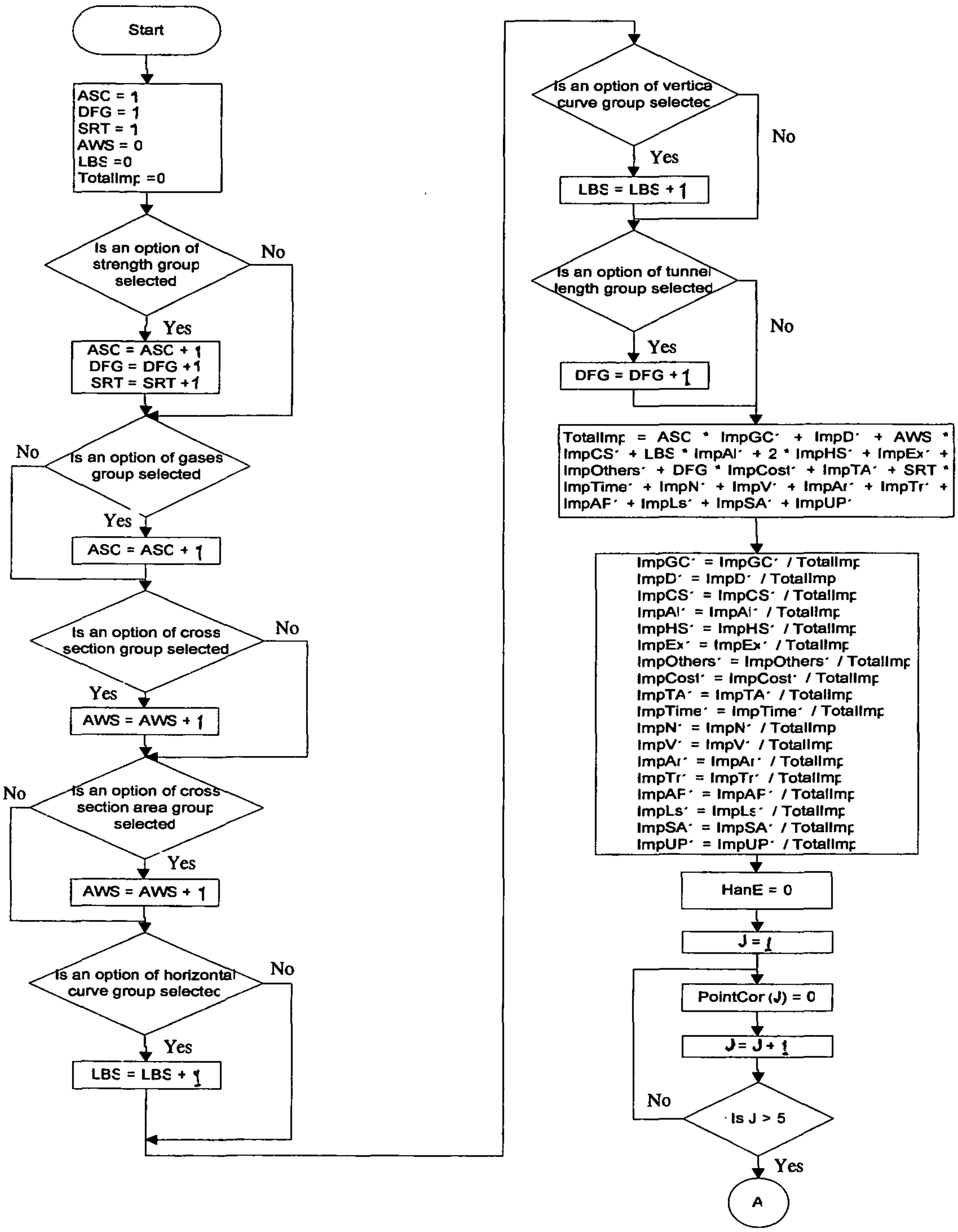


Figure 5.18a Chart of calculations of basic tunnelling & excavation methods efficiencies

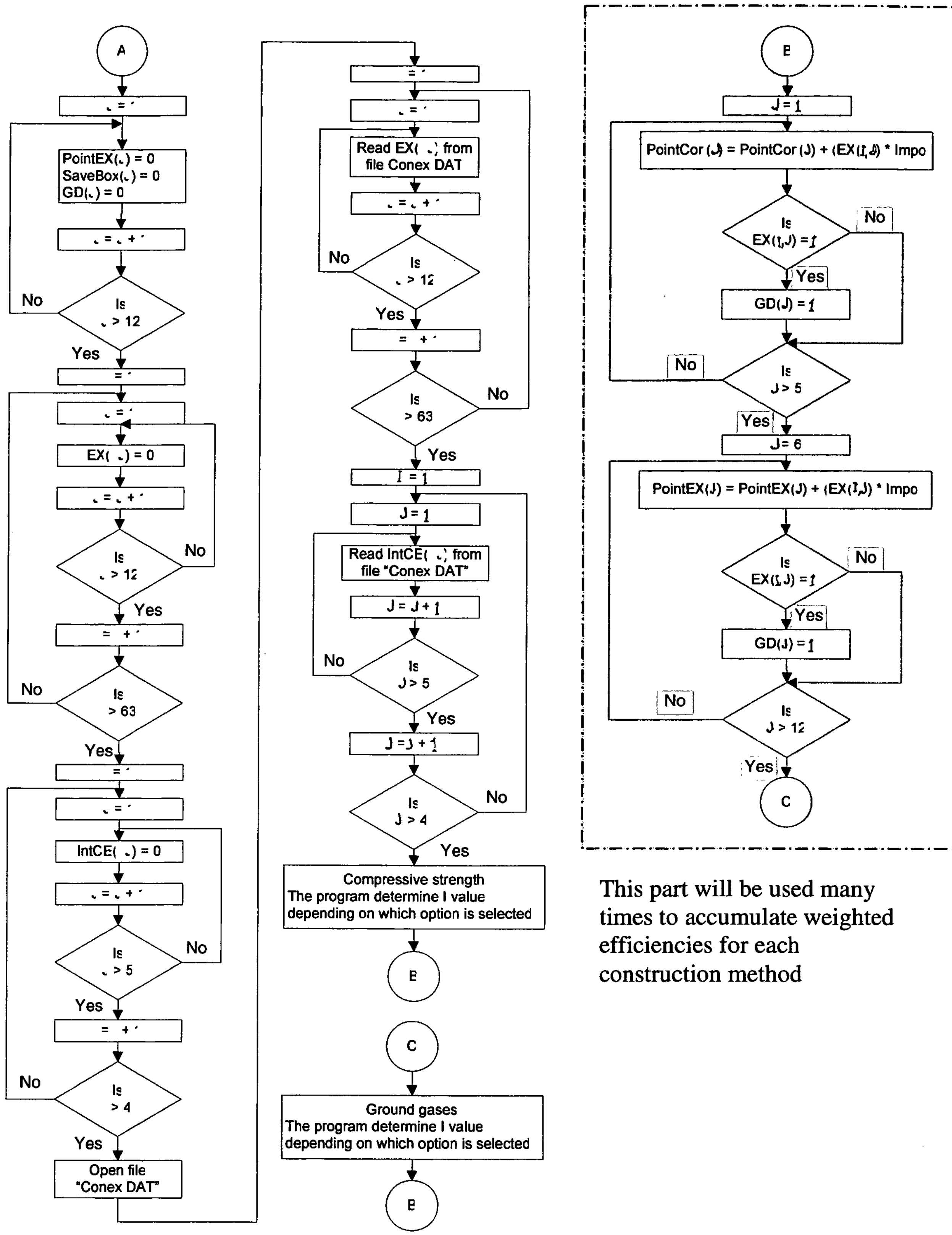


Figure 5.18b Chart of calculations of basic tunnelling & excavation methods efficiencies

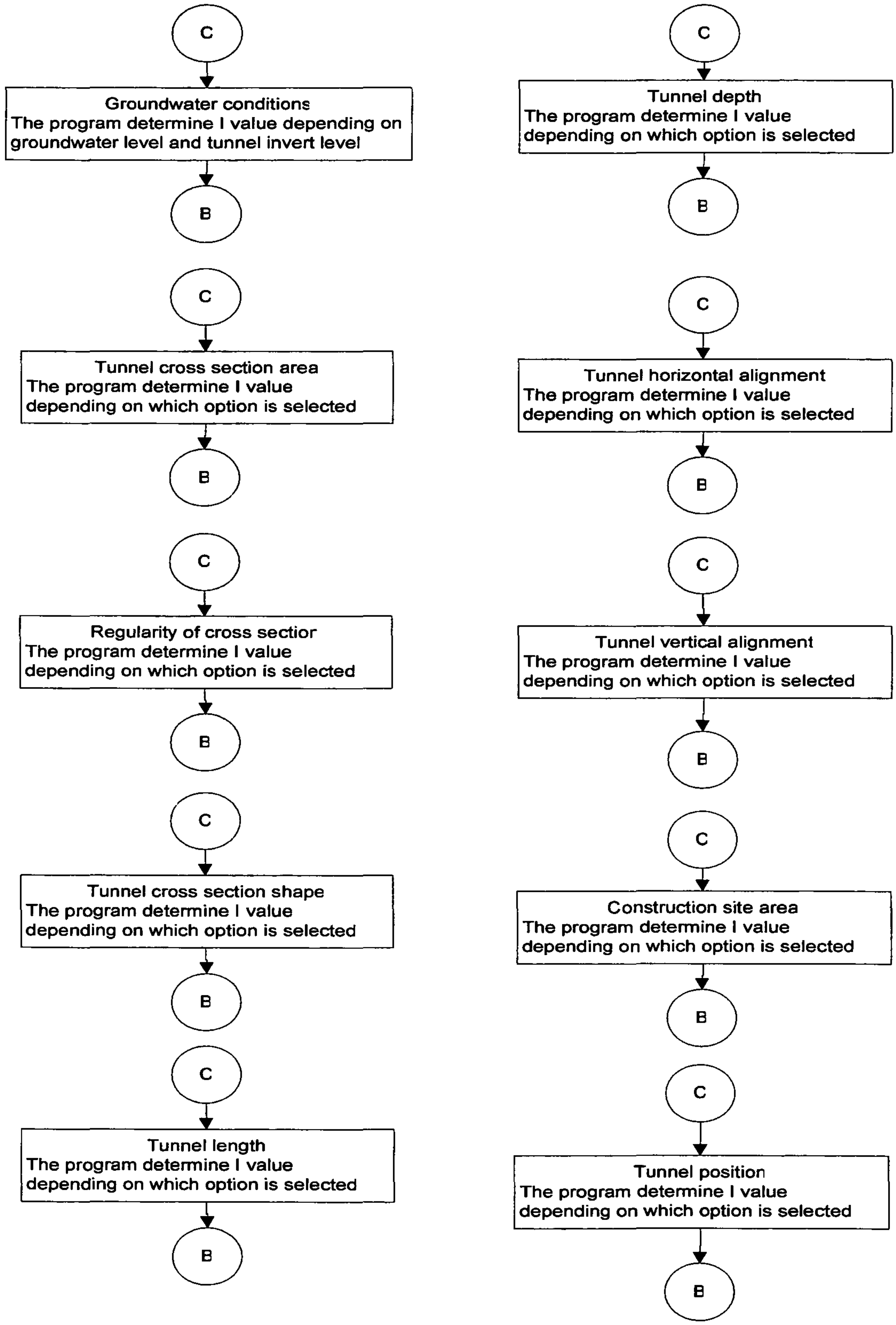


Figure 5.18c Chart of calculations of basic tunnelling & excavation methods efficiencies

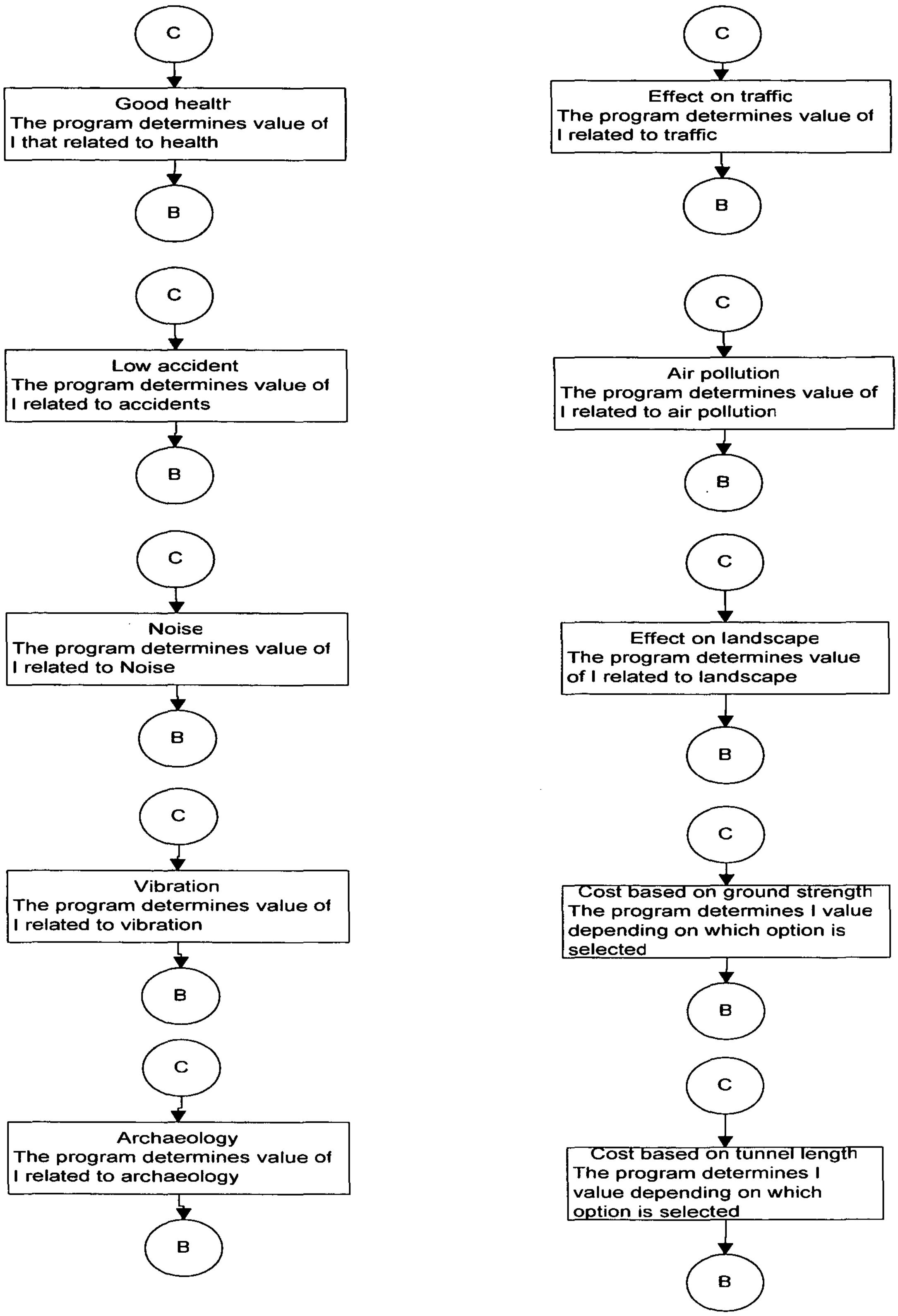


Figure 5.18d Chart of calculations of basic tunnelling & excavation methods efficiencies

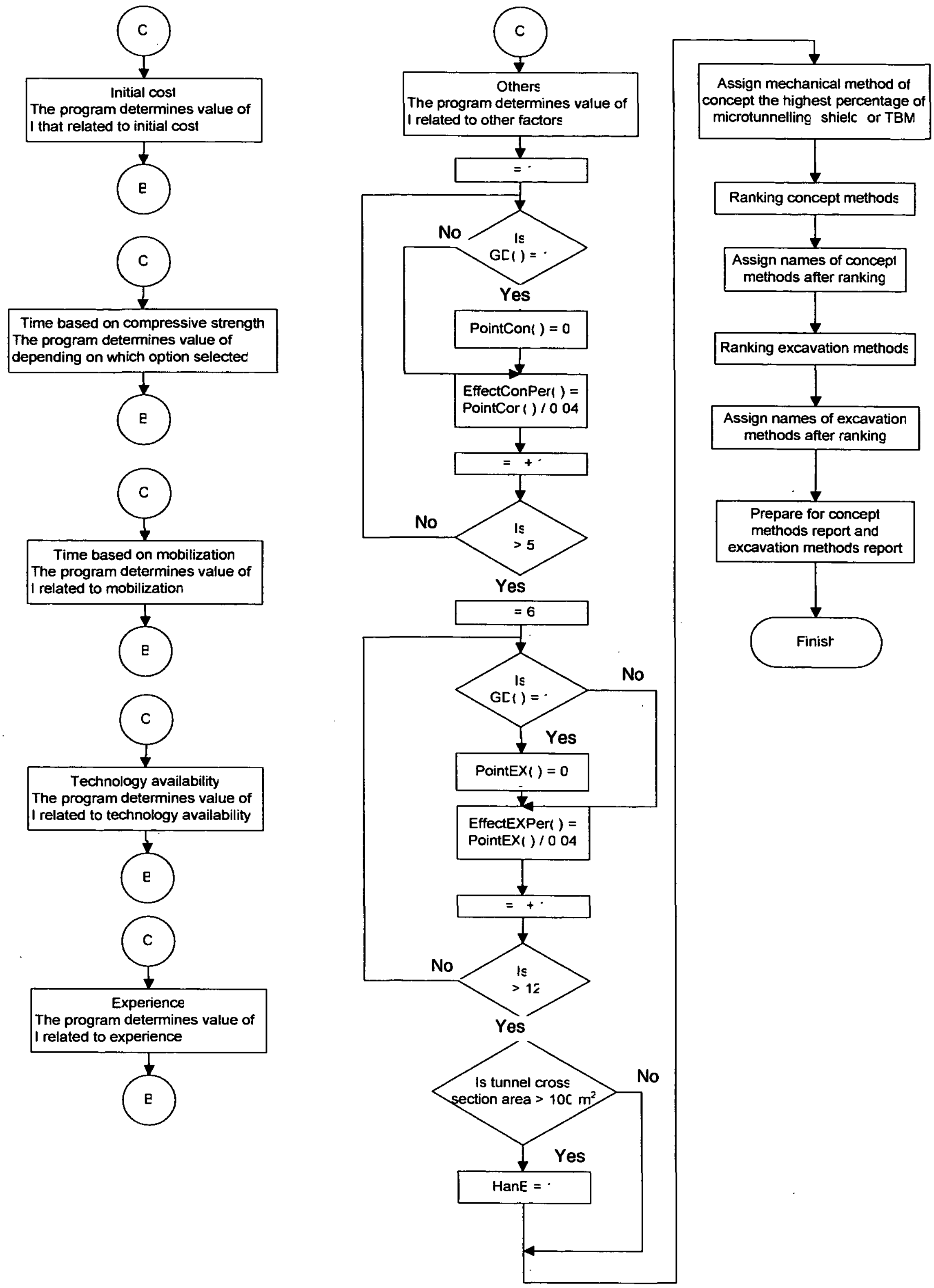


Figure 5.18e Chart of calculations of basic tunnelling & excavation methods efficiencies

After selecting technical data that represent the project, the user clicks button *"Execute"* to start calculations of the basic tunnelling and excavation methods efficiencies.

Flow chart in figure 5.18 shows the logic used in the program for calculations. The program will start to calculate the importance percentage of each controlling factor related to other factors. Efficiency degrees in basic tunnelling methods and excavation methods matrix (appendix "A") are written in a file "Conex.Dat". The program will open this file to read values of *"EX(I,J)"*. Efficiency degrees that the user may feed the program with them for controlling factors *"Technology availability"*, *"Experience"*, or *"Others"* will be assigned also to variables *"EX(I,J)"* to be used during calculations.

This part of the flow chart that is inside the doted box is used to accumulate weighted efficiency of each construction method. Controlling factors shown in (figure 5.18c, d, and e) are connected with this part of the program with two connectors *"B"* and *"C"*.

Each option in the screen will assign a value to variable *"I"*. Value of *"I"* will be the number of line that has efficiency degrees related to that option in file *"Conex.Dat"*. The program uses these efficiency degrees with the importance degree of the controlling factor to estimate weighted efficiencies. The variable *"Impo"* in the flow chart will have each time a different value, because it will have each time the importance degree of the controlling factor involved in calculations.

If the efficiency degree of a method for one or more of controlling factors is "1" then the value of variable *"GD(J)"* will be "1". The accumulated weighted efficiencies for these methods will be deleted and their value will be zero.

The variable that has the accumulated weighted efficiencies of basic tunnelling methods is called *"PointCon(J)"* and the variable that has the accumulated weighted efficiencies of excavation methods is called *"PointEX(J)"*.

The program in the next step starts to calculate efficiency percentage of each method by dividing the accumulated weighted efficiencies of the method by 0.04. Efficiency percentages of basic tunnelling methods are saved in the program under a variable called *"EffectConPer(J)"*. *"EffectEXPer(J)"* is the variable that keeps the efficiency percentages of excavation methods.

The program will rank efficiency degrees of micro-tunnelling machine, shield machine and TBM of excavation to assign the highest efficiency percentage of them to mechanical method of basic tunnelling activity. Then the program starts to rank basic tunnelling methods and assign names to them. Next step is raking the excavation methods and assign names to them.

When user clicks button *"Basic tunnelling methods report"*, the program starts to show a report about basic tunnelling methods and their efficiency percentages ranked in descending order. Clicking button *"Excavation Report"* will activate a screen that shows a report about excavation methods.

As shown in figures 5.19 and 5.20 the screen of the report has three options. *"File"* has submenu which include option *"End"* to terminate the program. *"Save"* button saves the report in edit format. The third option is *"Print"* which enables the user to save the report as "pdf" file that can be opened using acrobat reader. User can print the report using the same option. The report shows project name and owner name at the top. *"Back"* button will hide the screen and go to previous one.

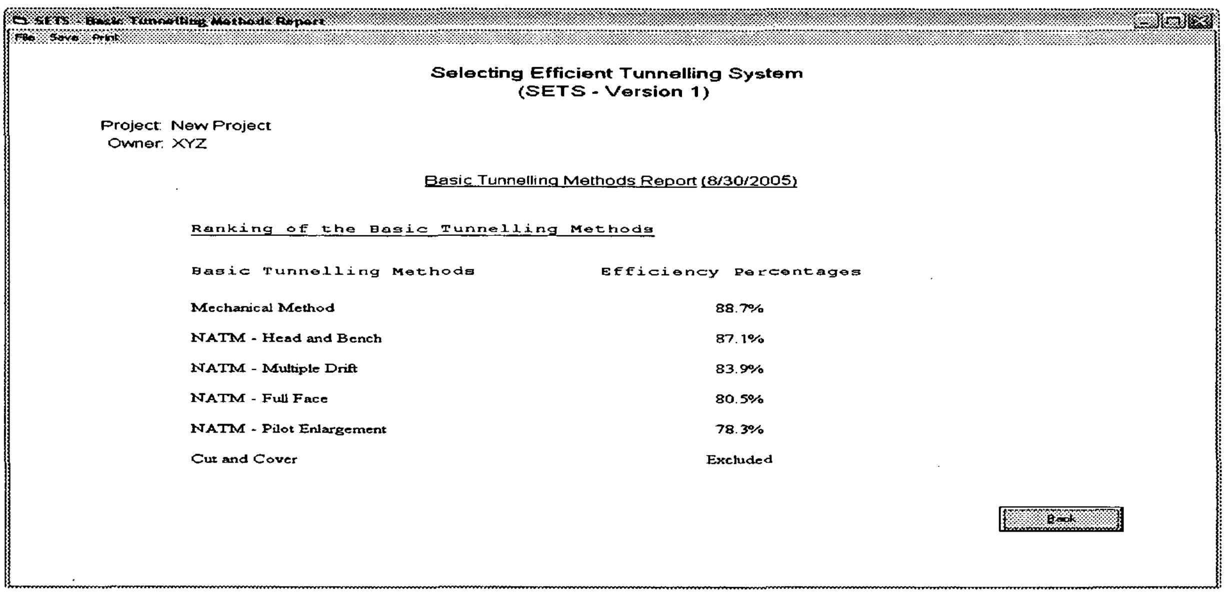


Figure 5.19 Basic tunnelling methods report

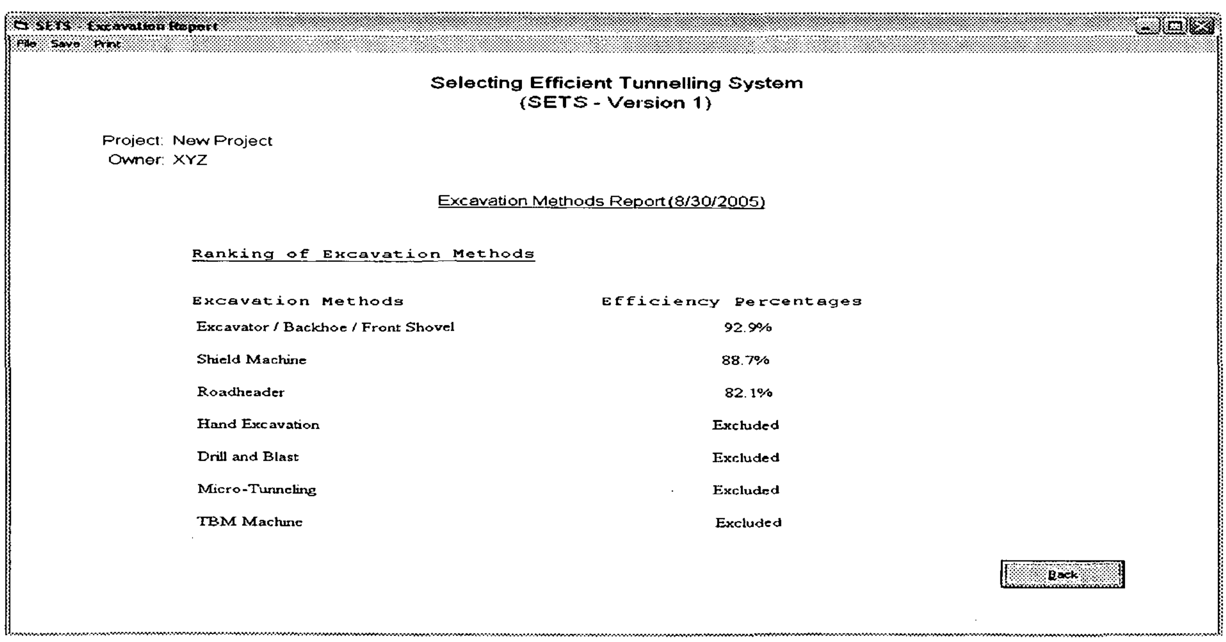


Figure 5.20 Excavation methods report

Clicking button *"Back"*, in screen *"Project Technical Data (Basic tunnelling methods & Excavation)"* (figure 5.17), will hide the screen and go back to screen *"Tunnelling activities and methods"*. From this screen, the user can select the next tunnelling activity to start enter its data.

5.4.2 Mucking activity

The user can start to deal with mucking activity by clicking button *"Mucking"* in screen *"Tunnelling activities and methods"* (see figure 5.7). By clicking this button, screen *"Importance degrees (Mucking activity)"* will show up. This screen contains 3 technical controlling factors and another 3 of non-technical controlling factors. When screen starts the cursor will be in the first field and other fields will have zero values (see figure 5.21).

"Efficiency degrees" button is disabled because importance degree of *"Others"* controlling factor is zero. When user assigns a value to *"Others"* controlling factor not zero this button will be available. Clicking this button will display screen *"Efficiency degrees of mucking methods"*. Figure 5.24 shows this screen.

The user can move from field to another by using tab button or clicking the field with the mouse. When cursor move to new field the value of the field will be deleted and the user can insert new value.

As written at the top of the screen, importance degrees should be in the range from 0 to 10. Non-numeric values are not accepted. The program will give two messages in case of wrong values. These two messages are similar to those messages in figures 5.11 and 5.12. Figure 5.22 shows the edit submenu.

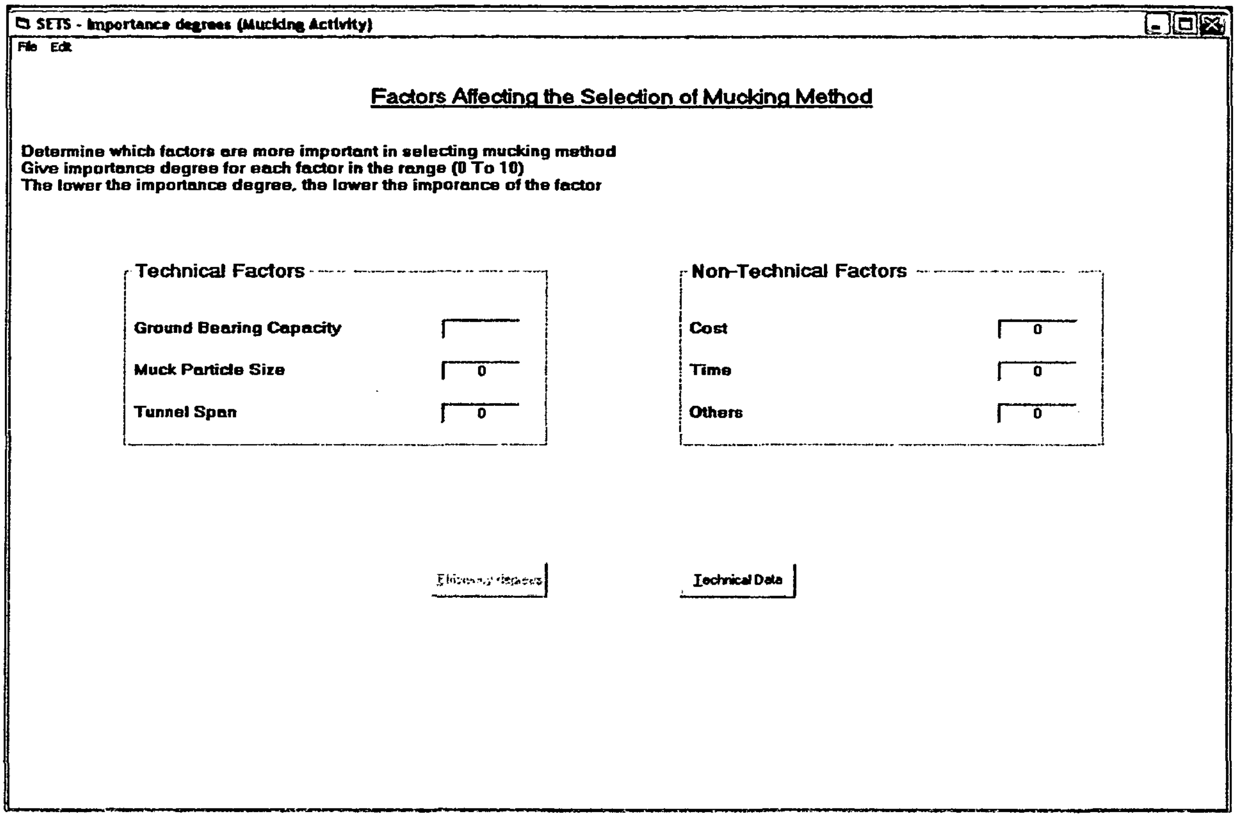


Figure 5.21 *"Importance degree (Mucking activity)"* screen

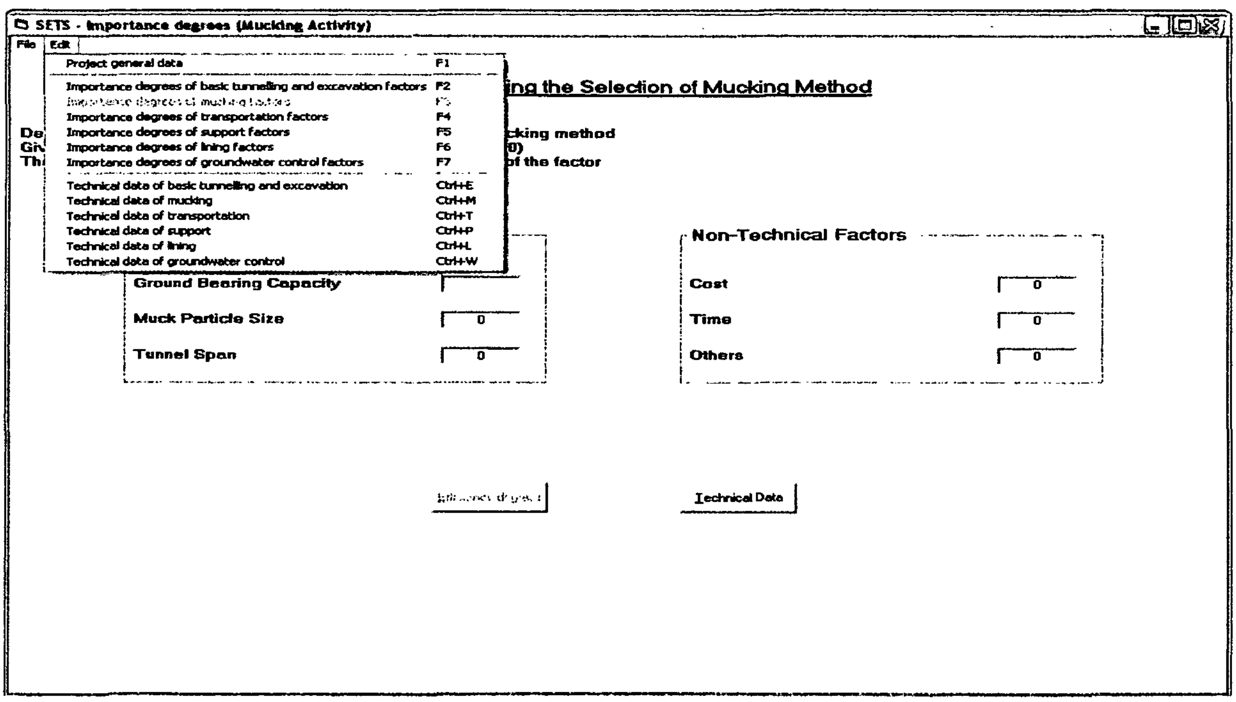


Figure 5.22 Edit submenu in screen *"Importance degree (Mucking activity)"*

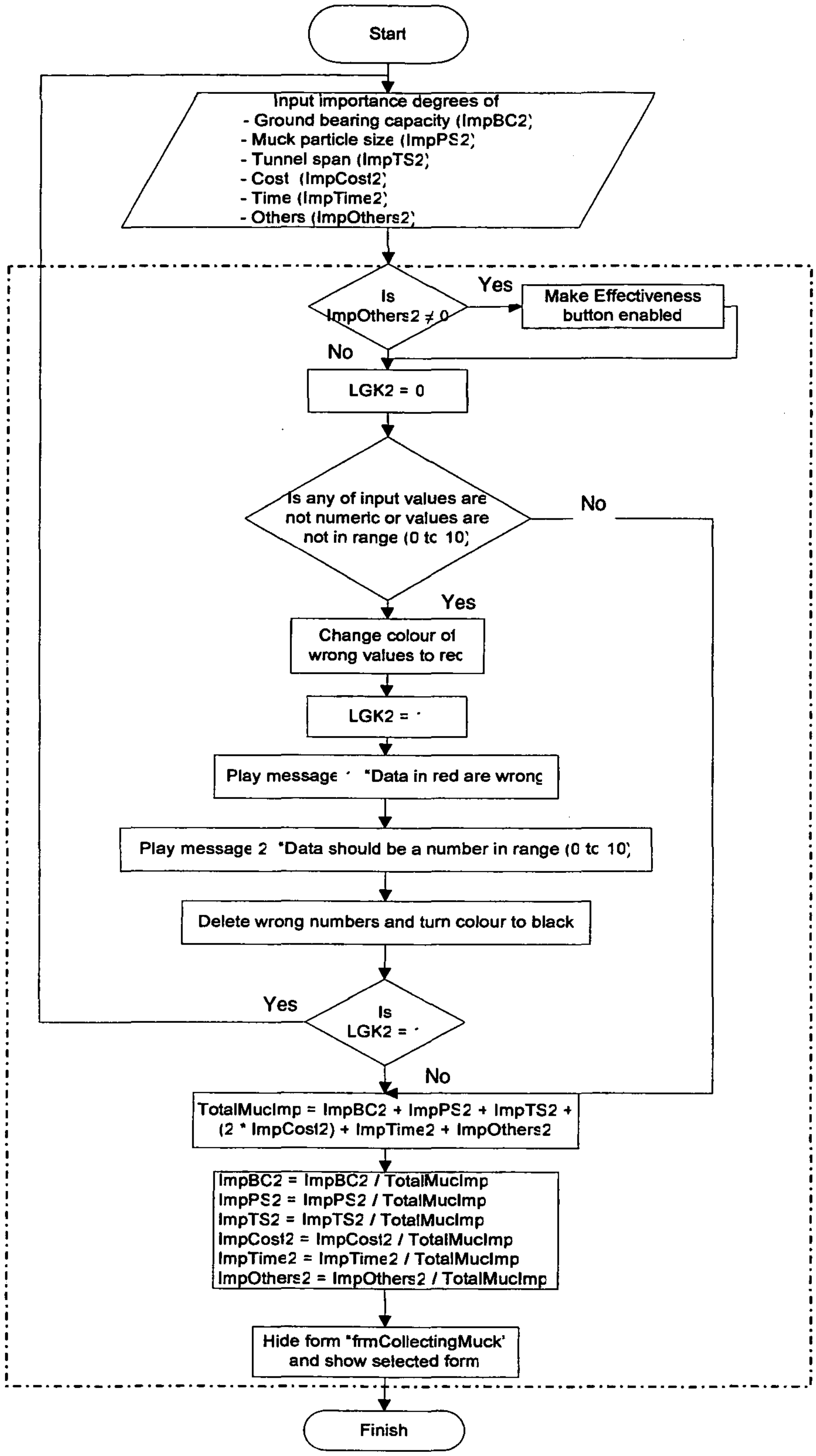


Figure 5.23 Calculations of importance percentages (Mucking activity)

Edit submenu is divided into three parts. First part is containing the option of displaying *"Project general data"* screen. The second part contains options of displaying importance degrees screens of tunnelling activities. Options of displaying technical data screens of tunnelling activities are grouped in the third part of edit submenu. In figure 5.22 the second option of the second group is not available.

In screen *"Importance degree (Mucking activity)"*, shortcut of button *"Efficiency degrees"* is *"Alt + e"* and shortcut of button *"Technical data"* is *"Alt + t"*.

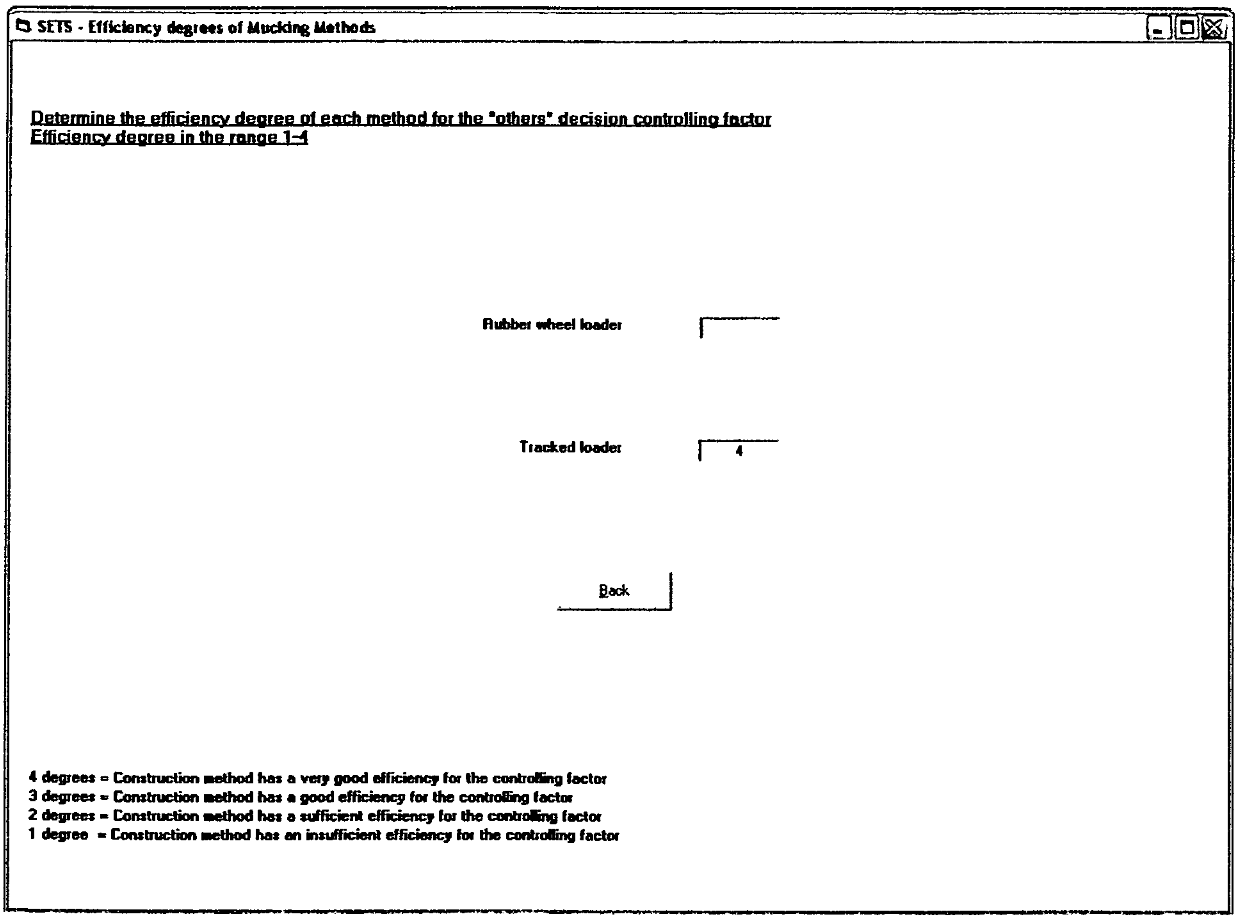


Figure 5.24 *"Efficiency degrees of mucking methods"* screen

Flow chart in figure 5.23 describes calculation procedures that the program does after feeding it by importance degrees of controlling factors that control mucking methods. Processes in the doted box will be done when user clicks any button to move forward for next screen. It is shown how the program checks values of importance degrees and how to demonstrate the messages to user.

When screen *"Efficiency degrees of mucking methods"* starts efficiency degrees assigned to mucking methods are "4". Description of the meaning of each degree is illustrated at the end of the screen. User of the program can insert new values, in range from 1 to 4, for efficiency degrees to be used with controlling factor *"Others"* during calculations.

Clicking the button *"Back"* will hide *"Efficiency degrees of mucking methods"* screen and the program will go back to screen *"Importance degree (Mucking activity)"*.

In screen *"Importance degree (Mucking activity)"* (figure 5.22), the user clicks button *"Technical data"* for moving to screen *"Project technical data (Mucking)"*. User will start to determine the technical data that matches with his project in this screen.

Figure 5.25 shows screen *"Project technical data (Mucking)"*. As shown in figure 5.25 there are three technical factors the program is dealing with them to determine the efficient mucking method. Technical factors are *"Ground bearing capacity"*, *"Muck particle size"*, and *"Tunnel span"*.

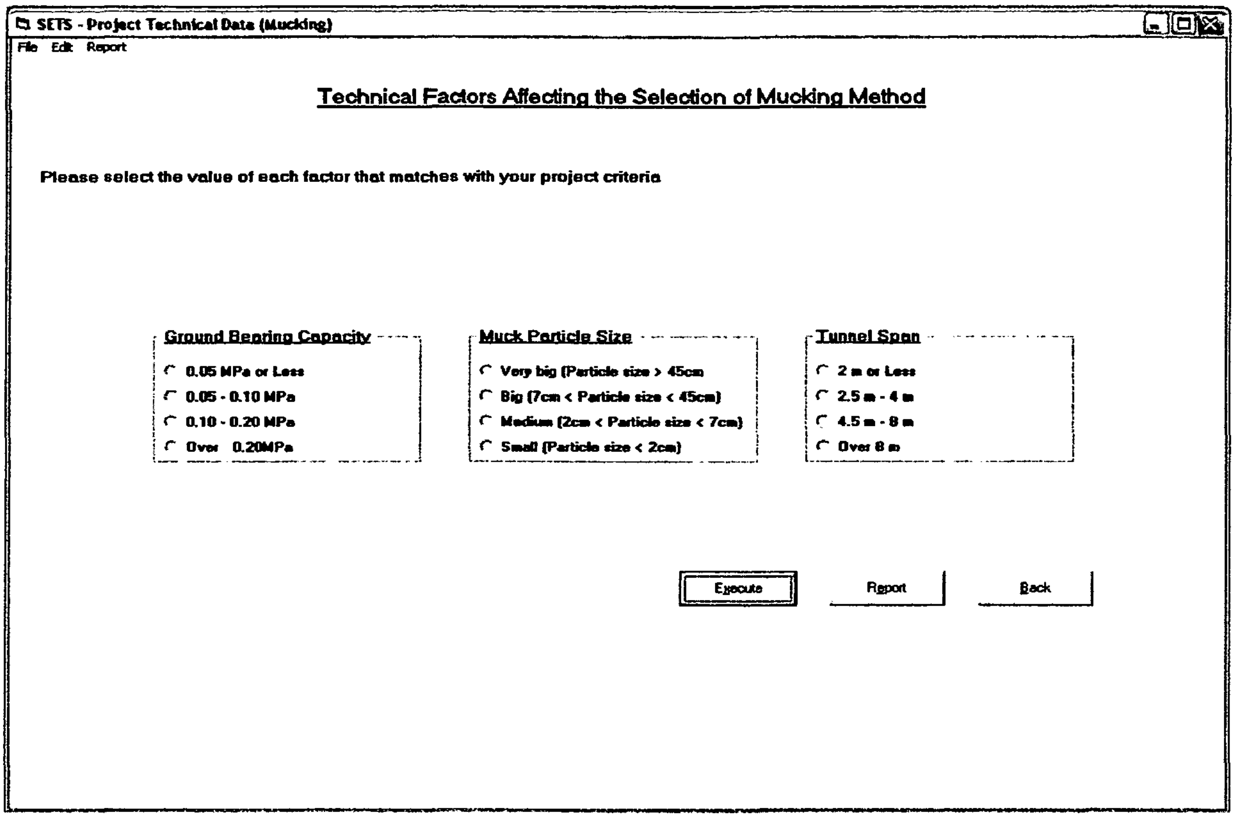


Figure 5.25 Screen *"Project technical data (Mucking)"*

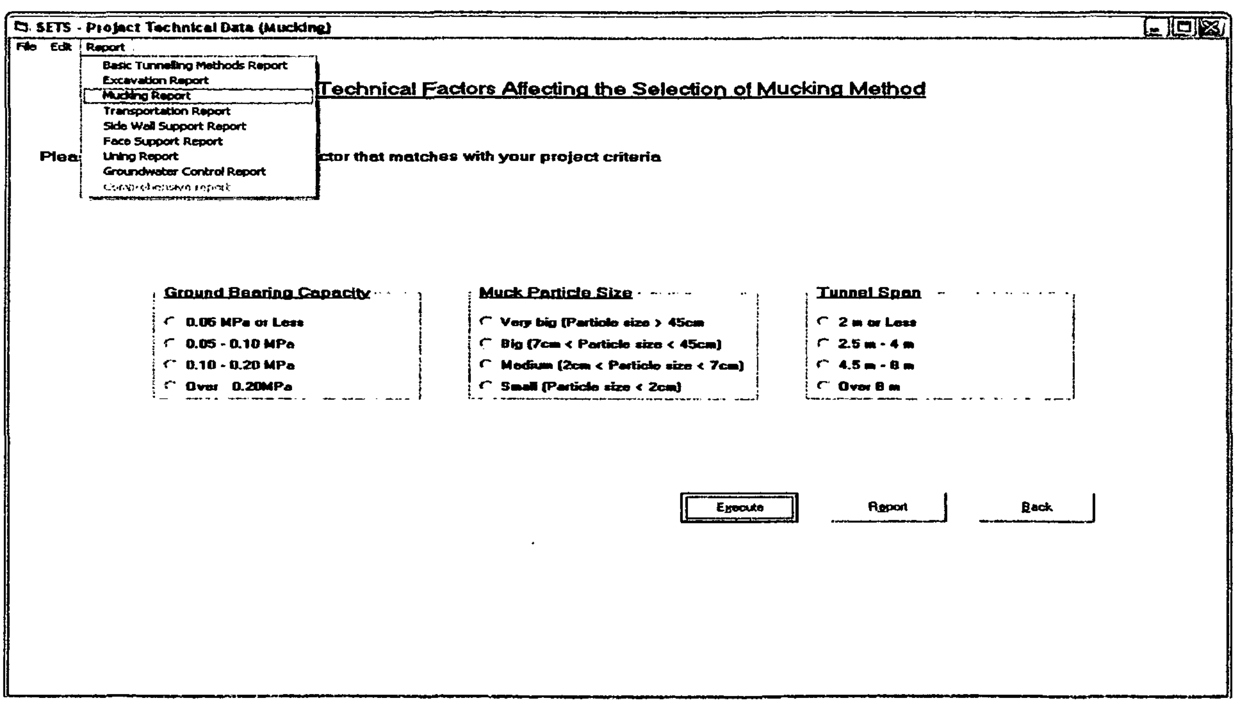


Figure 5.26a Submenu of *"Report"* option

Technical data in this screen should match with technical data for basic tunnelling and excavation activity. For instance, tunnel span value should be matched with both the values of tunnel cross section area that the user fed the program by it for basic tunnelling and excavation activity and value of tunnel height in screen *"Project general data"*. Screen *"Project technical data"* has three buttons *"Execute"*, *"Report"*, and *"Back"*. It has three menu options *"File"*, *"Edit"* and *"Report"* as well (see figures 5.25 and 5.26). Figure 5.27 shows flow chart that illustrates the logic and the procedures of calculating mucking methods efficiency percentages and how the program ranks them.

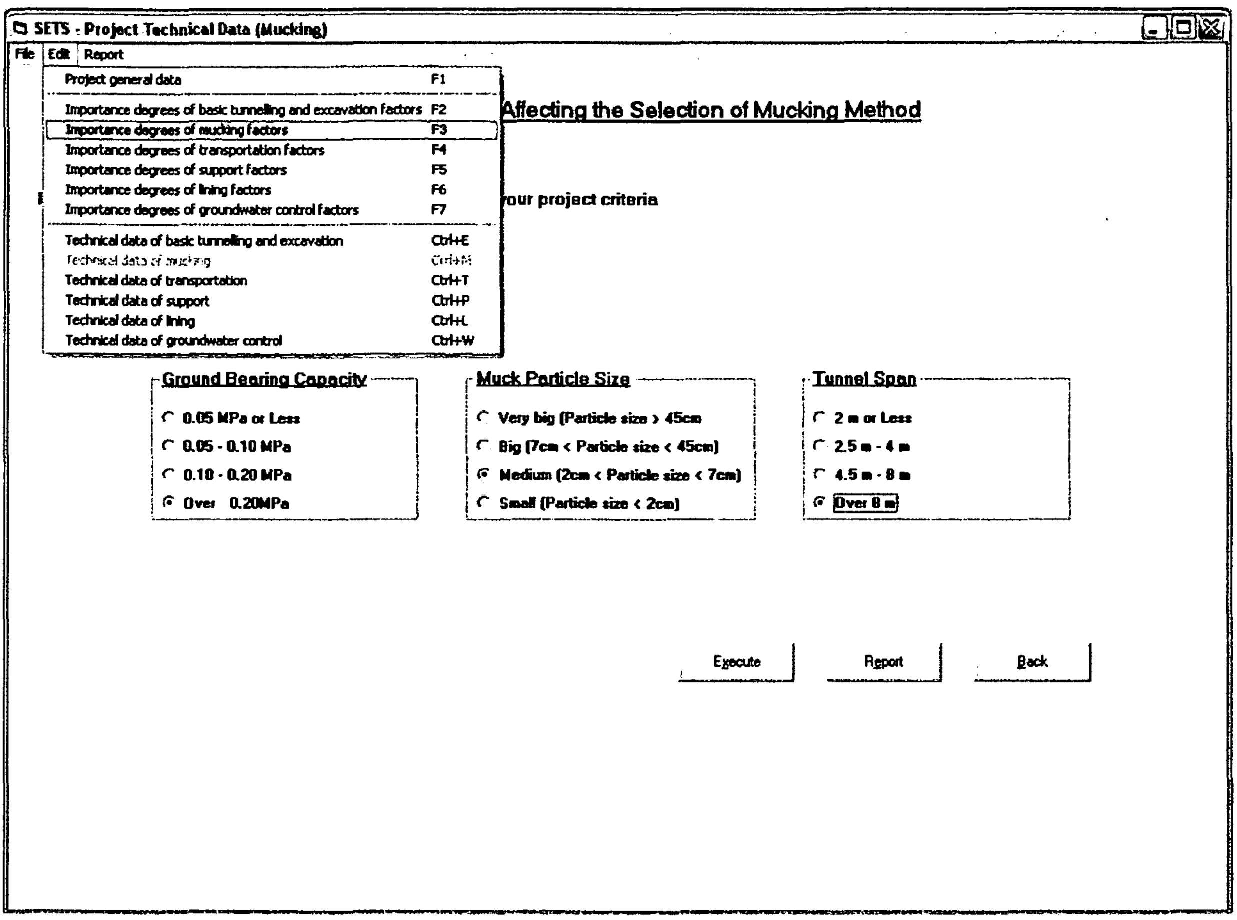


Figure 5.26b Submenu of *"Edit"* option

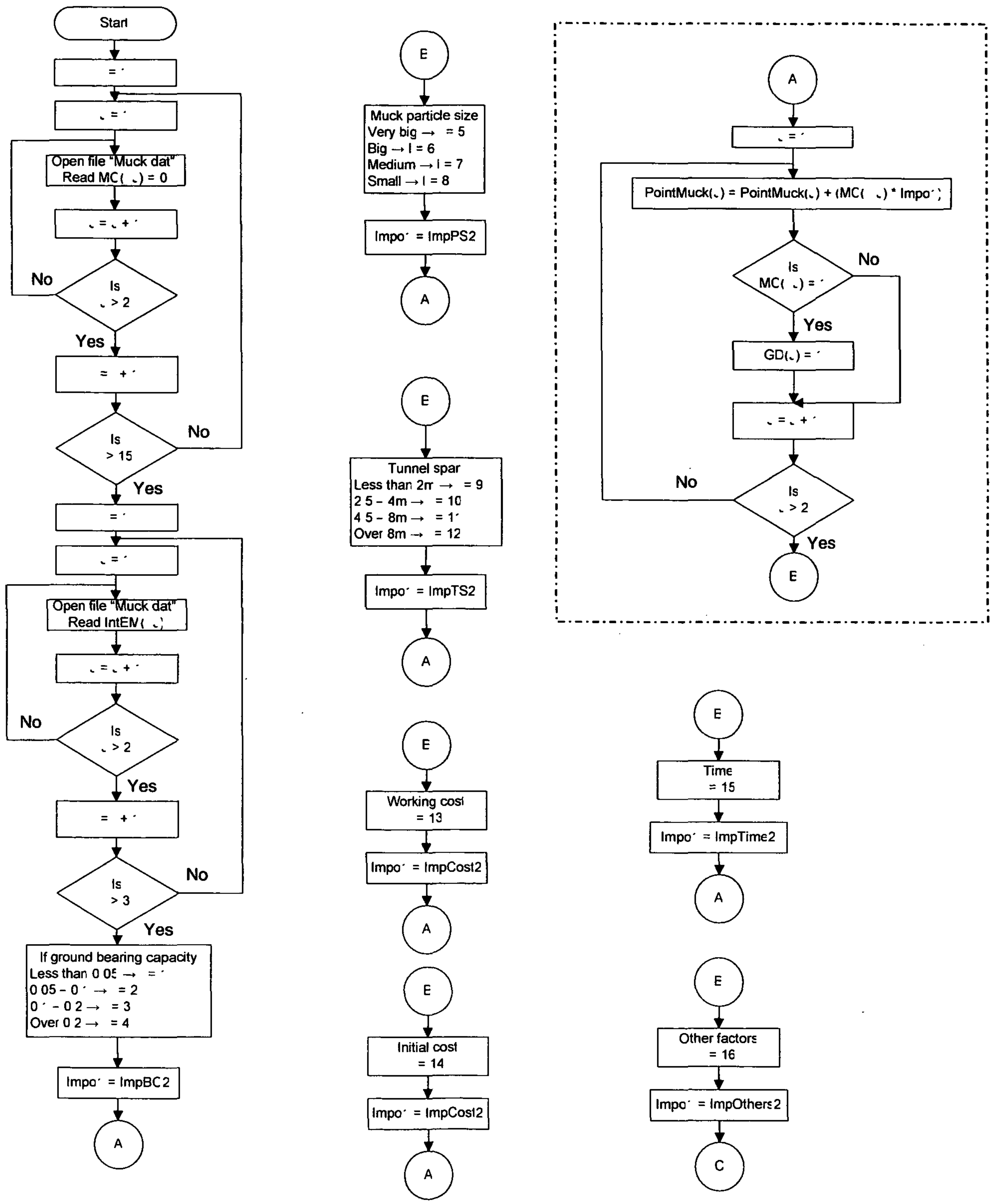


Figure 5.27a Calculation procedures for mucking methods' efficiencies

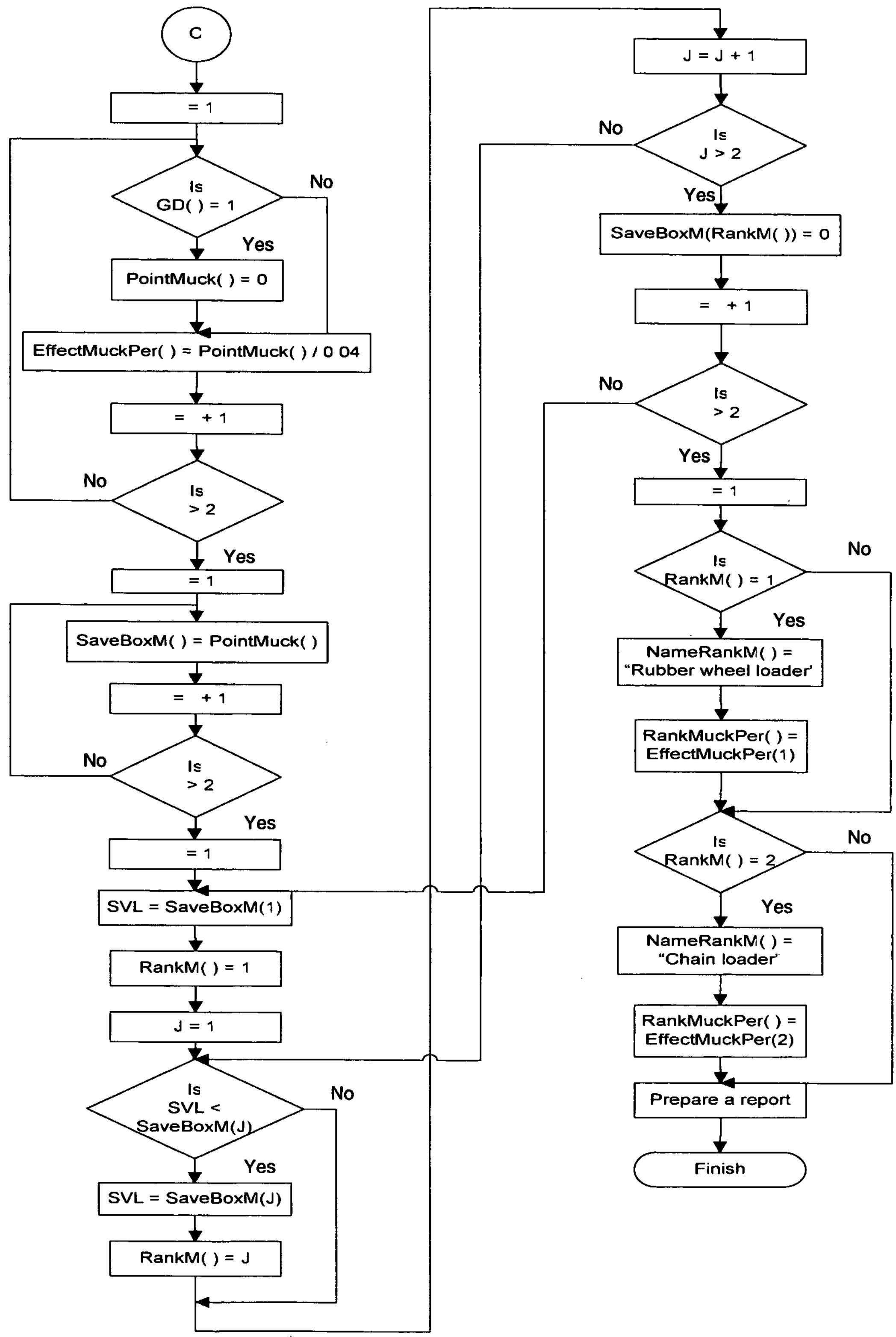


Figure 5.27b Calculation procedures for mucking methods' efficiencies

The program opens file *"Muck.dat"* to read efficiency degrees that shown in average matrices. Each line of file *"Muck.dat"* represents efficiency degrees for one option in screen *"Project technical data (Mucking)"*. For instance, efficiency degrees, when ground bearing capacity equals to 0.05 MPa or less, is written as the first line in file *"Muck.dat"*. Efficiency degrees will be assigned to variable "MC(I,J)". "I" represents line number and "J" is the mucking method. The program will read also values of "IntEM(I,J)", which are efficiency degrees of excavation and mucking methods working together.

When user selects options for technical factors, "I" will get a value. This value will be the line number that has efficiency degrees of that option. After determining value of "I"" the program will start to calculate weighted efficiencies for mucking methods using efficiency degrees and importance percentage that calculated in figure 5.23. This part of flow chart in figure 5.27 is used to calculate weighted efficiencies of mucking methods, so it will be called for each controlling factor.

If a mucking method is excluded because of one controlling factor or more, value of variable *"GD(J)"* will be "1". The program will cancel weighted efficiencies of that method. Efficiency percentages of methods will be calculated by dividing weighted efficiencies of the method by 0.04. This value is the highest value that a method can get. The final step of calculations is ranking the methods and giving names for them.

Clicking button *"Execute"* in screen *"Project technical data (Mucking)"* will start to make calculations as shown in figure 5.27. Button *"Report"* will display a report screen that shown in figure 5.28. Button *"Back"* will display the main screen of activities *"Tunnelling activities and methods"*.

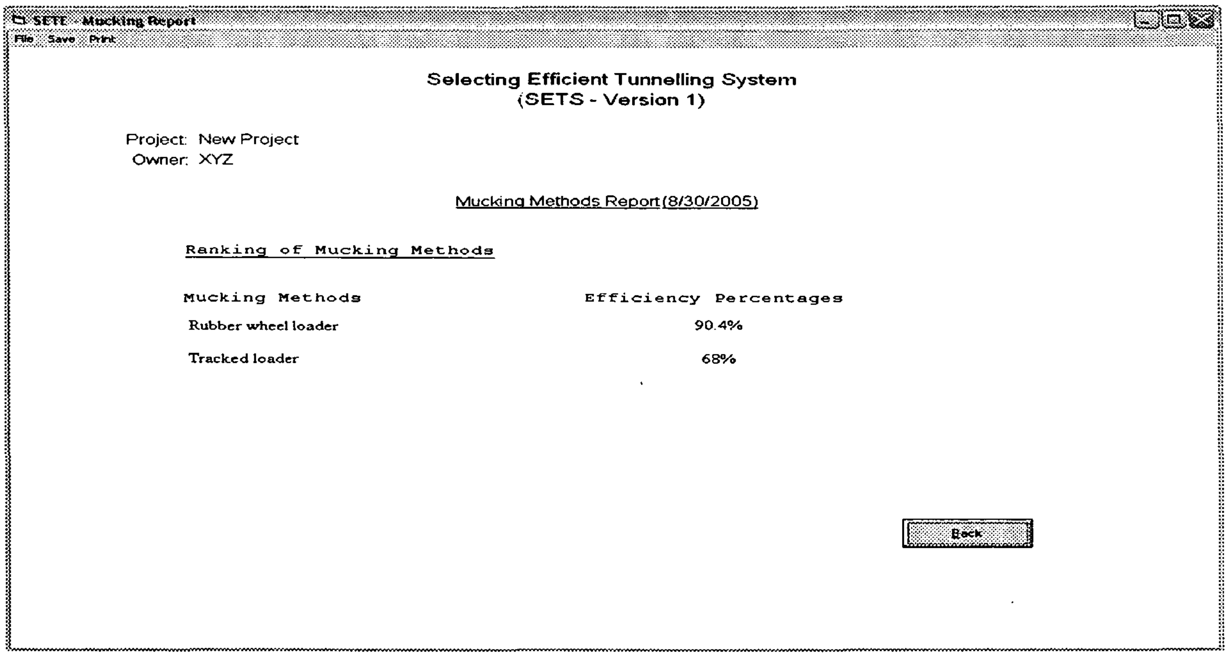


Figure 5.28 Report screen of mucking methods

Report screen show the program name and its version. Project name and owner name is written at the top of the screen. User of "SETS" can save the report in edit format on hard drive of the computer "C" using option *"Save"*. Saving the report as "pdf" file and printing it can be done using option *"Print"*. Button *"Back"* will hide the report screen and screen of technical data will be displayed. The user can use shortcut of button *"Back"* which is *"Alt + B"*.

5.4.3 Transportation activity

To start feeding the program with data concerning transportation activity, the user clicks button *"Transportation"* in screen *"Tunnelling activities and methods"*, figure 5.8, or selects the option of transportation importance degrees from edit menu of any screen.

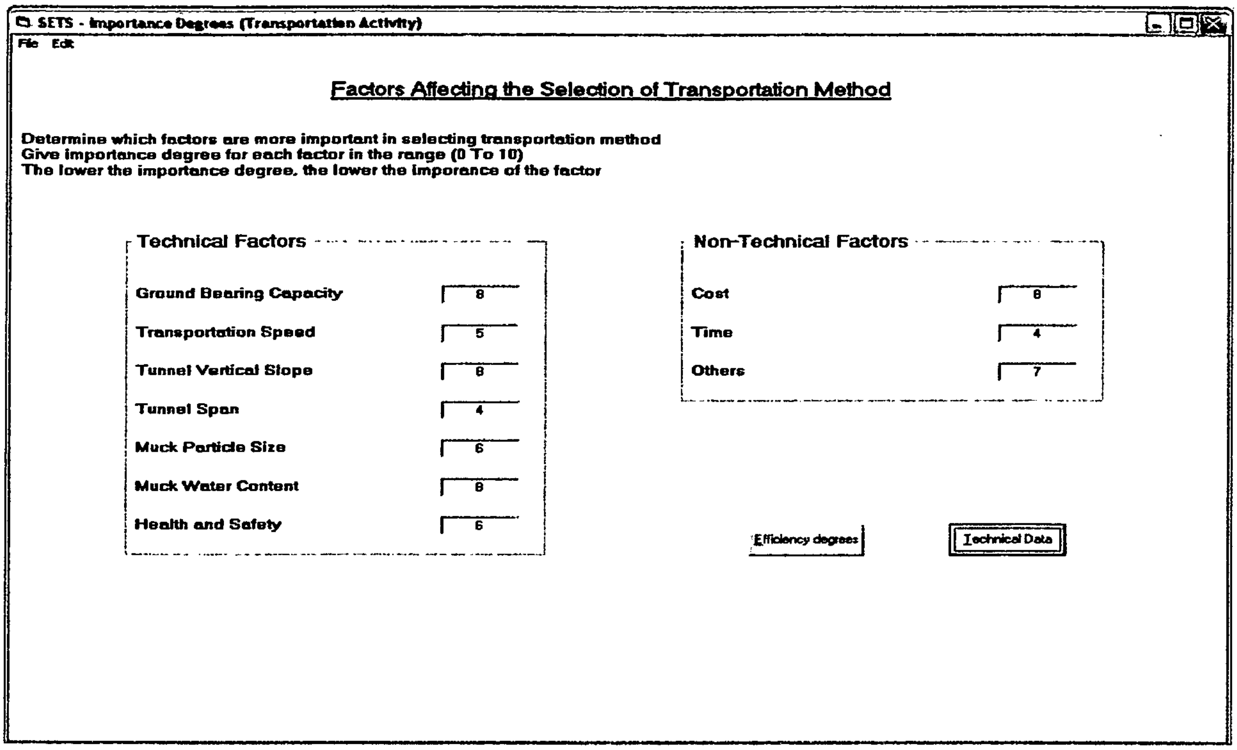


Figure 5.29 *"Importance degrees (Transportation activity)"* screen

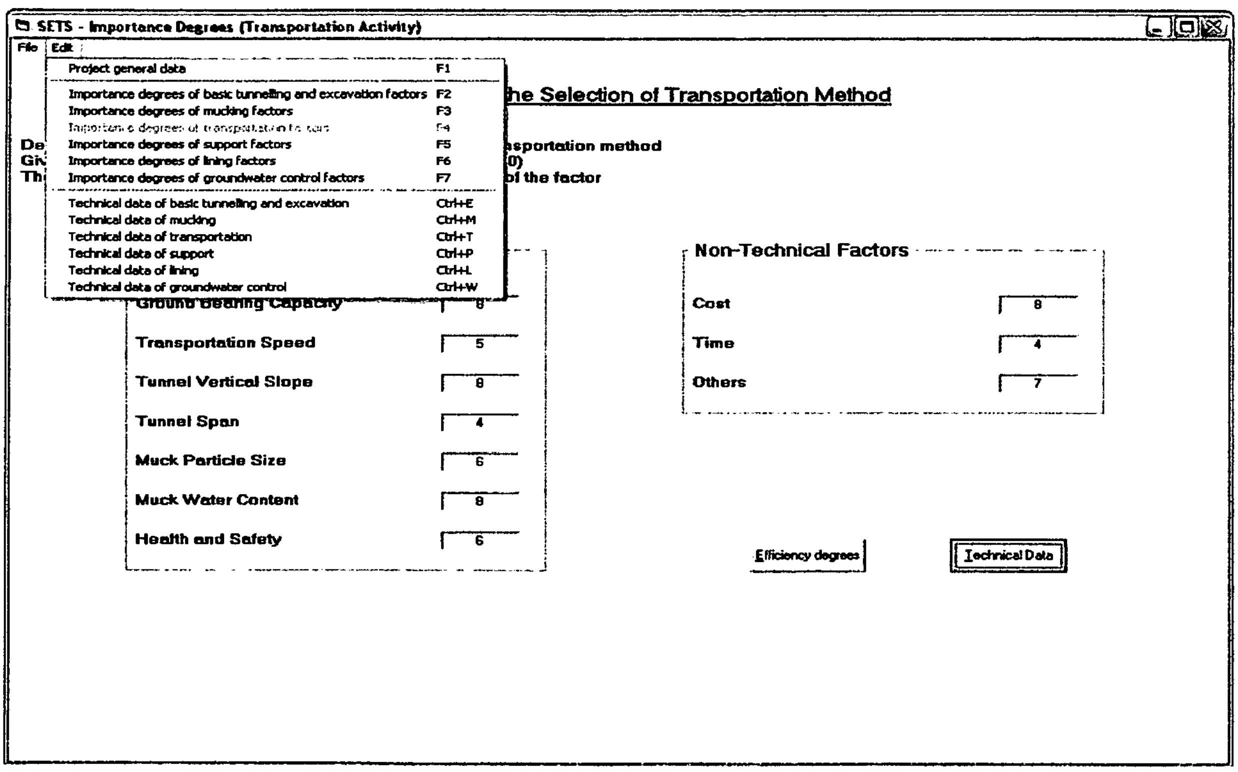


Figure 5.30 Submenu of *"Edit"* option

Figure 5.29 shows importance degrees screen of transportation activity. There are 7 technical controlling factors and 3 non-technical factors for transportation activity. *"Efficiency degrees"* button is available in figure 5.29 because controlling factor *"Others"* has a value bigger than zero. Instructions of how to insert the importance degrees are written at the top of the screen. There are two menu options, which are *"File"* and *"Edit"*. The option *"File"* has submenu option *"End"* which is used to terminate the program. Submenu of *"Edit"* option is the same like *"Edit"* options in previous explained screens (see figure 5.30).

Clicking button *"Efficiency degrees"* will display screen *"Efficiency degrees of transportation methods"*. In this screen, user can insert efficiency degrees of transportation methods for other factor from his point of view. Figure 5.31 shows screen of *"Efficiency degrees of transportation methods"*.

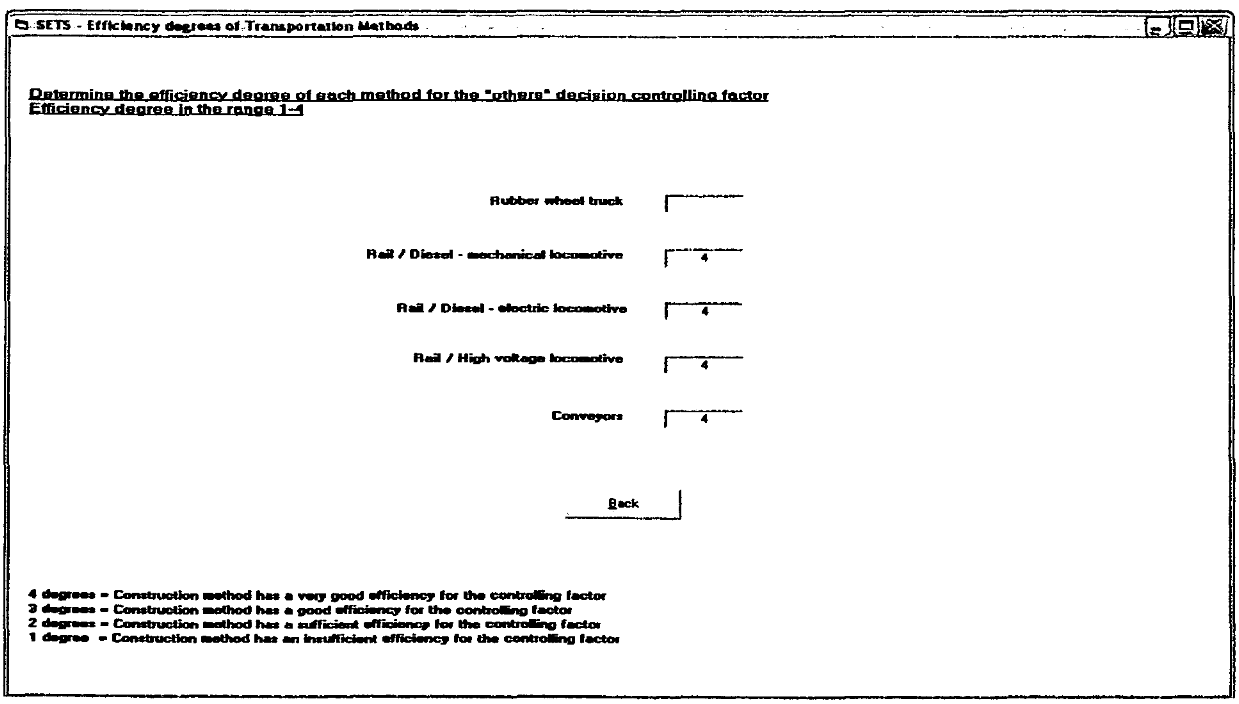


Figure 5.31 Screen of *"Efficiency degrees of transportation methods"*

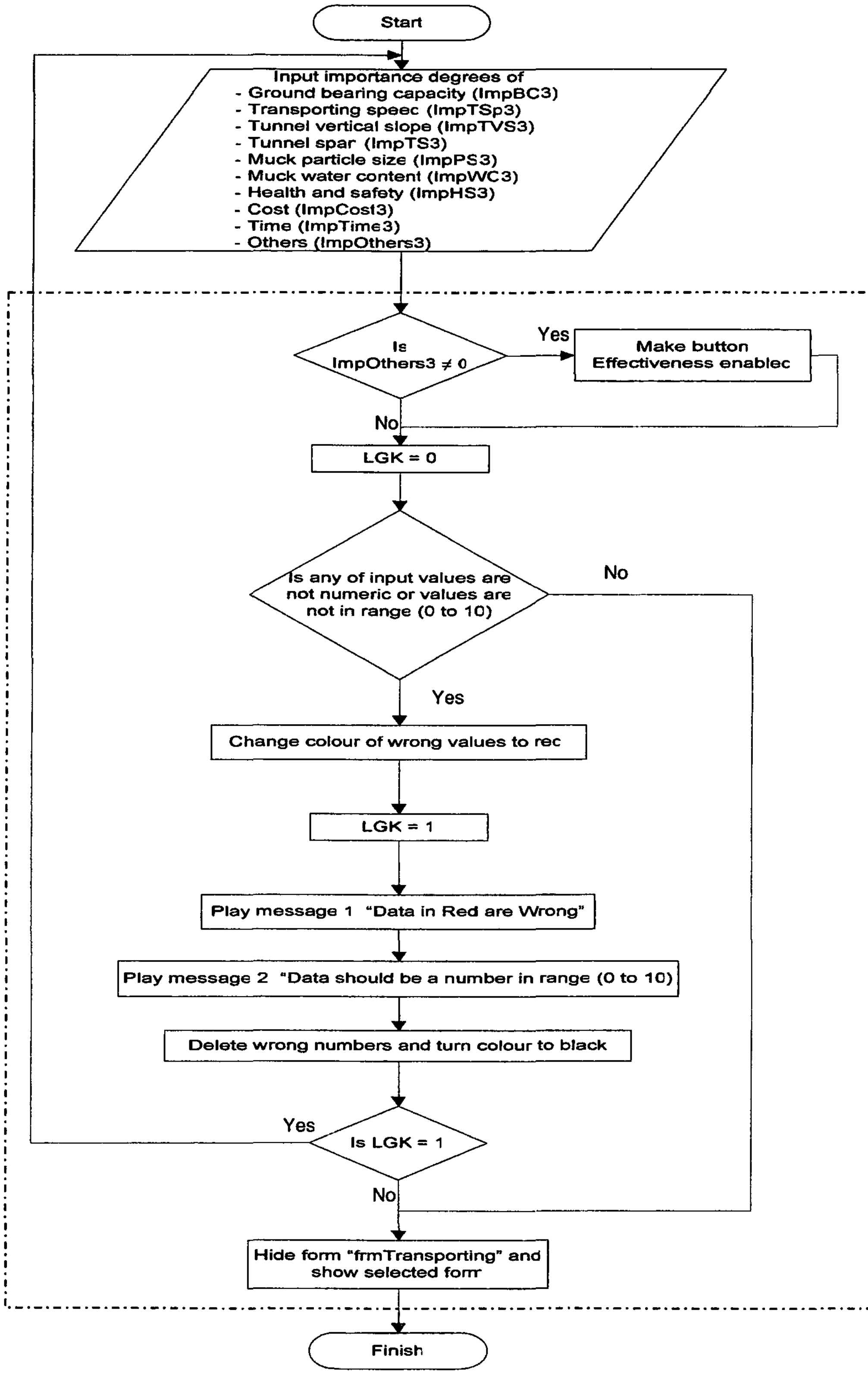


Figure 5.32 Checking values of importance degrees

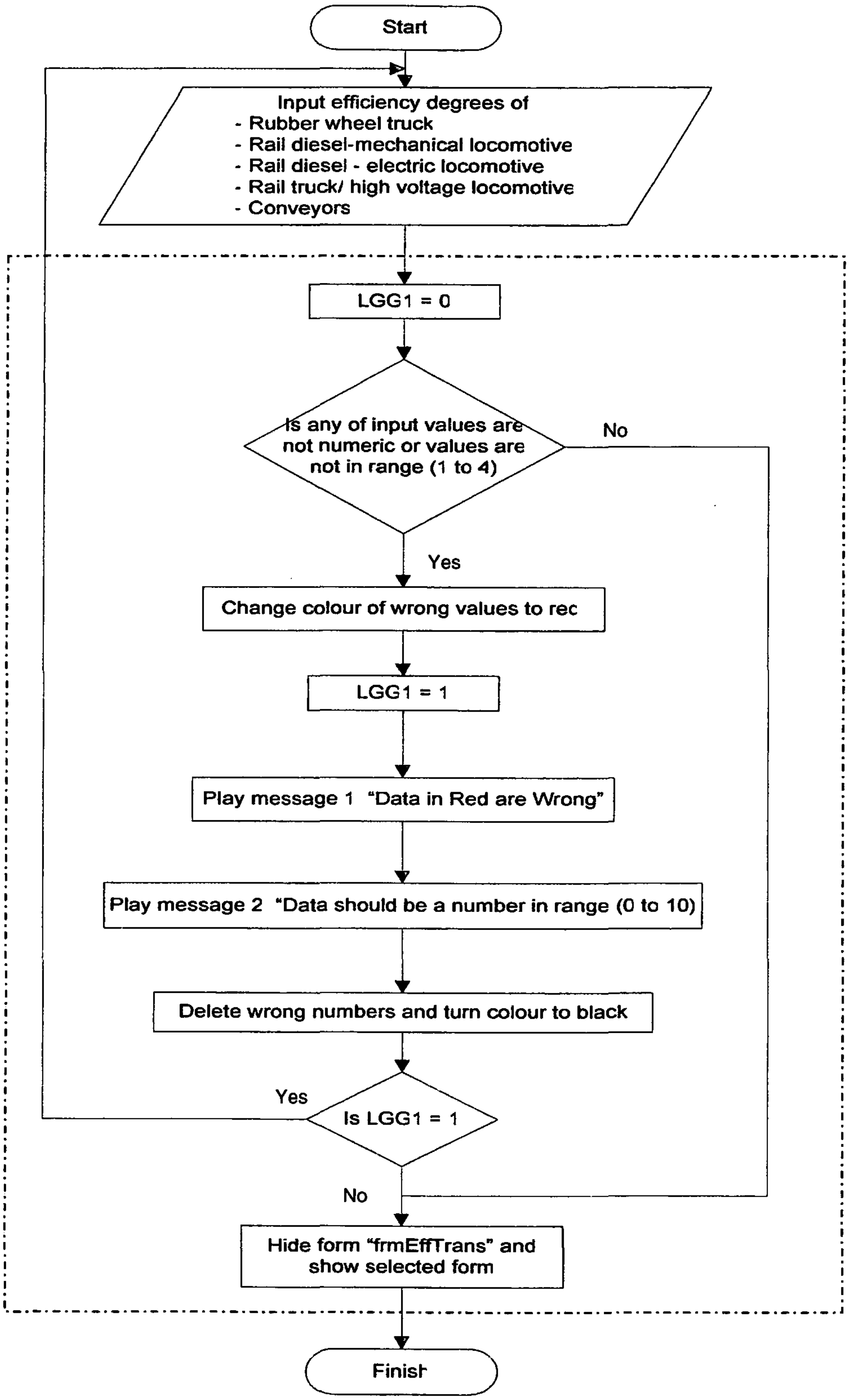


Figure 5.33 Process of *"Efficiency degrees of transportation methods"* screen

When user selects any option to move from screen *"Importance degrees (Transportation activity)"* to any other screen, the program will start to perform process that shown in flow chart of figure 5.32. Logic of calculations is similar to logic of calculations of other activities.

In screen *"Efficiency degrees of transportation methods"* the user clicks button *"Back"* after inserting efficiency degrees values to transportation methods. The program will check the values and if they are not numeric or out of range (1 to 4) it will not accept them. This process is shown in figure 5.33.

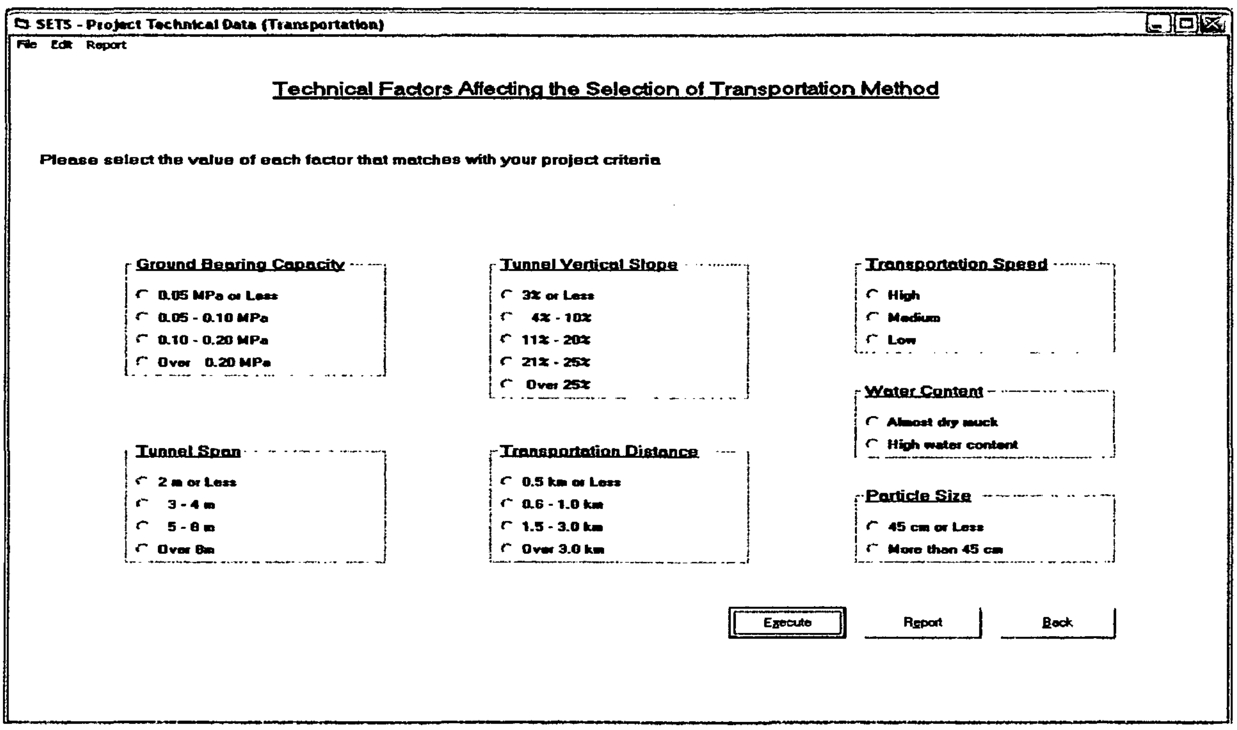


Figure 5.34 *"Project technical data (Transportation)"* screen

Clicking button *"Technical data"* in screen *"Importance degrees (Transportation activity)"* will display screen *"Project technical data (Transportation)"* that shown in figures 5.34 and 5.35.

This screen has seven technical factors. User can select the options that match with his project by clicking the radio button that he wants. For each group, the user can select only one option. There are three menu options for this screen. *"File"* and *"Edit"* submenus are similar to these options in other screens. *"Report"* option enables user to retrieve reports of other activities (see figure 5.35).

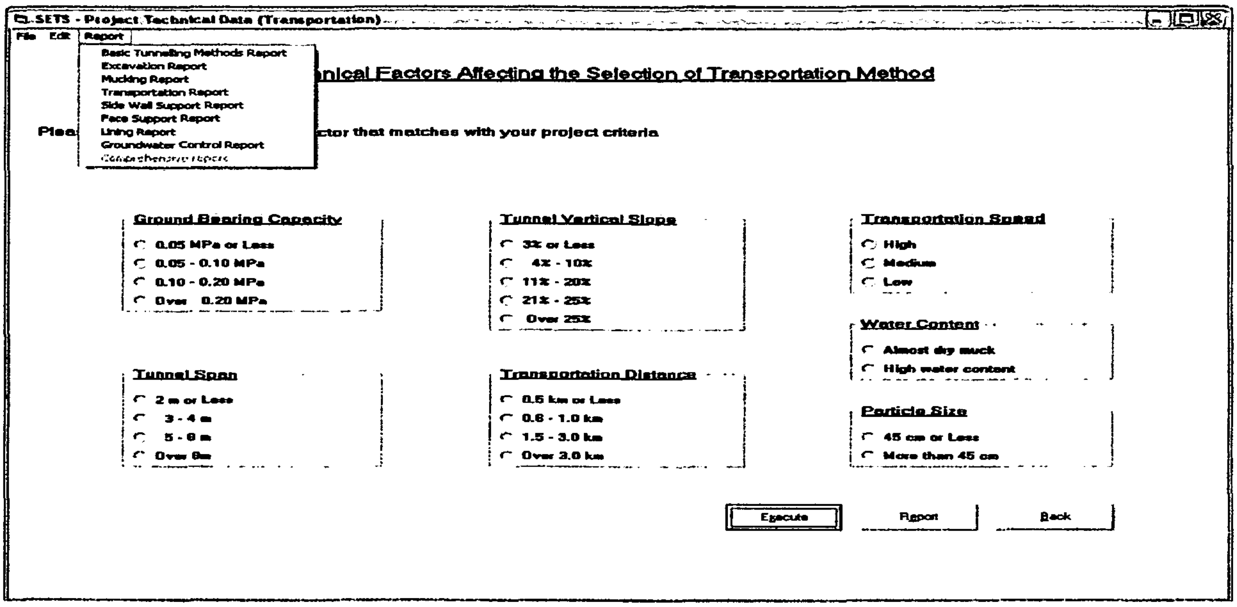


Figure 5.35 Submenu of *"Report"* option

Button *"Report"* in screen *"Project technical data (transportation)"* will show a report about transportation methods including their efficiency percentages and rank. *"Back"* button will hide this screen and *"Tunnelling activities and methods"* screen will show up. By clicking *"Execute"* button the program will start calculations to determine efficiency percentages of transportation methods. The program will rank methods in descending order. Flow chart in figure 5.36 shows calculation steps.

At the beginning, the program will start to calculate importance percentages of controlling factors by summing them and then divide each value by the total.

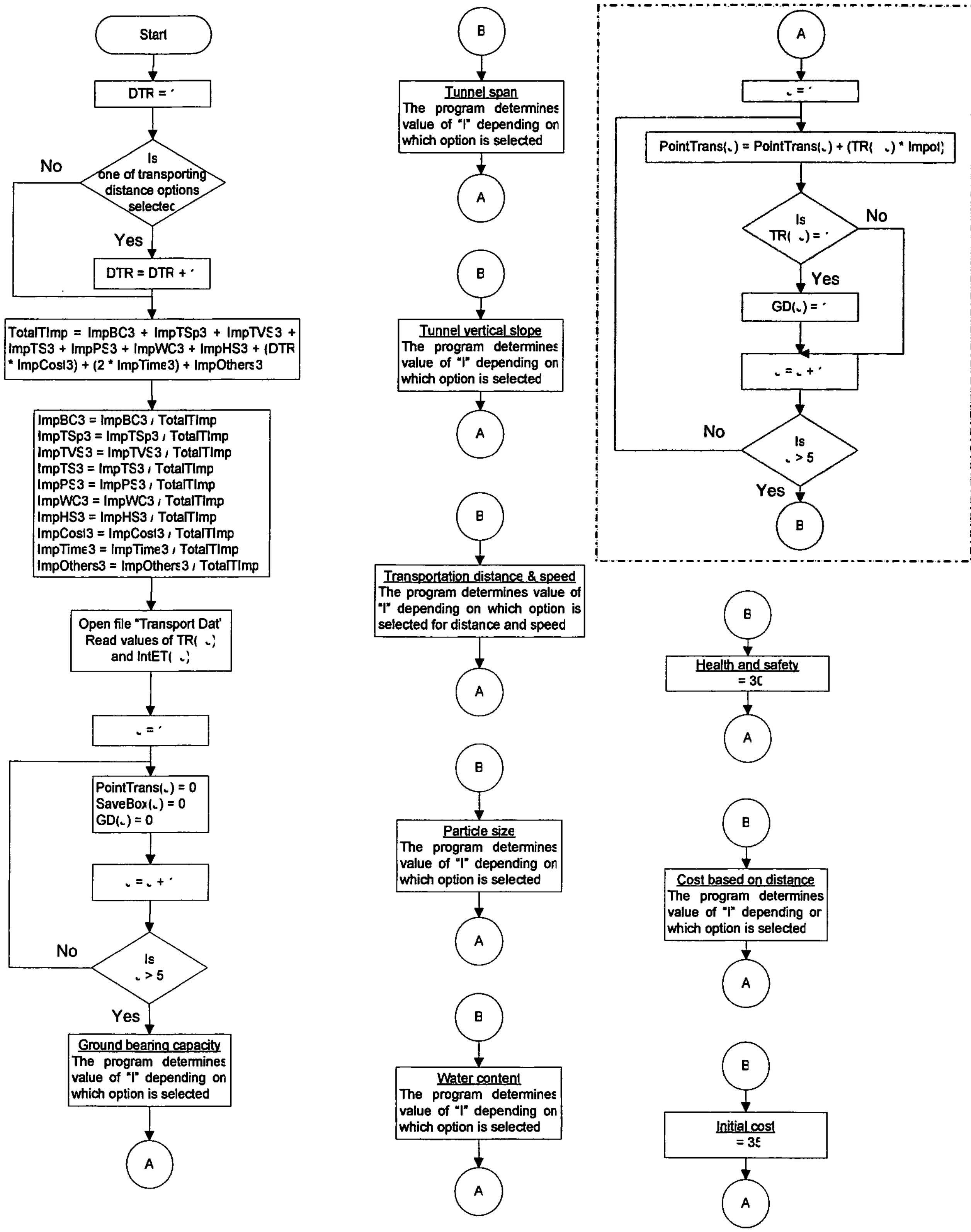


Figure 5.36a Calculation steps of transportation methods' efficiencies

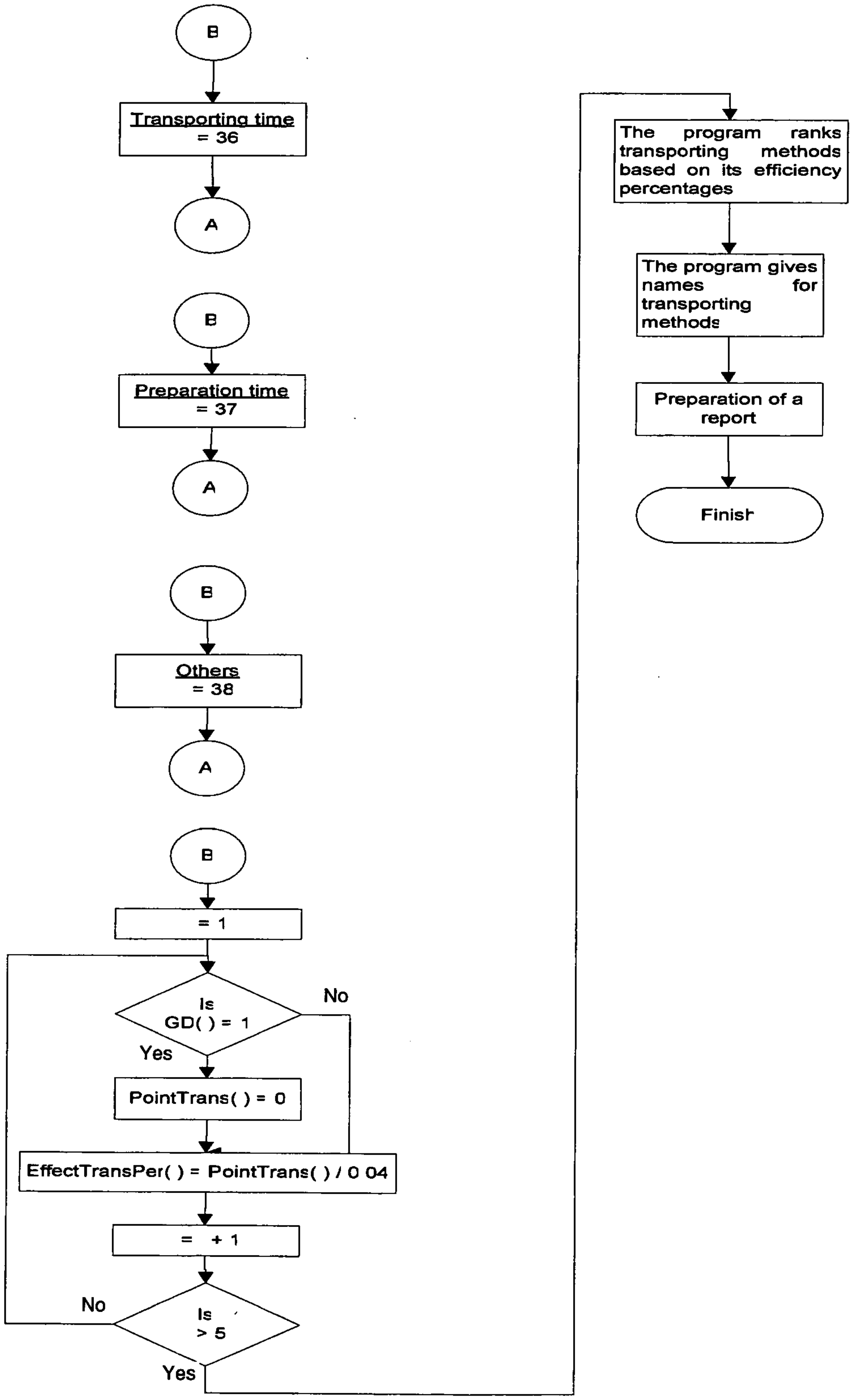


Figure 5.36b Calculation steps of transportation methods' efficiencies

The program opens file *"Transport.dat"* to read values of *"TR(I,J)"* and *"IntET(I,J)"*. The first group of values are efficiency degrees of transportation methods for the controlling factors. Each line in file *"Transport.dat"* represents efficiency degrees of methods for one option in screen *"Project technical data (Transportation)"*. The value of *"I"* in variable *"TR(I,J)"* represents number of the line and *"J"* represent transportation methods. The second group of values are efficiency degrees of transportation methods working together with excavation methods.

For each technical factor, the program will determine the value of "I" depending on which option is selected for this factor. The value of "I" refers to line number and which efficiency degrees will be involved in calculations. Using efficiency degrees and importance percentages the program will go to this part of calculations in doted box to accumulate weighted efficiencies of each transportation method. If any of transportation methods cannot work because of a technical or non-technical factor, the program will assign zero value for their weighted efficiencies. After calculating weighted efficiencies the program will calculate efficiency percentage of each transportation method and then it will rank methods in descending order. A report will be prepared and clicking button *"Report"* will show it up. Figure 5.37 shows screen of the report.

Figure 5.37 shows that the screen has the same form like other report screens and options in this screen are similar to options in other report screens and they perform the same functions. The date shown with the title of the report is the date of report and the program assigns automatically the date of the day that user is using the program to report.

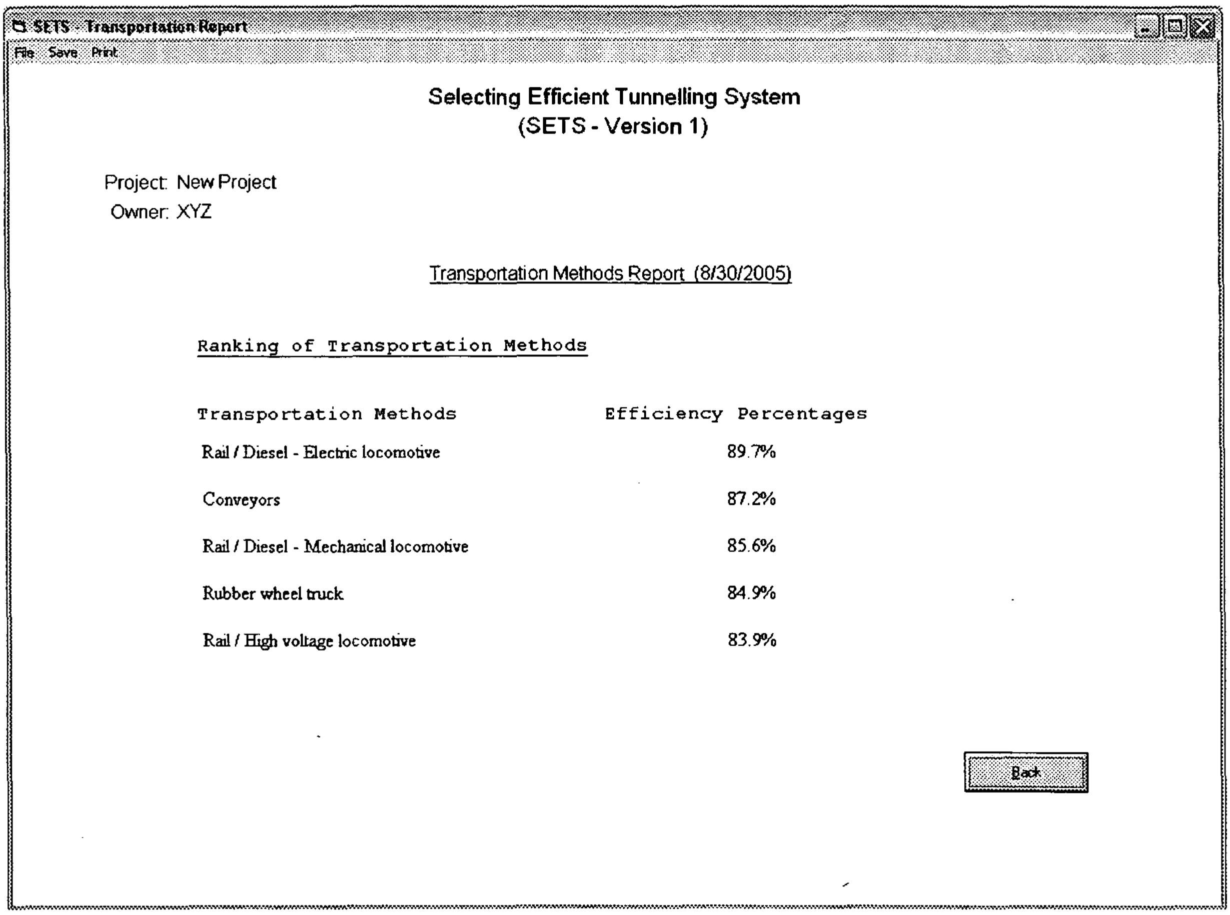


Figure 5.37 Report screen of transportation activity

5.4.4 Support activity

Button *"Support"* in *"Tunnelling activities and methods"* screen will display screen *"Importance degree (Support activity)"*. In this screen, the user will insert importance degree values for controlling factors of support activity. As shown in figure 5.38, there are four technical controlling factors and three non-technical controlling factors for this activity. The cursor will show up in the first field. Other fields will have a zero value. As usual, moving from one field to another can be done by tab button or clicking the field with the mouse. Tab button will move the cursor from one field to another in order but with the mouse, user can select any field he wants randomly.

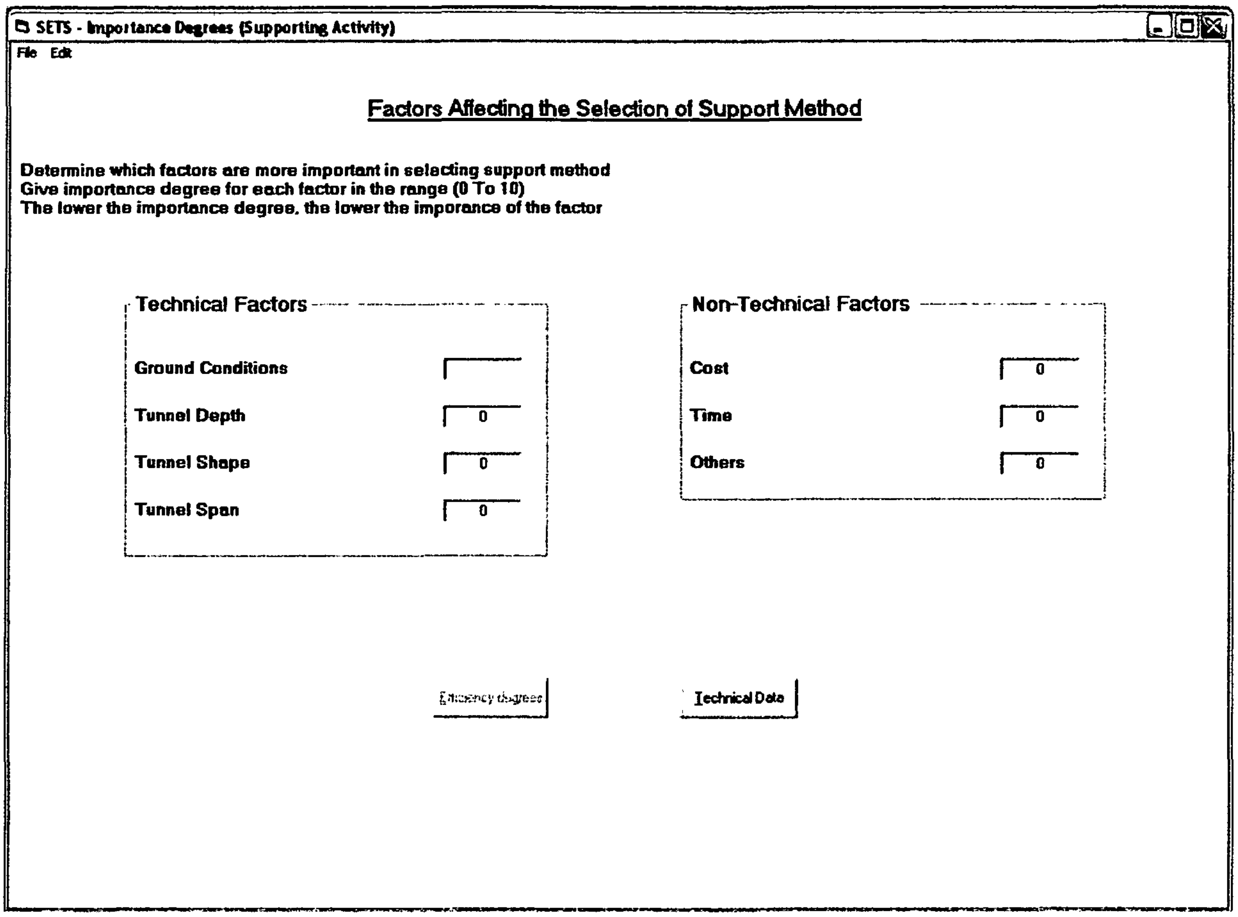


Figure 5.38 *"Importance degrees (Support activity)"* screen

Logic used of importance degrees' screens are the same. User should feed the program with numbers in the range of (0 to 10). If values are out of this range, the program will display two messages, as described before, to give the user information about wrong fields. The button *"Efficiency degrees"* will be enabled if importance degree of *"Others"* factor is not zero. When user uses any option or button to move from this screen, the processes shown in figure 5.39 will be done.

Clicking the button *"Efficiency degrees"* will display the screen *"Efficiency degrees of support methods"* which is shown in figure 5.40.

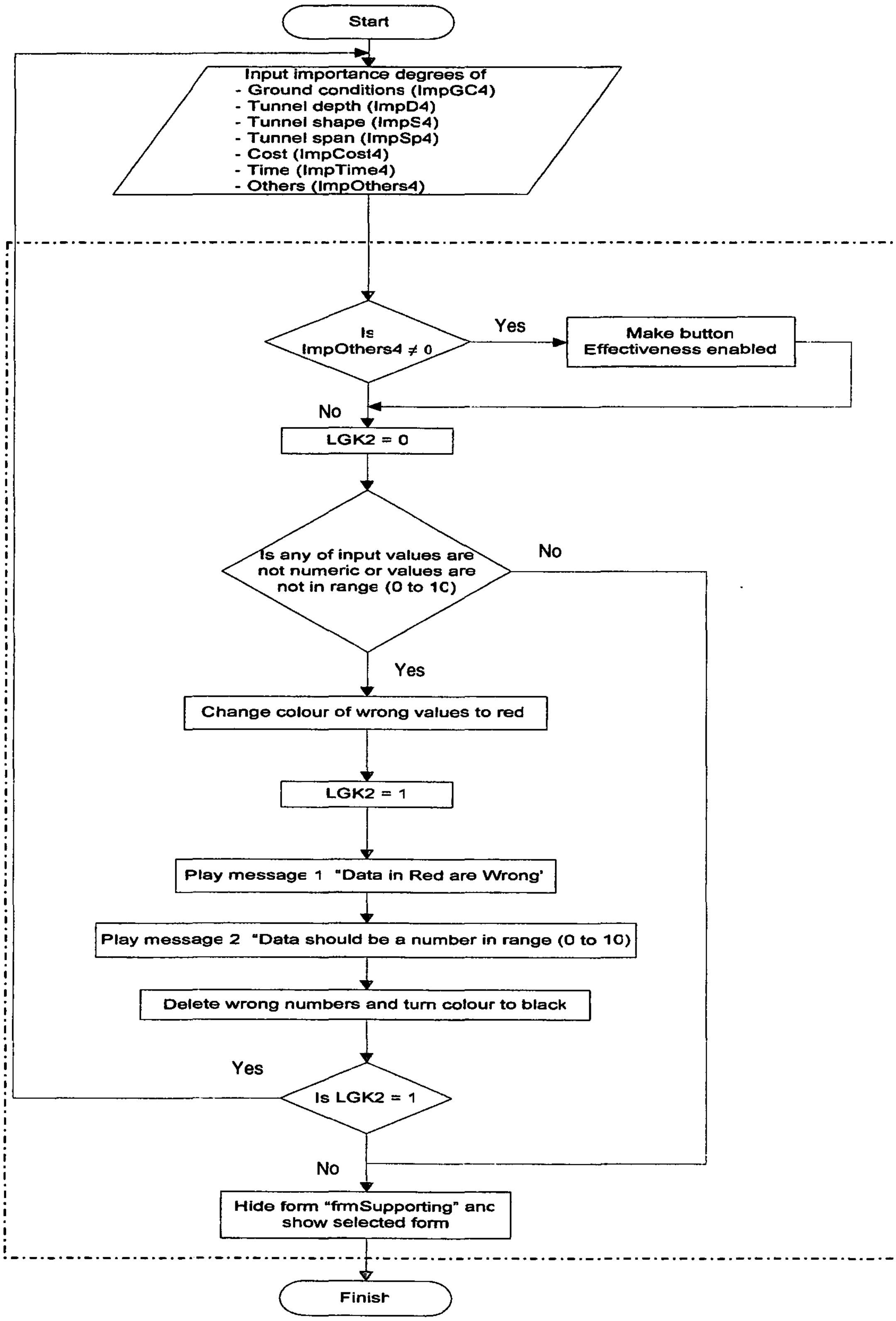


Figure 5.39 Checking values of importance degree for support activity

In screen *"Efficiency degrees of support methods"*, there are three groups. The first group is methods for side wall and crown support. The second group is face support methods. The last group is support methods for cut and cover.

Screen form is similar to other screens that perform the same function. At the top of the screen, there are instructions about how to insert the values in this screen and at the end there is explanation of the values indication. The default value for methods efficiency is "4". The button *"Back"* will hide this screen and go back to screen of importance degrees.

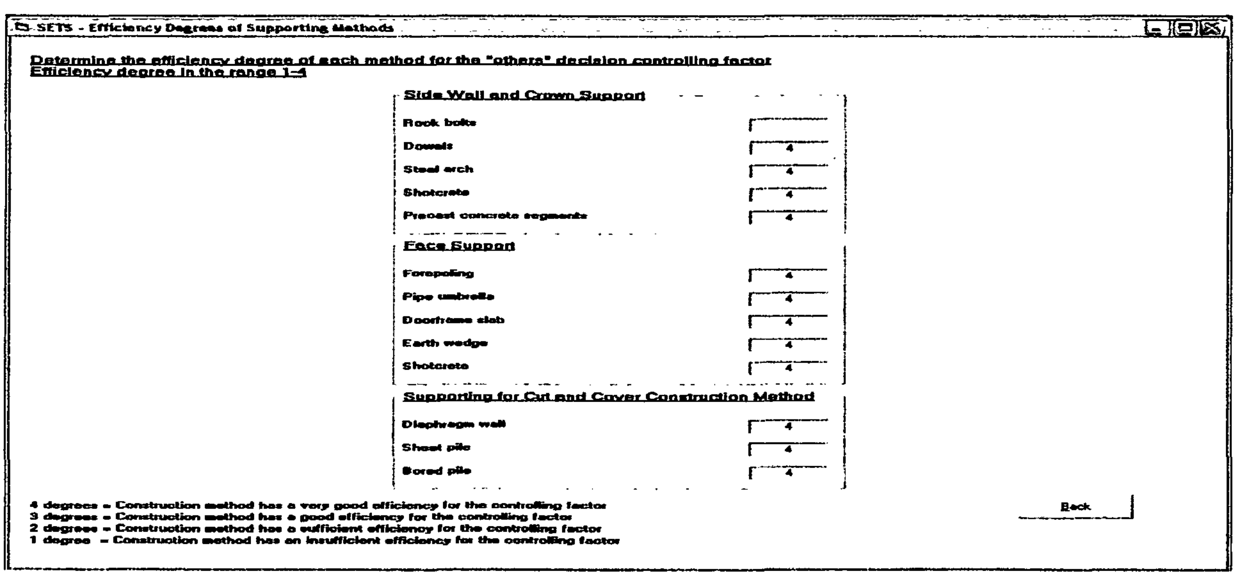


Figure 5.40 *"Efficiency degrees of support methods"* screen

Efficiency values of screen *"Efficiency degrees of support methods"* will be assigned to variable *"SP(27,J)"*. *"J"* represents support methods.

The button *"Technical data"* in the screen *"Importance degrees (Support activity)"* will display the screen *"Project technical data (Support)"* (see figure 5.41).

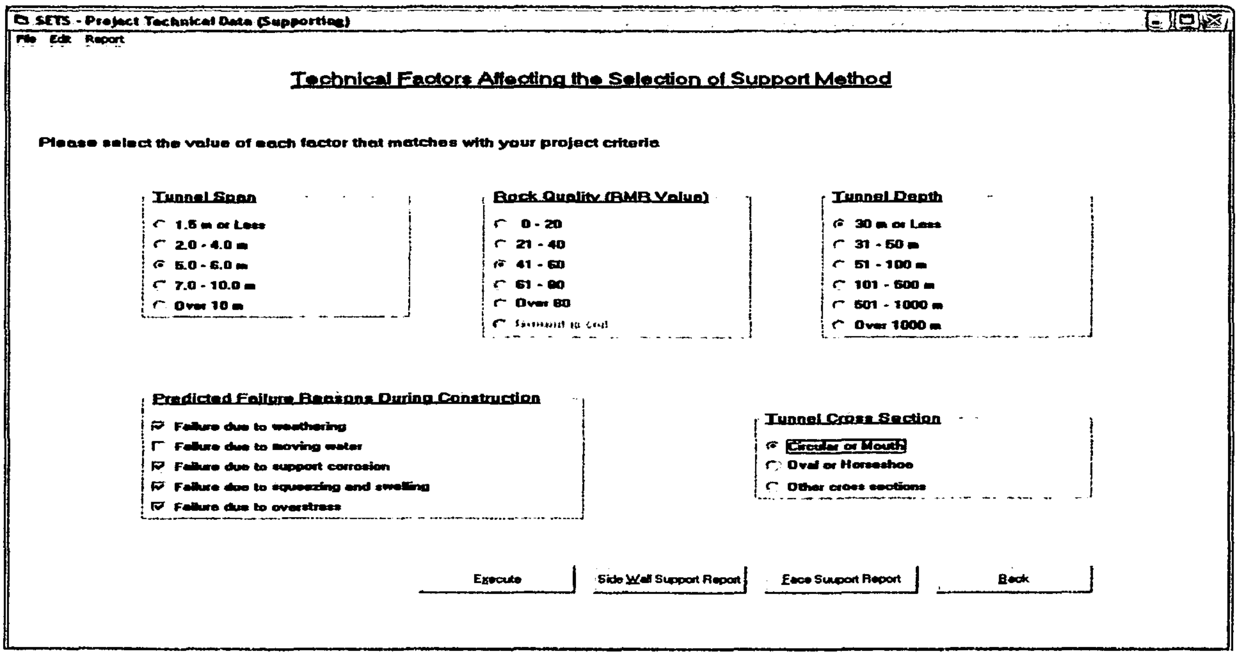


Figure 5.41 Screen of *"Project technical data (Supporting)"*

There are five technical factors in the screen *"Project technical data (Support)"*. Data in this screen should match with data of previous activities. When user selects option *"Rock"* in the screen *"Project general data"*, the option *"Ground is soil"* of the technical factor *"Rock quality (RMR value)"* in the screen *"Project technical data (Support)"* will not be enabled as shown in figure 5.41. If the *"Soil"* option is selected in the screen *"Project general data"*, all ranges of RMR value will be disabled and the only option that will be enabled is the *"Ground is soil"*.

For the radio buttons the user can only select one option for every technical factor. For the technical factor *"Predicted failure reasons during construction"* user can select more than one reason of failure. This factor has check boxes that enable the user to select many options.

The screen *"Project technical data (Support)"* has four buttons and three menu options. Menu options have the same function like the menu options in previous screens. The user can terminate the program using submenu option *"End"* of the option *"File"*. Editing and screen can be done using submenu of *"Edit"* option. The user can retrieve any activity report using the option *"Report"*. Figures (5.42 and 5.43) show submenus of *"Edit"* and *"Report"* options respectively.

The *"Execute"* button will start calculations of efficiency percentages for support methods. The flow chart in figure 5.44 shows calculation steps. User can obtain two reports, one for side wall support and the second is for face support. The two buttons *"Side wall support report"* and *"Face support report"* display the two reports (see figures 5.45 and 5.46). The last button is the *"Back"*. This button is used to hide this screen and display the screen of *"Tunnelling activities and methods"*.

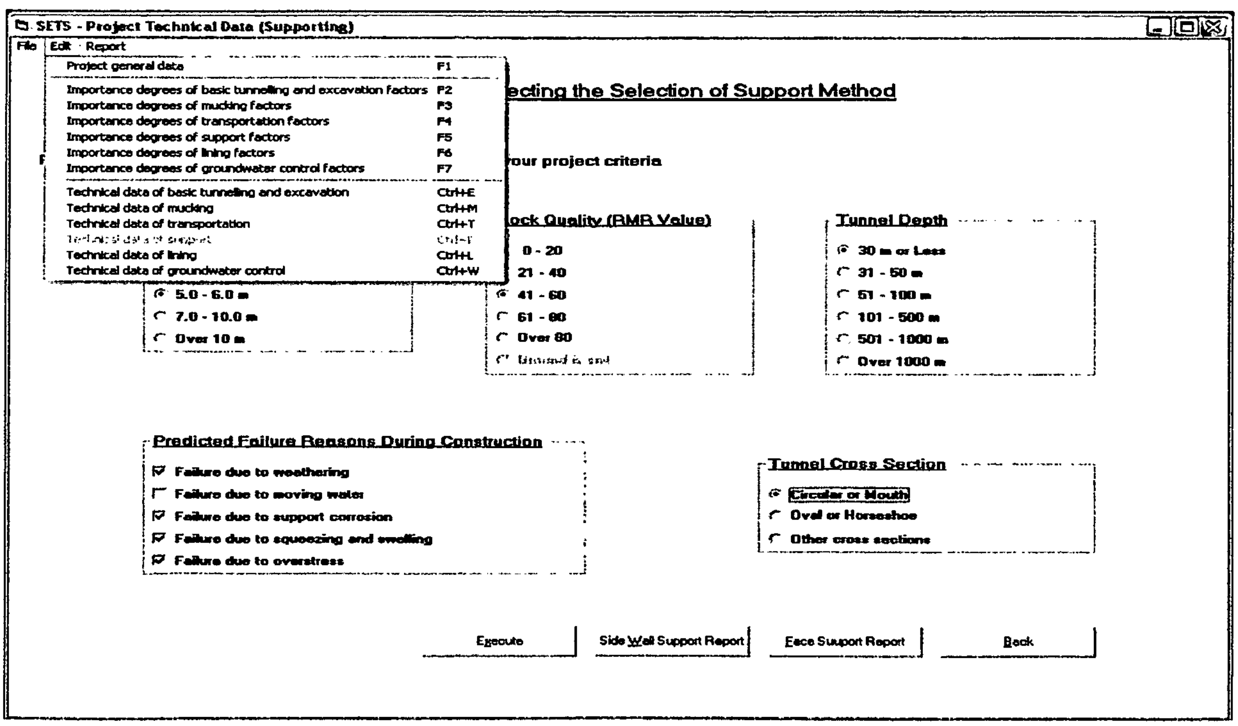


Figure 5.42 Submenu of *"Edit"* option

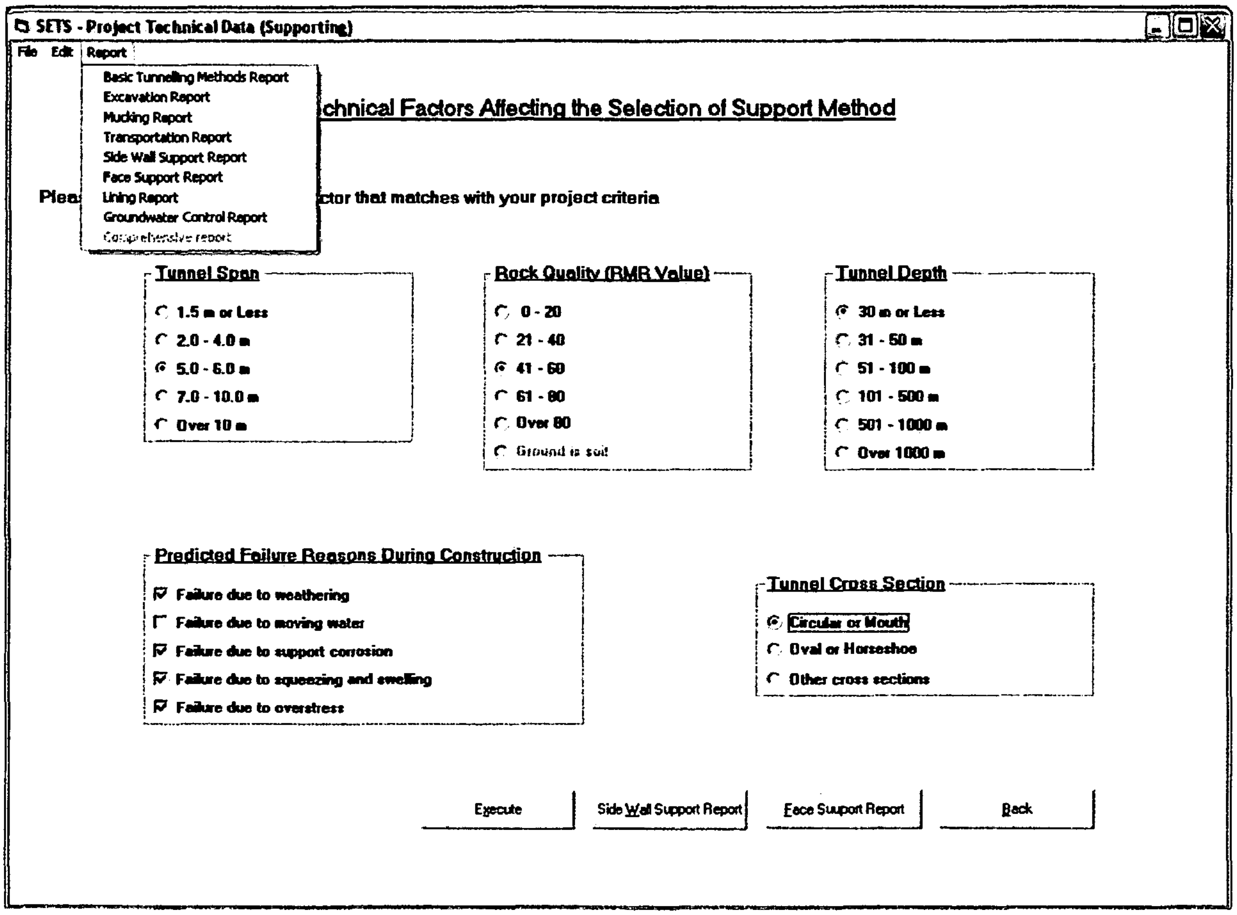


Figure 5.43 Submenu of *"Report"* option

"IntCCC(J)", *"IntES(I,J)"*, *"IntEF(I,J)"*, and *"IntECC(I,J)"*. The file *"Support.dat"* is on the same folder of the program and it is an edit file. The variable *"SP(I,J)"* includes efficiency degrees of support methods for controlling factors. *"I"* value is the number of line in the file *"Support.dat"*. *"J"* value is support methods. When *"J"* value is in range (1 to 5), it refers to side wall support and range (6 to 10) refers to face support, last range (10 to 13) refers to support of cut and cover. Variables start with *"Int"* represent efficiency degrees of support methods working with basic tunnelling and excavation methods. Table 5.3 shows variables and values that are assigned to these variables.

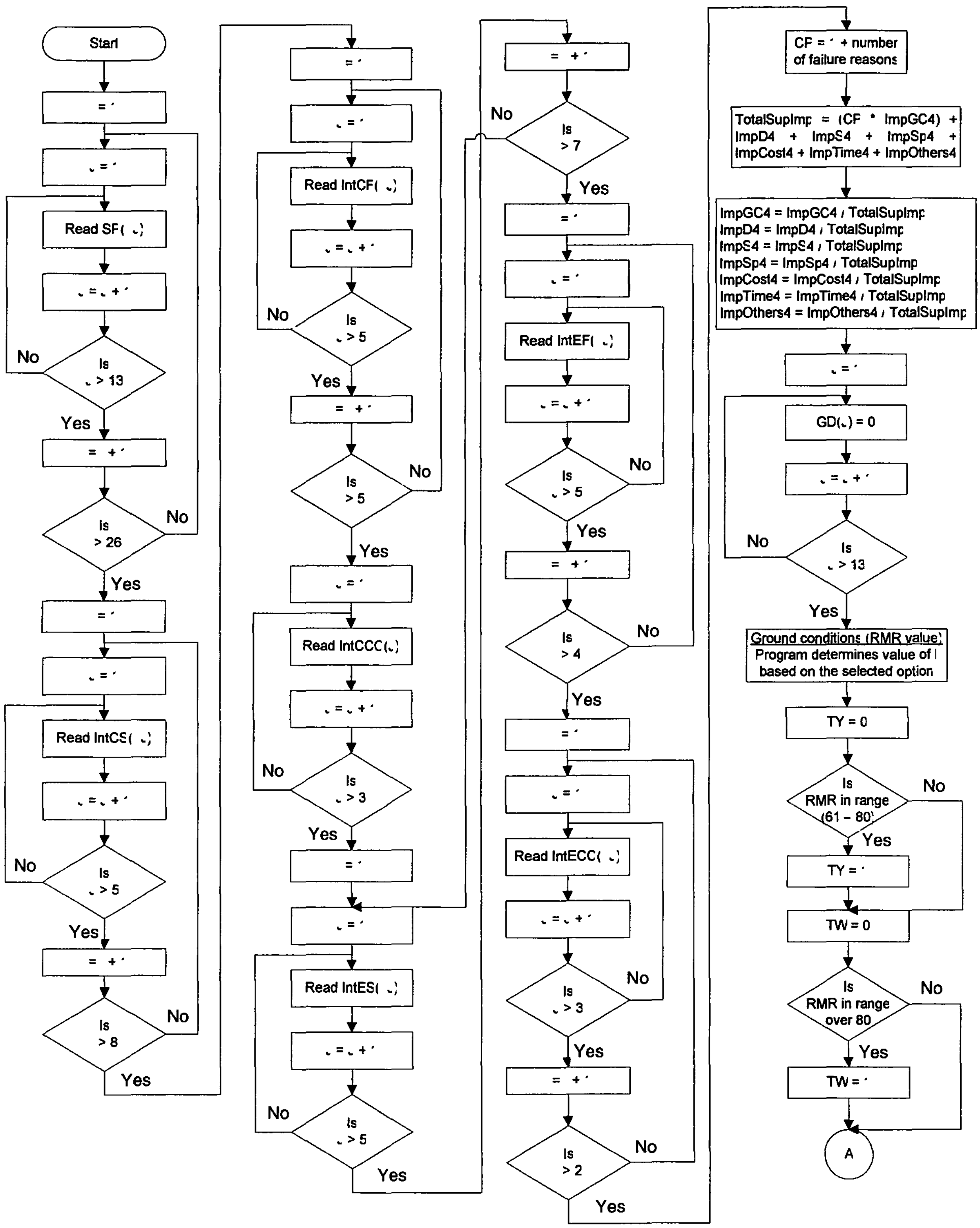


Figure 5.44 Calculation steps of support methods efficiency percentages

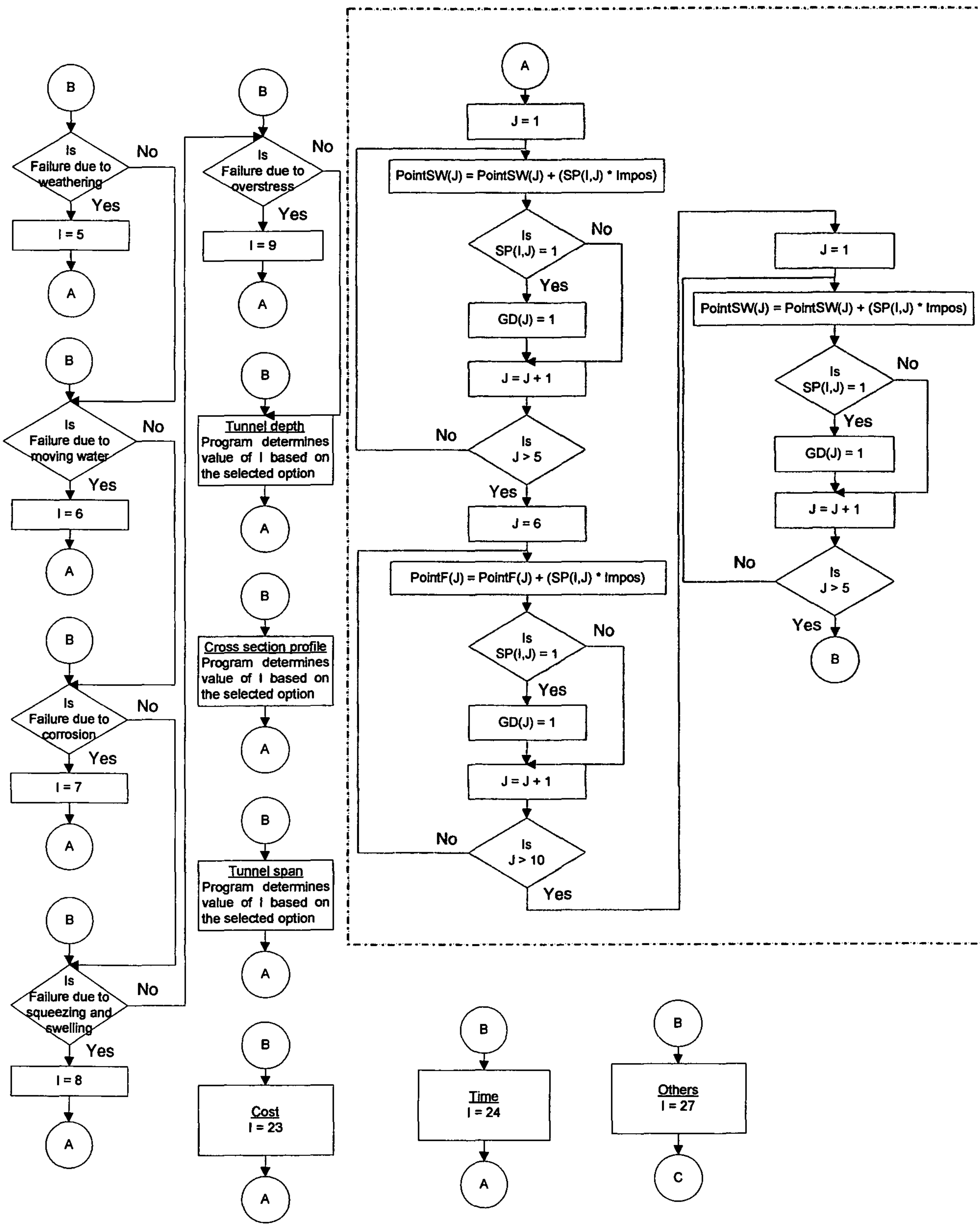


Figure 5.44 Calculation steps of support methods efficiency percentages (continue)

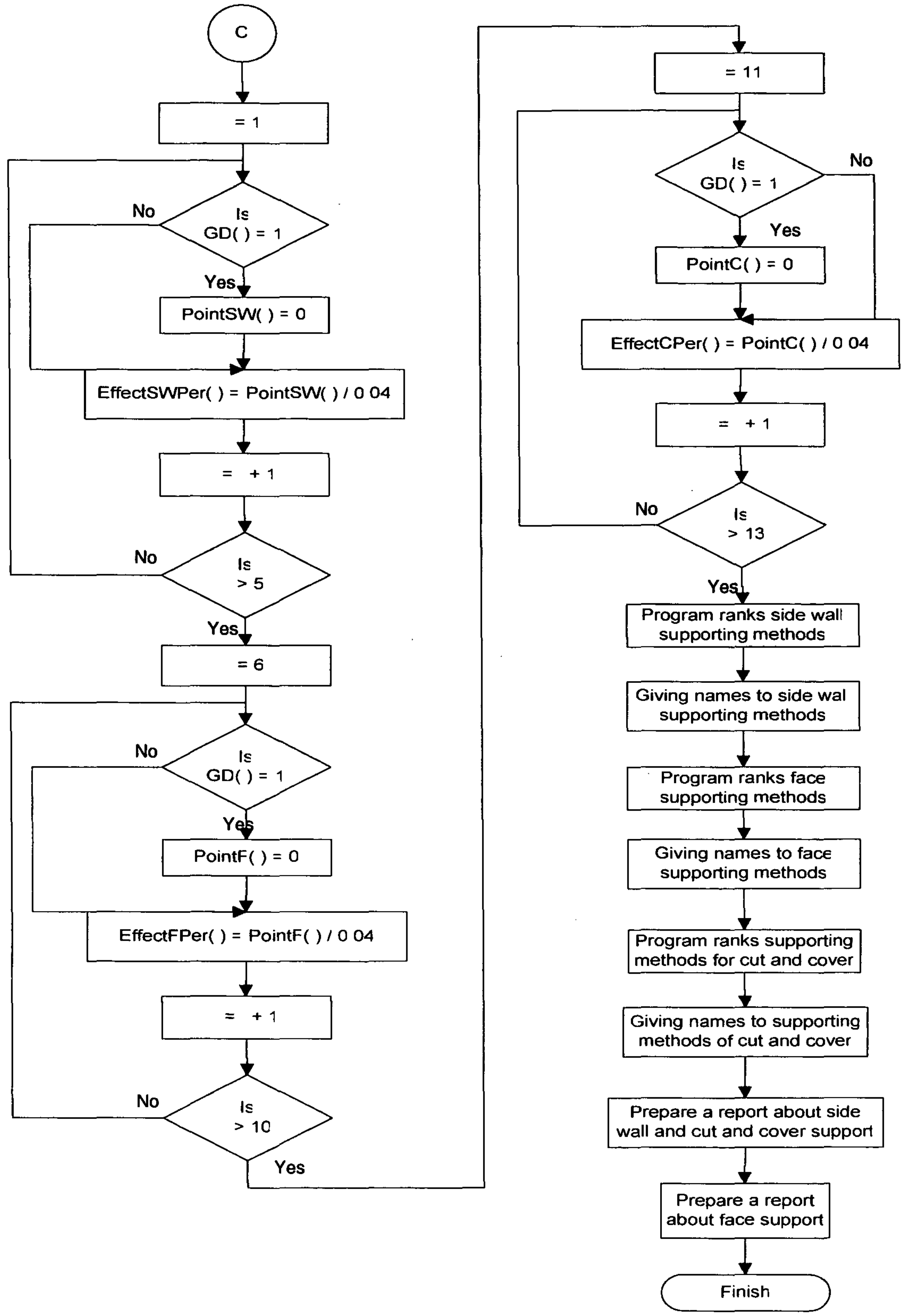
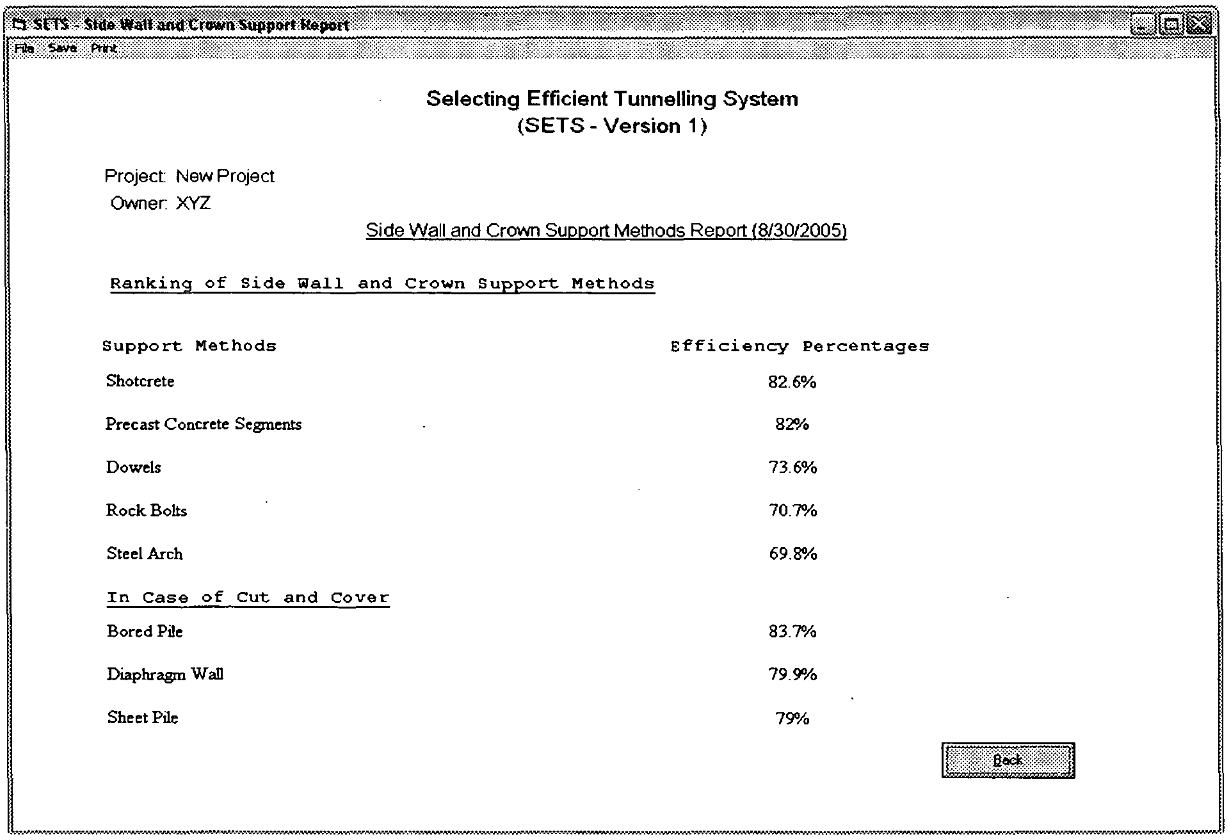


Figure 5.44 Calculation steps of support methods efficiency percentages (continue)


SETS - Side Wall and Crown Support Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: New Project
Owner: XYZ

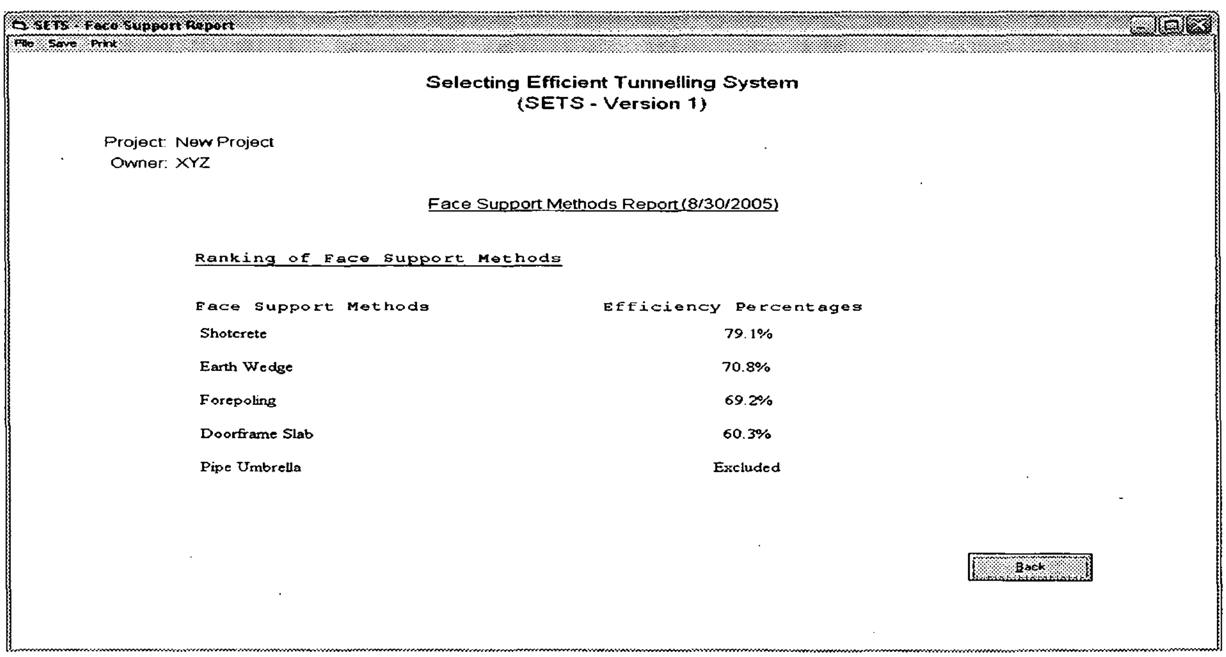
Side Wall and Crown Support Methods Report (8/30/2005)

Ranking of Side Wall and Crown Support Methods

Support Methods	Efficiency Percentages
Shotcrete	82.6%
Precast Concrete Segments	82%
Dowels	73.6%
Rock Bolts	70.7%
Steel Arch	69.8%
In Case of Cut and Cover	
Bored Pile	83.7%
Diaphragm Wall	79.9%
Sheet Pile	79%

Back

Figure 5.45 Side wall supporting report


SETS - Face Support Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: New Project
Owner: XYZ

Face Support Methods Report (8/30/2005)

Ranking of Face Support Methods

Face Support Methods	Efficiency Percentages
Shotcrete	79.1%
Earth Wedge	70.8%
Forepoling	69.2%
Doorframe Slab	60.3%
Pipe Umbrella	Excluded

Back

Figure 5.46 Face support report

Table 5.3 Variables and their values

Variable name	Value of variable
SP(I,J)	Efficiency degrees of support methods for controlling factors
IntCS(I,J)	Efficiency degrees of basic tunnelling and side wall support methods working together
IntCF(I,J)	Efficiency degrees of basic tunnelling and face support methods working together
IntCCC(J)	Efficiency degrees of support methods working with cut and cover
IntES(I,J)	Efficiency degrees of excavation and side wall support methods working together
IntEF(I,J)	Efficiency degrees of excavation and face support methods working together
IntECC(I,J)	Efficiency degrees of excavation and support methods working together for cut and cover

Calculations of support methods efficiency percentages start by opening the file *"Support.dat"* to read values of *"SP(I,J)"*, *"IntCS(I,J)"*, *"IntCF(I,J)"*,

The second step is to calculate importance percentages of controlling factors by summing them and divide every value by the total summation value. The program determines values of *"I"* which represent the line numbers that include efficiency degrees of support methods for the selected option of controlling factors.

When RMR value is in the range (61 – 80) the ground is in good condition and there is no need for face support. The variable *"TY"* is used to represent this case. RMR value over 80 means that there is no need for any kind of support. The variable *"TW"* is used by the program to show that.

The program accumulates weighted efficiencies of side wall support, face support, and cut and cover support methods using procedures in doted box. Then the program calculates efficiency percentages of support methods. Ranking and giving a name to support methods are the final steps of calculations. The program will prepare two reports that shown in figures 5.45 and 5.46.

Report screens have the same form and options like other report screen that explained before for other activities.

5.4.5 Lining activity

The button *"Lining"* in screen *"Tunnelling activities and methods"*, (figure 5.7), will display screen *"Importance degrees (Lining activity)"*. User of the program can display this screen by selecting its option from submenu of *"Edit"*. Figure 5.47 shows that there are five technical factors and three non-technical factors for lining activity. When the *"Others"* factor has non-zero value, the button *"Efficiency degrees"* will be enabled.

The *"Efficiency degrees"* button will display the screen of *"Efficiency degrees of lining methods"* that shown in figure 5.48. Flow charts in figures 5.49 and 5.50 illustrate the process of checking values of the screens *"Importance degrees (Lining activity)"* and *"Efficiency degrees of lining methods"* respectively.

Figure 5.51 shows the screen of *"Project technical data (Lining)"*. There are five groups of technical data. Q-value should match with RMR value that was in support activity. Table 5.4 is the relation between Q-value and RMR-value.

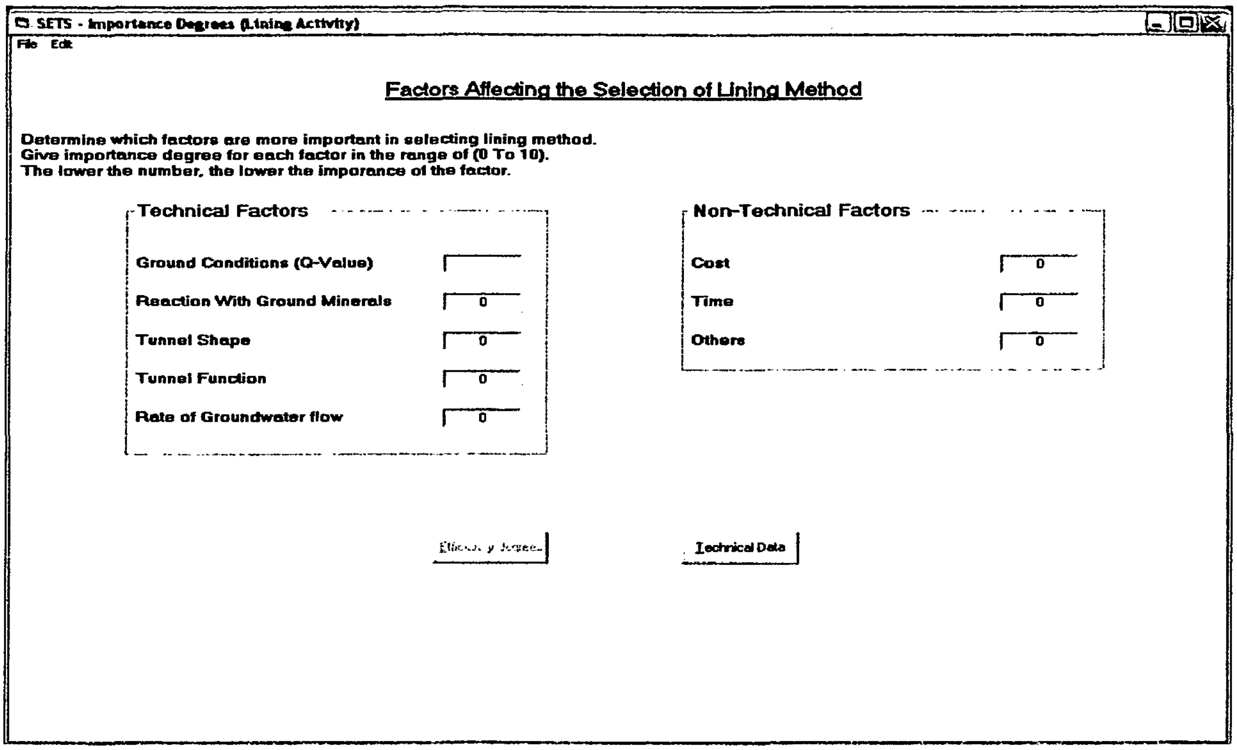


Figure 5.47 Screen of *"Importance degrees (Lining activity)"*

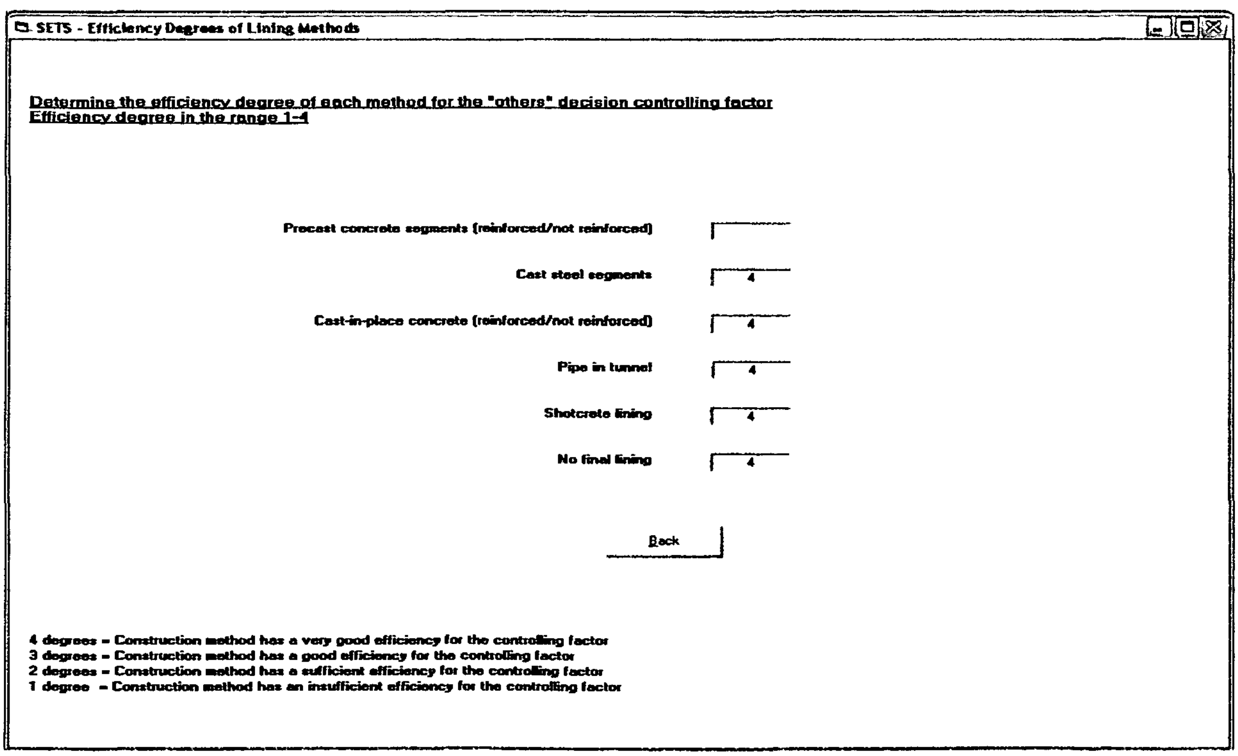


Figure 5.48 Screen of *"Efficiency degrees of lining methods"*

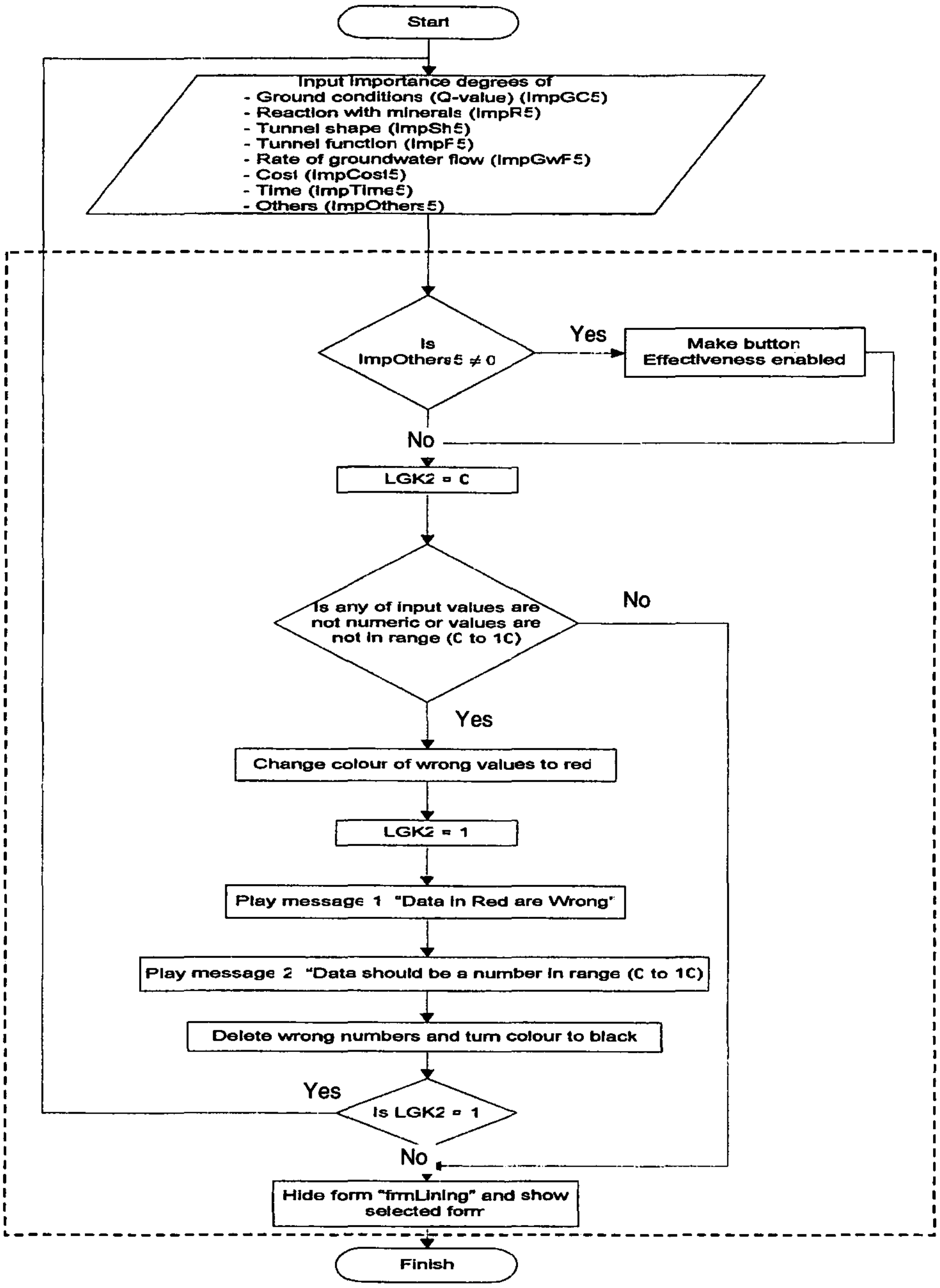


Figure 5.49 Checking values in screen *"Importance degrees (Lining activity)"*

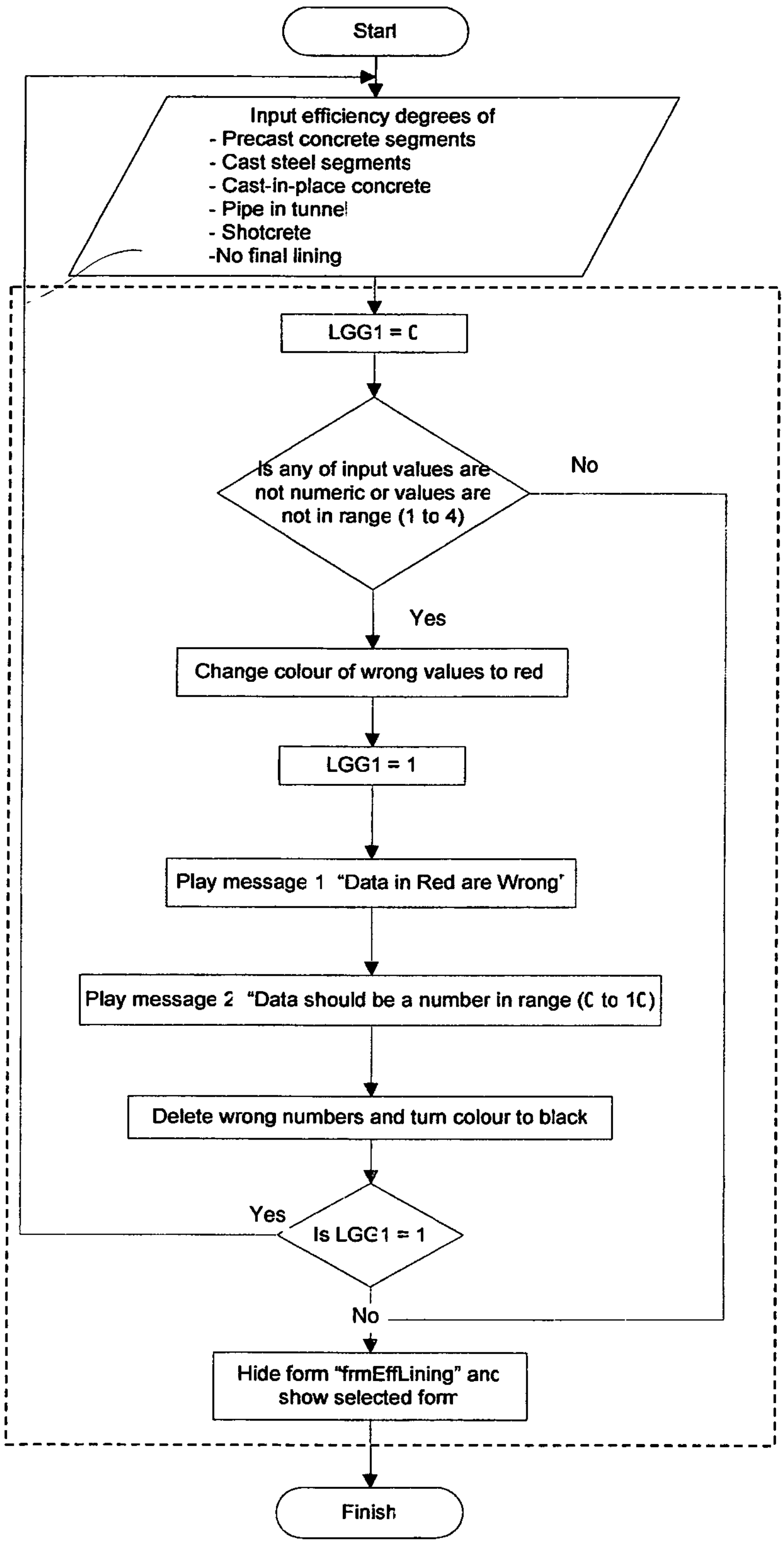


Figure 5.50 Checking values in screen *"Efficiency degrees of lining methods"*

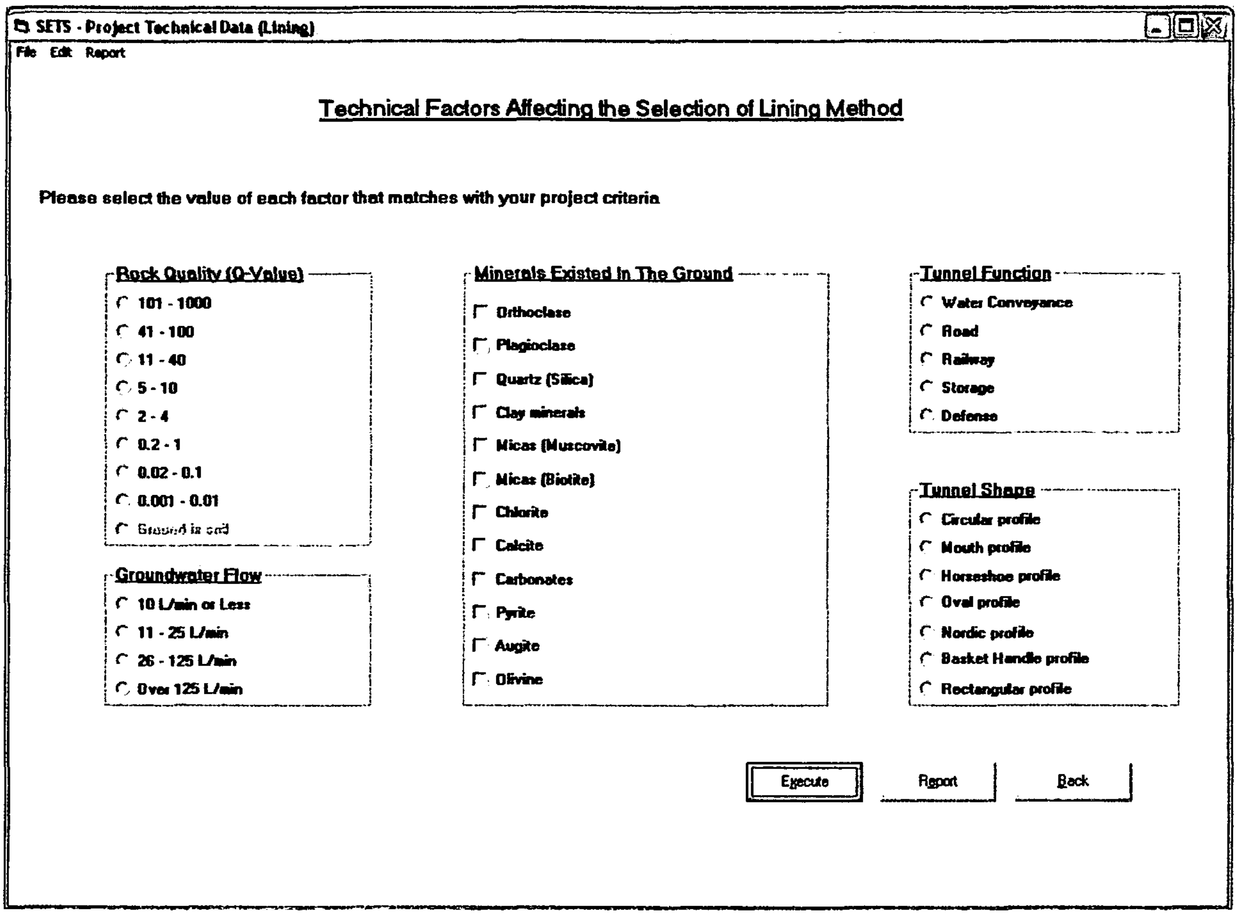


Figure 5.51 Screen of *"Project technical data (Lining)"*

Table 5.4 Relation between Q and RMR values

<table>
<tr><th>Q - Value</th><th>RMR – Value</th></tr>
<tr><td>101 – 1000</td><td>Over 80</td></tr>
<tr><td>41 – 100</td><td rowspan="3">61 – 80</td></tr>
<tr><td>11 – 40</td></tr>
<tr><td>5 – 10</td></tr>
<tr><td>2 – 4</td><td rowspan="2">41 – 60</td></tr>
<tr><td>0.2 – 1</td></tr>
<tr><td>0.02 – 0.1</td><td>21 – 40</td></tr>
<tr><td>0.001 – 0.01</td><td>0 – 20</td></tr>
</table>

For the technical factor *"Minerals in ground"*, user can select more than one option by clicking the check box. There are three menu options in this screen that have the same functions like menu options of technical screens of other activities. The button *"Report"* will show a report about lining methods. The *"Back"* button will hide this screen and go back to the screen *"Tunnelling activities and methods"*. The *"Execute"* button will start calculations as shown in flow chart of figure 5.52.

The program opens file *"Lining.dat"* to read values of efficiency degrees of lining methods for controlling factors *"LN(I,J)"*, efficiency degrees of lining methods working with basic tunnelling methods *"IntCL(I,J)"*, efficiency degrees of lining methods working with excavation methods *"IntEL(I,J)"*, and efficiency degrees of lining methods working with support methods *"IntSL(I,J)"*. Then the program will calculate importance percentages of the controlling factors by summing importance degrees and then divide every efficiency degree by the total. The program uses this part of flow chart in doted box to accumulate weighted efficiencies for every method. Figure 5.52b shows the accumulation process for all factors. The program will calculate efficiency percentages of methods and it will exclude methods that cannot work because they cannot match with one or more of controlling factors (see figure 5.52c). Last step is to rank methods and give names to methods. The program will prepare a report about lining methods that can be shown by clicking the button *"Report"*. Figure 5.53 shows the lining report.

5.4.6 Groundwater control activity

Groundwater control activity has the same structure like other activities. User will insert importance degrees for controlling factors in the screen *"Importance degrees (Groundwater control activity)"* that shown in figure 5.54. This screen

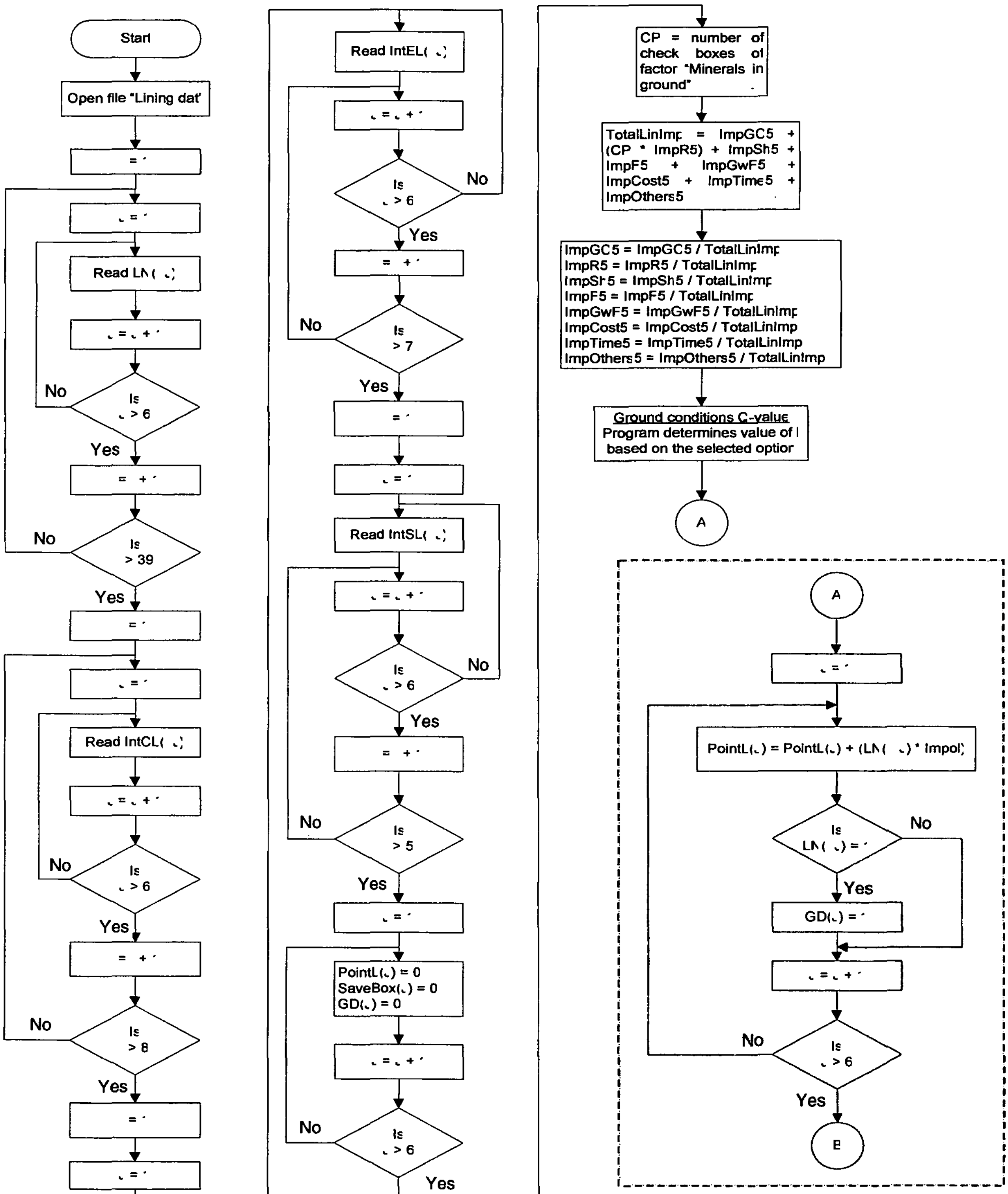


Figure 5.52a Calculation steps of lining efficiency percentages

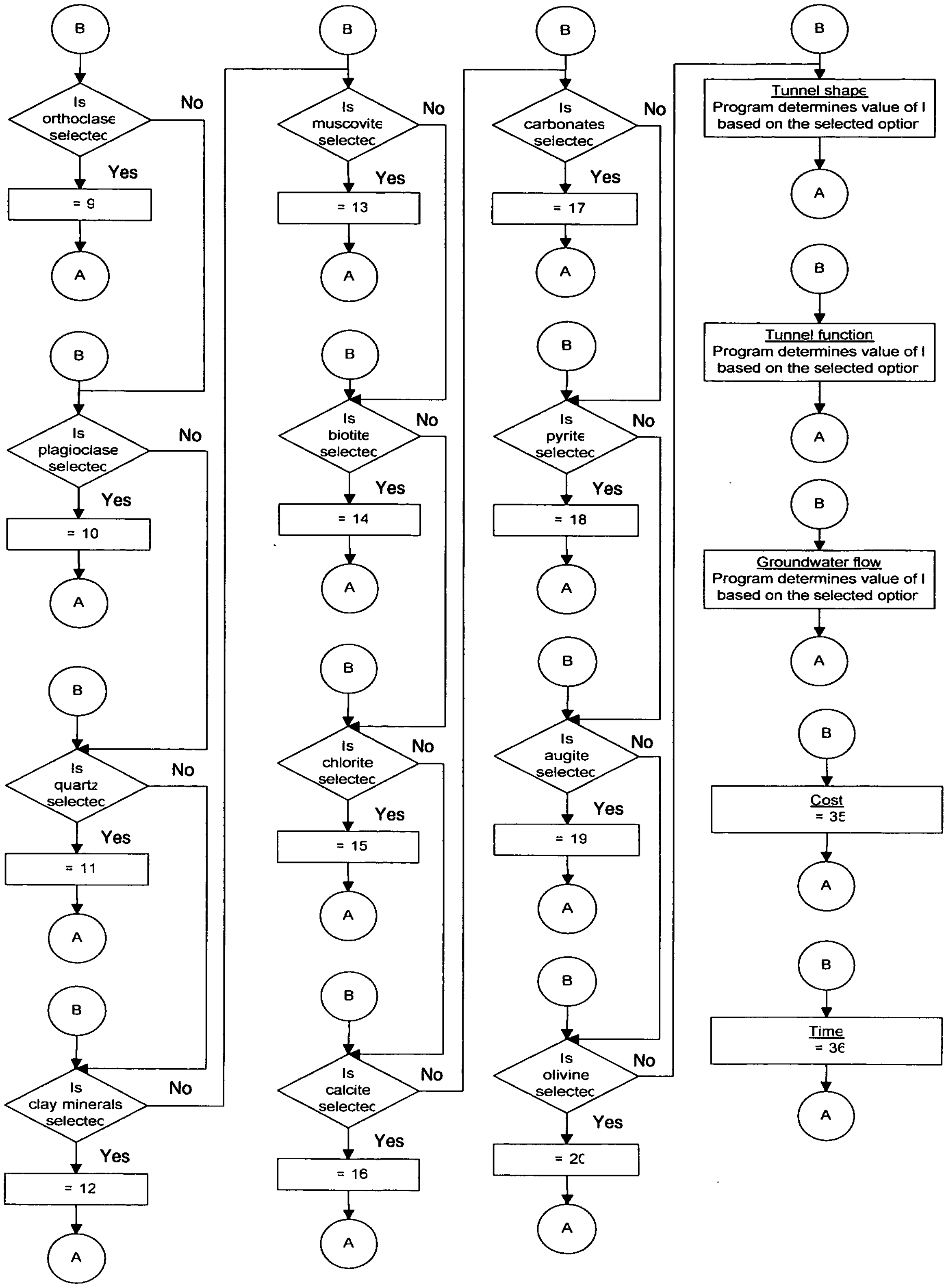


Figure 5.52b Calculation steps of lining efficiency percentages

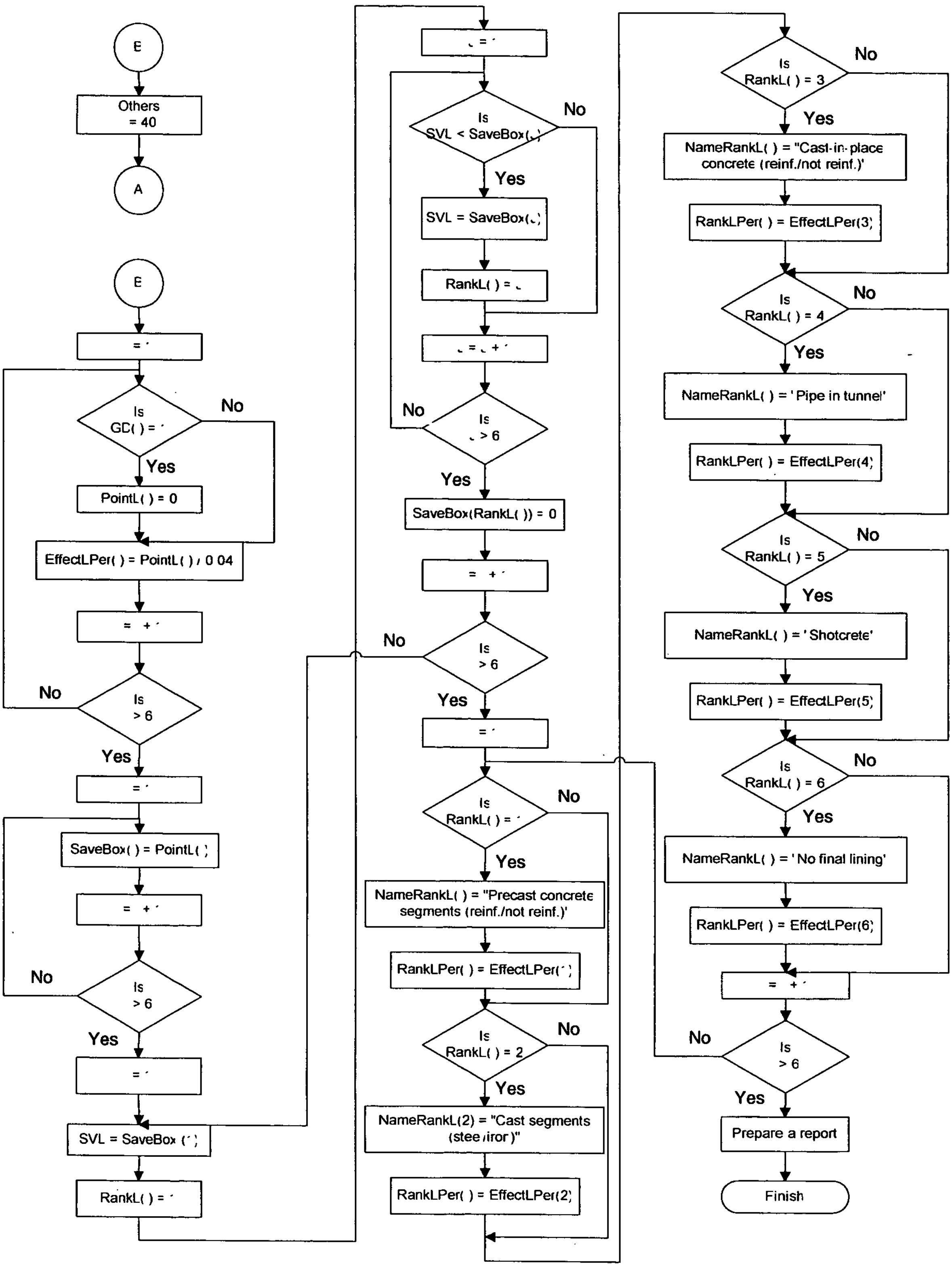


Figure 5.52c Calculation steps of lining efficiency percentages

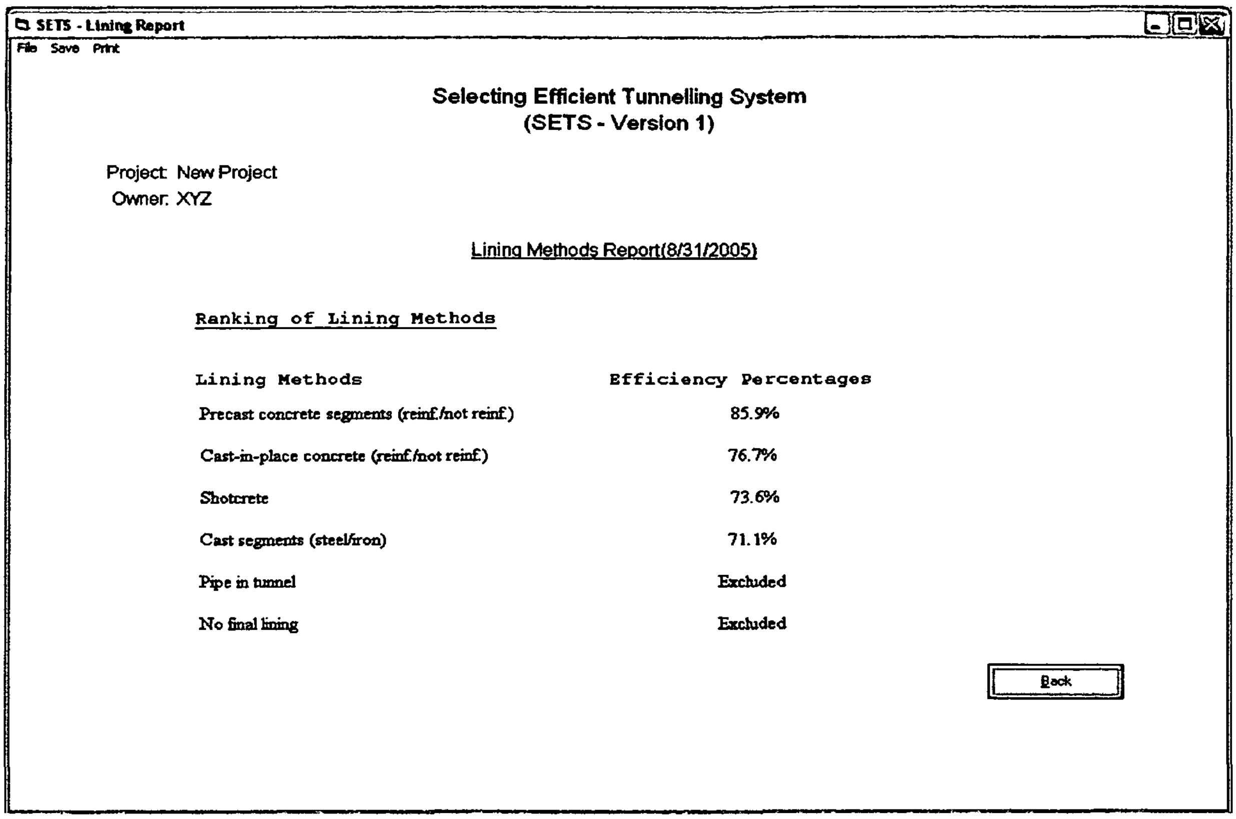


Figure 5.53 Screen of lining report

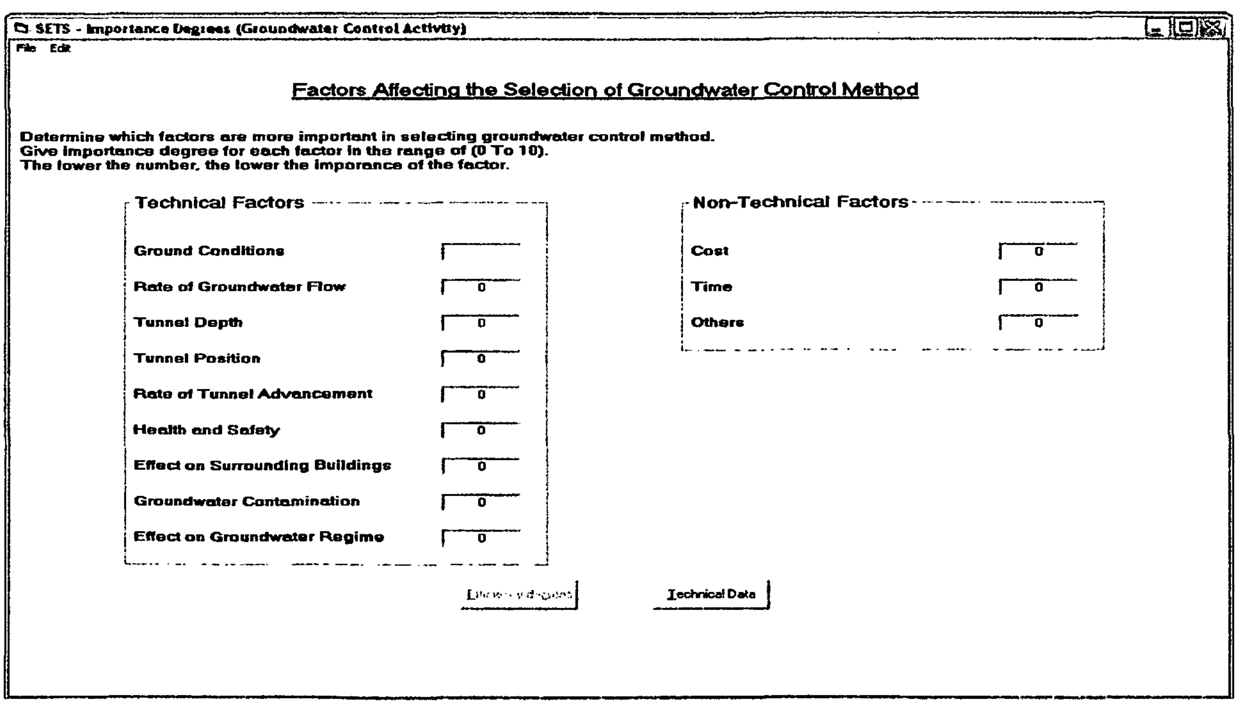


Figure 5.54 Screen of *"Importance degrees (Groundwater control activity)"*

has the same options like other importance degrees' screens. When the *"Others"* controlling factor has non-zero value, the button *"Efficiency degrees"* will be enabled. Clicking this button will display the screen *"Efficiency degrees of groundwater methods"* that shown in figure 5.55. Flow chart of figure 5.56 shows how the program checks the importance degrees' values to be sure that they are in range of (0 – 10).

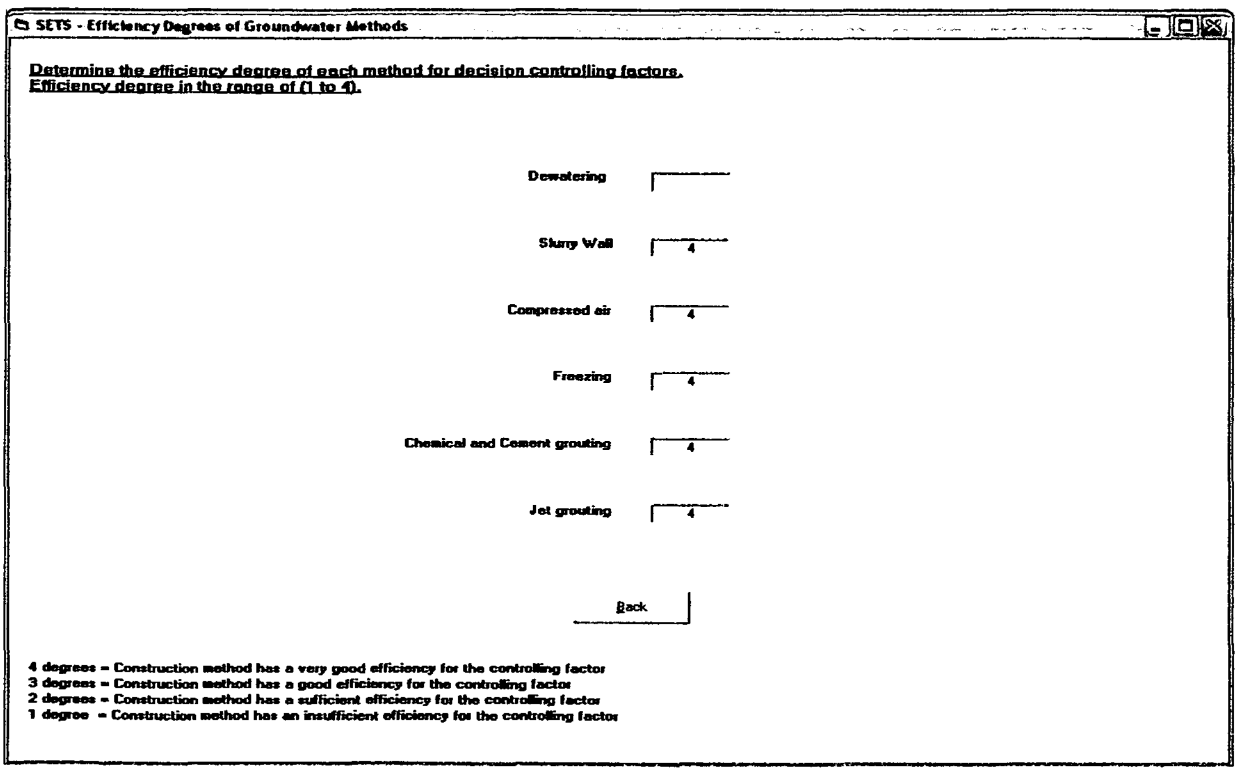


Figure 5.55 Screen of *"Efficiency degrees of groundwater methods"*

Figure 5.57 shows screen of the *"Project technical data (Groundwater control)"*. In this screen, the user can select technical data that match with his project. There are five groups of technical data in this screen. If user selects the option *"Soil"* in the screen *"Project general data"*, the option of *"Ground is rock"* in *"Ground conditions"* will be disabled. The *"Rock"* option in the screen

"Project general data" will make all options of *"Ground conditions"* halted except the option *"Ground is rock"*.

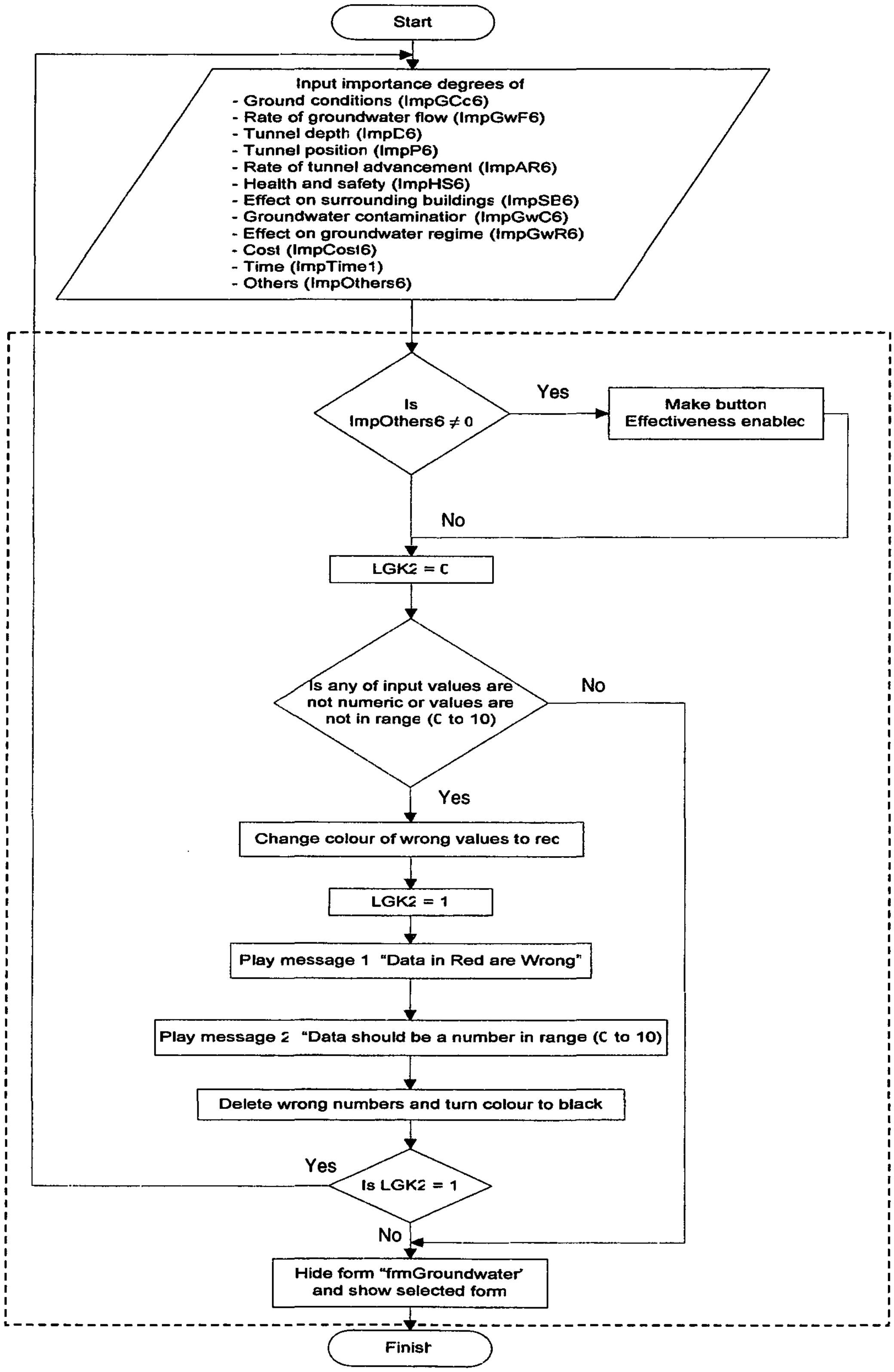


Figure 5.56 Checking importance degrees' values of groundwater control factors

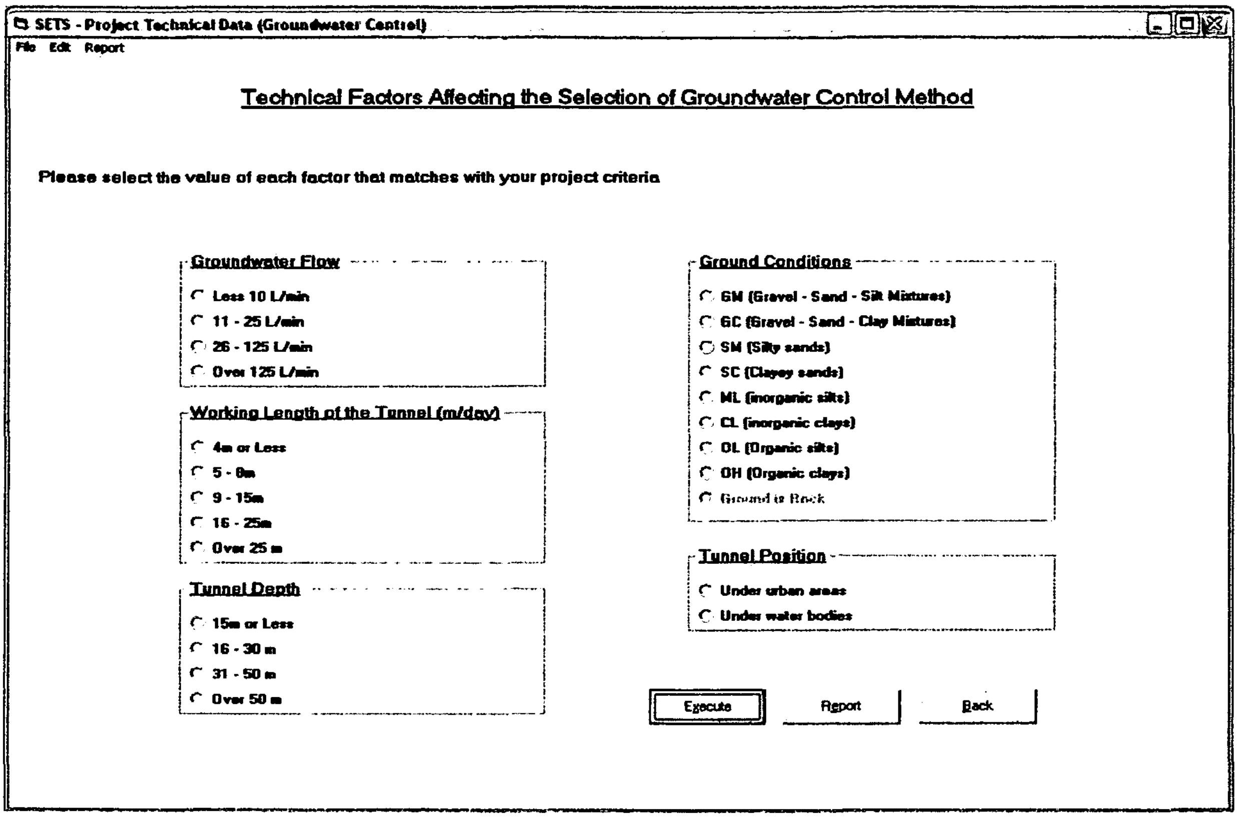


Figure 5.57 Screen of *"Project technical data (Groundwater control)"*

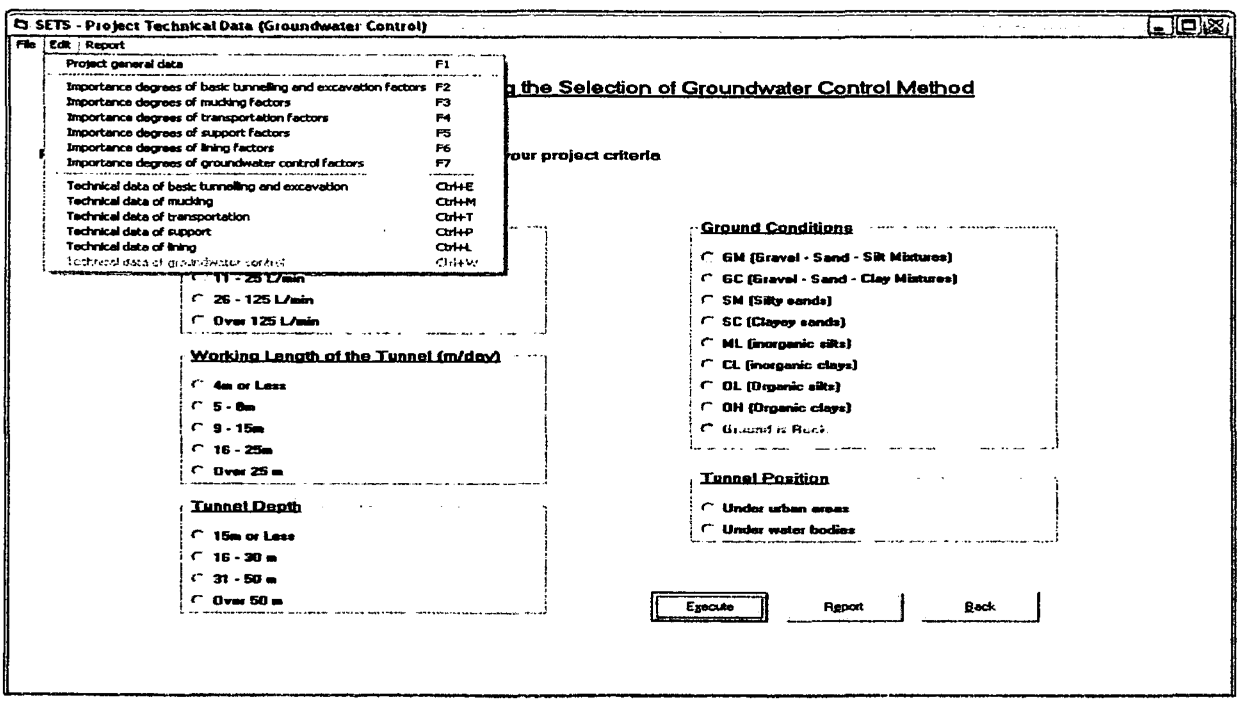


Figure 5.58 *"Edit"* submenu of screen *"Project technical data (Groundwater control)"*

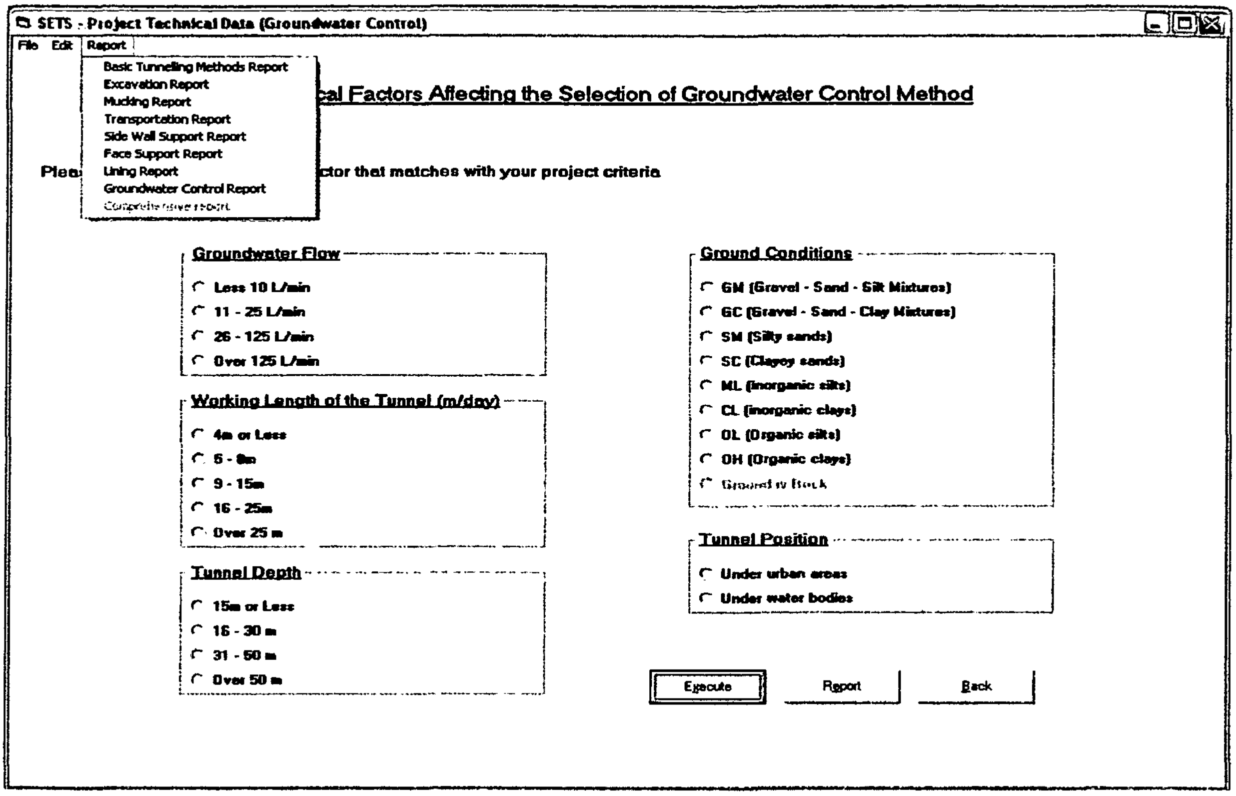


Figure 5.59 *"Report"* submenu of screen *"Project technical data (Groundwater control)"*

Submenus of *"Edit"* and *"Report"* options are shown in figures 5.58 and 5.59. User can retrieve any screen using edit submenu. He can show up any report about tunnelling activities using submenu of the *"Report"* option.

The program starts to calculate efficiency percentages of groundwater control methods when the user clicks button the *"Execute"*. Flow chart in figure 5.60 shows calculation steps.

File *"Grouwat.dat"* will be opened to read efficiency degrees of groundwater control methods for controlling factors *"GW(I,J)"*, efficiency degrees of basic tunnelling methods working with groundwater control methods *"IntCGW(I,J)"*, and efficiency degrees of excavation methods working together with groundwater control methods *"IntEGW(I,J)"*.

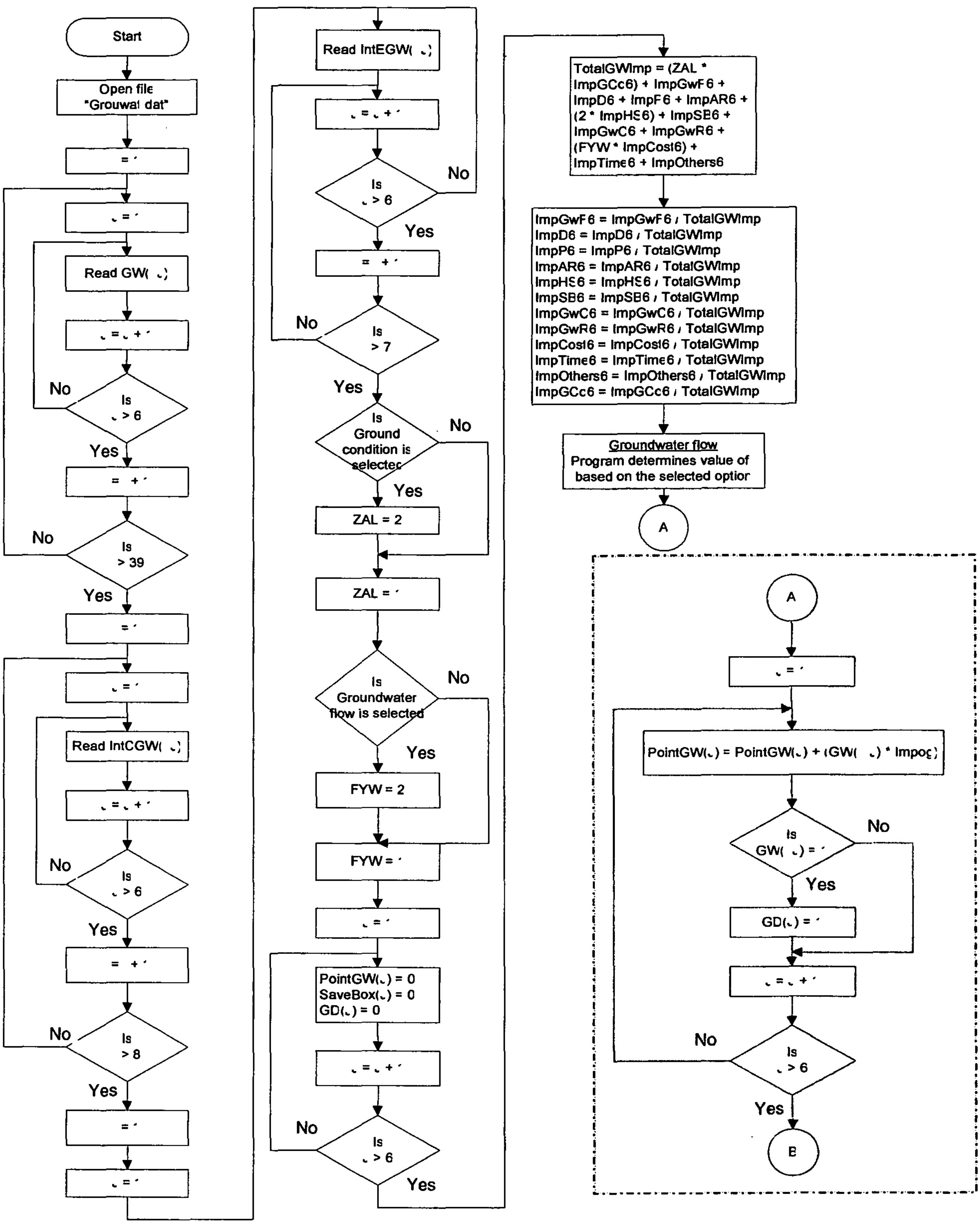


Figure 5.60a Calculation procedures of groundwater control methods' efficiencies

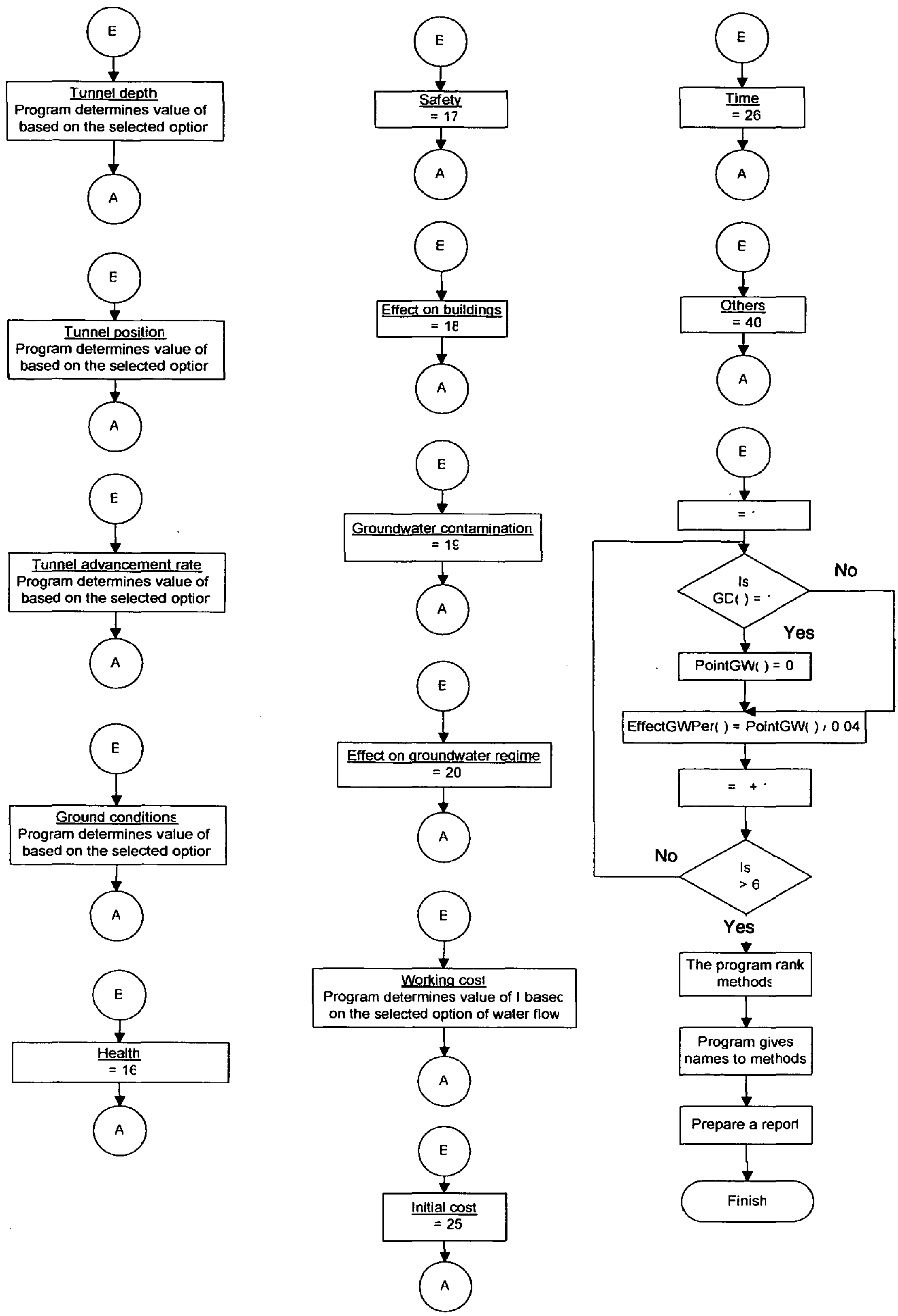


Figure 5.60b Calculation procedures of groundwater control methods' efficiencies

The program will calculate importance percentages before start of accumulating the weighted efficiencies of methods. Efficiency percentages of methods will be calculated using weighted efficiencies of each method. Then the program ranks methods and give names to them. Clicking the button *"Report"* in the screen *"Project technical data (Groundwater control)"* will show up a report about groundwater controlling methods. Figure 5.61 shows the report screen.

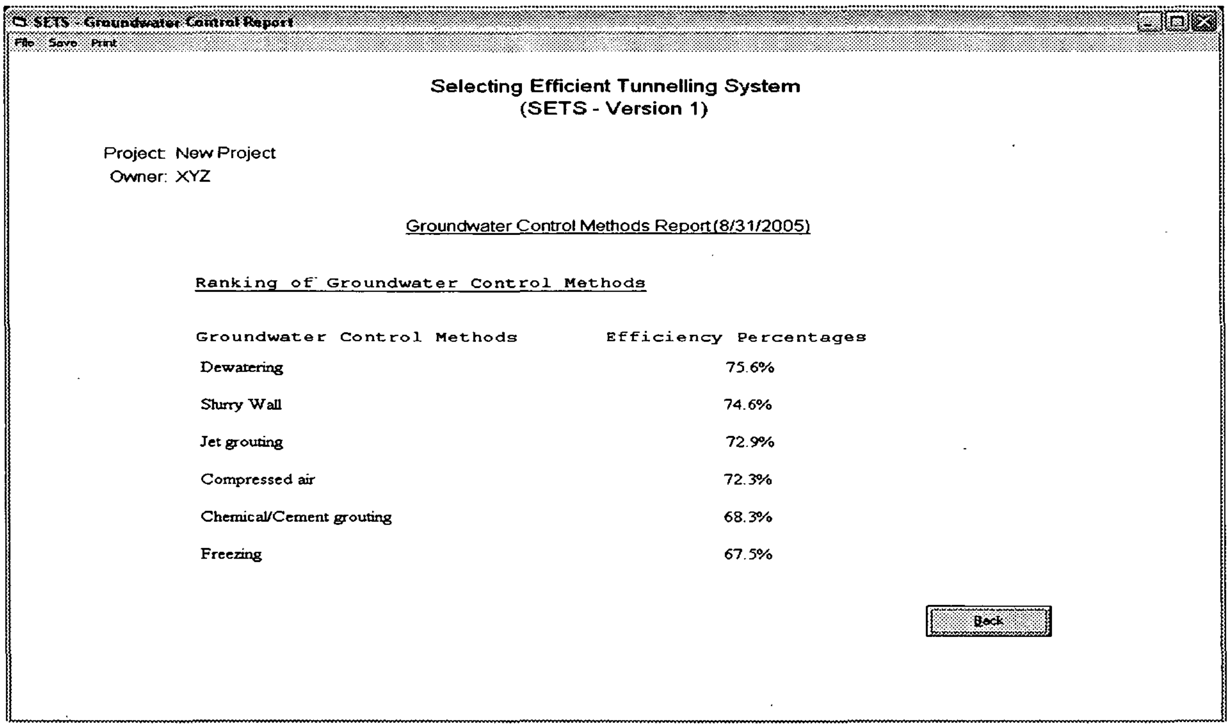


Figure 5.61 Report screen of groundwater control methods

5.4.7 Alternative tunnelling systems

The program will calculate alternative tunnelling systems after finishing calculations of efficiency percentages of tunnelling activities. Clicking the button *"Execute"* for all tunnelling activities means that the program now ready to start calculations of comprehensive report about tunnelling systems. The option of *"Comprehensive report"* in submenu of the *"Report"* in any screen of tunnelling activities will be enabled after clicking all *"Execute"* buttons. Figure

5.59 shows that the options *"Comprehensive report"* are disabled before clicking the button *"Execute"*. In figure 5.62, option *"Comprehensive report"* is enabled after clicking the button *"Execute"* knowing that the button *"Execute"* of other activities was clicked before.

When user clicks the option *"Comprehensive report"*, the program will start to calculate alternative tunnelling system as shown in figure 5.63. Flow chart, in figure 5.63, shows that the program will start to find the possible matches between basic tunnelling and excavation methods. The program will calculate at the beginning the efficiency percentage of methods working together *"IntCE(I,J)"*. Then, efficiency percentages of all possible pairs between basic tunnelling and excavation methods *"SysEffCE(I,J)"* will be calculated.

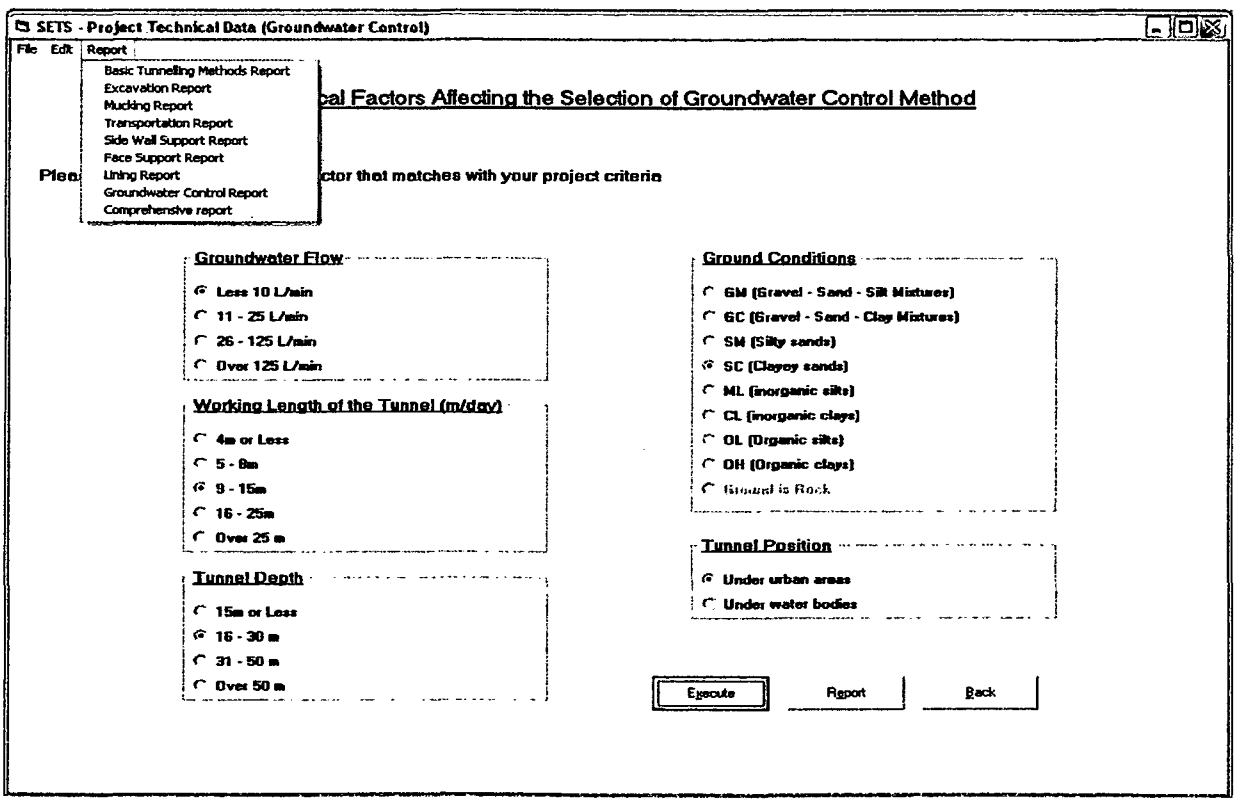


Figure 5.62a Option *"Comprehensive report"* is enabled

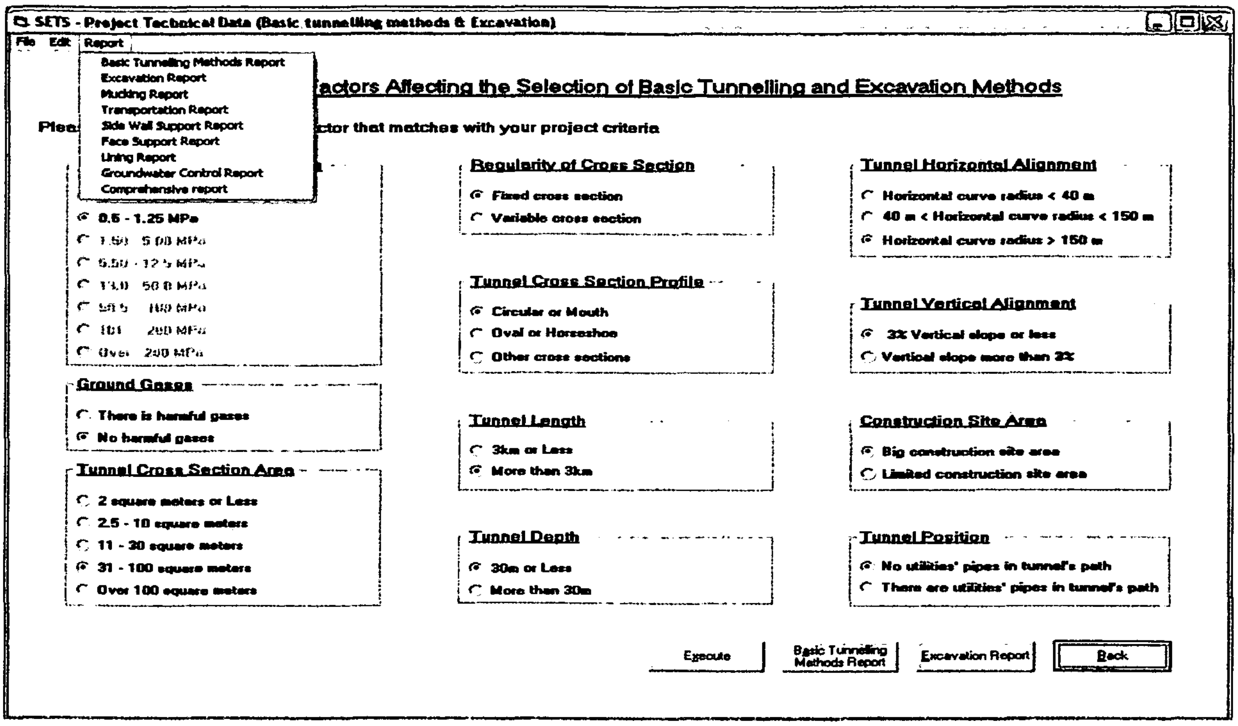


Figure 5.62b Option *"Comprehensive report"* is enabled

The *"CI"* variable is the number of possible pairs between basic tunnelling and excavation methods. Values of *"SysEffCE(I,J)"* will be ranked in descending order. Ranked basic tunnelling methods based on the combination with excavation methods will be saved in variable *"RECon(k)"* and excavation methods will be saved in variable *"REEx(k)"*. The same process will be done for "mucking - excavation methods" and "transportation - excavation methods". Ranked excavation methods with mucking will be saved in *"REEM(I)"* and mucking methods will be saved in *"REME(I)"*. Efficiency percentages of matched pairs between mucking and excavation methods will be saved in *"SysEffEM(I,J)"*. Ranked transportation methods that match with excavation methods will be in *"RETE(I)"* and excavation methods will be in *"REET(I)"*. Efficiency percentages of matched pairs between excavation and transportation methods will be in *"SysEffET(I,J)"*.

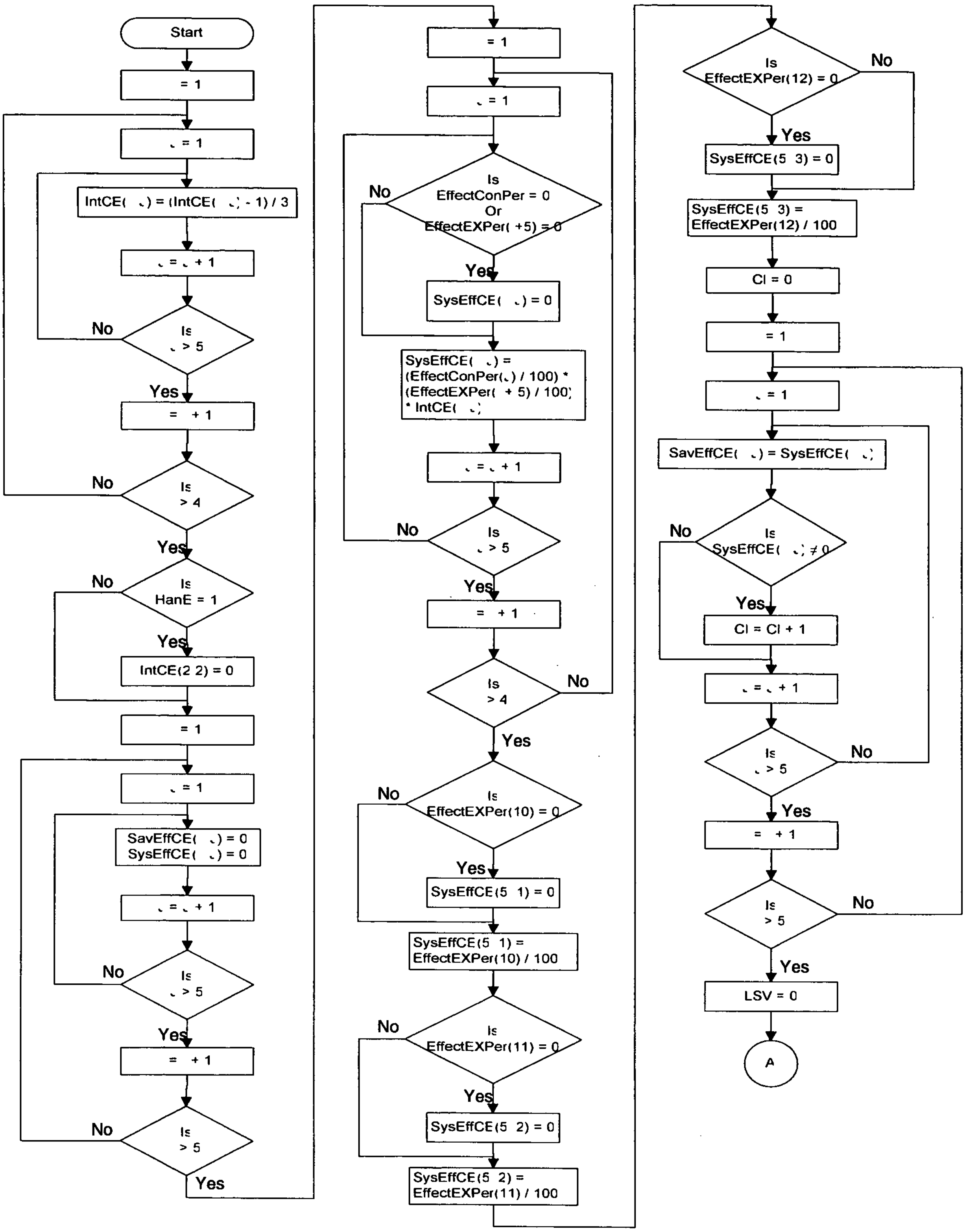


Figure 5.63a Flow chart of comprehensive report calculations

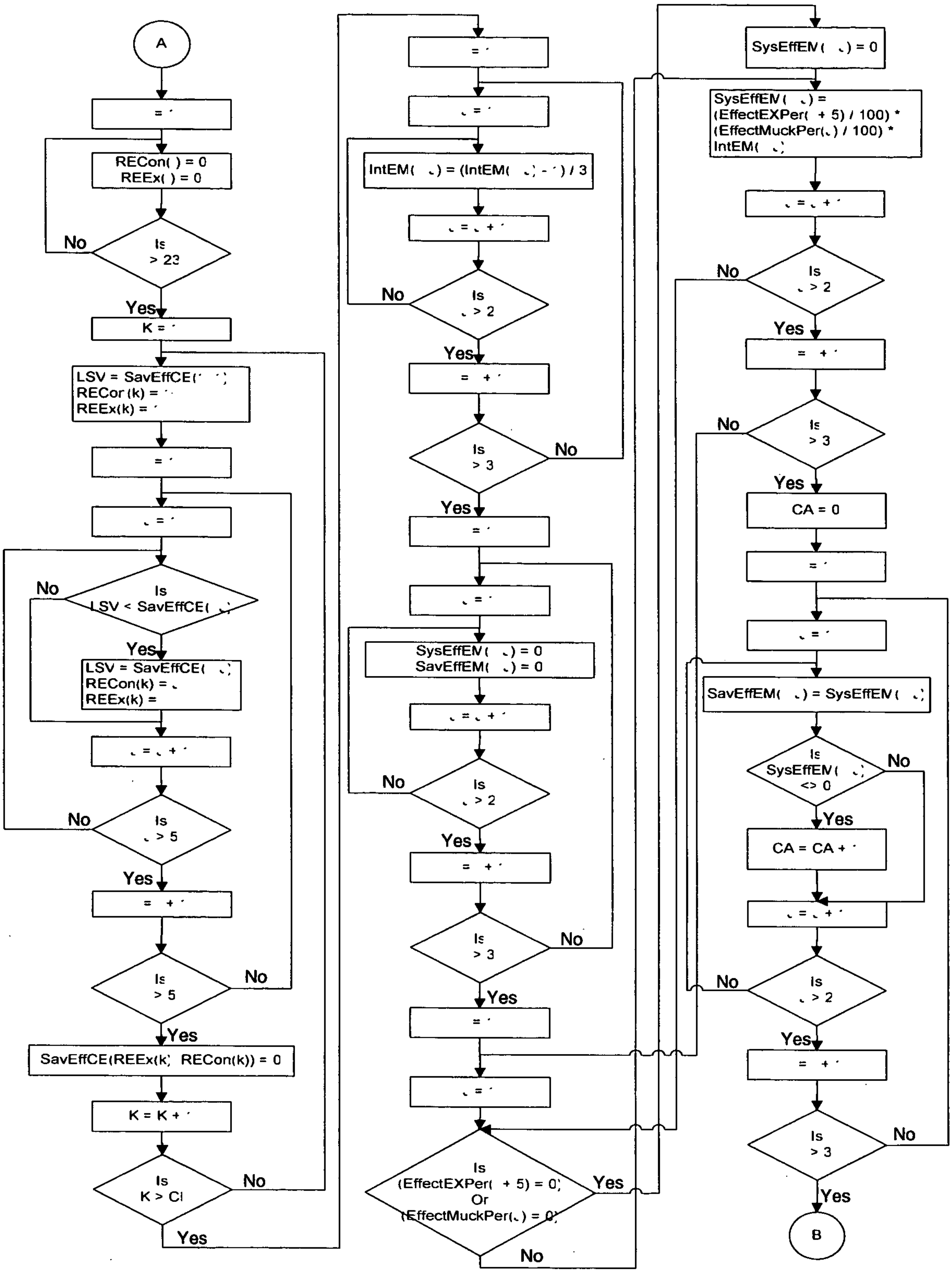


Figure 5.63b Flow chart of comprehensive report calculations

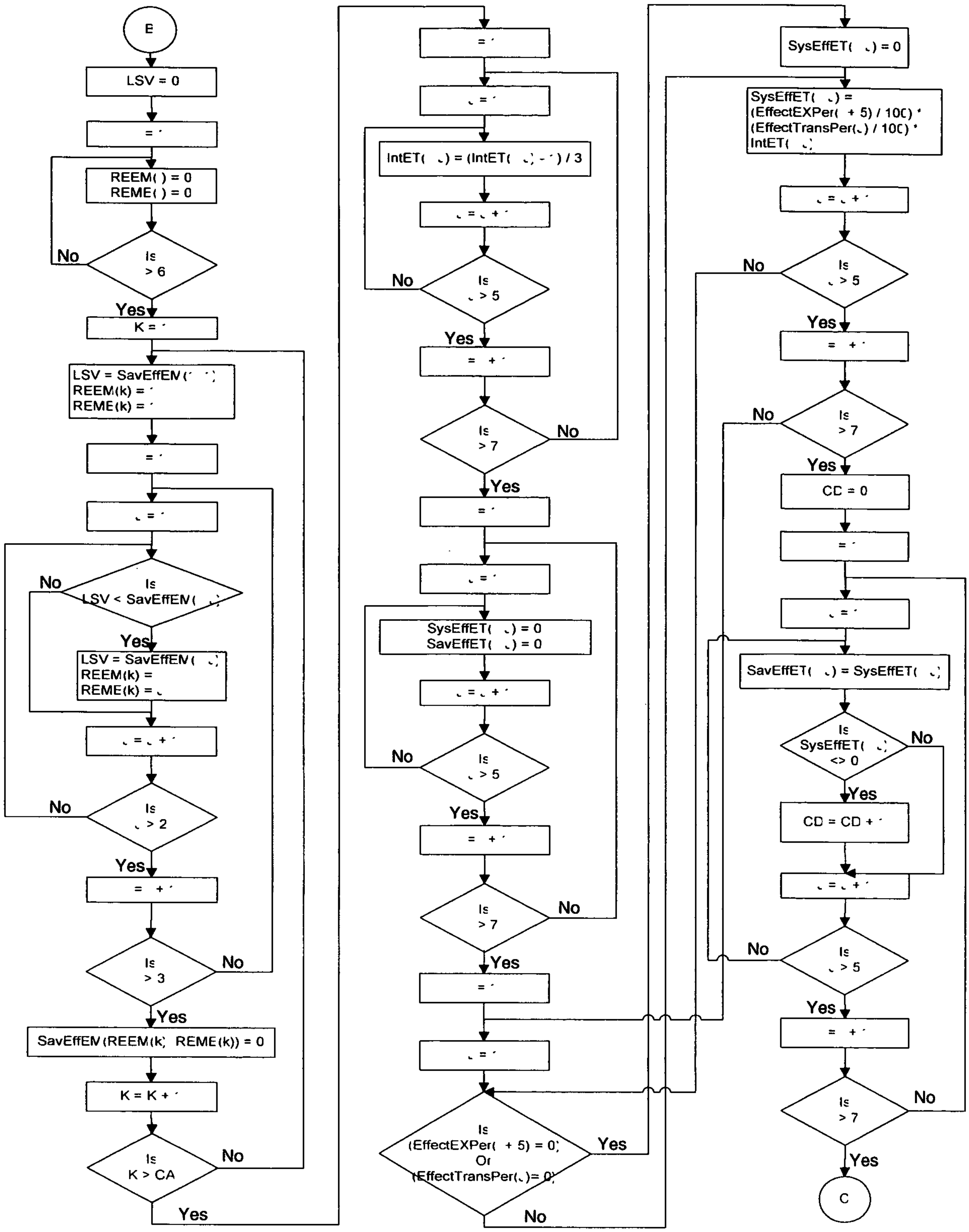


Figure 5.63c Flow chart of comprehensive report calculations

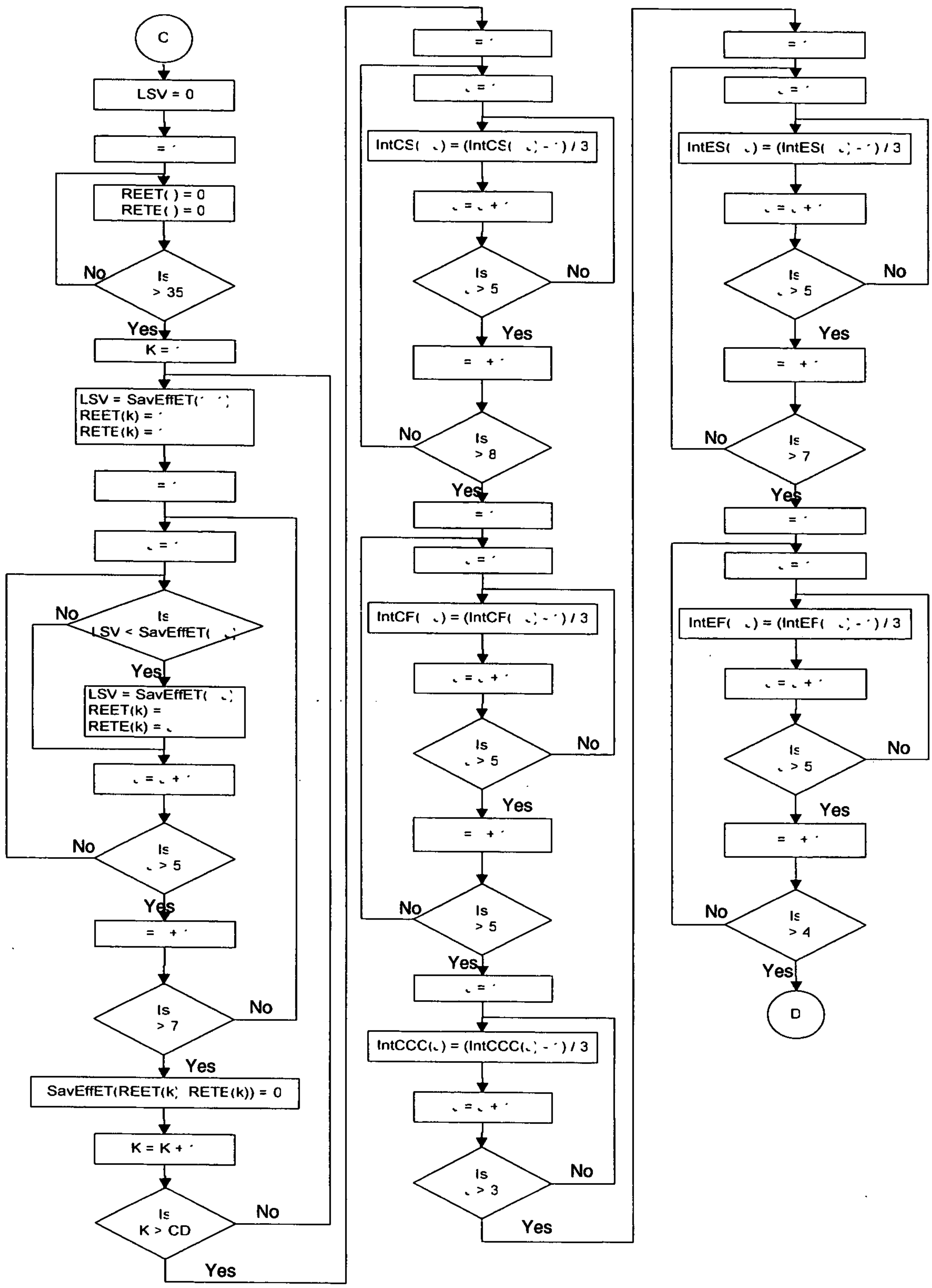


Figure 5.63d Flow chart of comprehensive report calculations

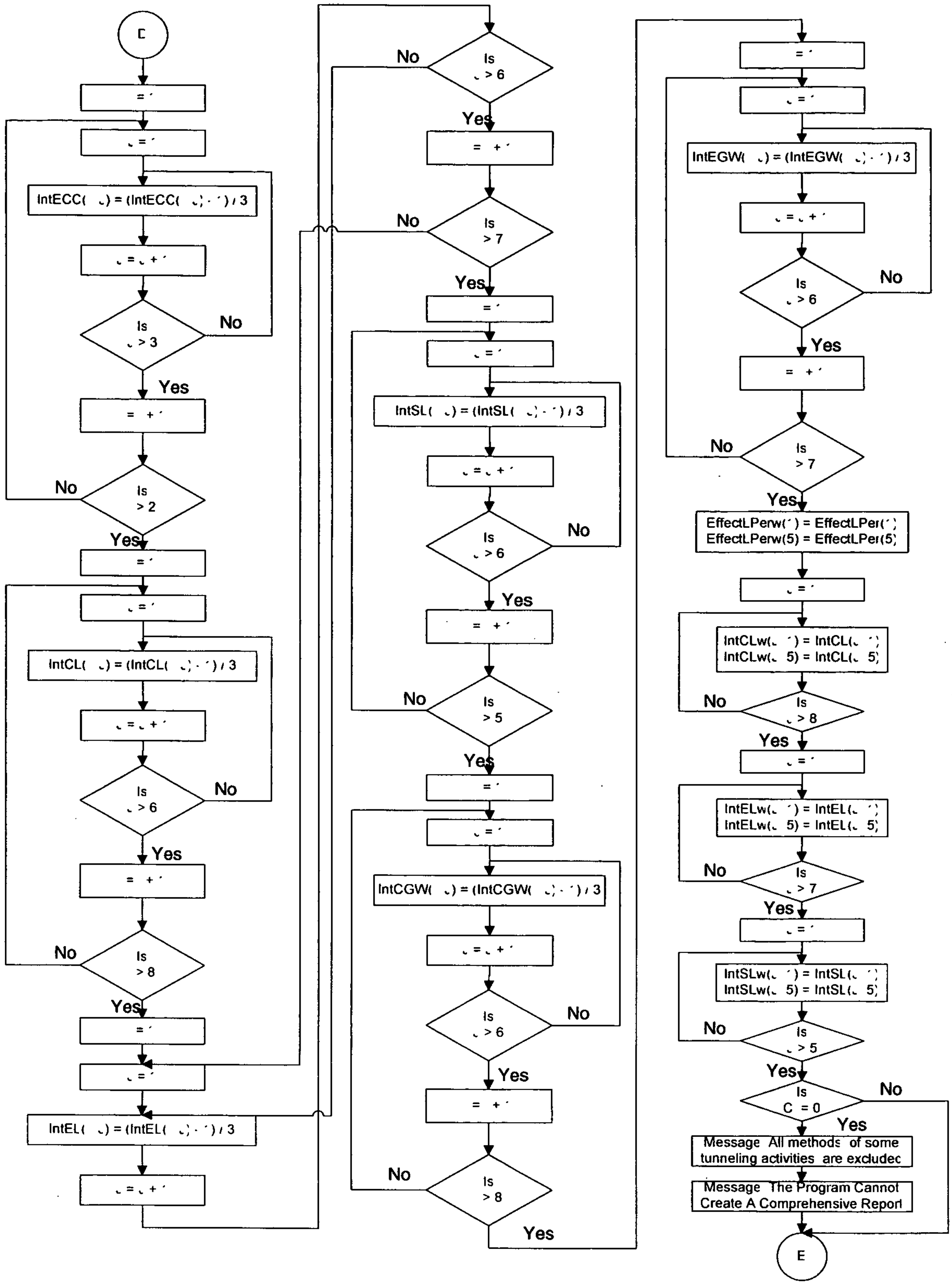


Figure 5.63e Flow chart of comprehensive report calculations

The program checks the value of *"CI"* variable that represent number of matches between basic tunnelling and excavation methods. Because pairs between basic tunnelling and excavation methods is the base to find tunnelling systems, zero value of variable *"CI"* means there is no any combinations between basic tunnelling and excavation methods. The program stop working at that point and it gives a message that all methods are excluded of a tunnelling activity and it will give another message to inform the user that the program cannot create a comprehensive report in this case.

The next step of the program is to start finding combinations of three activities. SETS will start to find combinations between basic tunnelling, excavation and mucking methods.

The program will start to read pairs of basic tunnelling and excavation methods and it will search for the best matches of mucking methods with each excavation method. Flow chart in figure 5.64 shows this process. The variable *"WSys(I,1)"* is presenting basic tunnelling method of the alternative system number *"I"*. *"WSys(I,2)"* represents the mucking method of alternative system *"I"* and *"WSys(I,3)"* is the transportation method.

After finding the mucking method the program will use the same procedure to find the transportation method. Figure 5.64 shows also calculations of finding the transportation method. Flow chart in figure 5.64 is a continuation of the flow chart in figure 5.63.

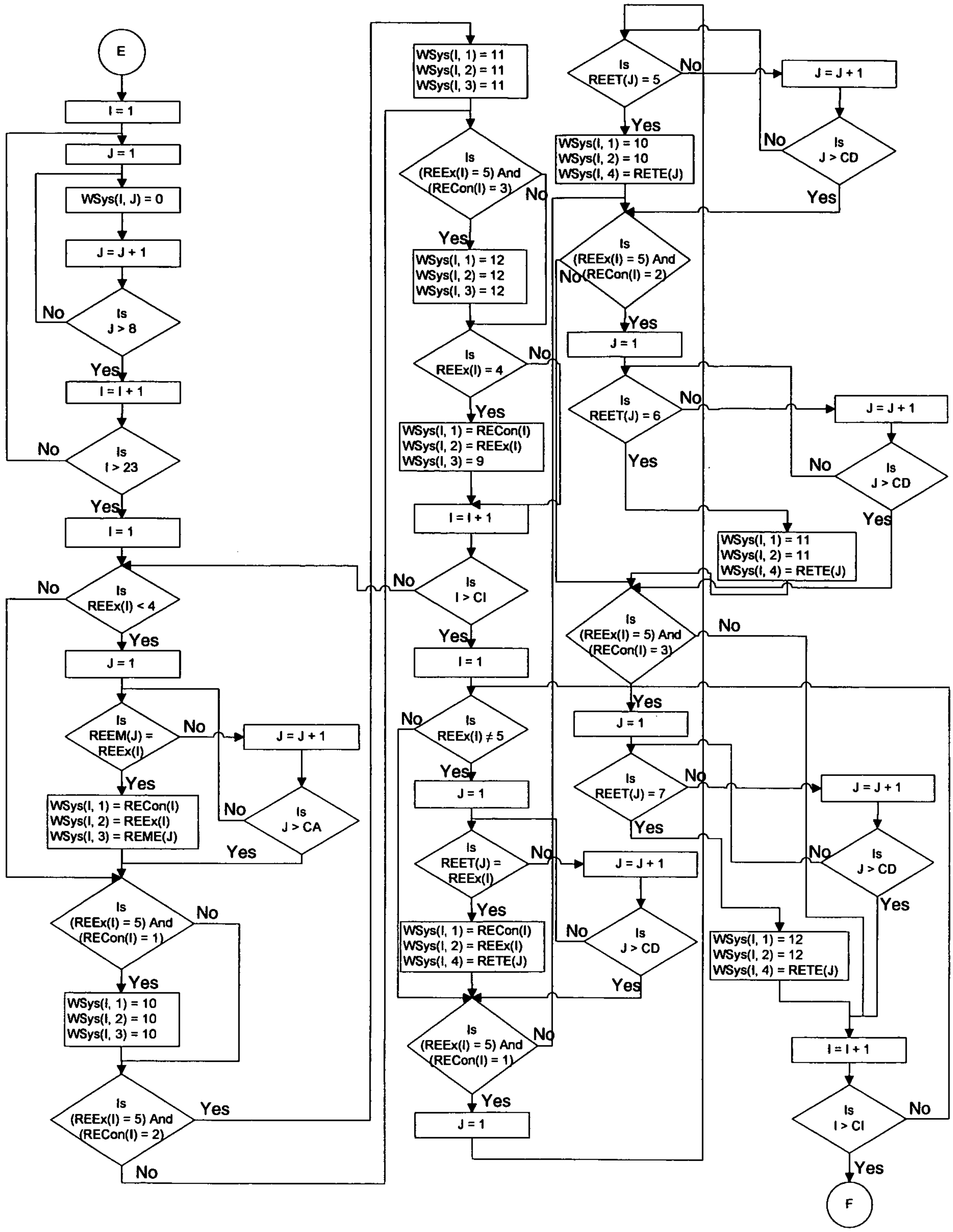


Figure 5.64 Finding mucking and transportation methods for tunnelling system

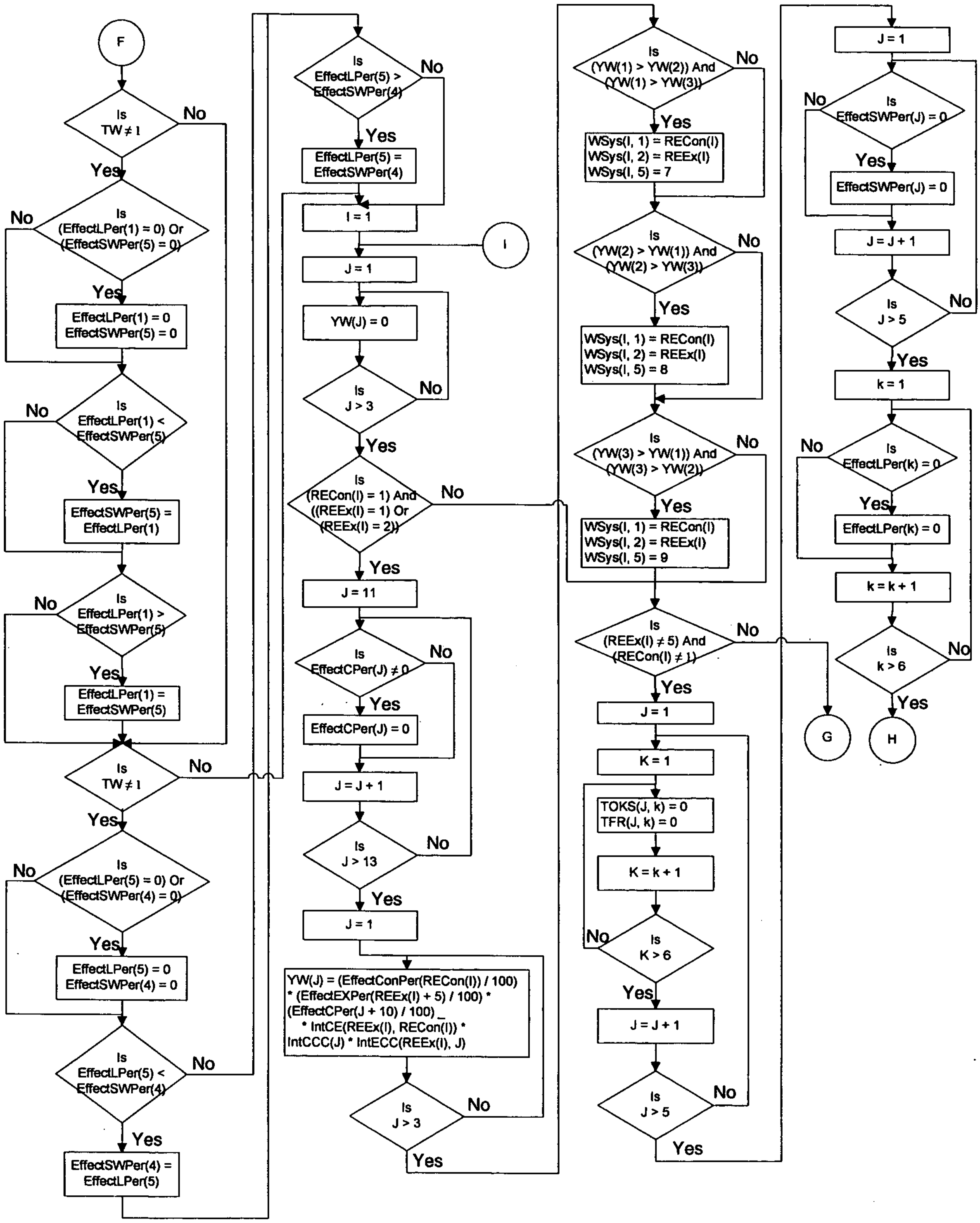


Figure 5.65a Adding support and lining methods to tunnelling systems

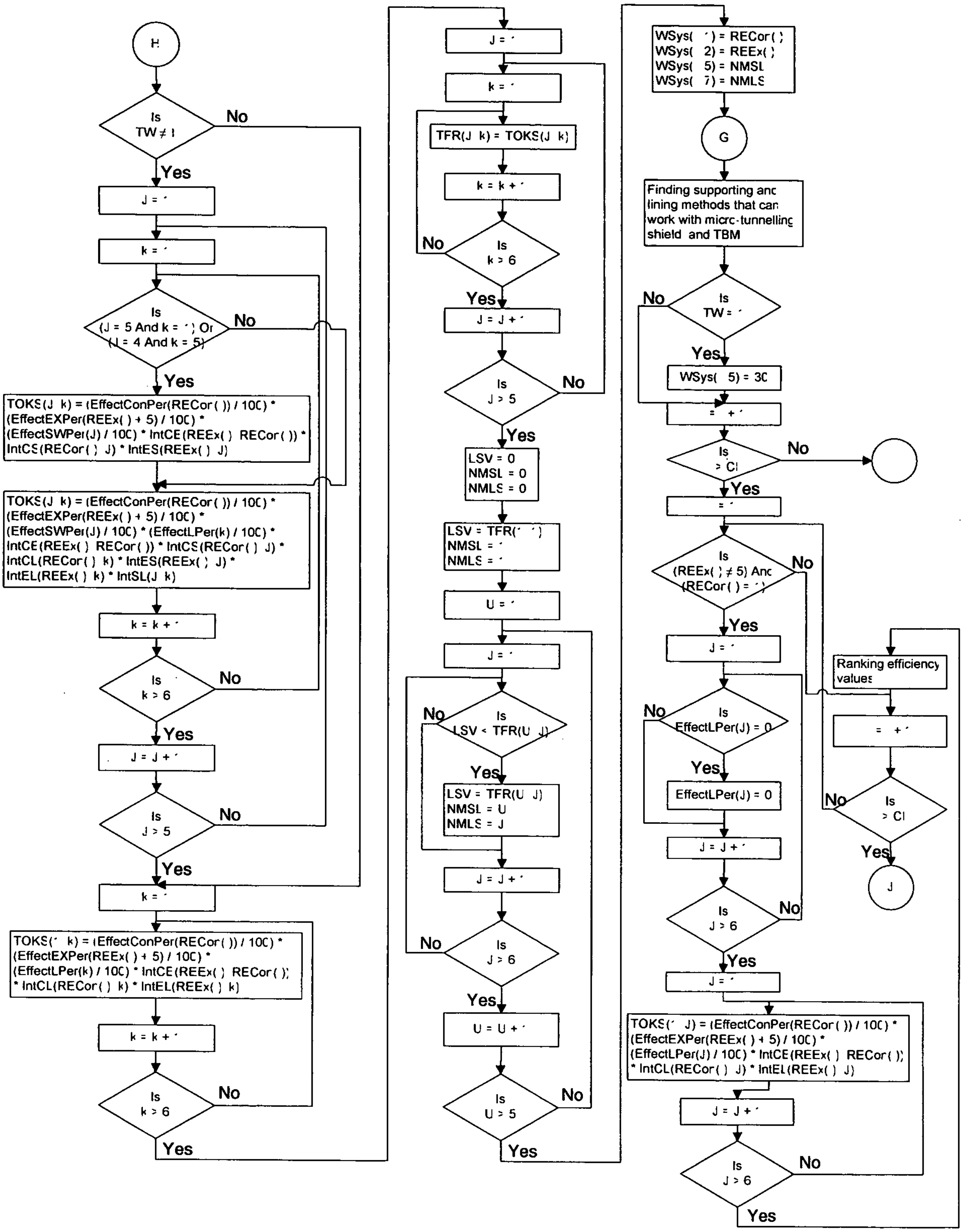


Figure 5.65b Adding support and lining methods to tunnelling systems

Figure 5.65 shows the logic that the program uses to add support and lining methods to tunnelling system. The program adds support and lining methods in the same step. The small efficiency percentage of the *"Precast concrete segments"* and *"Shotcrete"* will be used during calculations of this step. In flow chart of figure 5.65, the program compare between efficiency percentage of *"Precast concrete segments"* as lining method *"EffectLPer(1)"* and its efficiency percentage as support method *"EffectSWPer(5)"* to use the small value during calculations. The same comparison will be done for *"Shotcrete"*. Comparison in case of *"Shotcrete"* will be between *"EffectLPer(5)"* and *"EffectSWPer(4)"*. Because support and lining methods are different in case of cut and cover, therefore the program will search for support and lining methods in two different steps.

There are three possible support methods for cut and cover. The program will calculate efficiency percentage *"YW(J)"* when each one of them is working. The program will take the method that will give the highest value of *"YW(J)"*.

Then, the program moves to find support and lining methods for case when neither cut and cover nor mechanical method is used. Condition *"REEx(I)* $\neq$ *5 and RECon(I)* $\neq$ *1)"* represents this case. The program starts to read pairs of basic tunnelling and excavation methods. For each pair, it calculates efficiency percentage *"TOKS(J,K)"* for all possibilities of support and lining methods working together with the pairs of basic tunnelling and excavation methods. Support and lining methods that will give the highest value of *"TOKS(J,K)"* will be considered as the best methods for that pair of basic tunnelling and excavation methods.

"SETS" applies the same logic to find support and lining methods for *"Micro-tunnelling"*, *"Shield"*, and *"TBM"*.

When the value of *"TW"* is "1" the program assigns a value of "30" to support methods which means that there is no need for support methods.

The program starts to find lining methods for cut and cover. Efficiency percentages *"TOKS(J,K)"* of the possible systems that can use different lining methods will be calculated and lining method that gives highest value will be considered as the best method for cut and cover.

Figure 5.66 shows calculation steps of the program to add face support and groundwater control methods to tunnelling systems. For face support, the program will start to calculate efficiency percentages of tunnelling systems when possible face support methods are added. Method that gives highest efficiency percentage will be considered as the best for tunnelling system. The program will use the same procedures to add groundwater control methods. Table 5.5 shows variables' names of tunnelling activities for tunnelling systems. *"I"* is system number.

Table 5.5 Variable name of tunnelling activities in the system

Tunnelling activity	Variable name of tunnelling system
Basic tunnelling methods	WSys(I,1)
Excavation	WSys(I,2)
Mucking	WSys(I,3)
Transportation	WSys(I,4)
Side wall support	WSys(I,5)
Face support	WSys(I,6)
Lining	WSys(I,7)
Groundwater control	WSys(I,8)

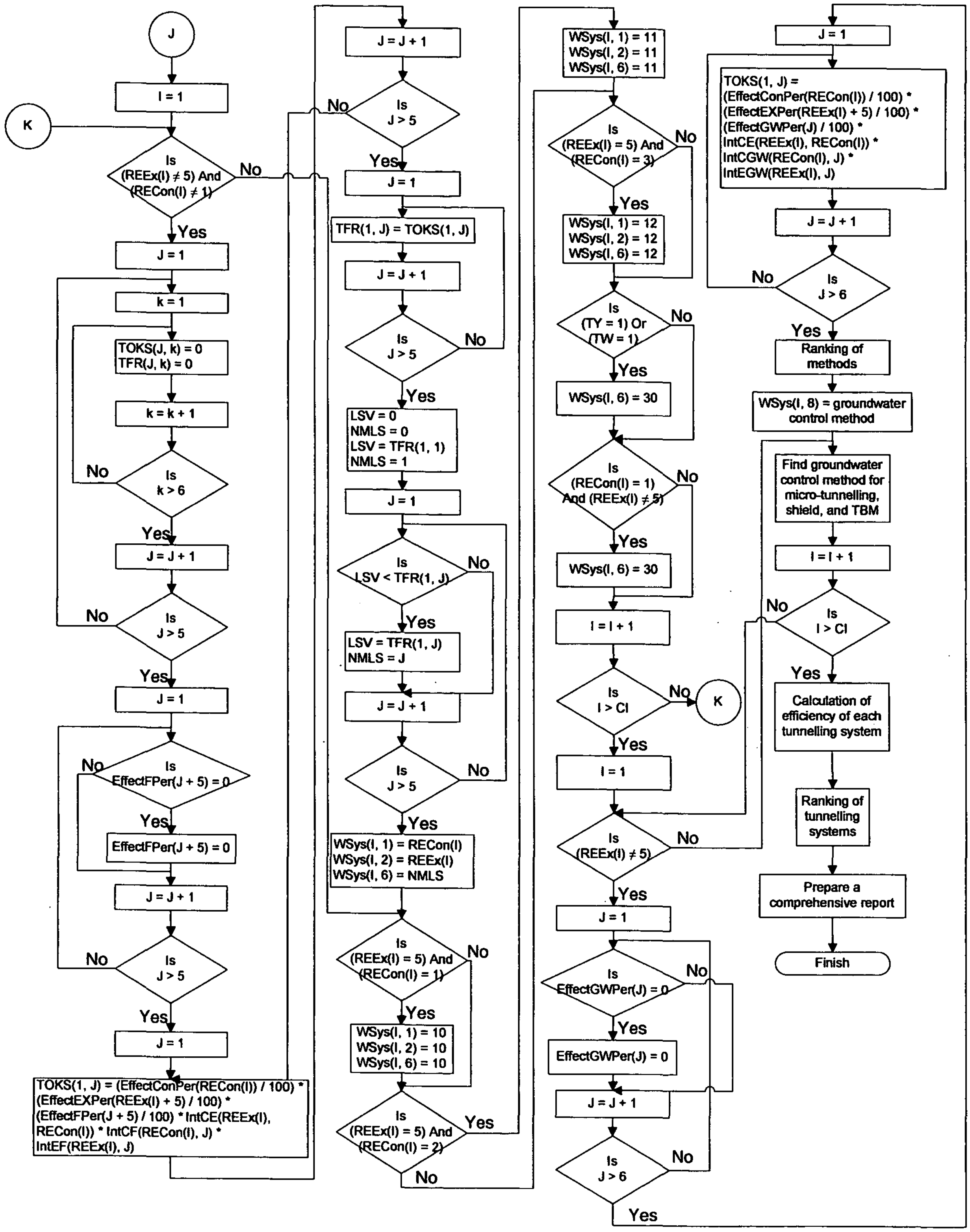


Figure 5.66 Adding face support and groundwater control methods to tunnelling system

After finding methods of all tunnelling activities, the program will calculate efficiency percentage of each tunnelling system by multiplying efficiency percentages of methods together and efficiency percentages of working of methods together will be multiplied as well. The program will rank tunnelling systems in descending order and it will prepare the comprehensive report that shown in figure 5.67.

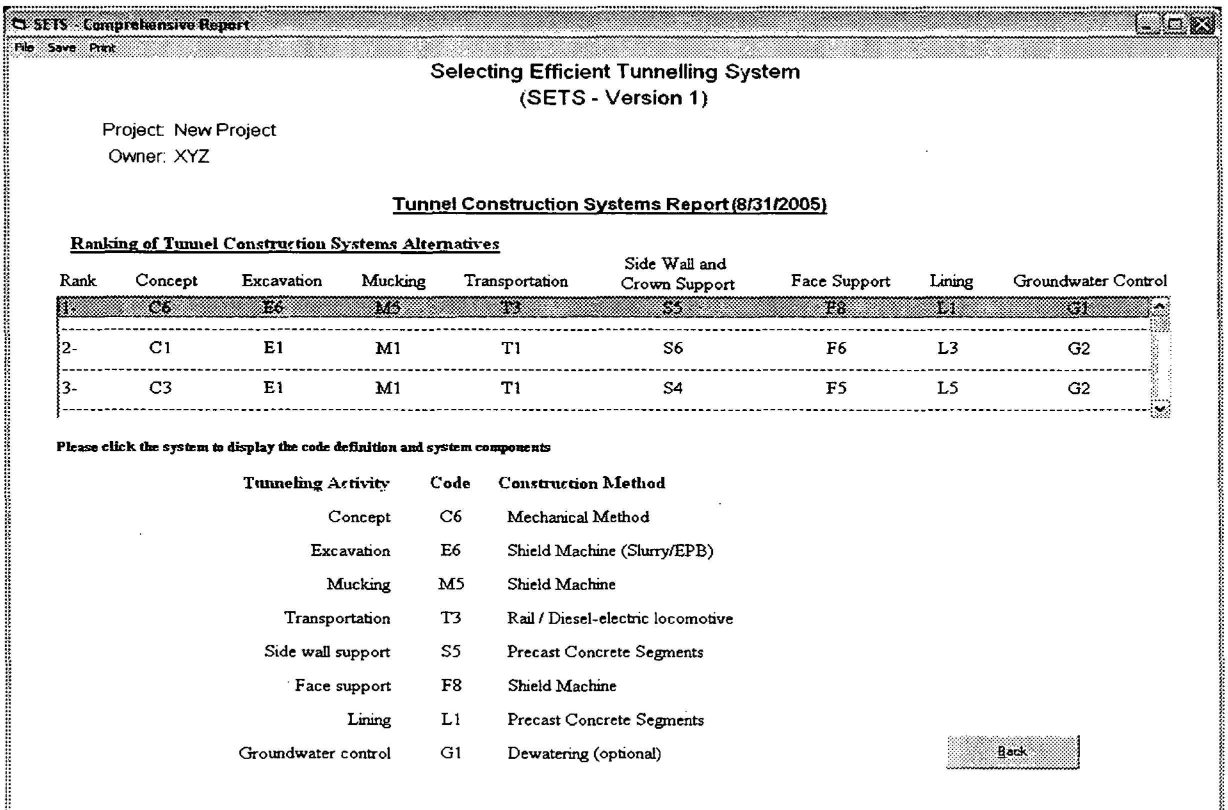


Figure 5.67 Screen of comprehensive report

Tunnelling systems in the comprehensive report screen is written in a list box. Explanation of the system symbols is shown under the list box. Clicking system with mouse will display the component of this system under list box. The *"Back"* button will hide this screen and show up the same screen which the comprehensive report option was clicked in it.

6 Application of the model in real projects

6.1 Introduction

The proposed model explained in chapter 4 and the SETS program is applied in real tunnel projects to compare the results of the program and the real situation. The program 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.

6.2 Wienerwald tunnel

A project of new double rail high speed connection between Vienna and St. Pölten is established as a part of the high speed connection between Vienna and Salzburg. The connection between Vienna and St. Pölten is divided into three sections:

Wienerwald	km 11,881 – km 25,550
Tullnerfeld	Km 25,550 – km 41,591
West	Km 41,591 – km 54,199 (Knoten Wagram)

6.2.1 Project description

Wienerwald tunnel is an essential section of this new high speed connection between Vienna and St. Pölten. Wienerwald tunnel is approximately 13.35 km long. It connects the suburban area of Vienna (Hadersdorf-Weidlingau) with Tullnerfeld. Figure 6.1 shows general layout of the tunnel.

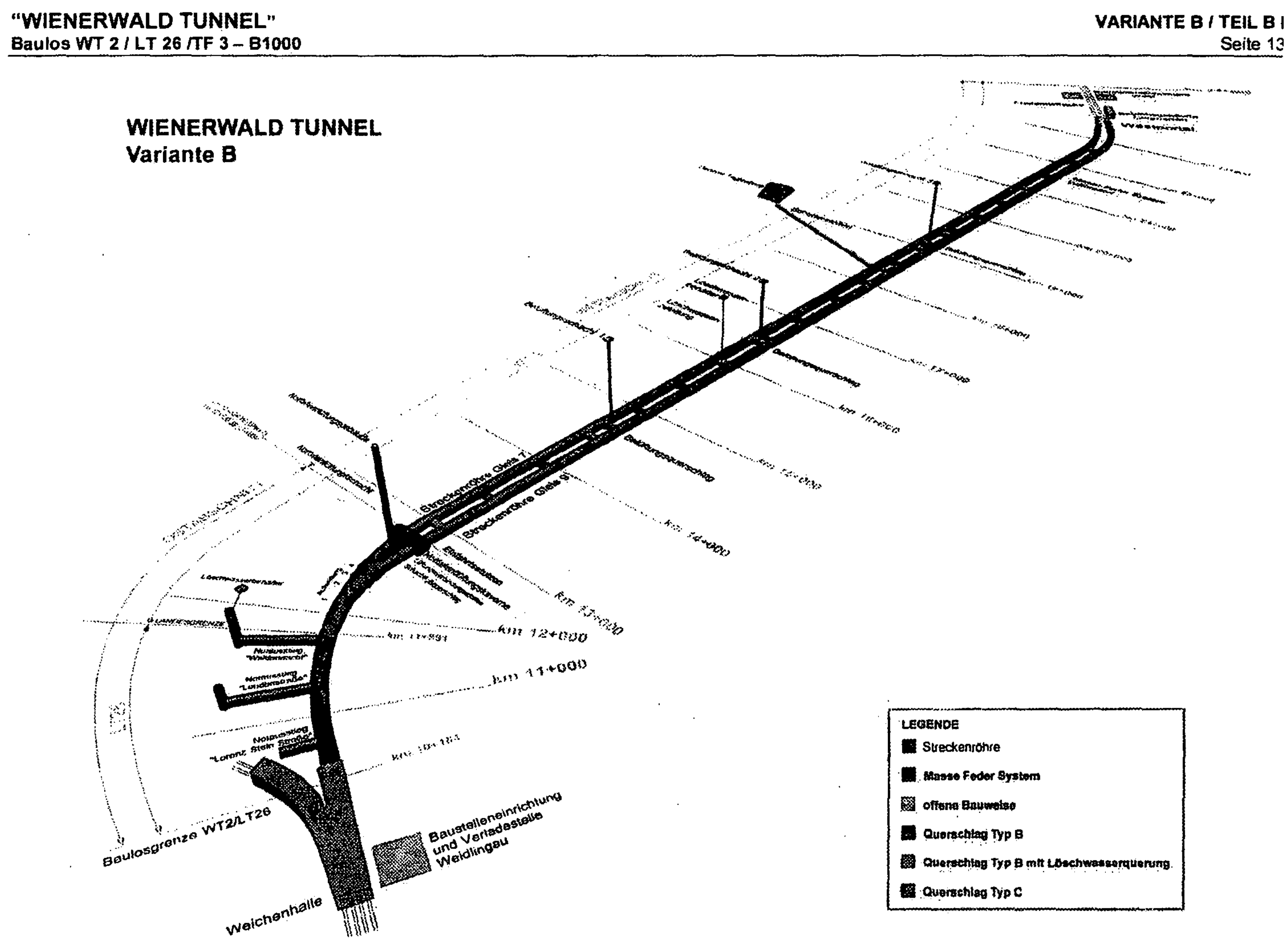


Figure 6.1 General layout of Wienerwald tunnel

Wienerwald tunnel is divided into two sections. East section is (Track 9 (km 10+164,000 – km 12+530,300)) and west section is (Track 9 (km 24+600 – km 12+530,300)). Constructing the west section starts from the west portal going to the east. It is planned to start activities of the west section by track 7 and after 6 months, activities of track 9 will start.

The tunnel, in its east section, has one tube with double tracks and the west section has two tubes each with one track. Diameter of each tube is 10.6m. Figure 6.2 shows tunnel cross section (west section).

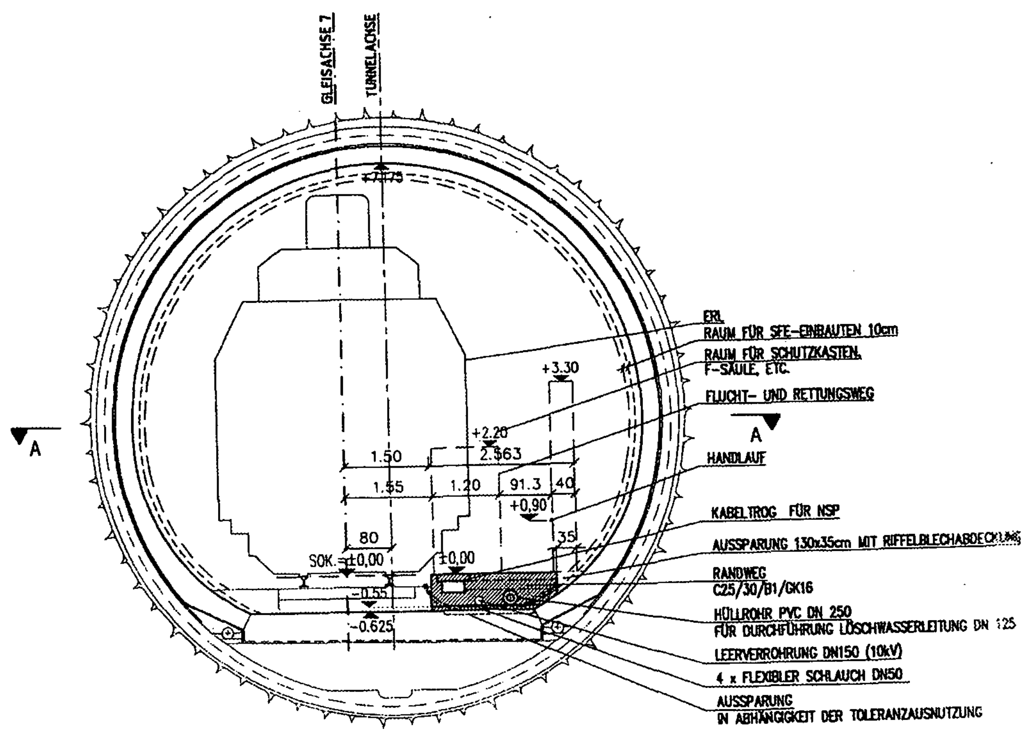


Figure 6.2 "Wienerwald" tunnel cross section

The two tubes of the west tunnel section are parallel and connected by crossovers in intervals of 500 m. For the double-railed tube, three emergency exits are planed for safety reasons, also a shaft construction works are to be established. The two tunnel tubes in the west section are provided by emergency and ventilation crossovers. At 15+900 km of track 9, there is a tank for fire-fighting water. In the west section of the tunnel, pollutant caching chamber is established and protection of freezing is provided as well.

The gradient of track 9 from km 10+164,000 until km 12+844,535 is 2.8001% and it continues with a gradient of 3.0000% until km 23+611,200. Track 7 has a gradient of 3.0000% from km 12+858,929 until km 23+61,221.

Wienerwald tunnel goes through two main types of ground conditions. The first is Flysch zone at the west of Vienna and after that there is small section of Molasse zone. The overburden above the tunnel is 240m. Figure 6.3 presents the geological profile of Wienerwald area. The average groundwater flow is less than 10 l/min.

Flysch is a remarkable formation, composed mainly of sandstones and sandy shale found extending from SW of Switzerland eastward along the northern Alpine zone to the Vienna basin.

Zone of Flysch encountered by the tunnel, in its northern section, is composed of dark shale deposits, which change with lime and lime-sand stone. In this section, ground has multicolour (red-brown, red until green shale). In south-east, there is *"Greifensteiner Decke"*, which takes the largest part of the Flysch zone in the project area (see figure 6.4). Flysch zone in *"Greifensteiner Decke"* is composed of sand stone, clay stone, and shale. There are some organic traces in this area. Methane gas is found in concentration between 0.1% and 6%.

The Molasse consists of marine sediments. Composition of Molasse zone is silt stone, clay stone, and sand stone.

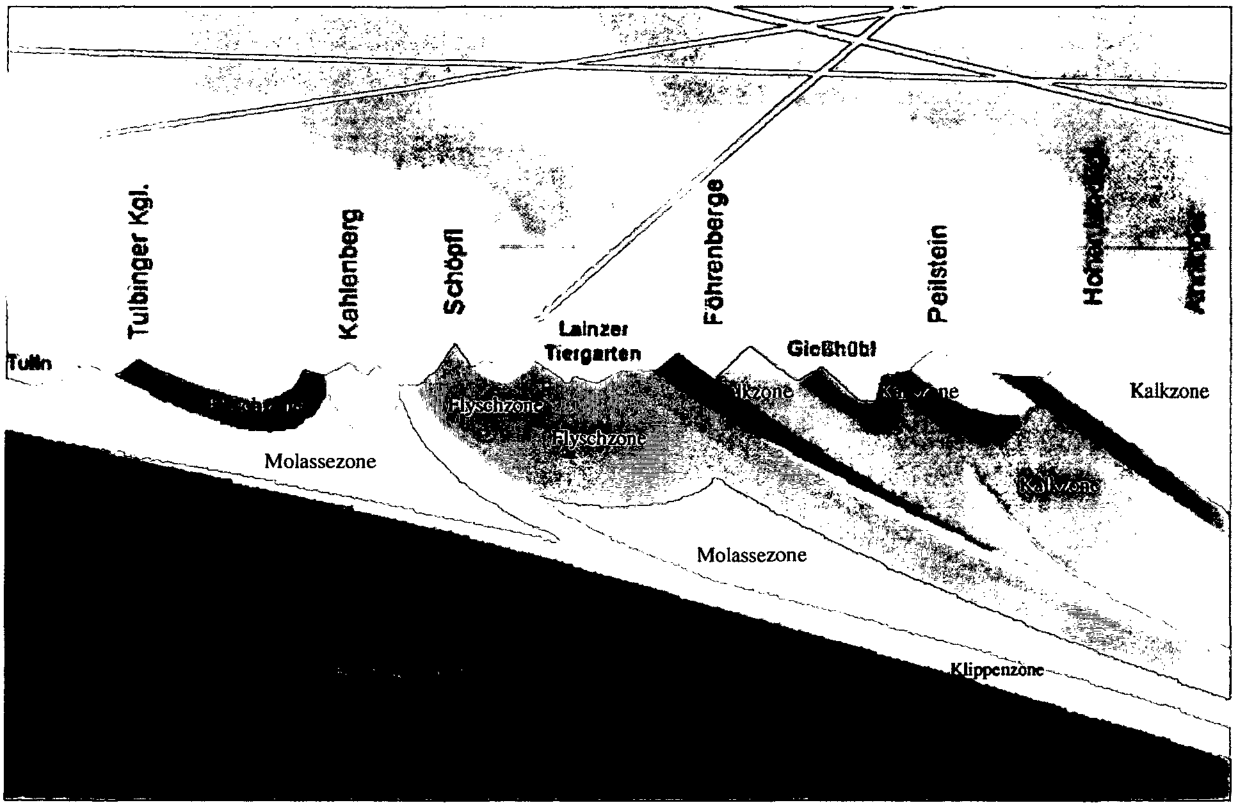


Figure 6.3 Geological profile of Wienerwald area [124]

Method of construction selected to construct the west section of Wienerwald tunnel is open face shield machine. Transportation of the muck is done by conveyors. A dewatering system is used to pump out groundwater.

The client of Wienerwald tunnel is *"Eisenbahn Hochleistungsstrecken AG"*. The designer is *"iC group"*. Project cost is 340 Million Euro. Work started in the project in August 2004 and the planned duration of the project is 6 years.

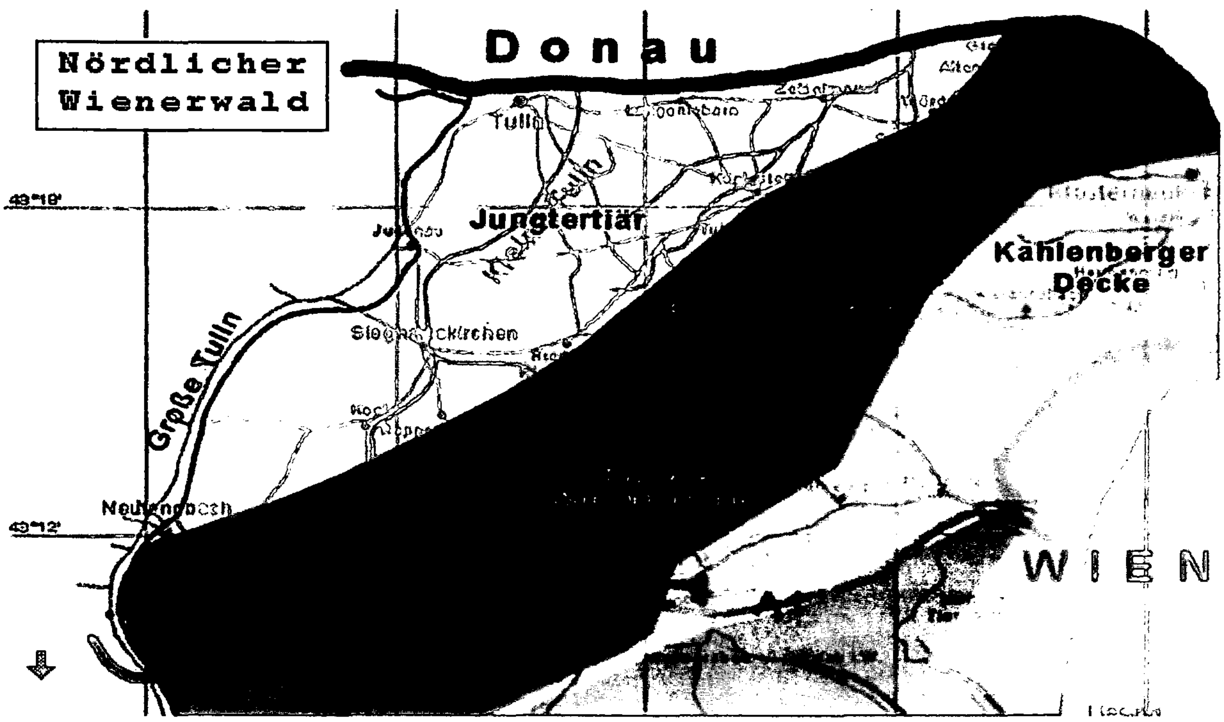


Figure 6.4 Northern of Wienerwald area [124]

6.2.2 Input data to SETS program (Wienerwald tunnel project)

A meeting with project designer was held. The following input data of the Wienerwald tunnel project were used to check the results of the program SETS and compare it with the actual used methods.

6.2.2.1 Data of the *"Project general data"* screen

Project name	Wienerwald (West section)
Client	HL-AG

Ground	Rock
Tunnel height	10.6 m
Groundwater level	(0) not determined
Tunnel invert level	180
Labour cost	High

6.2.2.2 Data of the *"Basic tunnelling methods"* and excavation activities

Importance degrees of basic tunnelling and excavation controlling factors - as determined by the designer - are shown in table 6.1.

Ground compressive strength changes from place to place through tunnel path. It varies from 1MPa to 100MPa. The lowest compressive strength is used to apply the program. Input technical data are as follow:

Ground compressive strength	0.5 – 1.25MPa
There is harmful gases	Yes
Tunnel cross section area	31 – 100m^2
Fixed cross section	Yes
Cross section shape	Circular
Tunnel length	More than 3km
Tunnel depth	More than 30m
Sharpest horizontal curve radius	Bigger than 150m (no curves)
Vertical slope	Less than 3%
Construction site	Big
There is utilities in tunnel's path	No

Results of the program are shown in figures 6.5 and 6.6. Figure 6.5 shows basic tunnelling methods report, on the other hand, figure 6.6 shows excavation report. Printed reports are in appendix B-1.

For basic tunnelling methods, mechanical method is the best selection for this project (see figure 6.5) and for excavation methods, excavator is the best method and shield machine comes in the second rank (see figure 6.6).

Table 6.1 Importance degrees for controlling factors (basic tunnelling and excavation methods-Wienerwald tunnel)

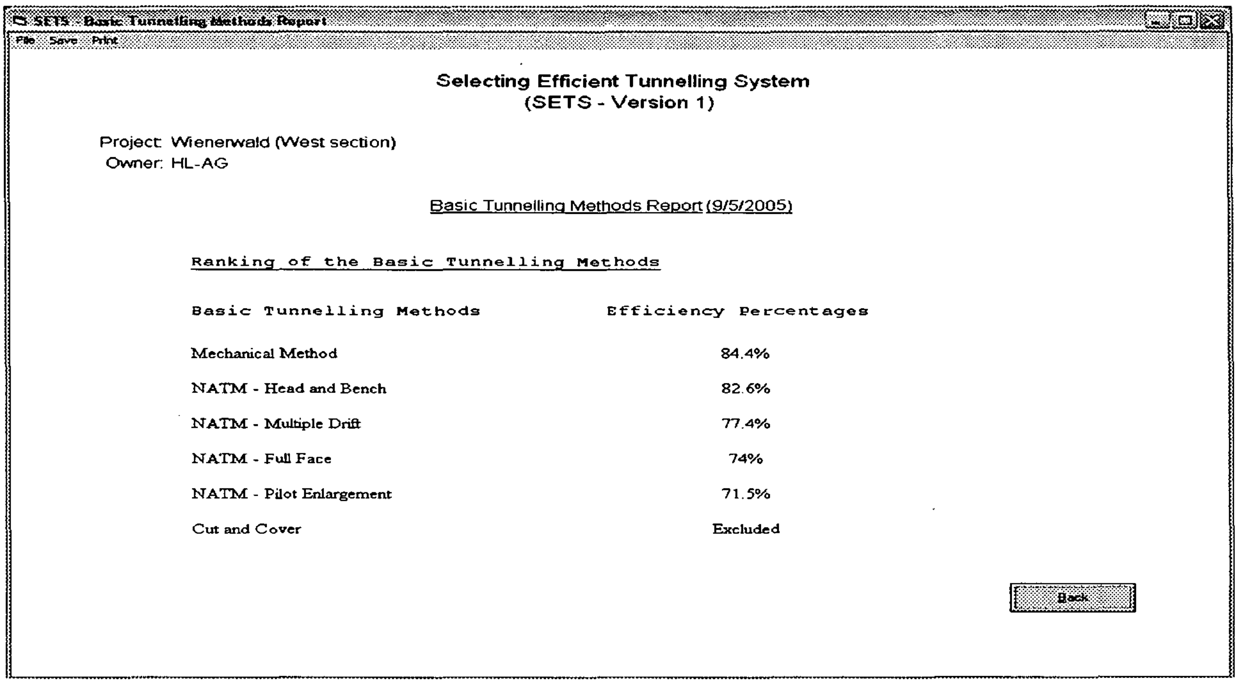
Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground conditions	9	Air pollution	0
Tunnel depth	9	Effect on landscape	0
Cross section	8	Limited site area	0
Tunnel alignment	1	Utilities in tunnel path	1
Health and safety	3	Cost	10
Noise	1	Time	3
Vibration	3	Technology availability	0
Archaeology	0	Experience	0
Effect on traffic	0	Others	0

6.2.2.3 Data of mucking activity

Importance degrees of controlling factors of mucking methods are shown in table 6.2.

Table 6.2 Importance degrees for controlling factors (mucking methods-Wienerwald tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground bearing capacity	1	Cost	1
Muck particle size	1	Time	1
Tunnel span	5	Others	0


SETS - Basic Tunnelling Methods Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (West section)
Owner: HL-AG

Basic Tunnelling Methods Report (9/5/2005)

Ranking of the Basic Tunnelling Methods

Basic Tunnelling Methods	Efficiency Percentages
Mechanical Method	84.4%
NATM - Head and Bench	82.6%
NATM - Multiple Drift	77.4%
NATM - Full Face	74%
NATM - Pilot Enlargement	71.5%
Cut and Cover	Excluded

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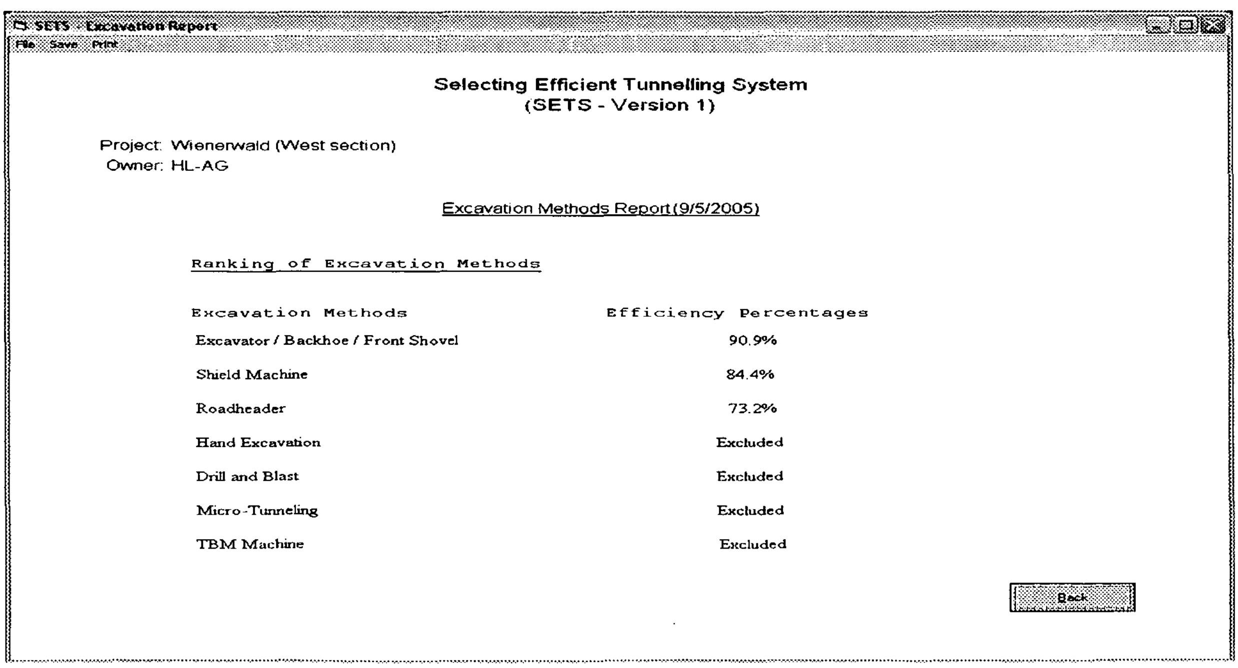
Figure 6.5 Basic tunnelling methods for Wienerwald tunnel


SETS - Excavation Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (West section)
Owner: HL-AG

Excavation Methods Report (9/5/2005)

Ranking of Excavation Methods

Excavation Methods	Efficiency Percentages
Excavator / Backhoe / Front Shovel	90.9%
Shield Machine	84.4%
Roadheader	73.2%
Hand Excavation	Excluded
Drill and Blast	Excluded
Micro-Tunneling	Excluded
TBM Machine	Excluded

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Figure 6.6 Excavation methods for Wienerwald tunnel

Input technical data for mucking activity are as follow:

Ground bearing capacity	Over 0.2MPa
Muck particle size	Small (particle size < 2cm)
Tunnel span	Over 8m

Mucking report is shown is figure 6.7. A printed report is in appendix B-1. The *"Rubber wheel loader"* comes at the first place with efficiency percentage of 92.7% and *"Tracked loader"* in the second place with efficiency percentage of 67.3% (see figure 6.7).

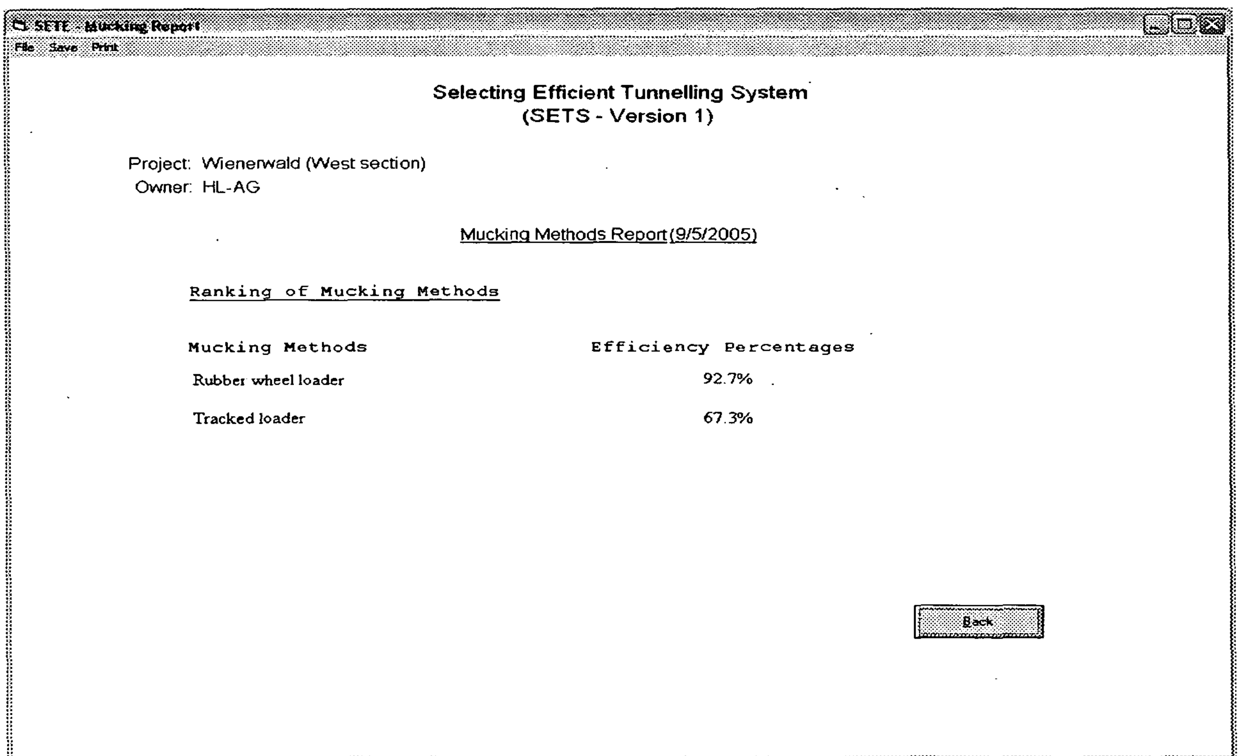


Figure 6.7 Mucking report of Wienerwald tunnel

6.2.2.4 Data of transportation activity

Table 6.3 shows importance degrees of transportation controlling factors. Input technical data are as follow:

Ground bearing capacity	Over 0.2MPa
Tunnel span	More than 8m
Tunnel vertical slope	Less than 3%
Transportation distance	Over 3km
Transportation speed	Medium
Muck water content	Almost dry
Muck particle size	Less than 45cm

Figure 6.8 shows transportation report of Wienerwald tunnel. Program calculations show that *"Conveyors"* has the highest efficiency percentage, then *"Rail/Diesel-electric locomotive"* comes in the second rank. A printed report is in appendix B-1.

Table 6.3 Importance degrees for controlling factors (transportation methods-Wienerwald tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground bearing capacity	1	Muck water content	1
Transporting speed	5	Health and safety	0
Tunnel vertical slope	1	Cost	2
Tunnel span	6	Time	3
Muck particle size	2	Others	0

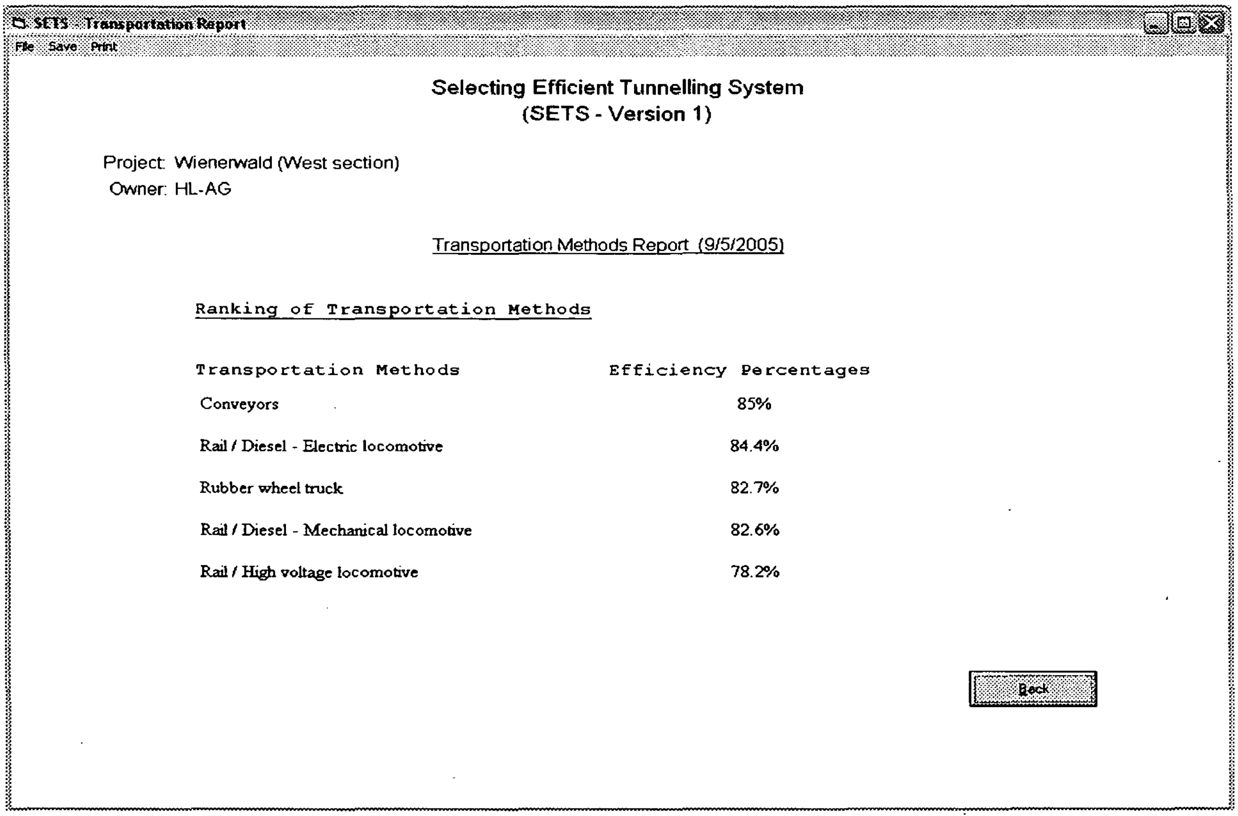


Figure 6.8 Transportation report of Wienerwald tunnel

6.2.2.5 Data of support activity

Controlling factors of support methods were assigned importance degrees by project designer as shown in table 6.4.

Table 6.4 Importance degrees for controlling factors (support methods-Wienerwald tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground Conditions	8	Cost	9
Tunnel Depth	10	Time	5
Tunnel Shape	6	Others	0
Tunnel Span	6		

Input technical data for support activity are listed below:

Tunnel span	Over 10m
Predicted failure reasons during construction	- Squeezing and swelling - Overstress
RMR-value	0-20
Tunnel depth	101-500
Tunnel cross section	Circular

Figure 6.9 is side wall support report. *"Shotcrete"* has the highest efficiency percentage and *"Precast concrete segments"* comes in the third rank. This rank can change in the comprehensive report. Appendix B-1 has a printed support report.

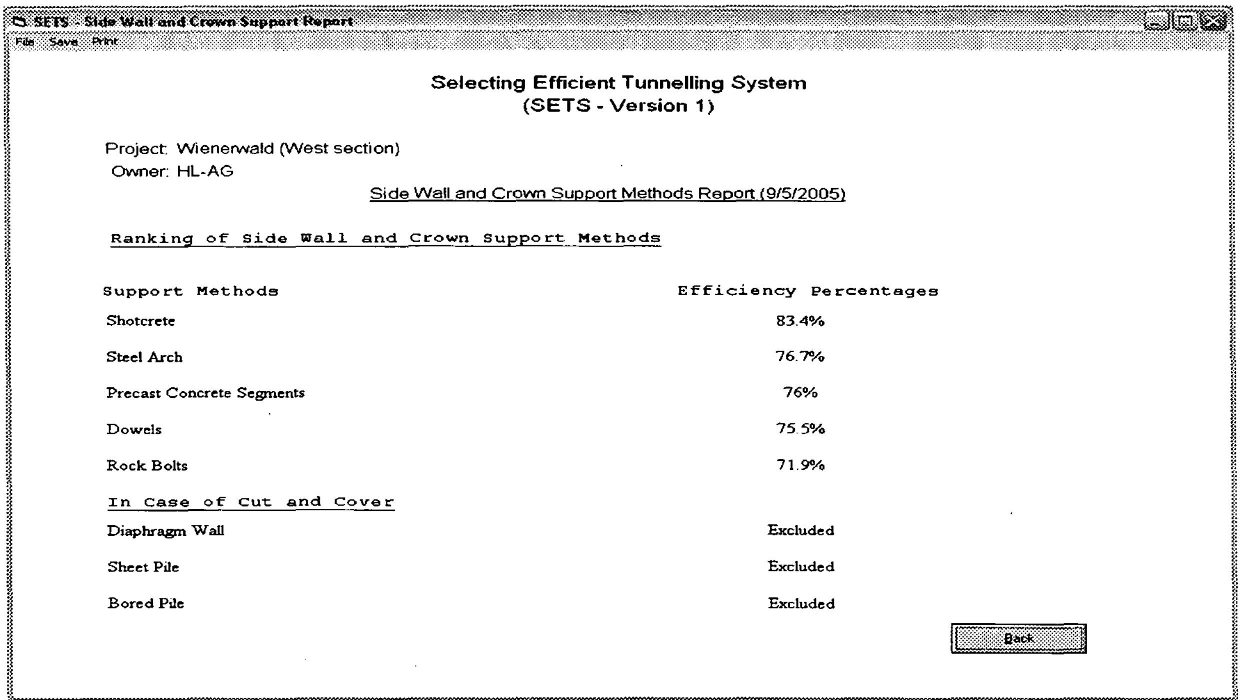
Figure 6.10 shows face support report. For face support, *"Shotcrete"* comes also in the first rank. When mechanical method is used, there is no need for face support.

6.2.2.6 Data of lining activity

Controlling factors of lining activity have importance degrees as shown in table 6.5.

Table 6.5 Importance degrees for controlling factors (lining methods-Wienerwald tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground conditions	6	Groundwater flow rate	1
Reaction with mineral	1	Cost	6
Tunnel shape	2	Time	6
Tunnel function	8	Others	0



SETS - Side Wall and Crown Support Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (West section)
Owner: HL-AG

Side Wall and Crown Support Methods Report (9/5/2005)

Ranking of Side Wall and Crown Support Methods

Support Methods	Efficiency Percentages
Shotcrete	83.4%
Steel Arch	76.7%
Precast Concrete Segments	76%
Dowels	75.5%
Rock Bolts	71.9%
In Case of Cut and Cover	
Diaphragm Wall	Excluded
Sheet Pile	Excluded
Bored Pile	Excluded

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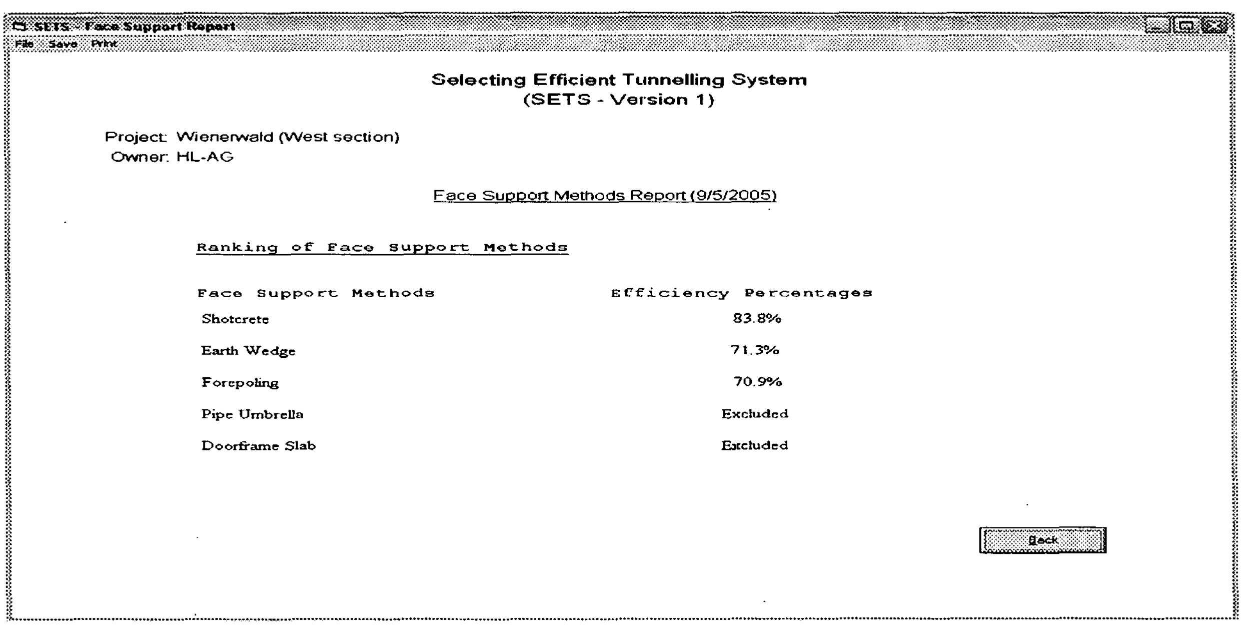
Figure 6.9 Side wall support report of Wienerwald tunnel



SETS - Face Support Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (West section)
Owner: HL-AG

Face Support Methods Report (9/5/2005)

Ranking of Face Support Methods

Face Support Methods	Efficiency Percentages
Shotcrete	83.8%
Earth Wedge	71.3%
Forepoling	70.9%
Pipe Umbrella	Excluded
Doorframe Slab	Excluded

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Figure 6.10 Face support report of Wienerwald tunnel

Input technical data of lining activity are listed below:

Q-value	0.001 – 0.01
Groundwater flow	Less than 10 l/min.
Minerals in ground	Quartz and clay minerals
Tunnel function	Railway
Tunnel shape	Circular

Figure 6.11 is the lining report resulting from program calculations. *"Shotcrete"* comes in the fourth rank of lining methods and *"Precast concrete segments"* takes the first rank with efficiency percentage of 86.7% (see figure 6.11).

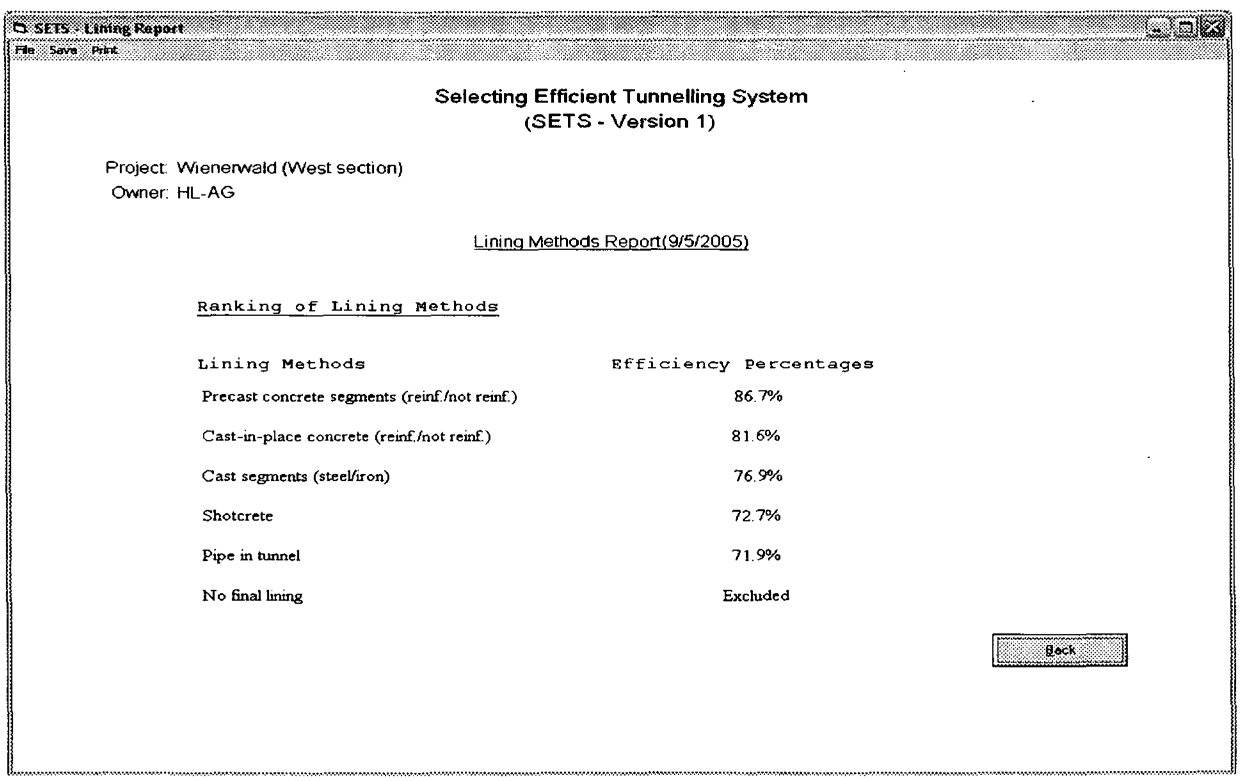


Figure 6.11 Lining report of Wienerwald tunnel

6.2.2.7 Data of groundwater control activity

Because rock is not permeable, groundwater flow is low. But existence of groundwater is bad; especially it has bad effect with shale.

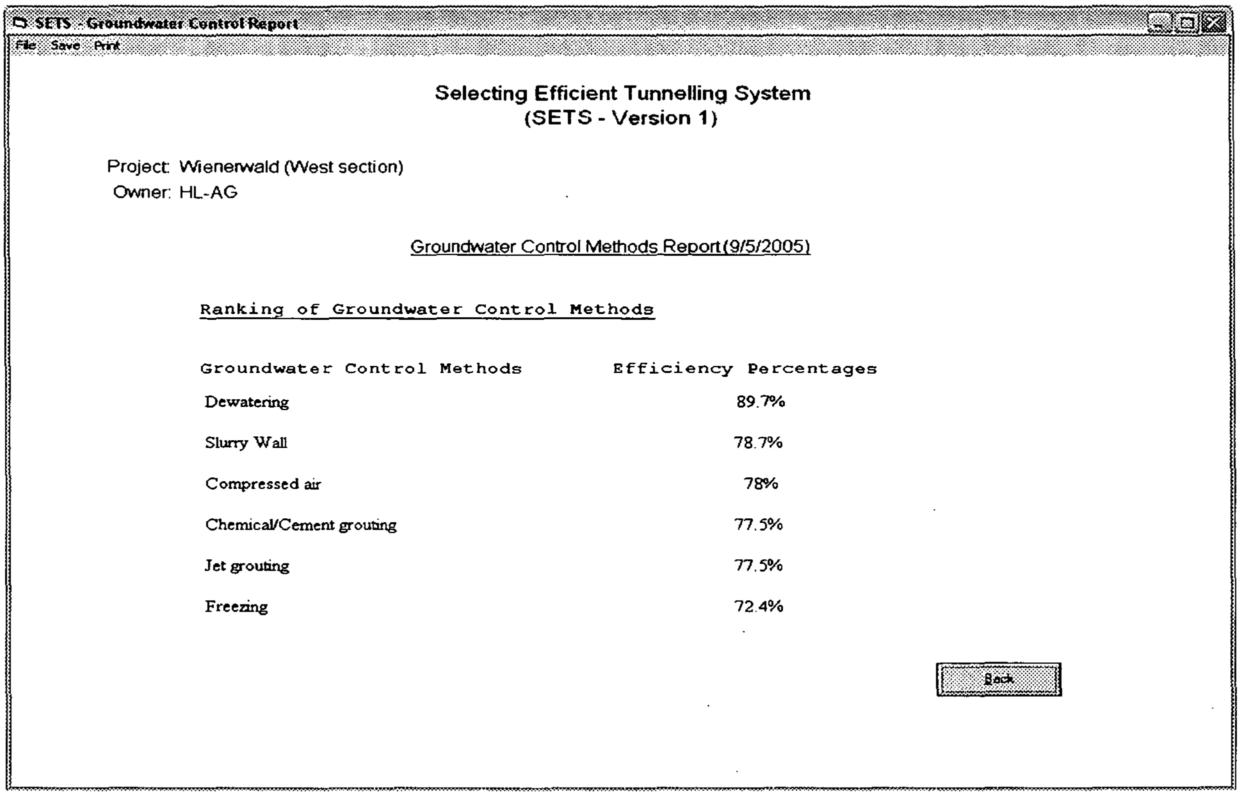
The following technical data were fed to the program to find groundwater control method that is efficient to work with this project.

Groundwater flow	Less than 10 l/min
Working length/day	16 – 25
Tunnel depth	Over 50m
Ground conditions	Ground is rock
Tunnel position	Urban areas

Importance degrees of controlling factors are shown in table 6.6.

Table 6.6 Importance degrees for controlling factors (groundwater control methods-Wienerwald tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground conditions	8	Effect on buildings	0
Groundwater flow rate	2	Groundwater contamination	0
Tunnel depth	0	Groundwater regime	2
Tunnel position	0	Cost	2
Advancement rate	1	Time	0
Health and safety	0	Others	0



SETS - Groundwater Control Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (West section)
Owner: HL-AG

Groundwater Control Methods Report (9/5/2005)

Ranking of Groundwater Control Methods

Groundwater Control Methods	Efficiency Percentages
Dewatering	89.7%
Slurry Wall	78.7%
Compressed air	78%
Chemical/Cement grouting	77.5%
Jet grouting	77.5%
Freezing	72.4%

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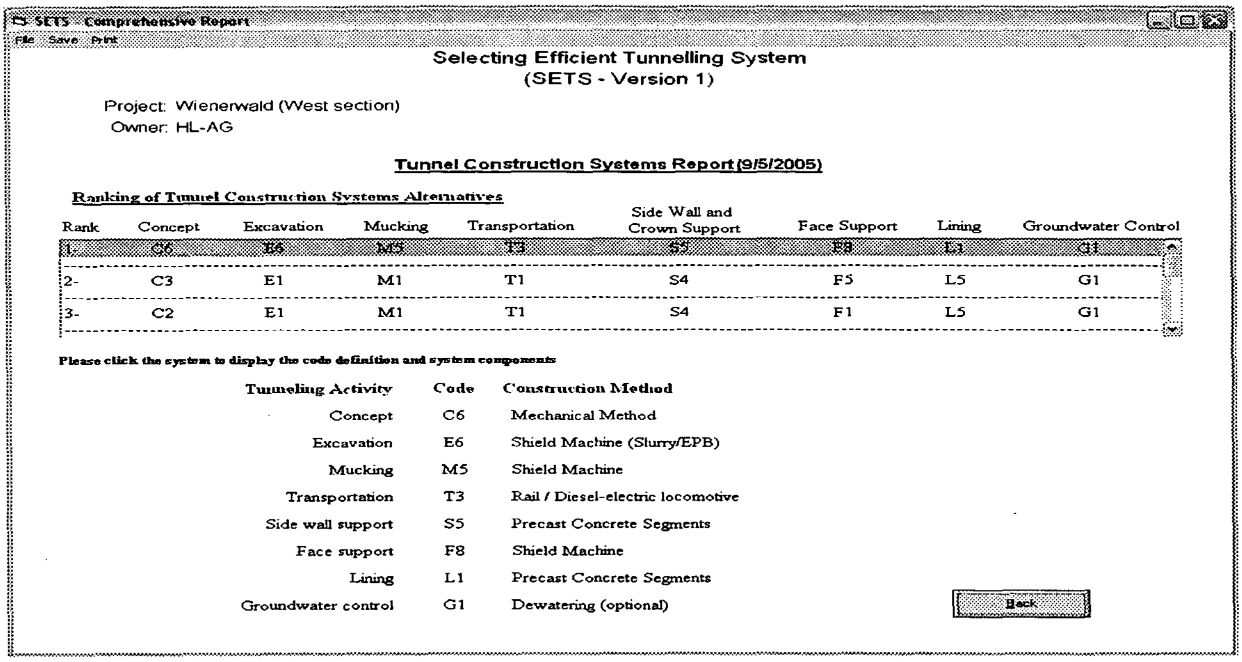
Figure 6.12 Groundwater control report of Wienerwald tunnel

Figure 6.12 shows groundwater control report of the Wienerwald tunnel. Dewatering system is in the first rank. The difference between efficiency percentages of dewatering and slurry wall that comes in the second position is 11%.

6.2.3 Alternative tunnelling systems

After calculating efficiency percentages of construction methods of all tunnelling activities, the program will start to calculate the possible tunnelling alternative systems. The program has found 9 alternative systems. Figure 6.13 shows comprehensive report about tunnelling alternative systems of Wienerwald tunnel.



SETS - Comprehensive Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (West section)
Owner: HL-AG

Tunnel Construction Systems Report (9/5/2005)

Ranking of Tunnel Construction Systems Alternatives

Rank	Concept	Excavation	Mucking	Transportation	Side Wall and Crown Support	Face Support	Lining	Groundwater Control
1-	C6	E6	M5	T3	S5	F8	L1	G1
2-	C3	E1	M1	T1	S4	F5	L5	G1
3-	C2	E1	M1	T1	S4	F1	L5	G1

Please click the system to display the code definition and system components

Tunneling Activity	Code	Construction Method
Concept	C6	Mechanical Method
Excavation	E6	Shield Machine (Slurry/EPB)
Mucking	M5	Shield Machine
Transportation	T3	Rail / Diesel-electric locomotive
Side wall support	S5	Precast Concrete Segments
Face support	F8	Shield Machine
Lining	L1	Precast Concrete Segments
Groundwater control	G1	Dewatering (optional)

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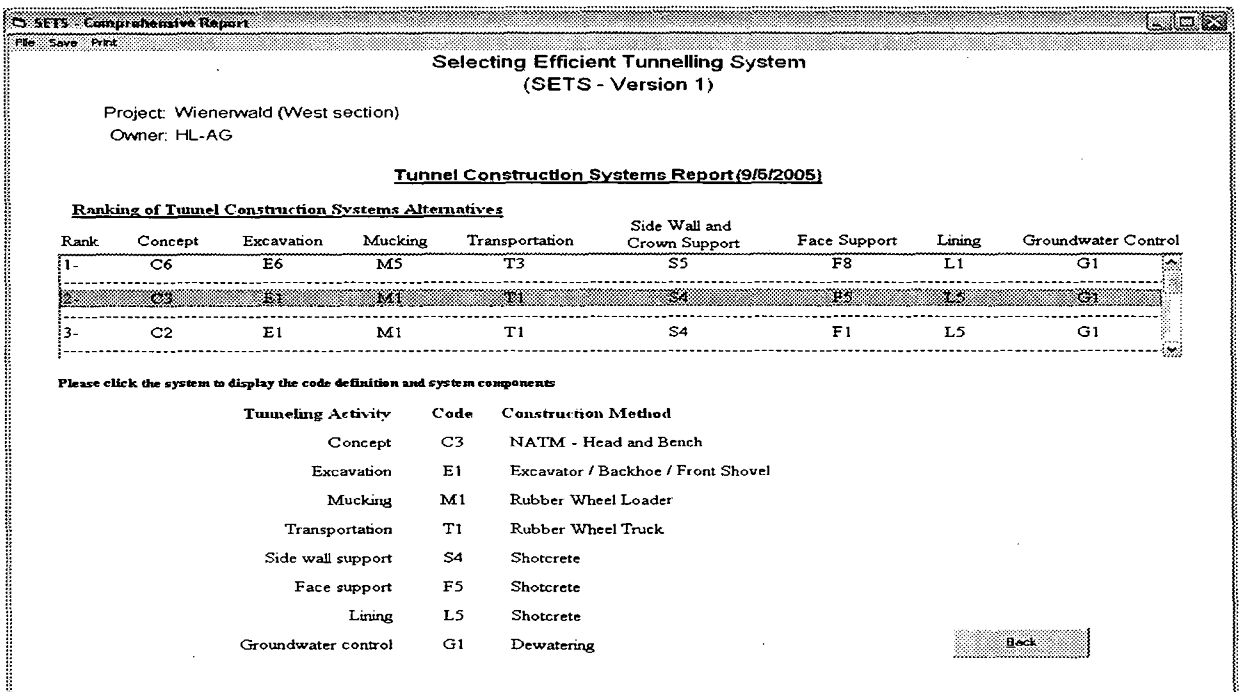
Figure 6.13a Comprehensive report about tunnelling systems of Wienerwald tunnel



SETS - Comprehensive Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (West section)
Owner: HL-AG

Tunnel Construction Systems Report (9/5/2005)

Ranking of Tunnel Construction Systems Alternatives

Rank	Concept	Excavation	Mucking	Transportation	Side Wall and Crown Support	Face Support	Lining	Groundwater Control
1-	C6	E6	M5	T3	S5	F8	L1	G1
2-	C3	E1	M1	T1	S4	F5	L5	G1
3-	C2	E1	M1	T1	S4	F1	L5	G1

Please click the system to display the code definition and system components

Tunneling Activity	Code	Construction Method
Concept	C3	NATM - Head and Bench
Excavation	E1	Excavator / Backhoe / Front Shovel
Mucking	M1	Rubber Wheel Loader
Transportation	T1	Rubber Wheel Truck
Side wall support	S4	Shotcrete
Face support	F5	Shotcrete
Lining	L5	Shotcrete
Groundwater control	G1	Dewatering

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Figure 6.13b Comprehensive report about tunnelling systems of Wienerwald tunnel

Figure 6.13 shows only three tunnelling systems and to see the 9 alternative systems see appendix B-1, the comprehensive report. Figure 6.13a shows that mechanical method *"Shield machine"* is the most efficient method for basic tunnelling and excavation activities. *"Precast concrete segments"* will be used for support and lining activities. Groundwater control can be done using *"Dewatering system"*. Groundwater control method is optional to be used with shield machine. The second alternative system is using *"NATM - Head and bench"* for basic tunnelling and *"Excavator"* for excavation. Figure 6.13b shows the elements of the second alternative system. Comparing the results of the program with that actual case, we can find that the first system, resulted from the program calculations, is used already in the actual case. This results increase the liability of the program.

6.3 "U2/2 Taborstraße" tunnel project

Underground metro line 2 (U2), in city of Vienna, connects *"Schottenring"* station and *"Karlsplatz"* station. It is planned to extend U2 from *"Schottenring"* side, under Danube channel, to reach *"Taborstraße"*, then it will be continued until *"Praterstern/Wien Nord"* station. U2 will be extended more until it reaches *"Aspernstraße"*. Figure 6.14 shows U2 path.

6.3.1 Project description

Construction work of project U2/2 includes constructing of two tunnel tubes and three stations. The two tubes run almost straight-lined toward the station *"Taborstraße"*. Distance between the two tubes is approximately 30m and its depth is about 18.5m from surface. Figure 6.15 shows project layout.

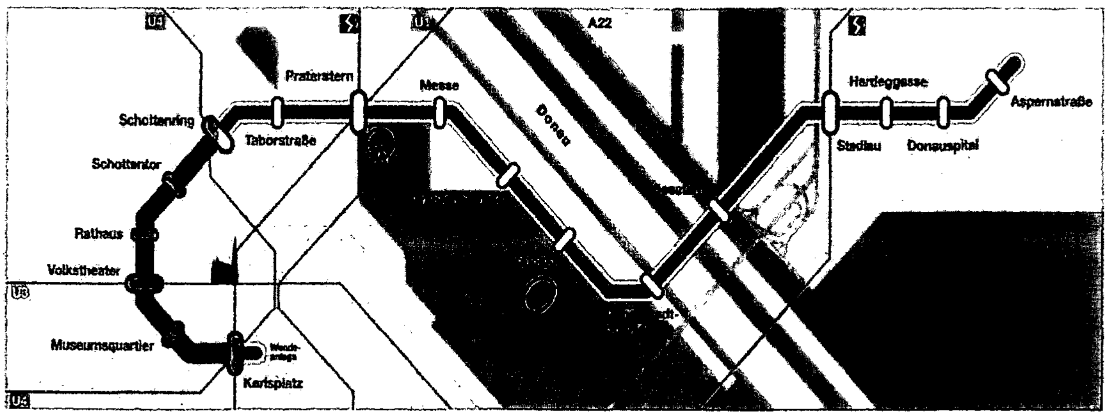


Figure 6.14 U2 path

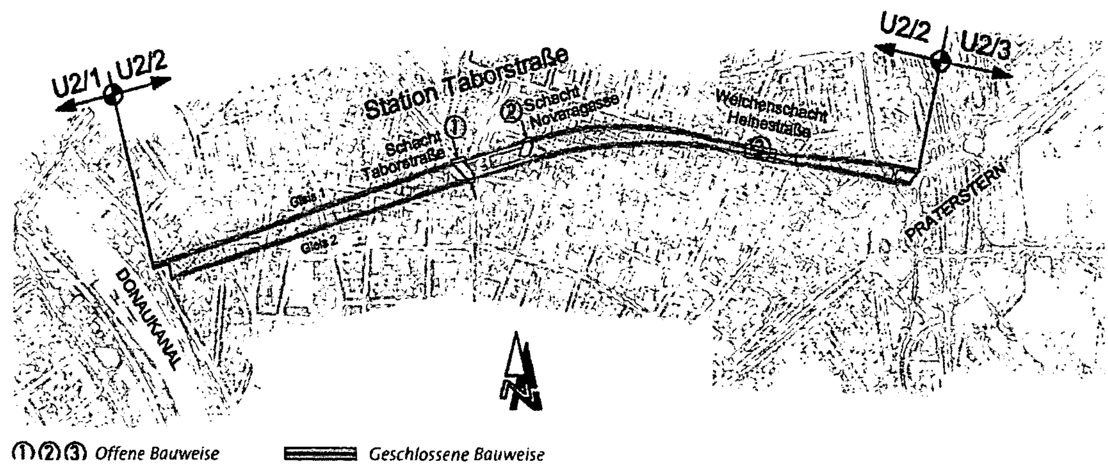


Figure 6.15 “U2/2 Taborstraße” tunnel layout

Each of the two tunnel tubes has an oval cross section. The cross section area of each tube is approximately 36m^2. Figure 6.16 shows the tunnel cross section.

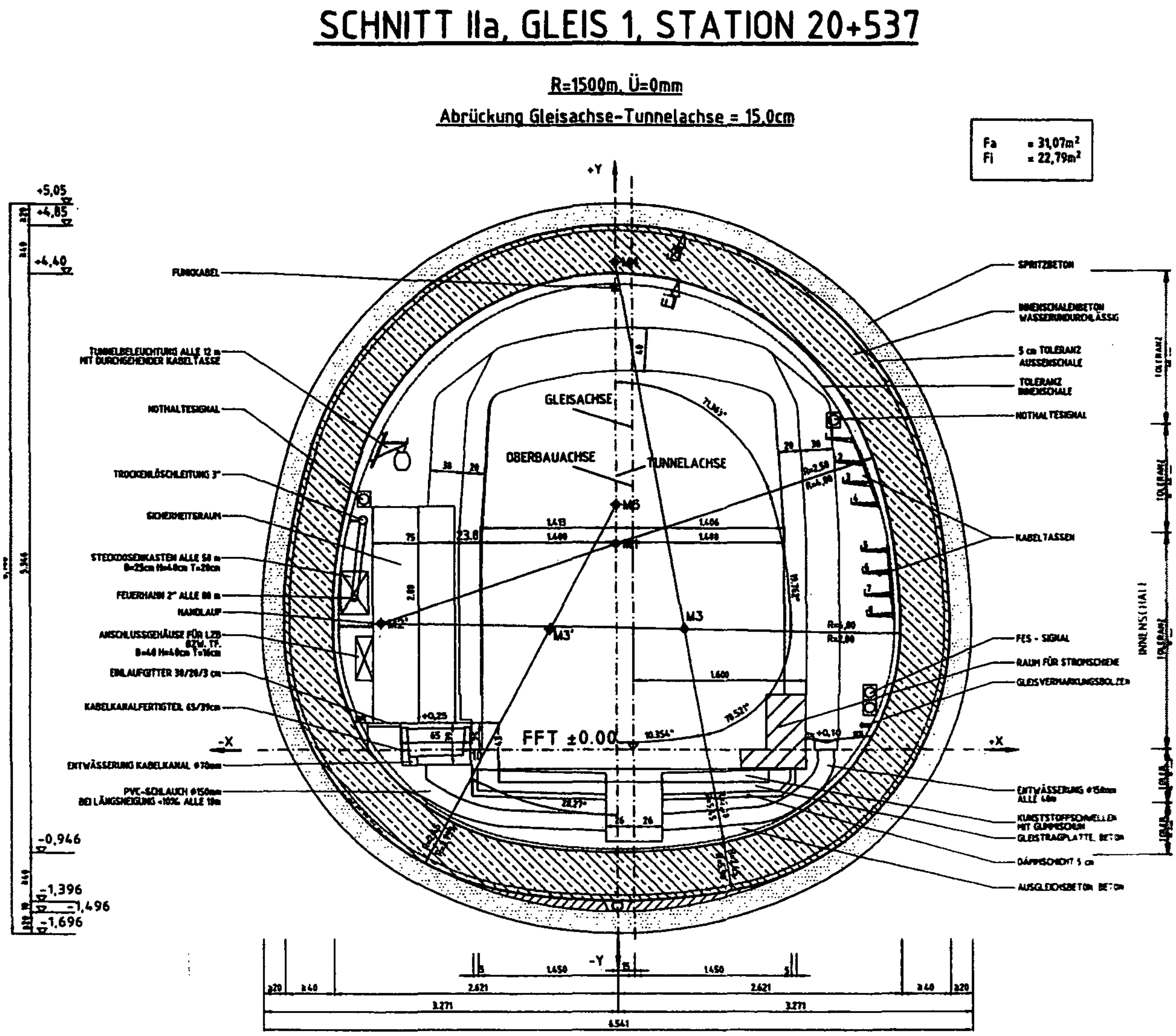


Figure 6.16 “U2 tunnel” cross section

After Taborstraße station, the two underground tubes run up to Heinestraße. The station in Heinestraße will be constructed using cut and cover method. An emergency exit is planned in the Heinestraße.

The owner of the project is *"Wiener Linien"*. Project cost is 111.0 Million Euro. Project started in June 2003 and the planned finish of the tunnel construction is in October 2006.

6.3.2 Method of construction

The two tubes of the section U2/2 is predominantly accomplished in closed construction method according to the NATM concept with accompanying groundwater lowering. Parts of the station in Taborstraße as well as the switch pit within the range Heinestraße are constructed using cut and cover construction method.

For NATM method of construction, a comprehensive measuring program at the surface is installed to measure soil behaviour during construction. An excavator is used for excavation and the shotcrete is used for supporting. In very weak areas, steel truss and steel lattices are used. Thickness of shotcrete ranges from 20 to 30 cm. A waterproof reinforced concrete with thickness 40cm will be used as lining for the tunnels.

In order to be able to drive the tunnel tubes in the dry conditions, a groundwater lowering is necessary. A dewatering system is installed and the collected water returns to Danube again. The main issue in groundwater lowering process is to maintain stability of the ground and no settlement will occur. Figure 6.17 shows a sketch for groundwater lowering process.

For cut and cover method which is used for constructing the stations, diaphragm walls will be used as a support method.

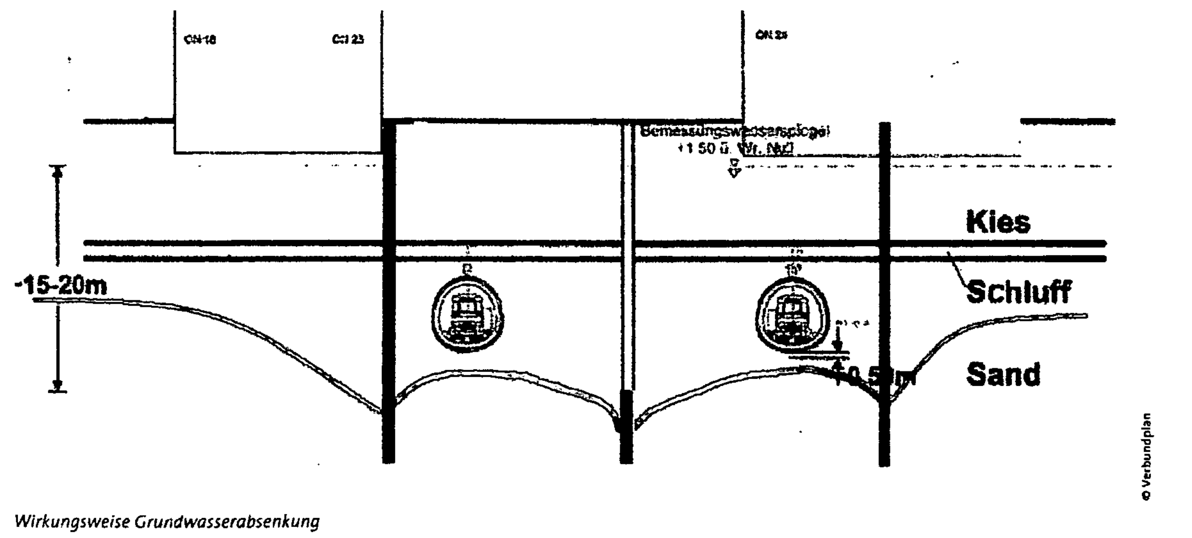


Figure 6.17 Groundwater lowering in project *"U2/2 taborstraße tunnel"*

6.3.3 Input data to SETS program (U2/2 taborstraße tunnel project)

Two meetings were held with the project manager of the owner. SETS program was tested using technical data of the project and importance degrees assigned to controlling factors by the project manager. The program was tested using data of the tunnel not the stations.

6.3.3.1 Data of the *"Project general data"* screen

Project name	U2/2 Taborstraße
Client	Wiener Linien
Ground	Soil
Tunnel height	6 m
Groundwater level	5m below surface
Tunnel invert level	18.5 below surface
Labour cost	Expensive

6.3.3.2 Data of the *"Basic tunnelling methods"* and excavation activities

The following data represent the technical data that fed to the program to calculate efficiency percentages of basic tunnelling and excavation methods. Table 6.7 shows importance degrees of controlling factors.

Ground compressive strength	0.4MPa or less
There is harmful gases	No
Tunnel cross section area	31 – 100m^2
Fixed cross section	Yes
Cross section shape	Oval
Tunnel length	More than 3km
Tunnel depth	Less than 30m
Sharpest horizontal curve radius	Bigger than 150m
Vertical slope	Less than 3%
Construction site	Limited
There is utilities in tunnel's path	Yes

The *"Cut and cover"* method of construction cannot be used for constructing the tunnel tubes, because the tunnel passes under 97 houses. It is not possible to demolish these houses. In table 6.7 importance degree of *"Others"* factor is "7" because cut and cover is assigned an efficiency degree of "1" in *"Efficiency degrees of basic tunnelling and excavation methods"* screen, (see figure 6.18).

Running of the program using data listed before will give results that shown in figures 6.19 and 6.20.

Table 6.7 Importance degrees for controlling factors (basic tunnelling and excavation methods-U2/2 taborstraße tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground conditions	8	Air pollution	2
Tunnel depth	5	Effect on landscape	2
Cross section	2	Limited site area	10
Tunnel alignment	4	Utilities in tunnel path	7
Health and safety	3	Cost	7
Noise	3	Time	7
Vibration	2	Technology availability	0
Archaeology	1	Experience	0
Effect on traffic	2	Others	7

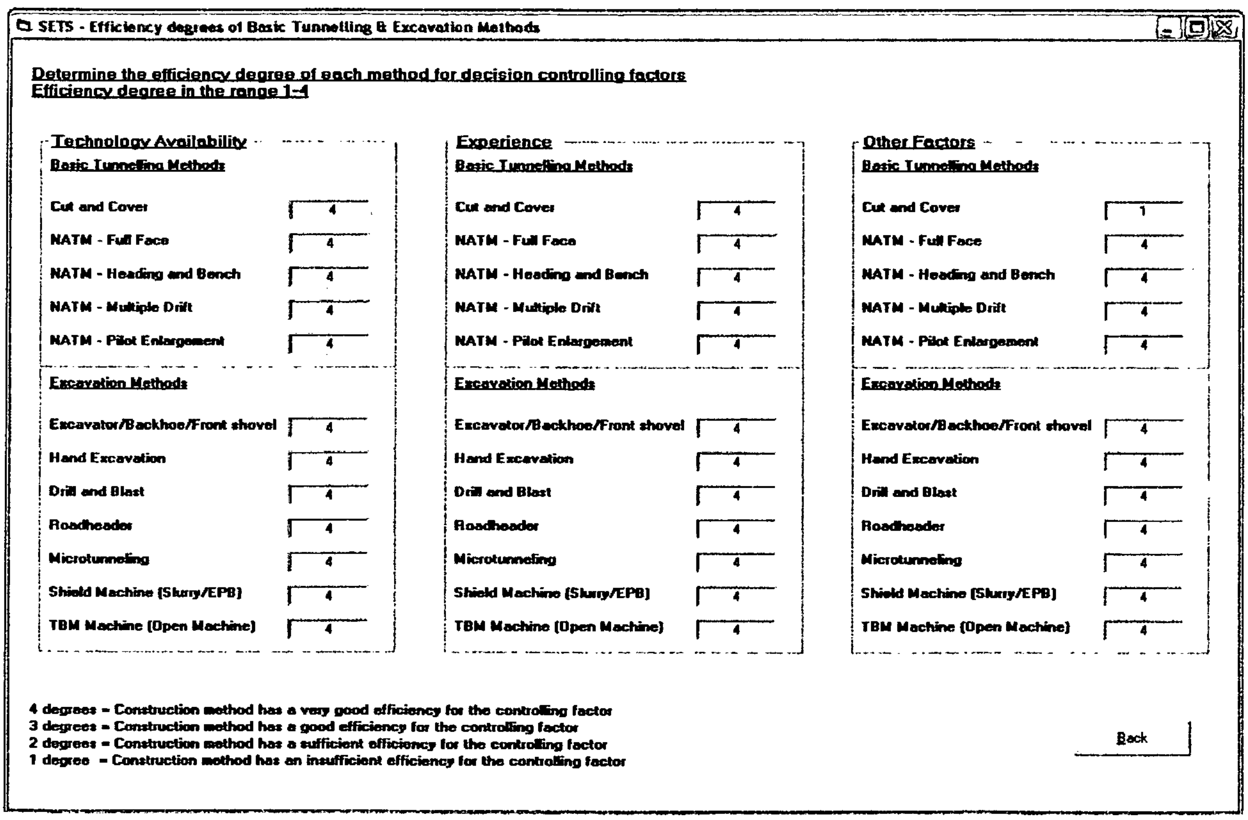
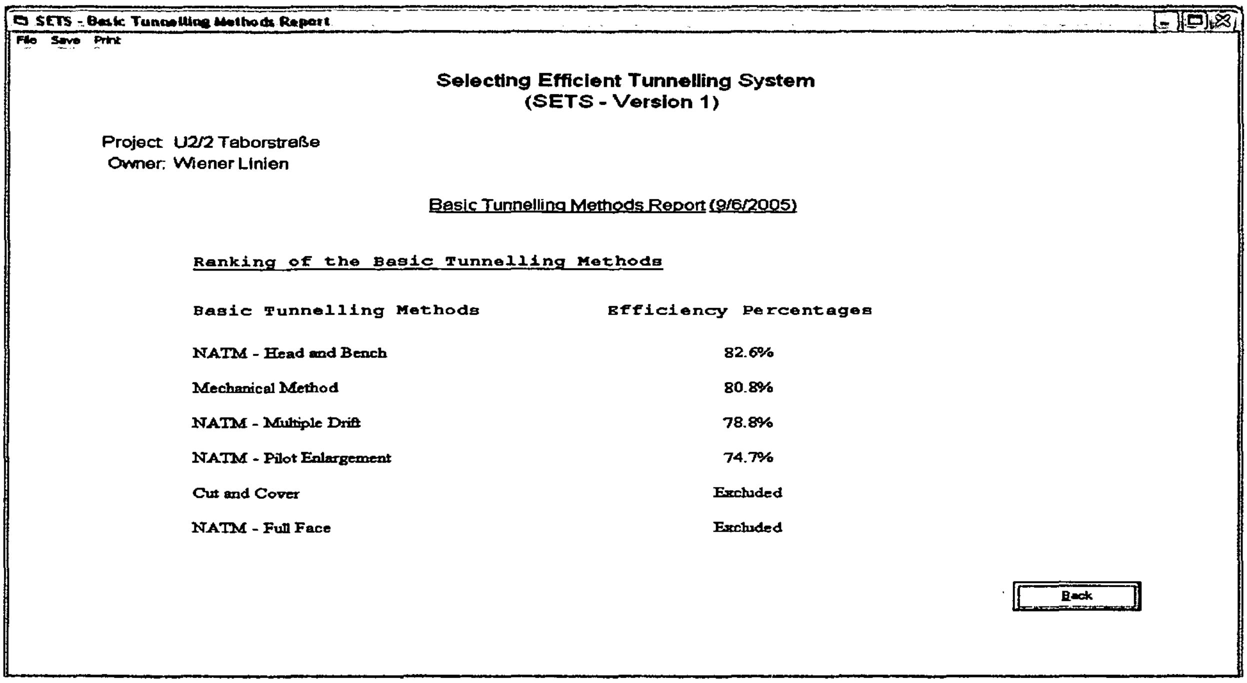


Figure 6.18 *"Efficiency degrees of basic tunnelling and excavation methods"* screen



SETS - Basic Tunnelling Methods Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße
Owner: Wiener Linien

Basic Tunnelling Methods Report (9/6/2005)

Ranking of the Basic Tunnelling Methods

Basic Tunnelling Methods	Efficiency Percentages
NATM - Head and Bench	82.6%
Mechanical Method	80.8%
NATM - Multiple Drift	78.8%
NATM - Pilot Enlargement	74.7%
Cut and Cover	Excluded
NATM - Full Face	Excluded

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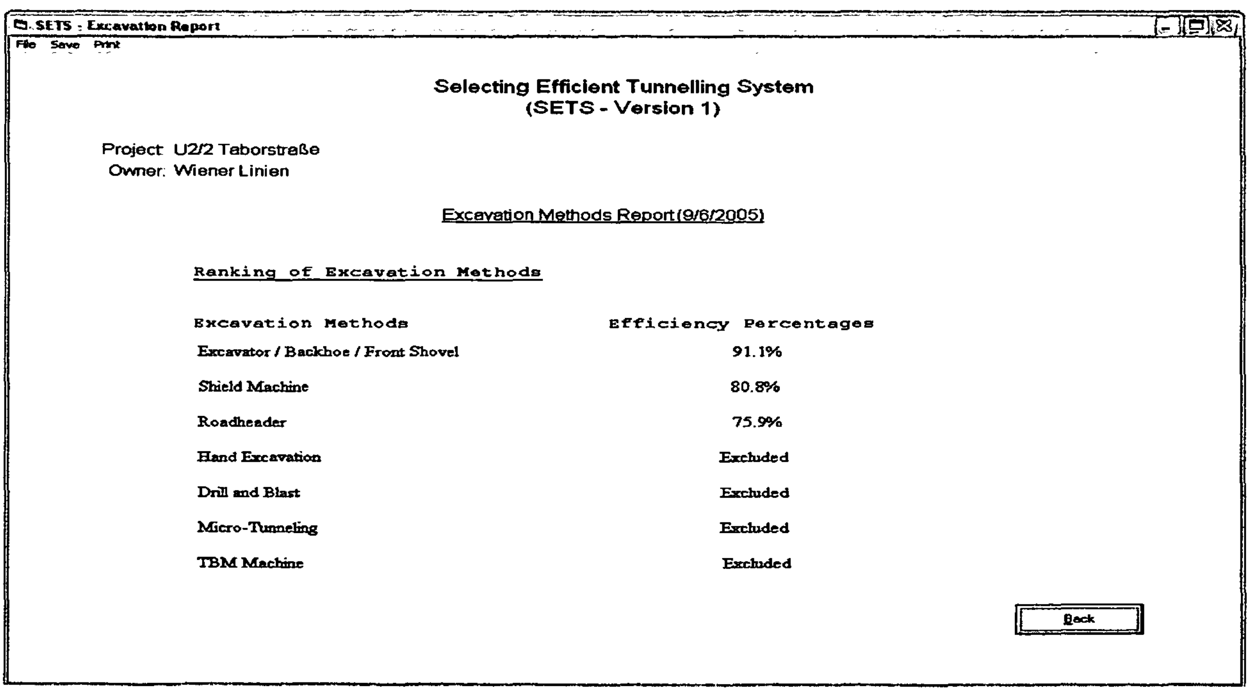
Figure 6.19 Basic tunnelling methods report of U2/2 Taborstraße tunnel



SETS : Excavation Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße
Owner: Wiener Linien

Excavation Methods Report (9/6/2005)

Ranking of Excavation Methods

Excavation Methods	Efficiency Percentages
Excavator / Backhoe / Front Shovel	91.1%
Shield Machine	80.8%
Roadheader	75.9%
Hand Excavation	Excluded
Drill and Blast	Excluded
Micro-Tunneling	Excluded
TBM Machine	Excluded

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Figure 6.20 Excavation report of U2/2 Taborstraße tunnel

For basic tunnelling methods, *"NATM-Head and bench"* construction method comes at the first rank with efficiency percentage 82.6%. *"Excavator"* has the highest efficiency percentage to work for this project according to calculations of SETS program (see figure 6.20).

6.3.3.3 Data of mucking activity

Table 6.8 shows importance degrees of mucking controlling factors as assigned by project manager.

Table 6.8 Importance degrees for controlling factors (mucking methods-U2/2 taborstraße tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground bearing capacity	3	Cost	6
Muck particle size	5	Time	8
Tunnel span	7	Others	0

Input technical data are as follow:

Ground bearing capacity	Over 0.2MPa
Muck particle size	Medium
Tunnel span	4.5 – 8m

Mucking report, in figure 6.21, shows that *"Rubber wheel loader"* is more efficient for this project than *"Tracked loader"*.

6.3.3.4 Data of transportation activity

Technical data of transportation activity is listed below. Importance degrees of transportation controlling factors are presented in table 6.9.

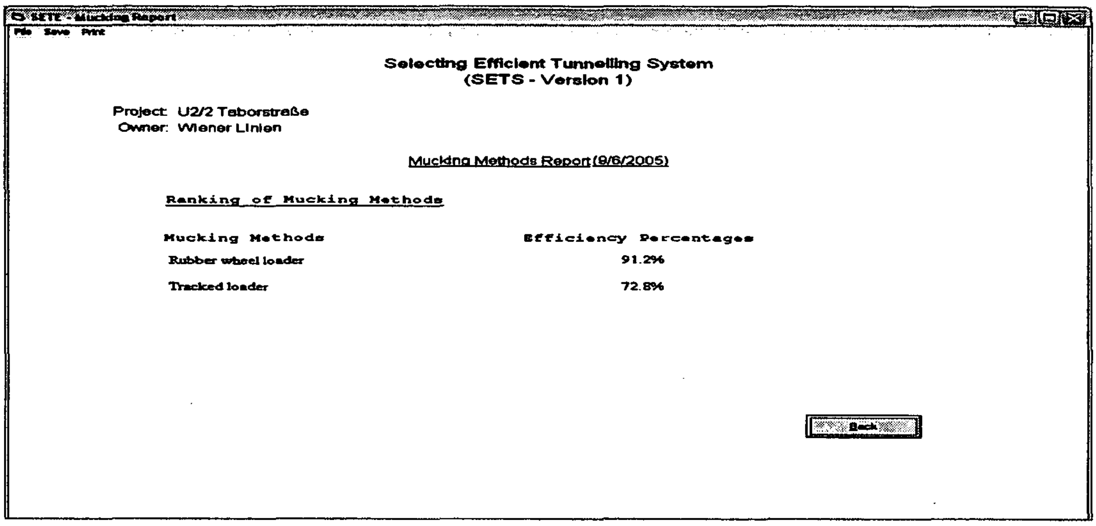


Figure 6.21 Mucking methods report of U2/2 Taborstraße tunnel

Ground bearing capacity	Over 0.2MPa
Tunnel span	5 – 8m
Tunnel vertical slope	Less than 3%
Transporting distance	1.5 – 3km
Transporting speed	Medium
Muck water content	Almost dry
Muck particle size	Less than 45cm

Table 6.9 Importance degrees for controlling factors (transportation methods-U2/2 taborstraße tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground bearing capacity	3	Muck water content	7
Transporting speed	7	Health and safety	2
Tunnel vertical slope	0	Cost	4
Tunnel span	7	Time	6
Muck particle size	6	Others	0

Figure 6.22 shows transportation report of U2/2 Taborstraße tunnel. *"Rubber wheel trucks"* has the highest efficiency percentage, it comes in the first rank and *"Conveyors"* comes in the second rank with efficiency percentage of 85.1%. Rail trucks occupied the last three positions in the rank.

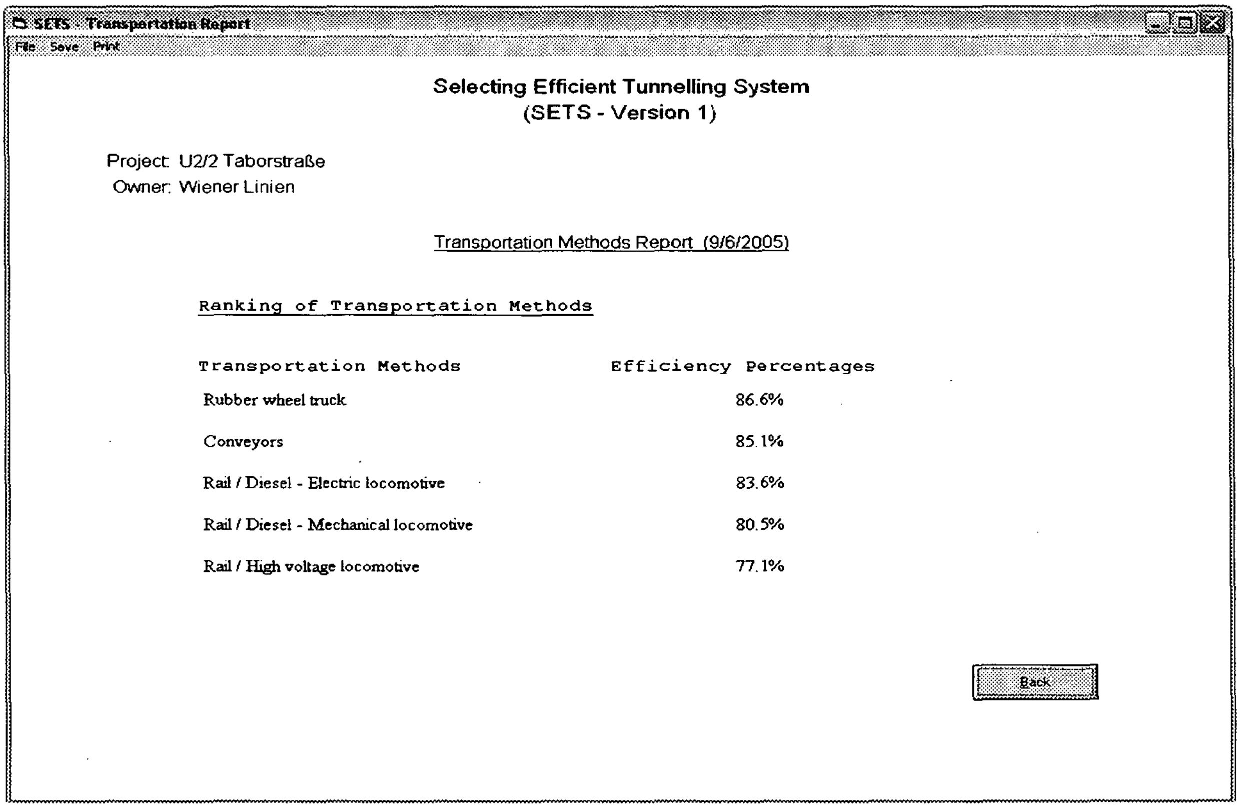


Figure 6.22 Transportation report of U2/2 Taborstraße tunnel

6.3.3.5 Data of support activity

Technical data of support activity are as follow:

Tunnel span	5 – 6m
RMR-value	Ground is soil

Tunnel depth	30m or less
Tunnel cross section	Oval or horseshoe

Table 6.10 below shows importance degrees of support controlling factors as determined by the project manager.

Table 6.10 Importance degrees for controlling factors (support methods-U2/2 taborstraße tunnel)

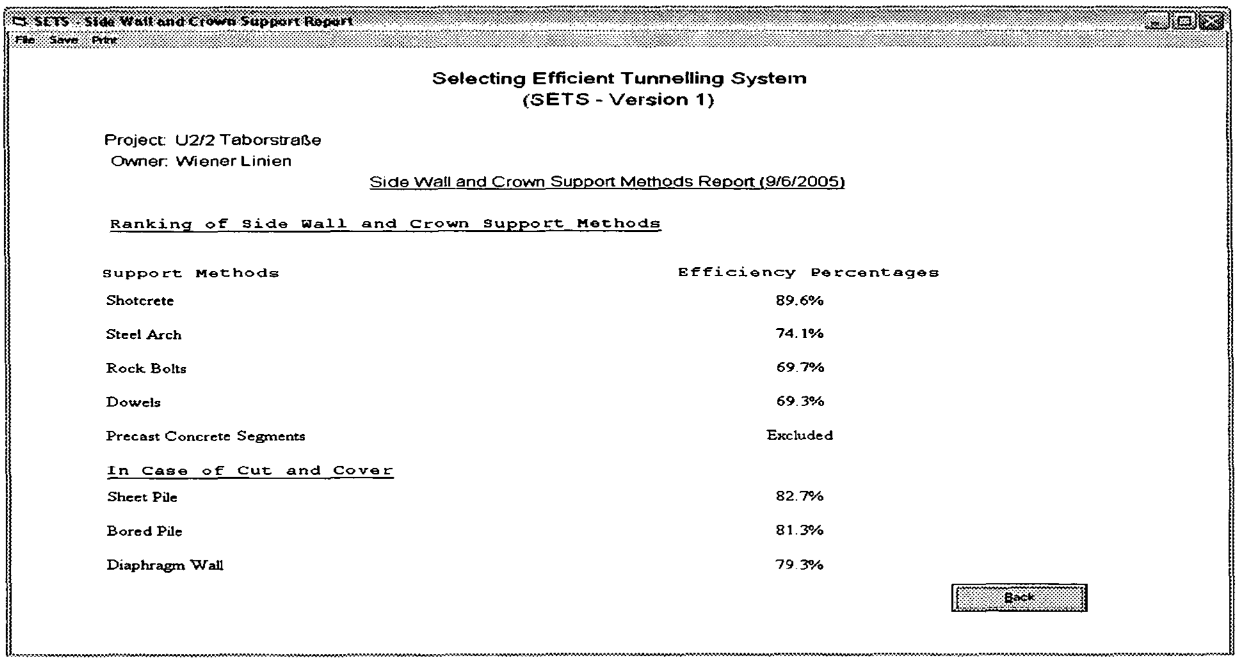
Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground Conditions	8	Cost	5
Tunnel Depth	6	Time	6
Tunnel Shape	4	Others	0
Tunnel Span	6		

Figure 6.23 shows side wall and crown support report and figure 6.24 shows face support report.

Side wall support report shows support methods in case of cut and cover despite this method was excluded in basic tunnelling methods report. When the program starts to calculate the comprehensive report, these methods will be excluded. *"Shotcrete"* comes at the first rank for side wall and face support methods (see figure 6.23).

6.3.3.6 Data of lining activity

Controlling factors of lining activity have importance degrees shown in table 6.11. Technical data of lining activity are as follow:


SETS - Side Wall and Crown Support Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße
Owner: Wiener Linien

Side Wall and Crown Support Methods Report (9/6/2005)

Ranking of Side Wall and Crown Support Methods

Support Methods	Efficiency Percentages
Shotcrete	89.6%
Steel Arch	74.1%
Rock Bolts	69.7%
Dowels	69.3%
Precast Concrete Segments	Excluded
In Case of Cut and Cover	
Sheet Pile	82.7%
Bored Pile	81.3%
Diaphragm Wall	79.3%

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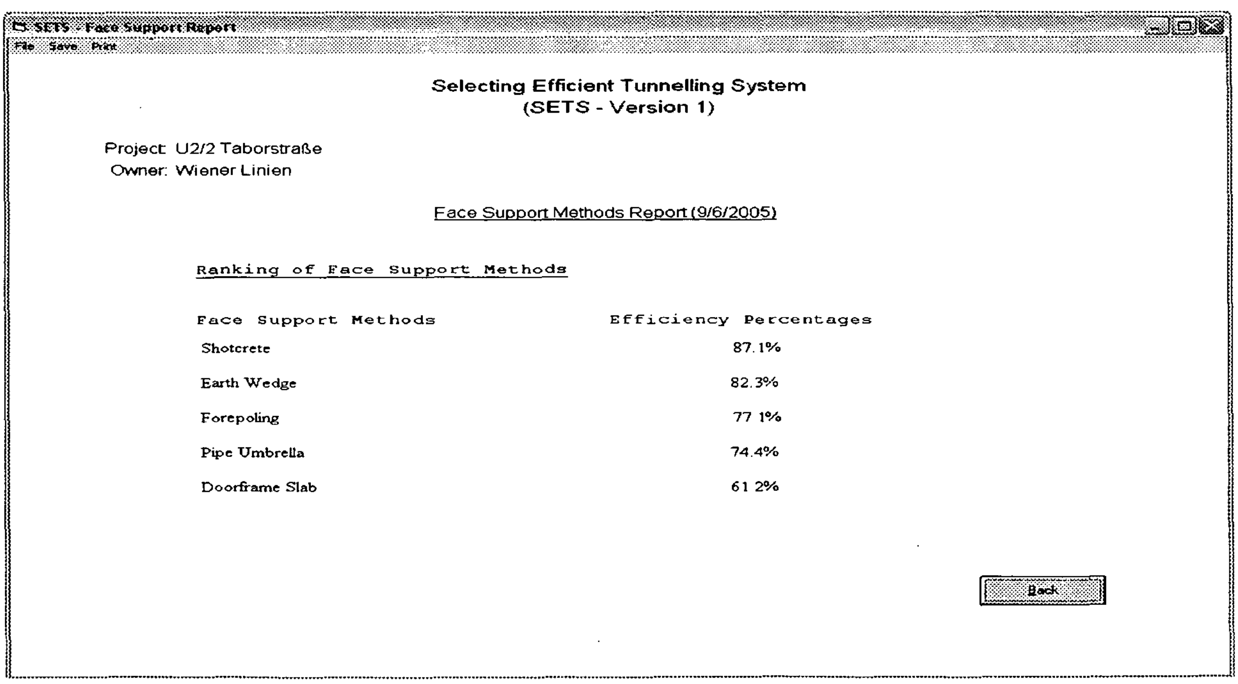
Figure 6.23 Side wall and crown support report of U2/2 Taborstraße tunnel


SETS - Face Support Report

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Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße
Owner: Wiener Linien

Face Support Methods Report (9/6/2005)

Ranking of Face Support Methods

Face Support Methods	Efficiency Percentages
Shotcrete	87.1%
Earth Wedge	82.3%
Forepoling	77 1%
Pipe Umbrella	74.4%
Doorframe Slab	61 2%

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Figure 6.24 Face support report of U2/2 Taborstraße tunnel

Q-value	Ground is soil
Groundwater flow	Less than 10 l/min.
Tunnel function	Railway
Tunnel shape	Oval

Table 6.11 Importance degrees for controlling factors (lining methods-U2/2 taborstraße tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground conditions	8	Groundwater flow rate	10
Reaction with mineral	1	Cost	6
Tunnel shape	4	Time	6
Tunnel function	5	Others	0

Figure 6.25 shows ranking of lining methods as calculated by SETS program. *"Cast-in-place concrete"* is in the first rank with efficiency percentage 83.4%. The difference between efficiency percentages of *"Cast segments (steel/iron)"* and *"Shotcrete"* is very low (0.1%).

6.3.3.7 Data of groundwater control activity

Technical data of groundwater control activity are as follow:

Groundwater flow	Less than 10 l/min.
Working length/day	4m or less
Tunnel depth	16 – 30m
Ground conditions	SM (silty sand)
Tunnel position	Urban areas

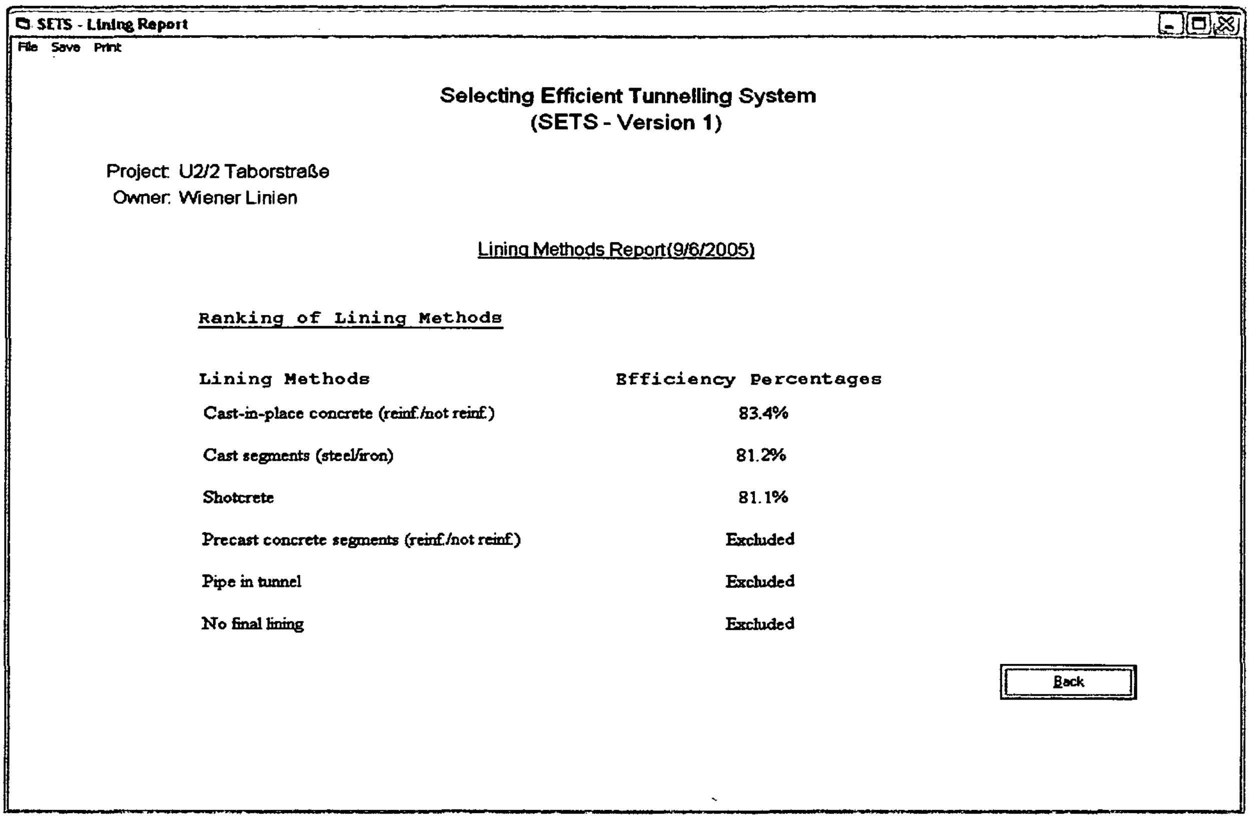


Figure 6.25 Lining report of U2/2 Taborstraße tunnel

Importance degrees of controlling factors are shown in table 6.12. There is a restriction on using *"Slurry wall"* as groundwater control method for this project because there is limited site area and tunnel tubes are constructed inside the city. Controlling factor *"Others"* in table 6.12 has importance degree of "7" and *"Slurry wall"* is assigned a low efficiency degree (1.5) in *"Relative effectiveness of groundwater methods"* screen as shown in figure 6.26.

Groundwater control report, in figure 6.27, demonstrates that *"Dewatering"* has the highest efficiency percentage and it takes the first rank in groundwater control report.

Table 6.12 Importance degrees for controlling factors (groundwater control methods-U2/2 taborstraße tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground conditions	10	Effect on buildings	10
Groundwater flow rate	9	Groundwater contamination	9
Tunnel depth	8	Groundwater regime	9
Tunnel position	9	Cost	9
Advancement rate	8	Time	9
Health and safety	7	Others	7

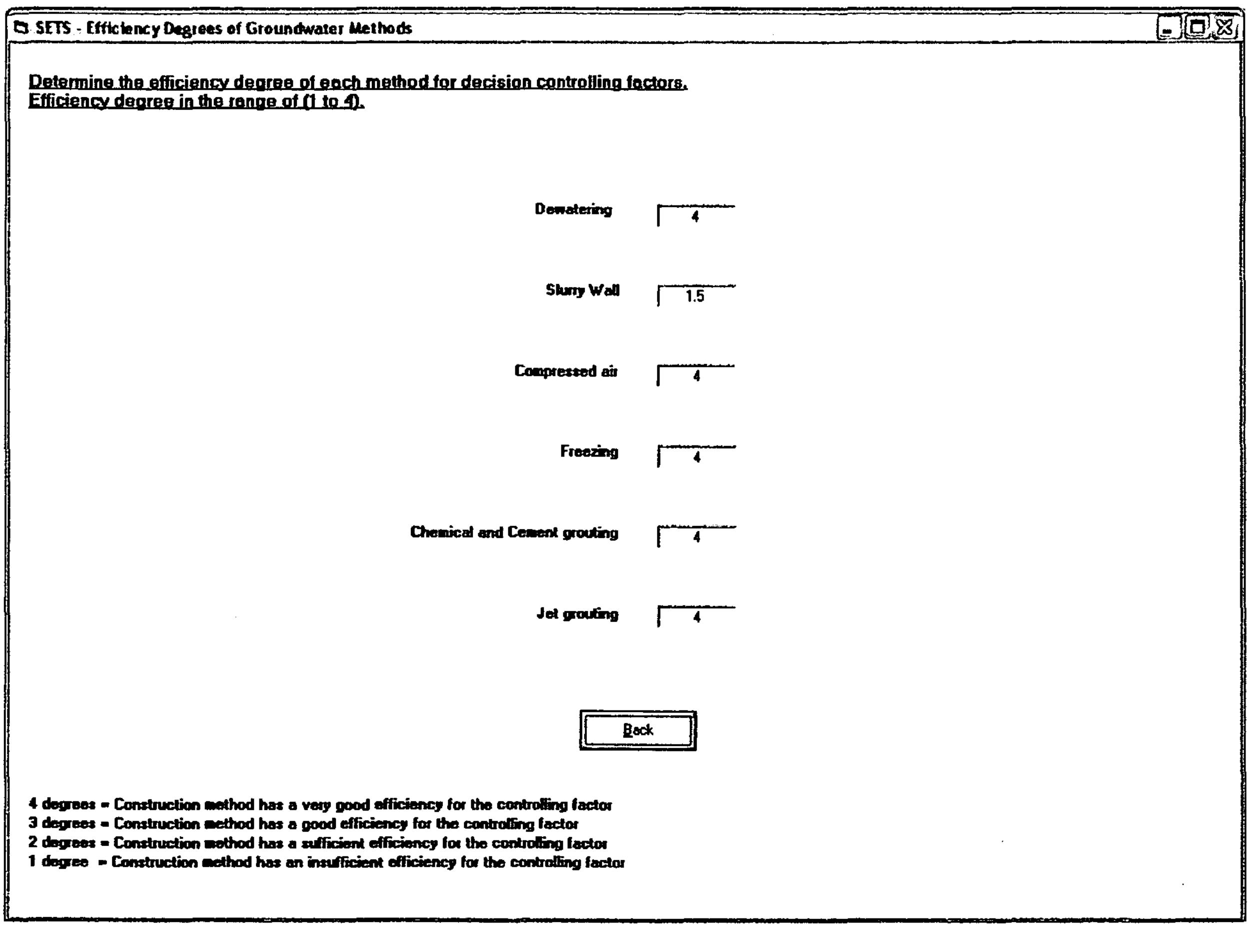
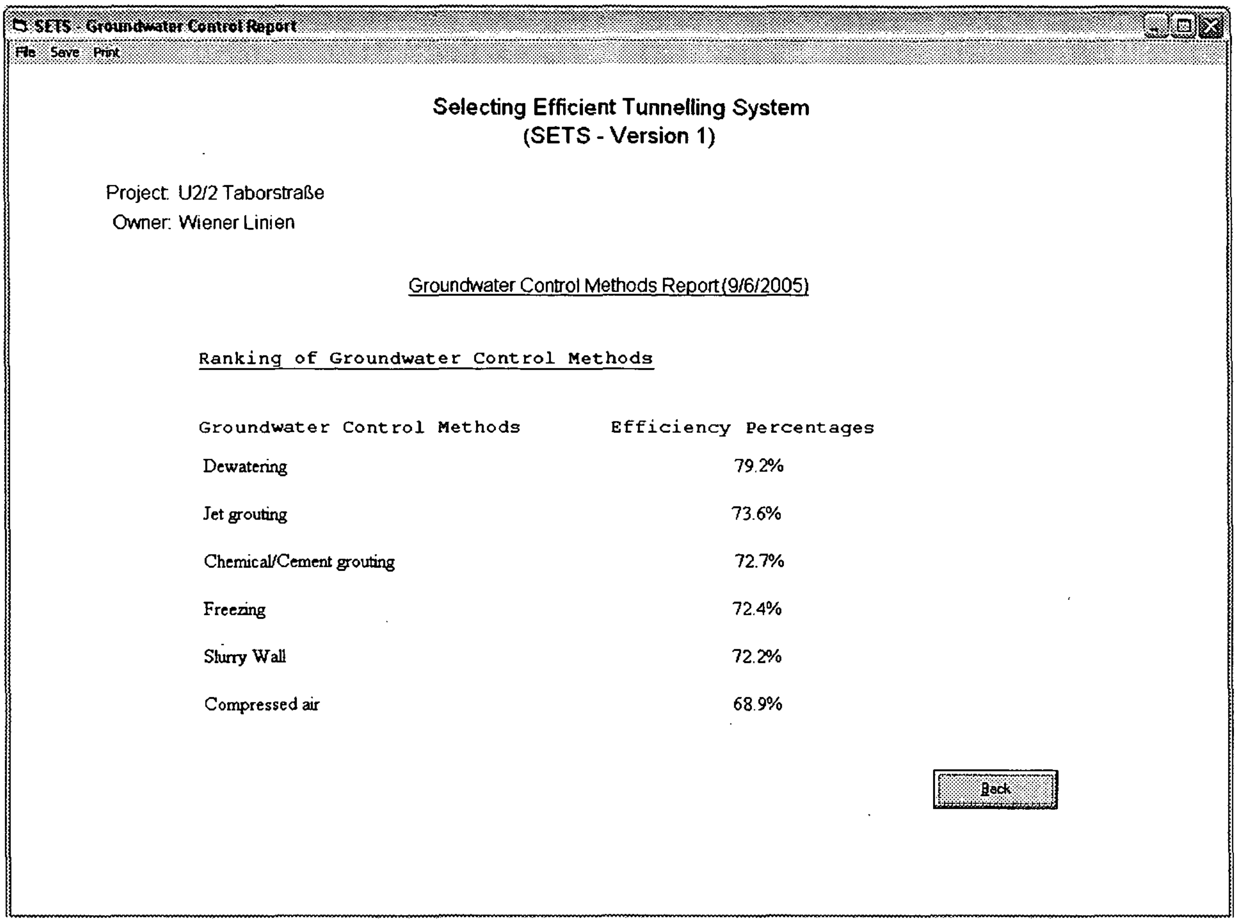


Figure 6.26 Efficiency degrees of groundwater control methods



SETS - Groundwater Control Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße
Owner: Wiener Linien

Groundwater Control Methods Report(9/6/2005)

Ranking of Groundwater Control Methods

Groundwater Control Methods	Efficiency Percentages
Dewatering	79.2%
Jet grouting	73.6%
Chemical/Cement grouting	72.7%
Freezing	72.4%
Slurry Wall	72.2%
Compressed air	68.9%

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Figure 6.27 Groundwater control report of U2/2 Taborstraße tunnel

6.3.4 Alternative tunnelling systems

SETS program was run to calculate the comprehensive report and find the alternative tunnelling system for this project. SETS program has found 7 alternative systems for U2/2 Taborstraße tunnel. The first system that has the highest efficiency percentage, as shown in figure 6.28, is similar to the system that already used in the actual case. Appendix B-2 has printed reports of U2/2 Taborstraße tunnel.

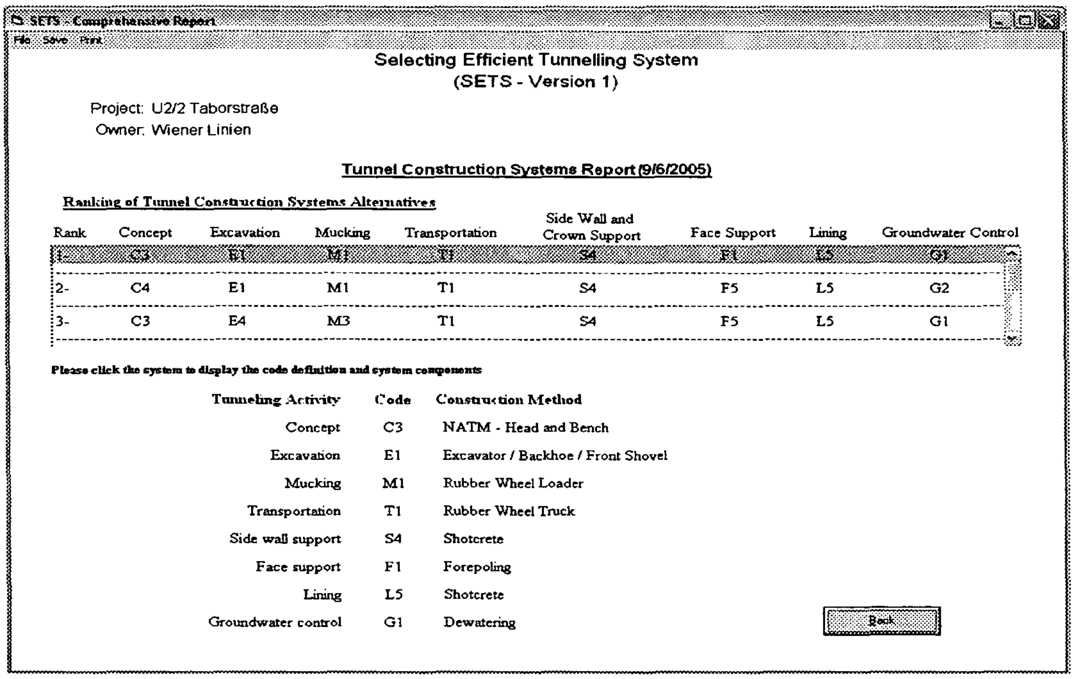


Figure 6.28 Comprehensive report of U2/2 Taborstraße tunnel

6.4 Gotthard base tunnel – Amsteg section lot 252

Gotthard base tunnel is an ambitious railway construction project between Erstfeld and Bodio. With the Gotthard base tunnel, a level-track high-speed railway will cross the Alps. The 57km twin tunnels with a distance of 40 m and diameters of about 9m will be connected by cross passages at every 325m. Gotthard base tunnel will incorporate the world's longest railway tunnel. Future passenger trains will journey at speeds of up to 250 km/h, adding further to the highly successful European high-speed network and bringing a huge reduction in travelling time.

The Gotthard Base Tunnel will cost around seven billion francs. The entire tunnel construction has been divided into five sections, each with its own separate access point:

· Erstfeld - northern portal

· Amsteg - horizontal access tunnel, 1.2km long

· Sedrun - two blind shafts, 800m deep and 8 m in diameter accessed through a horizontal tunnel about 1km long

· Faido - a 2.7km long inclined access tunnel (adit) with a 12% gradient and a height difference of 300m

· Bodio - southern portal

Nearly 90% of the Gotthard Base Tunnel has rock that is suitable for mining using TMBs. SETS program was applied for the section of *"Amsteg lot 252"*. Figure 6.29 shows Amsteg section of Gotthard base tunnel.

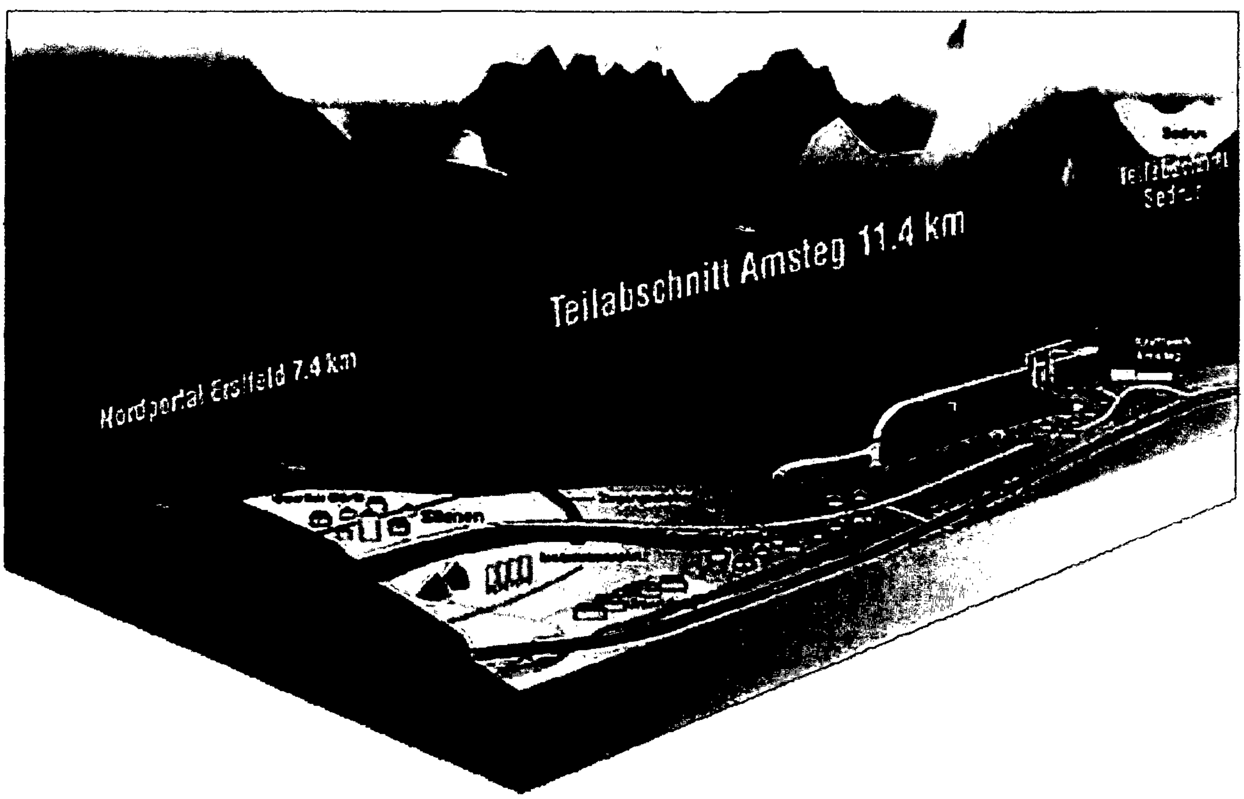


Figure 6.29 Amsteg section of Gotthard base tunnel [125]

6.4.1 Project data of "Amsteg section lot 252"

A form contains data that is required to apply the program was sent to the project manager. The following data about the project were obtained:

Client	Alptransit AG
Contractor	JV Murer – Strabag AG
Designer	IG GBTN
Project Cost	660 Mio CHF
Project Start Date	02/2002
Project Finish Date	03/2009
Tunnel length up to the section limit	11350 m
Excavated diameter	9.58 m
Inclination	4.08‰
Curve radius	> 5000 m
Type of heading	Gripper-TBM
Tunnel finishing	Shotcrete with concrete invert construction
Muck handling	conveyor

6.4.2 Construction method

Starting from the intermediate point Amsteg, two tunnel boring machines are excavating about 11 km of the two tubes of the Gotthard base tunnel to the south, to the meeting point with the advance of the Sedrun section.

6.4.3 Input data to SETS program (Gotthard base tunnel project)

SETS program was run using data of Amsteg section lot 252. Importance degrees of controlling factors are assigned by project manager.

6.4.3.1 Data of the *"Project general data"* screen

Project name	Gotthard base tunnel (Amsteg section lot 252)
Client	Alptransit AG
Ground	Rock
Tunnel height	9.58 m
Groundwater level	Not determined (0)
Tunnel invert level	550
Labour cost	Expensive

6.4.3.2 Data of the *"Basic tunnelling methods"* and excavation activities

Importance degrees of basic tunnelling and excavation controlling factors are shown in table 6.13. Because *"Others"* controlling factor has a value, methods of construction were assigned efficiency degrees in screen of *"Efficiency degrees of basic tunnelling and excavation methods"* (see figure 6.30).

Table 6.13 Importance degrees for controlling factors (basic tunnelling and excavation methods- Gotthard base tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground conditions	8	Air pollution	10
Tunnel depth	8	Effect on landscape	2
Cross section	3	Limited site area	7
Tunnel alignment	3	Utilities in tunnel path	5
Health and safety	10	Cost	10
Noise	3	Time	4
Vibration	2	Technology availability	0
Archaeology	0	Experience	0
Effect on traffic	7	Others	9

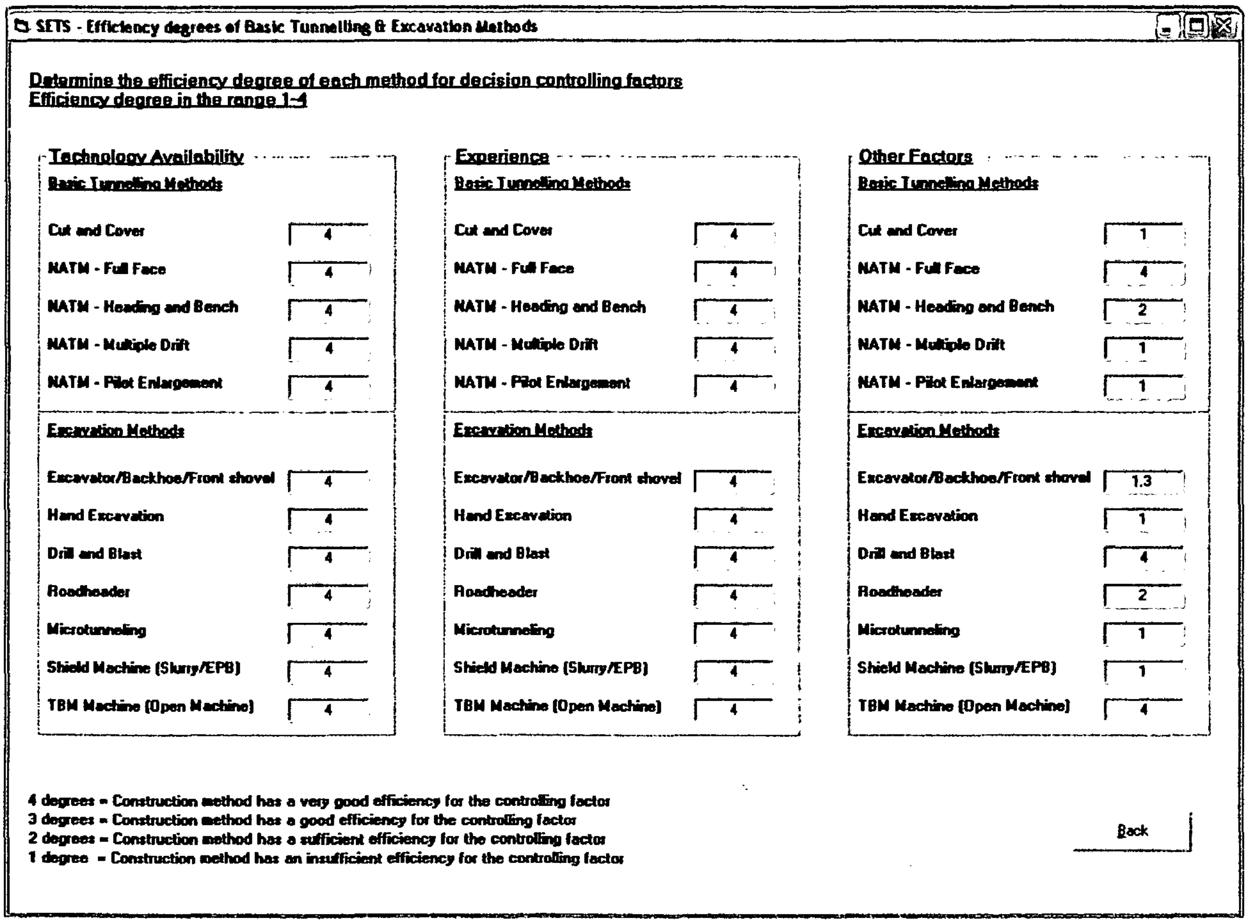


Figure 6.30 Efficiency degrees of basic tunnelling and excavation methods

Input technical data as follow:

Ground compressive strength	Over 200MPa
There is harmful gases	No
Tunnel cross section area	31 – 100m^2
Fixed cross section	Yes
Cross section shape	Circular
Tunnel length	More than 3km

Tunnel depth	More than 30m
Sharpest horizontal curve radius	Bigger than 150m
Vertical slope	Less than 3%
Construction site	Big
There is utilities in tunnel's path	No

"Basic tunnelling methods" and excavation reports are shown in figures 6.31 and 6.32 respectively. Results show that there are only two excavation methods that can be used for this project, which are *"Drill and blast"* and *"TBM"*.

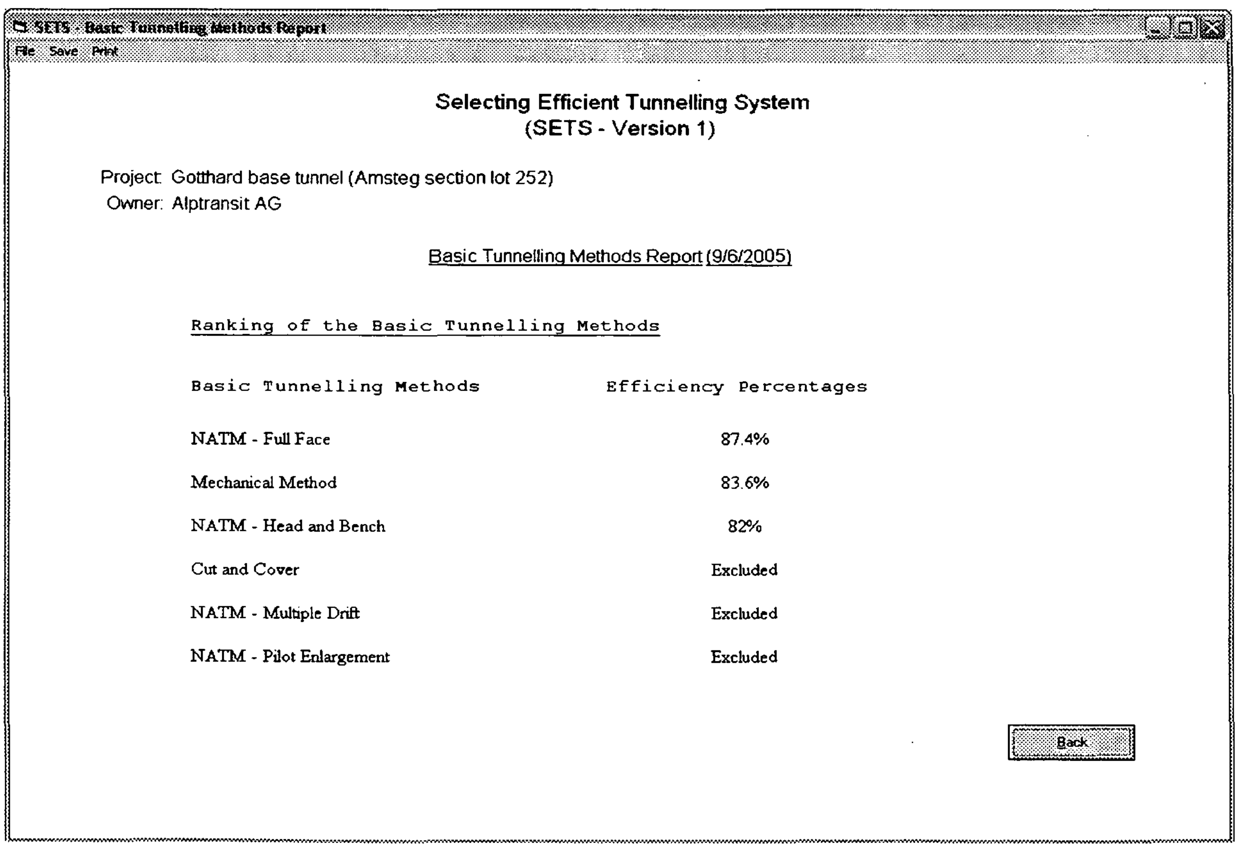
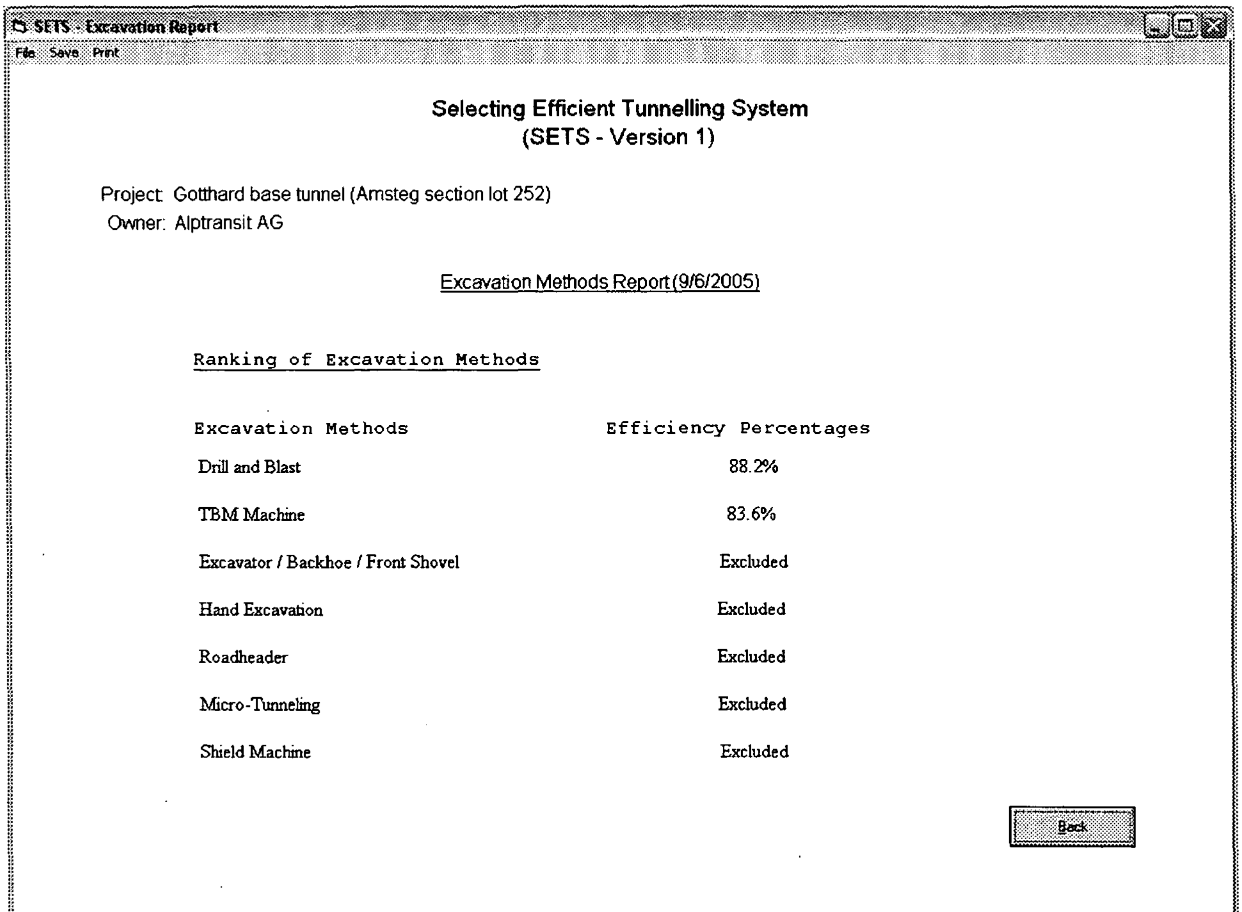


Figure 6.31 "Basic tunnelling methods" report of *"Amsteg tunnel lot 252"*


SETS - Excavation Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)
Owner: Alptransit AG

Excavation Methods Report (9/6/2005)

Ranking of Excavation Methods

Excavation Methods	Efficiency Percentages
Drill and Blast	88.2%
TBM Machine	83.6%
Excavator / Backhoe / Front Shovel	Excluded
Hand Excavation	Excluded
Roadheader	Excluded
Micro-Tunneling	Excluded
Shield Machine	Excluded

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Figure 6.32 Excavation report of *"Amsteg tunnel lot 252"*

6.4.3.3 Data of mucking activity

Technical data of mucking activity are listed below. Table 6.14 presents importance degrees of mucking controlling factors.

Ground bearing capacity	Over 0.2MPa
Muck particle size	Medium
Tunnel span	Over 8m

Table 6.14 Importance degrees for controlling factors (mucking methods-Gotthard base tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground bearing capacity	8	Cost	10
Muck particle size	9	Time	8
Tunnel span	0	Others	0

Mucking report, resulting from the program, is shown in figure 6.33. *"Rubber wheel loader"* has the highest efficiency percentage compared with *"Tracked loader"*.

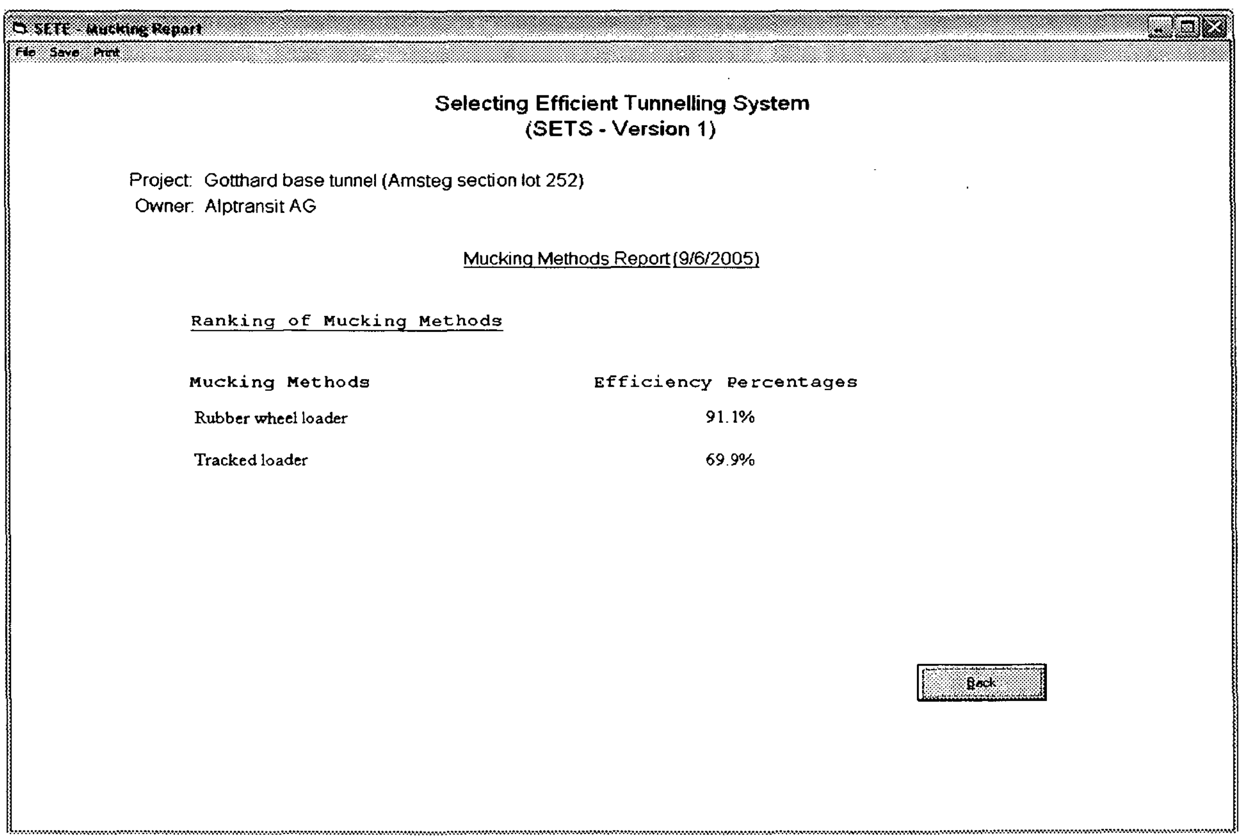


Figure 6.33 Mucking report of *"Amsteg tunnel lot 252"*

6.4.3.4 Data of transportation activity

Table 6.15 presents importance degrees of transportation controlling factors. Technical data are as follow:

Ground bearing capacity	Over 0.2MPa
Tunnel span	Over 8m
Tunnel vertical slope	Less than 3%
Transporting distance	Over 3km
Transporting speed	High
Muck water content	Almost dry
Muck particle size	Less than 45cm

Table 6.15 Importance degrees for controlling factors (transportation methods-Gotthard base tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground bearing capacity	3	Muck water content	8
Transporting speed	9	Health and safety	10
Tunnel vertical slope	0	Cost	10
Tunnel span	0	Time	10
Muck particle size	7	Others	0

Figure 6.34 shows transportation report. *"Conveyors"* comes in the first place with efficiency percentage of 82.6%.

6.4.3.5 Data of support activity

Table 6.16 shows importance degrees of support controlling factors. Ground conditions controlling factor has the highest importance degree.

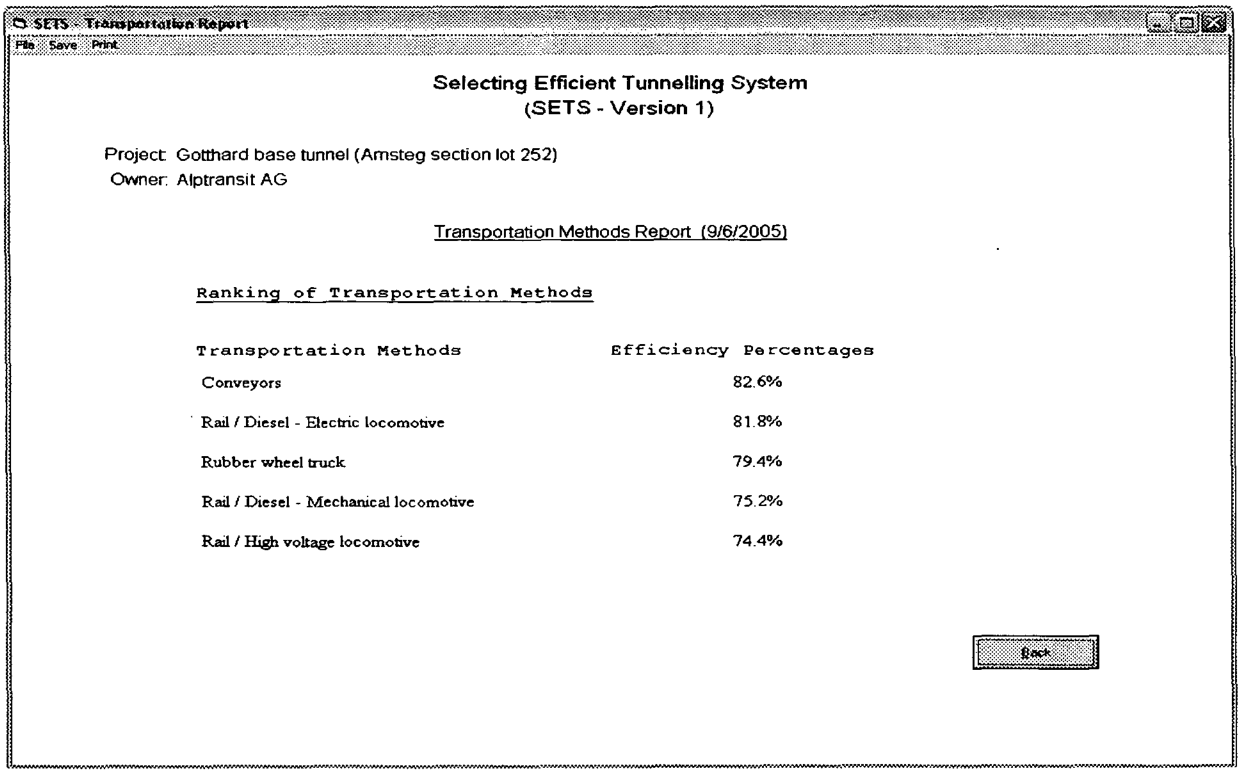


Figure 6.34 Transportation report of *"Amsteg tunnel lot 252"*

Table 6.16 Importance degrees for controlling factors (support methods-Gotthard base tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground Conditions	8	Cost	3
Tunnel Depth	5	Time	7
Tunnel Shape	6	Others	0
Tunnel Span	3		

Technical input data are:

Tunnel span	7 – 10m
Predicted failure	Due to overstress

RMR-value	61 – 80
Tunnel depth	Over 1000m
Tunnel cross section	Circular

Figure 6.35 shows side wall and crown support report. *"Shotcrete"* comes in the first rank for side wall support. The difference in efficiency percentages between *"Shotcrete"* and *"Dowels"* that occupy the second rank is 3.4%. Face support report in figure 6.36 shows that there is no need for face support, because RMR value is in range of (61 – 80).

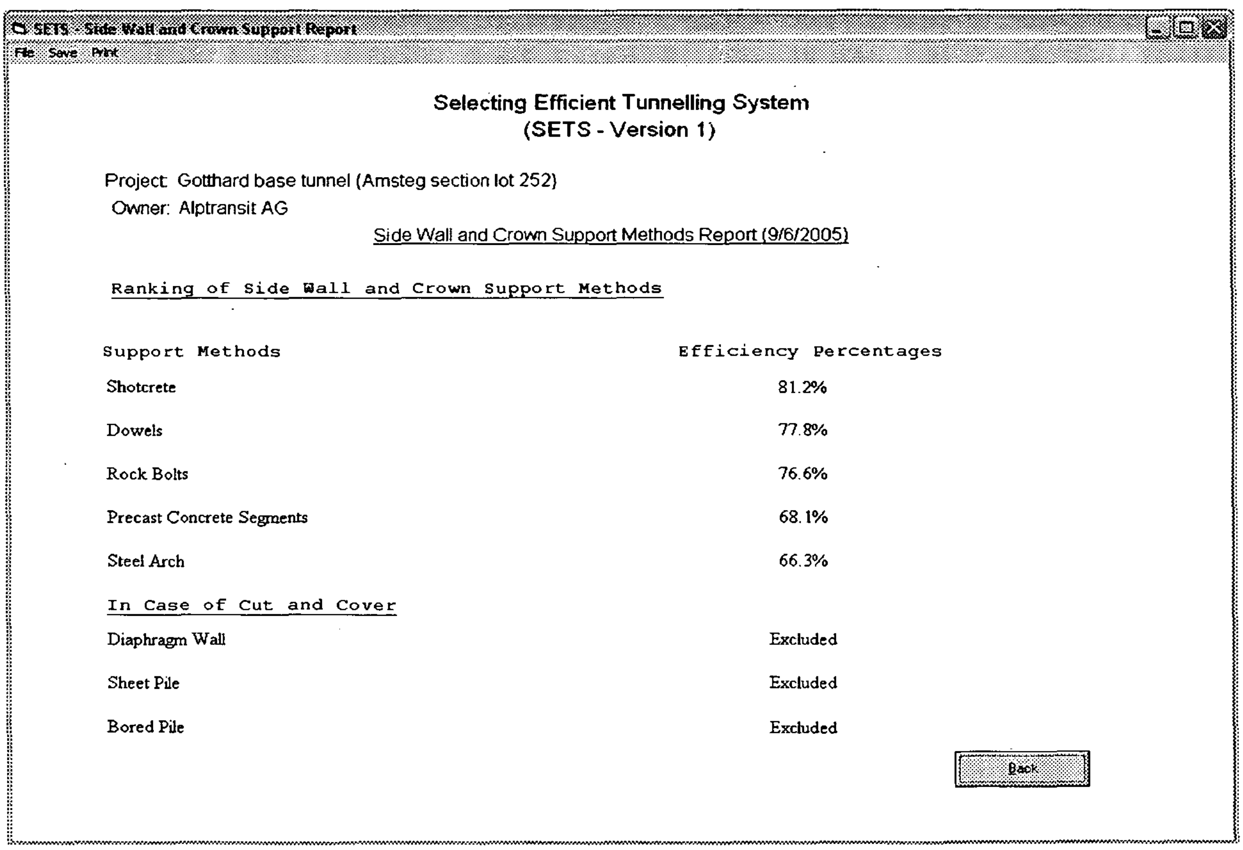
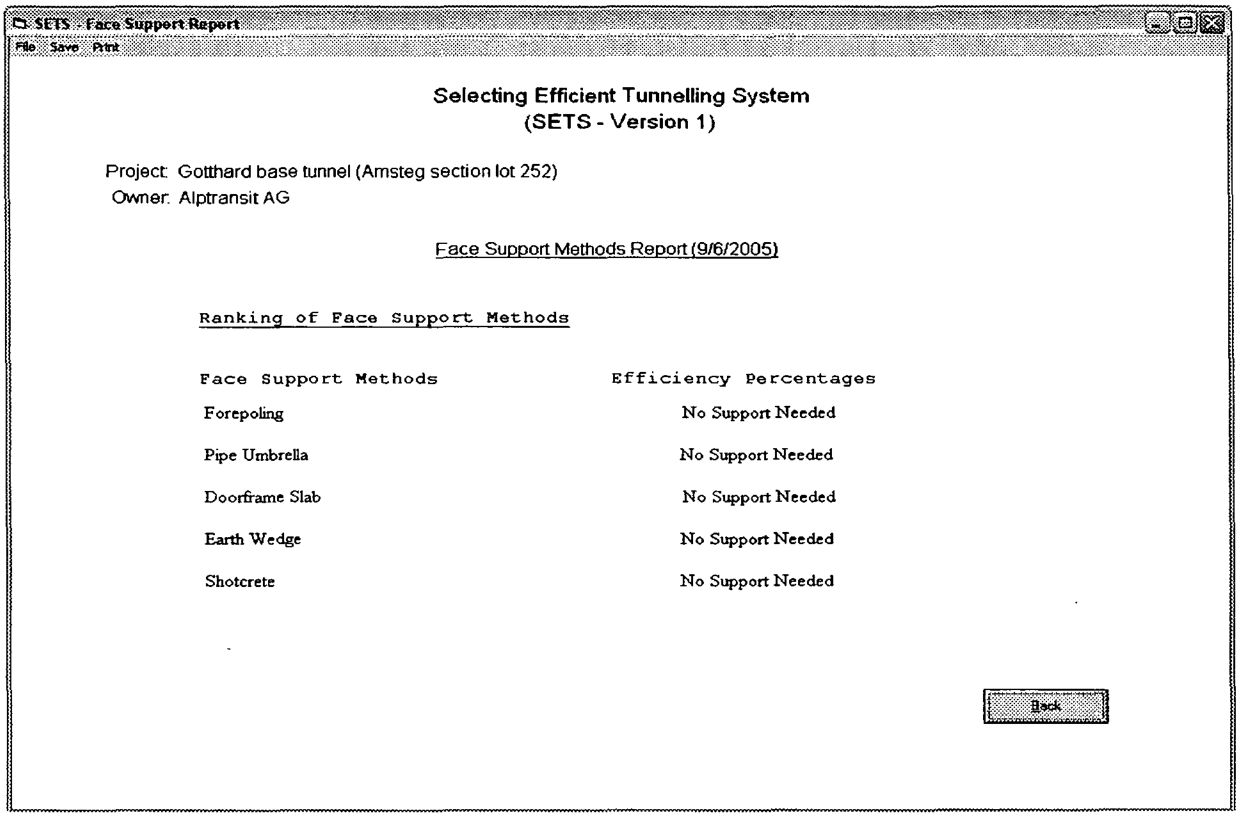


Figure 6.35 Side wall and crown support of *"Amsteg tunnel lot 252"*


SETS - Face Support Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)
Owner: Alptransit AG

Face Support Methods Report (9/6/2005)

Ranking of Face Support Methods

Face Support Methods	Efficiency Percentages
Forepoling	No Support Needed
Pipe Umbrella	No Support Needed
Doorframe Slab	No Support Needed
Earth Wedge	No Support Needed
Shotcrete	No Support Needed

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Figure 6.36 Face support of *"Amsteg tunnel lot 252"*

6.4.3.6 Data of lining activity

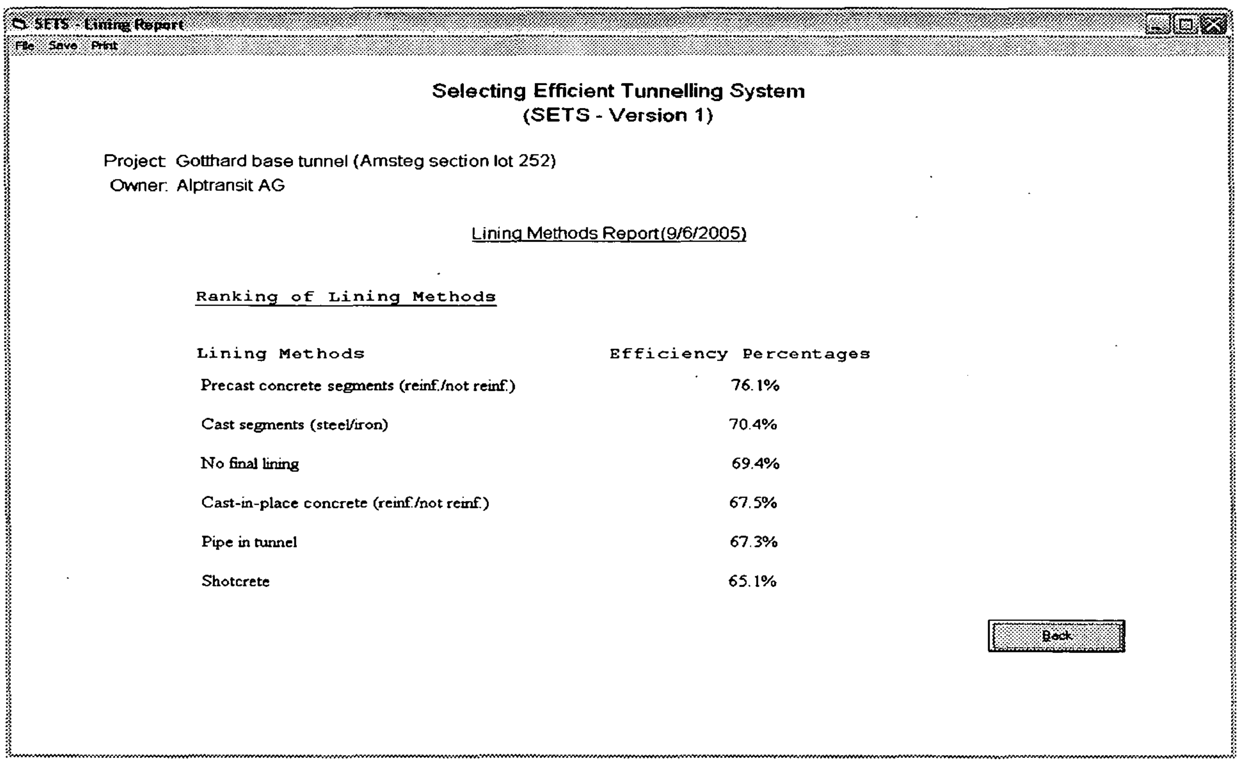
Controlling factors of lining activity have importance degrees as shown in table 6.17. *"Cost"* and *"Time"* are the most important controlling factors.

Table 6.17 Importance degrees for controlling factors (lining methods-Gotthard base tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground conditions	4	Groundwater flow rate	6
Reaction with mineral	6	Cost	10
Tunnel shape	3	Time	10
Tunnel function	3	Others	0

Technical input data are as follow:

Q-value	41 - 100
Groundwater flow	26 – 125 l/min.
Ground minerals	Quartz, muscovite, biotite, and chlorite
Tunnel function	Railway
Tunnel shape	Circular


SETS - Lining Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)
Owner: Alptransit AG

Lining Methods Report(9/6/2005)

Ranking of Lining Methods

Lining Methods	Efficiency Percentages
Precast concrete segments (reinf./not reinf.)	76.1%
Cast segments (steel/iron)	70.4%
No final lining	69.4%
Cast-in-place concrete (reinf./not reinf.)	67.5%
Pipe in tunnel	67.3%
Shotcrete	65.1%

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Figure 6.37 Lining report of *"Amsteg tunnel lot 252"*

Figure 6.37 is lining report, which shows that "Precast concrete segments" is the most efficient lining method for this project according calculations of SETS program.

6.4.3.7 Data of groundwater control activity

Technical input data for groundwater control activity are listed below. Table 6.18 shows importance degrees of groundwater controlling factors.

Groundwater flow	26 – 125min.
Tunnel depth	Over 50m
Ground conditions	Ground is rock
Tunnel position	Urban areas

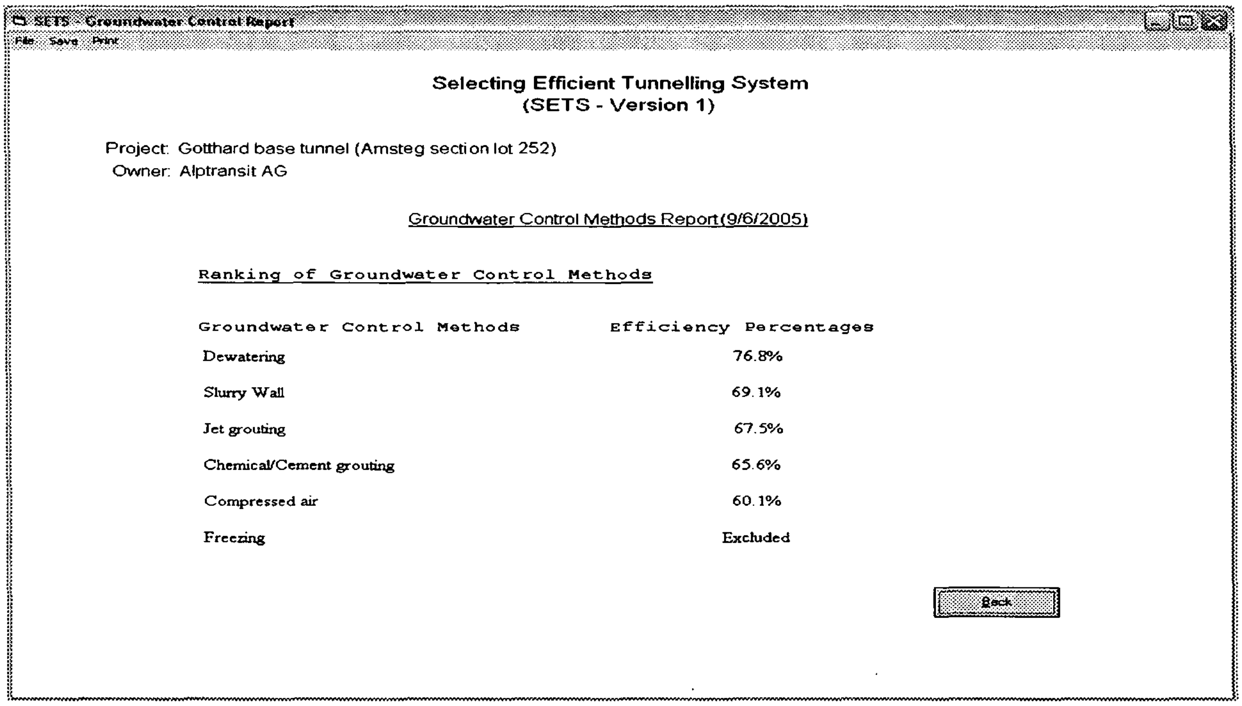
Table 6.18 Importance degrees for controlling factors (groundwater control methods-Gotthard base tunnel)

Controlling Factors	Importance Degree	Controlling Factors	Importance Degree
Ground conditions	5	Effect on buildings	0
Groundwater flow rate	9	Groundwater contamination	0
Tunnel depth	9	Groundwater regime	0
Tunnel position	1	Cost	8
Advancement rate	3	Time	8
Health and safety	2	Others	0

Figure 6.38 shows groundwater controlling methods report. *"Freezing"* method is excluded as shown in the report and the other methods can be used but they have different efficiency percentages.

6.4.4 Alternative tunnelling systems

Comprehensive report in figure 6.39 shows that program SETS has found only three alternative tunnelling systems for this project. The first system in comprehensive report is "TBM". It is similar to the actual case.



SETS - Groundwater Control Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)
Owner: Alptransit AG

Groundwater Control Methods Report(9/6/2005)

Ranking of Groundwater Control Methods

Groundwater Control Methods	Efficiency Percentages
Dewatering	76.8%
Slurry Wall	69.1%
Jet grouting	67.5%
Chemical/Cement grouting	65.6%
Compressed air	60.1%
Freezing	Excluded

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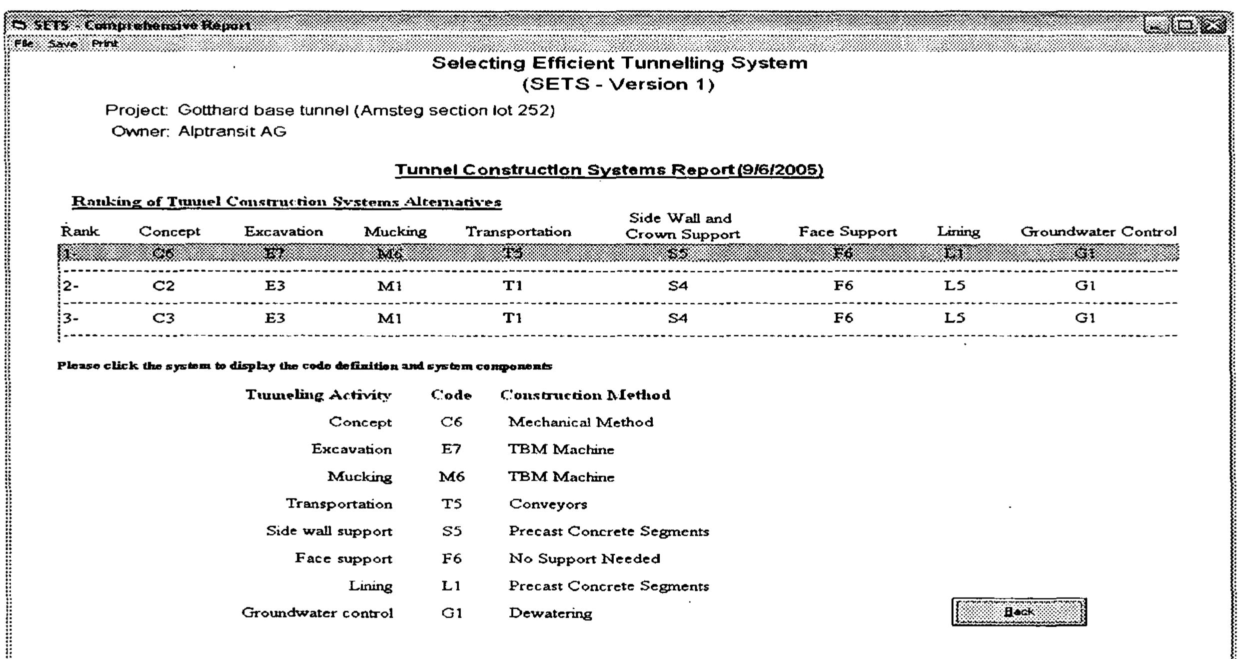
Figure 6.38 Groundwater control report of *"Amsteg tunnel lot 252"*



SETS - Comprehensive Report

File Save Print

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)
Owner: Alptransit AG

Tunnel Construction Systems Report(9/6/2005)

Ranking of Tunnel Construction Systems Alternatives

Rank	Concept	Excavation	Mucking	Transportation	Side Wall and Crown Support	Face Support	Lining	Groundwater Control
1-	C6	E7	M6	T5	S5	F6	L1	G1
2-	C2	E3	M1	T1	S4	F6	L5	G1
3-	C3	E3	M1	T1	S4	F6	L5	G1

Please click the system to display the code definition and system components

Tunneling Activity	Code	Construction Method
Concept	C6	Mechanical Method
Excavation	E7	TBM Machine
Mucking	M6	TBM Machine
Transportation	T5	Conveyors
Side wall support	S5	Precast Concrete Segments
Face support	F6	No Support Needed
Lining	L1	Precast Concrete Segments
Groundwater control	G1	Dewatering

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Figure 6.39 Comprehensive report of *"Amsteg tunnel lot 252"*

There is difference between supporting and lining methods resulting from the program which are the *"Precast concrete segments"* and that already used in the project. The *"Precast concrete segments"* can be used in the project but *"Shotcrete"* and *"Cast-in-place concrete"* had been selected as tunnel finishing in the real project. Other system elements are like methods used in construction site. Results of the program still good and accepted specially it is designed to give decision maker a view over the efficient tunnelling systems in the preliminary stage. Appendix B-3 contains printed reports of *"Amsteg tunnel lot 252"*.

7 Conclusions and recommendations

The proposed model, in this research, is an easy tool to determine the efficient tunnelling systems in the preliminary stage of a tunnel project. The model selects construction methods which satisfy efficiently project conditions to form tunnelling systems.

In the preliminary stage (conceptual phase of the project), the decision maker needs to know the alternative tunnelling systems which are available for his/her project to start the calculations of the feasibility of each system and select one of the tunnelling systems to be used for his/her project.

The model of this research provides the decision maker with a comprehensive report about the alternative tunnelling systems for his particular project. Each tunnelling system include a *"Basic tunnelling method"*, excavation method, mucking method, transportation method, initial support method, lining method and groundwater control method. The *"Basic tunnelling methods"* include methods such as cut and cover, NATM and mechanical method. Excavation methods include methods such as excavators, drill and blast and TBMs. Mucking methods include rubber wheel loader and the tracked loader. Transportation methods include methods such as rubber wheel trucks and conveyors. Support methods include methods such as rock bolts, steel arches and shotcrete. Lining methods include methods such as precast concrete segments, cast-in-place concrete and shotcrete. Groundwater control methods include methods such as dewatering, compressed air and freezing. The model will select construction methods which will give the highest efficiency of the tunnelling system during constructing the tunnel, based on project conditions which are represented in the model as the controlling factors.

Controlling factors were selected based on previous researches in this field, and then it was adapted after taking the opinions of tunnel experts.

The model calculates the efficiency percentage for each construction method and it combines methods of different tunnelling activities to form tunnelling systems. The model calculates the efficiency percentage of each tunnelling system and it ranks the systems in a descending order.

A computer program was developed to perform calculations of the proposed model. The program was written using *"Visual Basic 6"* programming language. The program will make the calculations and shows the results in reports that can be printed or saved on the computer to be reviewed in future.

The model was tested using data of three real projects, which are *"Wienerwald tunnel"*, *"U2/2 Taborstraße tunnel"* and *"Gotthard tunnel – Amsteg section lot 252"*. Results of the program were compatible with the actual tunnelling systems used in these projects.

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. 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.

For future researches, it is recommended to establish an evaluation system for tunnel projects that can calculate efficiency degrees of construction methods for the controlling factors. This evaluation system can be connected to SETS program to update the efficiency degrees that used in calculations.

SETS program presented in this research can be improved to make a data base for the program and it will enable the program to save data of projects. Dealing with the program will be easier because user can change some input data from time to time and he/she will not need to enter the whole data again.

References

1. Adams, E., (2001), "Micro-tunnelling Innovations", Internet site: http://www.czstt.cz/nodig2001prague/Data/Adams-79.doc.

2. Aebersold, W., (1994), "Betrieb und erzielte Leistung mit dem Mixschild", Referate der Studientagung vom 26 Mai 1994 in Schönbühl, Fachgruppe für Untertagebau, SIA Dokumentation D0116, Grauholztunnel II.

3. Anon, (1970), "Logging of Cores for Engineering Purposes", Engineering Group working party report, Quarterly Journal of Engineering Geology, 3, pp 1-24.

4. Atalah, A., and Hadala, P., (1996), "Micro-tunnelling database for the USA and Canada from 1984 to 1995", *Proc., Specialty Conf.: Pipeline Crossings*, Burlington, Vt., 332-339.

5. Barton, N., (2002), "Some new Q-value correlations to assist in site characterization and tunnel design", International Journal of Rock Mechanics & Mining Sciences, Pergamon, 39, pp 185-216.

6. Barton, N., (2000), "TBM tunnelling in jointed and faulted rock", A.A. Balkema/Rotterdam/Brookfield.

7. Barton, N., (1988), "Rock Mass Classification and Tunnel Reinforcement Selection Using the Q-system", ASTM STP 984, Rock Classification Systems for Engineering Purposes.

8. Barton, N., (1976), "Recent experiences with the Q-system of tunnel support design", Proc. Symposium on Exploration for Rock Engineering, Johannesburg, Volume 1, pp 107-117.

9. Barton, N., Lien, R., and Lunde, J., (1974), "Engineering Classification of Rock Masses for the Design of Tunnel Support", Rock Mechanics, Vol. 6, No. 4.

10. Bell, F. G., (1993), "Engineering Geology", Blackwell Scientific publications, Vienna.

11. Bieniawski, Z. T., (1989), "Engineering Rock Mass Classifications: a complete manual for engineers and geologists in mining, civil and petroleum engineering", Wiley, New York.

12. Bieniawski, Z. T., (1979), "The Geomechanics Classification in Rock Engineering Applications", Proc. 4th International Congress on Rock Mechanics, ISRM, Montreux, A.A.Balkema, Rotterdam, Vol. 2, pp 41-48.

13. Bieniawski, Z. T., (1976), "Rock Mass Classification in Rock Engineering", Proc. Symposium on Exploration for Rock Engineering, Johannesburg, Volume 1, pp97-106.

14. Bieniawski, Z. T., (1974), "Geomechanics Classification of Rock Masses and its Application in Tunnelling", Proc. Third International Congress on Rock Mechanics, ISRM, Denver, Volume 11A, pp 27-32.

15. Boyd, R. J., (1986), "Hard Rock Continuous Mining Machine: Mobile Miner MM-120" Rock Excavation Engineering Seminar (Howarth, D. F. et al., eds.). Dept. Mining and Met. Eng., University of Queensland.

16. Brandl, H., (1995), "Soil properties in connection with NATM", International Association of Civil Engineering Students – Bureau of Vienna, summer course "NATM".

17. Broch, E., "Rock tunnelling", internet site: http://www.ita-aites.org/cms/fileadmin/filemounts/general/pdf/ItaAssociation/WhatIsITA/commemorativeBook/broch.pdf.

18. Bruland, A., Johannessen, B. E., Lislerud, A., Movinkel, T., Myrvold, K., and Johannessen, O., (1988), "Hard Rock Tunnel Boring", Project Report 1-88: 183pp. Trondheim: Norwegian Institute of Technology.

19. Cambridge economic policy associates, (July, 2003), "Report to the London underground PPP Arbiter: definitions and terminology – annex 1", Internet site: http://www.ppparbiter.org.uk/pdf_folder/cepa_r1ax1_0703.pdf

20. Campo, D. W., and Richards, D. P., (2000), "Tunneling Beneath Cairo", Journal of Civil Engineering, ASCE, Vol. 70, No. 1, Jan. 2000, pp 36-41.

21. Cassinelli, F. et al. (1982), "Power Consumption and Metal Wear in Tunnel Boring Machines: Analysis of Tunnel Boring Operation in Hard Rock" Proceedings, Tunneling'82, 73-81. London.

22. Colgan, P. M., (1999), "Tunnels and Tunnelling Methods" Internet site: http://www.casdn.neu.edu/~geology/department/staff/colgan/class_notes/1250/1250-9.htm.

23. Dalgiç, S., (2002), "A Comparison of Predicted and Actual Tunnel Behaviour in the İstanbul Metro, Turkey", Engineering Geology, Elsevier Science B. V., 63, pp 69-82.

24. Deere, D. U., Peck, R. B., Parker, H. W., Monsees, J. F., and Schmidt, B., (1970), "Design of tunnel support systems", Highway Research Record, Number 339, pp 26-33.

25. Deere, D. U., (1968), "Geological Considerations", Rock Mechanics in Engineering Practice, Editors K. G. Stagg and O. C. Zienkiewcz, published by John Wiley & Sons, London, pp 1-20.

26. Deere, D. U., (1964), "Technical description of rock cores for engineer purposes", Rock Mechanics and Engineering Geology, Volume 1, Number 1, pp 17-22.

27. Einstein, H. H., Indermitte, C. A., Sinfield, J. V., Descoeudres, F., and Dudt, J. –P., (1999), "The Decision Aida for Tunneling" Transp. Res. Rec. 1656, Transportation Research Board, Washington, D.C.

28. Einstein, H. H., Dudt, J. P., Halabe, V. B., and Descoeudres, F., (1992), "Decision Aids in Tunneling; Principle and Practical Application" Monograph prepared for the Swiss Federal Office of Transportation.

29. Einstein, H. H., (1991), "Strategies for subsurface investigation", Underground Structures: Design and Construction, Editor R. S. Sinha, Elsevier, pp 81-91.

30. "Equipment and Technology Review", (2002), World Tunnelling, Mining Journal Ltd., Vol. 15, No. 8, October 2002, pp 403-405.

31. Farmer, I. W. and Glossop, N. H., (1980), "Mechanics of Disc Cutter Penetration" Tunnels and Tunneling 12 (6), 22-25.

32. Fugeman, I. C. D., Hawley, J., and Myers, A. G., (1992), "Major Underground Structures", Proc. Instn Civ. Engrs, Civ. Engng., Channel Tunnel, Part 1: Tunnels, pp 87-102.

33. Gehring, K., and Kogler, P., (1997), "Mechanized tunnelling: where it stands and where it has to proceed from a manufacturers view point", Tunnels for People, Golser, Hinkel & Schubert (eds), Balkema, Rotterdam.

34. Girmscheid, G., and Schexnayder, C., (2002), "Drill and Blast Tunnelling Practices", Practice Periodical on Structural Design and Construction, ASCE, Vol. 7, No. 3, August 2002, pp125-135.

35. Glossop, R. and Skempton, A. W. (1945), "Particle-Size in Silts and Sands", Journal of the Institute of Civil Engineers, London, England.

36. Golder, and James, F. (1976), "Tunnelling technology – an appraisal of the state of the art for application to transit systems", Ministry of Transportation and Communications, Research and Development Division.

37. Golser, J., (1995), "History, Definition, Principles", International Association of Civil Engineering Students – Bureau of Vienna, summer course "NATM".

38. Graham, P. C., (1976), "Rock Exploration for Machine Manufacturers" Proceedings, Symposium on exploration for rock engineering, Johannesburg, 173-180. Rotterdam: Balkema.

39. Grima, M. A., Bruines, P. A., and Verhoef, P. N. W., (2000), "Modeling Tunnel Boring Machine Performance by Neuro-Fuzzy Methods" Tunneling and Underground Space Technology, Vol. 15, No. 3, pp. 259-269.

40. Haas, C., and Einstein, H. H., (2002), "Updating the Decision Aids for Tunnelling", Journal of Construction Engineering and Management, ASCE, Vol. 128, No. 1, February 1, 2002, pp 40-48.

41. Halabe, V. B. H., (1995), "Resource Modeling for the DAT" PhD Thesis, Massachusetts Institute of Technology.

42. Hegab, M. Y., and Salem, O., M., (2004), "Productivity analysis for Boulac's wastewater micro-tunnels in Egypt", *Practice Periodical on Structural Design and Construction*, ASCE, Vol. 9, No. 2, May 2004, pp. 116-120.

43. Hencher, S. R., "Recognising the significance of complex geological conditions",

44. Hiller, D., (2002), "Noise and Vibration Impacts of Tunnels", *Tunnels and Tunnelling International*, June 2002, pp 31-33.

45. Hoek, E., (2001), "Big Tunnels in Bad Rock", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 127, No. 9, September 2001, pp 726-740.

46. Hoek, E., Kaiser, P. K., and Bawden, W. F., (1995), "Support of Underground Excavations in Hard Rock", A.A.Balkema, Rotterdam.

47. Hoek, E., and Brown, E. T., (1994), "Underground Excavations in Rock", published by E&FN Spon, an imprint of chapman & Hall, 2-6 Boundary Row, London SE1 8HN, UK.

48. Hoek, E., and Brown, E. T., (1980), "Empirical Strength Criterion for Rock Masses", Journal Geotechnical Engineering, ASCE, 106, pp 1013-1035.

49. Hughes, H. M., (1986), "The Relative Cuttability of Coal-Measures Stone" Min. Sci. Technol. 3 (2), 95-109.

50. Hustrulid, W., (1991), "Drill and blasting", Underground Structures: Design and Construction, Editor R. S. Sinha, Elsevier, pp 141-225.

51. Ioannou, P. G., (1987), "Geologic Prediction Model for Tunnelling", Journal of Construction Engineering and Management, ASCE, Vol. 113, No. 4, December 1987.

52. Indermitte, C. A. and Einstein, H. H., (2002), "Decision Aids for Tunnelling – SIMSUPER – User's manual", Massachusetts Institute of Technology, Department of Civil and Environmental Engineering.

53. Innaurato, N., Mancini, R., Rondena, E., and Zaninetti, A., (1991), "Forecasting and Effective TBM Performance in Rapid Excavation of a Tunnel in Italy" 7th Internationaler Kongress uber Felsmechanik; Berichte, Aachen, Deutschland, Bd. 2 (W. Wittke, ed.), 985-990. Rotterdam: Balkema.

54. Isaksson, T., (2002), "Model for estimation of time and cost based on risk evaluation applied on tunnel projects", Doctoral Thesis, Division of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm, Sweden.

55. Isaksson, M., and Lindblad, M., (1997), "Störningsorsaker vid tunneldrivning – Fallstudie Siebergtunneln", Examensarbete vid avd. för Jord-och Bergmekanik, inst. För Anläggning och Miljö, Kungl. Tekniska Högskolan.

56. Jackson, M. (2000), "An analysis of flexible and reconfigurable production systems", dissertation No. 640, Linko¨ping University, Linko ping, Ch. 6, pp. 85-104.

57. Jodl, H. G., (1995), "Modern tunnelling – Why", International Association of Civil Engineering Students – Bureau of Vienna, summer course "NATM".

58. Jodl, H. G., (1995), "Construction method NATM", International Association of Civil Engineering Students – Bureau of Vienna, summer course "NATM".

59. Johannessen, O., (1990), "Drillability, Drilling Rate Index Catalogue", Report 13-90. The University of Trondheim, The Norwegian Geotechnical Institute of Technology, Division of Construction Engineering and Department of Geology, 170pp.

60. Klein, S. J., "Design aspects of Micro-tunnelling projects", Internet site: http://www.microtunneling.com/education/Papers/ndsu9502.htm.

61. Kovári, K., (2003), "History of the sprayed concrete lining method – part I: milestones up to the 1960s", Journal of Tunnelling and Underground Space Technology, Elsevier, Vol. 18, pp. 57 – 69.

62. Kovári, K., (2003), "History of the sprayed concrete lining method – part II: milestones up to the 1960s", Journal of Tunnelling and Underground Space Technology, Elsevier, Vol. 18, pp. 71 – 83.

63. Kurosawa, K. (1991), Advances in Industrial Engineering, Vol. 14: Productivity Measurement and Management at the Company Level: the Japanese Experience, Elsevier Science, Amsterdam.

64. Lauffer, H., (1958), "Gebirgsklassifizierung für den Stollenbau" Geologie und Bauwesen, Volume 24, Number 1, pp 46-51.

65. Leu, S. S., Chen, C. N., and Chang, S. L., (2001), "Data mining for tunnel support stability: neural network approach", Automation in Construction, Elsevier Science B. V., 10, pp 429-441.

66. Liebsch, H., (2000), "The Development of the Tunnelling Method", Decades of Underground Railway Construction in Vienna, pp 34-41.

67. Liebsch, H. and Haberland, C., (1998), "Soft ground tunnelling in urban areas by NATM", Journal of Felsbau, Vol. 16, No. 2, pp 78-90.

68. Lislerud, A. et al., (1983), "Hard Rock Tunnel Boring" Project Report 1-83. Trondheim: Norwegian Institute of Technology.

69. Madkour, A., Hudson, M. A., and Bellarosa, A., (1999), "Construction of Cairo metro line 2", Proc. Instn. Civ. Engrs, Civ. Engng, Vol. 132, pp 103-117, internet site: http://fbe.uwe.ac.uk/public/geocal/caa/tunnels/ce1999_Cairo_metro.pdf.

70. Mahtab, M. A., and Grasso, P., (1992), "Geomechanics Principles in the Design of Tunnels and Caverns in Rocks", Elsevier Press, 250 pages.

71. Maidl, B., (1988), "Handbuch des Tunnel – Und Stollenbaus" Band I: Konstruktion und Verfahren: 1994, zweite Auflage pp 163-178, Band II: Grundlagen und Zusatsleistungen für Planung und Ausführung, Verlag Glückauf GmbH, Essen, pp 210-211.

72. Marie, J., "Tunnelling: Mechanics and hazards", http://www.umich-edu/~gs265/tunnel.htm.

73. Mawdesley, M. J. and Qambar, S., (2000), "Systems thinking and construction productivity", Conference Proceedings: International conference on systems thinking in management, Geelong, Australia, November 8-10, 2000.

74. McCusker, T. G., (1991), "Other tunnel construction methods", Underground Structures: Design and Construction, Editor R. S. Sinha, Elsevier, pp 403-459.

75. McFeat-Smith, I. and Tarkoy, P. J. (1979), "Assessment of Tunnel Boring Performance" Tunnels and Tunneling, 33-37.

76. McFeat-Smith, and Fowell, (1977), "Correlation of Rock Properties and the Cutting Performance of Tunneling Machines" Proceeding of a Conference on Rock Engineering, Newcastle upon Tyne, 581-602.

77. Melbye, T. and Garshol, K. F., (2000), "Sprayed Concrete for Rock Support", MBT International Underground Construction Group, Division of MBT (Switzerland) Ltd.

78. Morawetz, R., (2000), "The Development of the Open Excavation Method", Decades of Underground Railway Construction in Vienna, pp 28-33.

79. Naval facilities engineering command (1986), "Soil mechanics-design manual", http://www.vulcanhammer.org.

80. Neely, A., Gregory, M. and Platts, K. (1995), "Performance measurement system design: a literature review and research agenda", International Journal of Operations & Production Management, Vol. 15 No. 4, pp. 80-116.

81. Nelson, P. P., Yousof, A. A. and Laughton, P. E., (1994), "Tunnel Boring Machine project data. Bases and construction simulation", Geotechnical Engineering Report GR94-4, Geotechnical Engineering Center, Department Civil Engineering, The University of Texas ar Austin.

82. Nelson, P. P., Sinha, R. S., and Handewith, H. J., (1991), "Machine Excavation", Underground Structures: Design and Construction, Editor R. S. Sinha, Elsevier, pp 226-307.

83. Nicholas, H. L., and Day, D. A., (1999), "Moving the Earth: The workbook of excavation", McGraw-Hill, fourth edition.

84. Nido, A., (1999), "Productivity projection model for micro-tunnelling operations based on a quantitative analysis of expert evaluation", *Independent Research Study*, Purdue Univ., West Lafayette, Ind.

85. Nussbaum, H., (1973), "Recent development of New Austrian Tunnelling Method", Journal of the construction division, ASCE, Vol. 99, No. CO1, pp. 115-132.

86. Oggeri, C. and Ova, G., (2004), "Quality in tunneling: ITA-AITES working group 16 – Final report", Tunnelling and Underground Space Technology, Elsevier, Vol. 19, pp 239-272.

87. Ozdemir, L. R. Miller and Wang, F. D. (1978), "Mechanical Tunnel Boring Prediction and Machine Design" Final project report to NSF APR73-07776-A03. Golden, CO: Colorado School of Mines.

88. "On-line classification of rock masses: background and basic reference", internet site http://137.204.208.136/rmr_ol/theory.htm

89. Parker, H. W., (1996), "Geotechnical Investigations, in Tunnel Engineering Handbook", Bickel, et al (eds).

90. Poisel, R., (1995), "Concepts of NATM", International Association of Civil Engineering Students – Bureau of Vienna, summer course "NATM".

91. Rabcewicz, L., (1964), "The new Austrian tunnelling method", part I. Water Power (November).

92. Raiffa, H., (1968), "Decision analysis", Addison-Wesley, pp. 309.

93. Robbins, R. J., (1984), "TBM's Have Achieved Impressive Speeds more than 400 ft in a Day", Tunnels and Tunneling, June 1984, 16.

94. Roxborough, F. F. and Phillips, H. R., (1975), "Rock excavation by disc cutter", *Int. J. rock Mech. Min. Sci. and Geomech.* Abstr. 12 (12), 361-366.

95. Sauer group, (1998), "Excavation and support systems", Internet site: http://dr-sauer.com/technical_info/tunnel_design_specialties/excavation_and_support.art.

96. Sauer, G., "Design Elements of NATM Road Tunnels" Internet site: http://www.dr-sauer.com/natm/d_natm.htm.

97. Sauer, G., "Light at the End of the Tunnel" Internet site: http://dr-sauer.com/technical_info/natm.lst/light_at_the_end_of_the.art.

98. Sauer, G., "Basic Theory of Soft Ground Tunnelling" Internet site: http://www.dr-sauer.com/natm/b_theory.htm.

99. Sauer, G.,"NATM In Soft Ground " Internet site: http://www.dr-sauer.com/natm/natmsg.htm.

100. Sauer, G., "Urban Tunnelling Consequences" Internet site: http://www.dr-sauer.com/natm/wt.htm.

101. Sinfield, J. V., and Einstein, H. H., (1996) "Evaluation of Tunneling Technology Using the "Decision Aids for Tunneling"", Tunneling and Underground Space Technology, Vol. 11, No. 4, pp 491-504.

102. Sink, D.S. and Tuttle, T.C. (1989), Planning and Measurement in your Organisation of the Future, ch. 5, Industrial Engineering and Management Press, Norcross, GA, pp. 170-84.

103. "Sprayed Concrete Linings (NATM) for Tunnels in Soft Ground", (1996), ICE design and practice guide, Thomas Telford publishing.

104. Sterling, R. L. and Godard, J. P., "Geoengineering Considerations in the Optimum Use of Underground Space", ITA-AITES, Internet site http://www.ita-aites.org/reports/geo202.pdf.

105. Sturk, R., (1998), "Engineering Geological Information-its Value and Impact on Tunnelling", Doctoral Thesis 1027, Inst. Of Civil &

Environmental Engineering, Dep. Of Soil and Rock Mechanics, Royal Institute of Technology, Sweden.

106. Sturk, R., Olsson, L., and Johansson, J., (1996), "Risk and decision analysis for large underground projects, as applied to the Stockholm ring road tunnels", Elsevier Science Ltd., Journal of Tunnelling and Underground Space Technology, Vol. 11, No. 2, pp 157-164.

107. Suhm, W. and Killmann, B., (2001), "Grounds for micro-tunnelling choice", *Tunnel & Tunnelling International*, June 2001, pp.33-34.

108. Sumanth, D. (1994), Productivity Engineering and Management, McGraw-Hill, New York, NY.

109. Sundin, N., Wänstedt, S., (1994), "A Boreability Model for TBM's" Proceedings, First North American Rock Mechanics Symposium, Austin, TX (Nelson, P. P and S.E. Laubach, eds.) 311-318. Rotterdam: Balkema.

110. Tangen, S., (2005), "Demystifying productivity and performance", Emerald group publishing limited, International Journal of Productivity and Performance Management, Vol. 54, No.1, 2005, pp 34-46.

111. Tangen, S., (2002), "Understanding the concept of productivity", Proceedings of the 7th Asia Industrial Engineering and Management Systems Conference (APIEMS2002), Taipei.

112. Tarkoy, P. J. (1973), "Predicting TBM Penetration Rates in Selected Rock Types" Proceedings, Ninth Canadian Rock Mechanics Symposium, Montreal.

113. Terzaghi, K., (1946), "Rock defects and loads on tunnel supports", Rock tunnelling with steel support, Editors R. V. Proctor and T. White, published by Commercial shearing and stamping co., Youngstown, pp 15-99. Also Harvard University, Graduate School of Engineering, Publication 418 – Soil Mechanics Series 25.

114. Touran, A., (1997), "Probabilistic Model For Tunneling Project Using Markov Chain" Journal of Construction Engineering and Management, ASCE, Vol. 123, No. 4, December, 1997, pp 444-449.

115. Urschiz, G., (1994), "Tunnelling: Practice and Innovation", Dissertation, Department of Civil Engineering, University of Nottingham, May 1994.

116. US Army Corps of Engineers, (1997), Manual No. 1110-2-2901- Engineering and Design – TUNNELS AND SHAFTS IN ROCK, http://www.usace.army.mil/inet/usace-docs/eng-manuals/em-1110-2-2901/toc.htm.

117. Varley, P. M. (1990), "Susceptibility of Coal Measures Mudstone to Slurrying during Tunnelling", Quarterly Journal of Engineering Geology, 23, 147-60.

118. Verhoef, P. N. W., (1997), "Wear of Rock Cutting Tools: Implications for the Site Investigation of Rock Dredging Projects" Rotterdam: Balkema.

119. Wagner, H., (2001), "Flexible Response to Difficult Ground and Controlled Tunnelling Technology", Modern Tunnelling Science and Technology, Editors T. Adachi, K. Tateyama, and M. Kimura, A.A.Balkema publishers, Volume 1, pp 21-28.

120. Walhstrom, E. E., (1973), "Tunnelling in Rock" Elsevier, 250 pages. Tested for three cases in Sweden, in mainly metamorphic and igneous rocks.

121. Wassmer, L., Treceno, O., Andreossi, E. and Re, S., (2001), "Tunnel boring machine (TBM) applications in soft ground conditions", IMIA meeting, Sydney, Internet site: http://www.imia.com/documents/wgp18.pdf.

122. Wickham, G. E., Tiedemann, H. R., and Skinner, E. H., (1974), "Ground Support Prediction Model: RSR concept" Proceedings, Rapid

Excavation and Tunneling, 2nd Conference, San Francisco, June 1974, Vol. 1, 691-707. New York: ASCE.

123. Wichham, G. E., Tiedemann, H. R., and Skinner, E. H., (1972), "Support determination based on geological predictions", Proc. First North American Rapid Excavation and Tunnelling Conference, AIME, New York, pp 43-64.

124. http://wienerwald-online.at/index.htm?geologtx.htm

125. http://www.agn-amsteg.ch/projekt.asp

PART I

Comparison of methods based on technical factors

Table A.1.1 Controlling factors for the basic tunnelling & excavation methods (The basic tunnelling methods & excavation matrix)

Factors \ Methods			The basic tunnelling methods						Excavation Methods						
				NATM											
			Cut & Cover	Full face	Heading & bench	Multiple drift	Pilot enlargement	Mechanical method	Excavator / Backhoe / Front shovel	Hand excavation	Drill & Blast	Roadheader	Micro-tunnelling	Shield Machine (Slurry / EPB)	TBM Machine (Open machine)
Ground Conditions	Compressive Strength	Less than 0.4 MPa	4	1.7,1.5,1	3	3.5	3.5	4	4	3.8	1	1.8	4	4	1
		0.4 - 1.25 MPa	4	2,1.4,1.1	2.6	3	2.5	4	4	4	1	1.8	3.5	4	1
		1.25 – 5.00 MPa	4	2,2,1.4	3.5	3.5	3	3.8	3.5	3.2	1	3	3.5	3.8	1
		5.00 – 12.5 MPa	3.6	2.2	4	2.8	2.8	3.5	2.2	2	1.8	3.4	3.5	3	2.6
		12.50 – 50 MPa	3.6	3	3.8	2.4	2.8	3.6	1.6	1.4	2.6	3	3.25	2.6	3.6
		50 – 100 MPa	3.4	3.4	3.4	2.2	2.6	3.8	1	1	3.6	2.4	2	2	3.8
		100 – 200 MPa	3	3.8	3	2	1.75	3.4	1	1	3.8	1.8	1.67	2	3.4
		Over 200 MPa	2.8	3.8	2.4	2	1	3	1	1	4	1	1	1.5	3
	GWT ≤ 0.5D & GWT≤ 7m		4	4	3.8	3	3	4	4	4	4	4	4	4	4
	GWT = D & GWT≤ 14m		3.8	4	4	3.5	3.5	4	4	4	4	4	4	4	4
	14m < GWT ≤ 30m		1.5	2	3	2.5	2	4	3.5	3	3.5	3.8	4	4	2.5
	GWT > 30m		1.2	1.5	2.5	2.5	2	4	2.5	1.5	2	2	4	4	1.5
	Existence of gases		3.75	2.25	2.25	2.75	2.75	3.67	3.25	1.3	2.25	3	3.67	2.25	2.75
Tunnel depth	Tunnel invert ≤ 30 m		3.83	2.5	3.33	3.5	2.5	3.75	3.6	2.4	2.8	3.4	3.75	3	2.4
	Tunnel invert > 30 m		1	3.5	3.83	3.17	2.67	3.8	3.2	2	3.6	3	3	3.6	3.8
Tunnel Cross Section	Variable cross section		3.5	3.4	3.67	3.6	2.67	1	4	3.17	3.8	3	1	1	1
	Circular or mouth cross section		4	4	4	4	4	4	4	4	4	4	4	4	4
	Oval or Horseshoe section		4	4	4	3.5	2.83	1.4	4	3.75	3.8	3.33	1	1.4	1.35
	Other cross sections		4	4	3.83	3.5	2.83	1	4	3.17	3.8	3.33	1	1	1
	Area	Less than 2 m^2	1	3.8	1	1	1	4	1.4	3.5	3	1	4	1	1
		2 – 10 m^2	1.6	3.17	2.33	1.5	1	2	2.33	3.17	3.33	2.33	1	2	1.67
		10 – 30 m^2	3	3	3.5	2.33	1.83	3	3.33	1.83	3.83	3.33	1	2.8	3
		30 – 100 m^2	3.83	2.5	3.83	3.67	3	4	3.33	1.33	3.8	2.5	1	4	4
		Over 100 m^2	3.67	2.33	3.67	3.67	2.83	2.67	3	2	4	2	1	2.67	2.17

Table A.1.1 (continued)

Factors	Methods	The basic tunnelling methods						Excavation Methods						
		Cut & Cover	NATM: Full face	NATM: Heading & bench	NATM: Multiple drift	NATM: Pilot enlargement	Mechanical method	Excavator / Backhoe / Front shovel	Hand excavation	Drill & Blast	Roadheader	Micro-tunnelling	Shield Machine (Slurry / EPB)	TBM Machine (Open machine)
Tunnel Alignment	Horizontal curve radius < 40m	3.5	2.67	3.33	2.33	2.2	1.83	3.33	3.83	3	2.67	1.83	1	1
	40m < Horizontal curve radius < 150m	3.67	3.17	3.67	3.17	2.8	2.33	3.67	3.33	3.67	3.5	3	2.33	2.17
	Horizontal curve radius > 150m	4	3.83	4	4	3.6	4	4	3	4	3.83	4	3.83	4
	Vertical slope < 3%	4	4	4	3.83	4	4	4	4	4	4	4	4	4
	Vertical slope > 3%	3.83	3.83	3.83	3.5	3.5	3.33	3.67	3.83	3.83	3.33	3.17	3.33	3.33
Health & Safety	Good health environment	3	2.83	2.67	2.67	2.67	3.67	3	1.83	2.5	2.17	3.67	3.33	3.17
	Few accidents	3.17	2.33	2.67	2.83	2.83	3.67	3.17	2.17	2.83	2.67	3.67	3.33	3.17
Environmental Conditions & Tunnel Position	Low noise for public	1.5	3.33	3.5	3.33	3.17	3.5	3.17	3.5	2.5	3	3.5	3.33	3.33
	Low vibration & effect on buildings	2.67	2.5	3.4	3.6	3.6	3.4	3.6	4	2.6	2.6	3.2	3.4	3
	Good for archaeological areas	2.83	3	3.17	2.67	2.83	1.83	3.33	3.5	1.2	2.5	1.33	1.83	1.33
	Low effect on traffic	2	3.67	3.33	3.33	3.17	3.8	3.4	4	3.4	3.4	3.8	3.6	3.2
	Low dust particles in air	1.67	3	3	2.83	3	4	3.17	3.5	2.5	2.67	3.67	4	3
	Low landscape effect	1.4	3.33	3.33	3	2.83	4	4	4	4	4	4	4	4
	Limited site area for start up	2	2.33	2.83	2.67	2.5	3.33	3	4	2.83	3	3.33	1.67	1.67
	Tunnel near sewer, gas, water pipes	2.33	2.33	2.83	2.83	3	2.67	3.17	4	2	2.83	2.67	2.33	2.5
Excavation Method	Excavator / Backhoe / Front shovel	4	4	3.67	3.67	3	1							
	Hand excavation	2.22	2.33	2.33	2.17	2.17	1							
	Drill & Blast	1	3.83	3.2	2.5	3.17	1							
	Roadheader	1	3.33	2.67	2.83	2.83	1							

Table A.1.2 Controlling factors for mucking material methods (Mucking methods matrix)

Factors	Mucking Methods	Rubber wheel loader	Tracked loader
Ground Bearing Capacity	Less than 0.05 MPa	1	2.33
	0.05 – 0.10 MPa	2.33	2.67
	0.10 – 0.20 MPa	3.67	3
	Over 0.20 MPa	4	3
Muck Particle Size	Very big particles (particle size > 45cm)	2.25	1.75
	Big particles (7cm < particle size < 45cm)	3	2.5
	Medium particles (2cm < particle size < 7cm)	4	2.5
	Small particles (particle size < 2cm)	4	2.75
Tunnel Span	Less than 2m	1.25	2.75
	2m – 4m	2.5	3
	4m – 8m	3.75	3
	Over 8m	3.75	2.5
Excavation Methods	Excavator / Front shovel / Backhoe	4	3
	Hand excavation	2.25	1.75
	Drill & Blasting	4	3

Table A.1.3 Controlling factors for material transportation methods (Transportation methods matrix)

Factors \ Transportation Methods					Rubber wheel truck	Rail - Locomotive type			Conveyors
						Diesel – mechanical locomotive	Diesel - electric locomotive	High voltage locomotive	
Ground Bearing Capacity	Less than 0.05 MPa				1.5	1	1	1	3.2
	0.05 – 0.10 MPa				2.5	2.75	3	3	4
	0.10 – 0.20 MPa				3.5	3.5	3.33	3.33	3.6
	Over 0.20 MPa				4	4	4	4	3.4
Transportation Length and Required Transportation Speed	Required Transportation speed	High speed	Transportation distance	Less than 0.5 km	2.6	2.4	2.5	2.25	3
				0.5 km – 1 km	2.6	2.6	2.5	2.75	3
				1km – 3km	2.6	2.6	2.25	2.5	4
				Over 3km	2.4	2.6	2.5	2.75	3.5
		Medium speed		Less than 0.5 km	3	3	3	2.75	2.25
				0.5 km – 1 km	3.2	3.4	3.25	3	2.75
				1km – 3km	3	3.2	3.25	3.25	3.25
				Over 3km	2.4	2.8	2.67	2.33	3
		Low speed		Less than 0.5 km	3.2	3.4	3.5	2.5	2.25
				0.5 km – 1 km	3.4	3.6	3.5	3	2.5
				1km – 3km	2.8	3.6	3.25	2.75	2.75
				Over 3km	2.2	3.2	2.75	2.75	3
Tunnel Vertical Slope	Less than 3%				4	4	4	4	4
	3% - 10%				2.8	2	2.25	2.25	4
	10% - 20%				2	1	1	1	3.75
	20% - 25%				1	1	1	1	3.5
	Over 25%				1	1	1	1	2.75
Tunnel Span	Less than 2m				1.4	2.2	2.25	2	3
	2m – 4m				2.4	3.4	3	2.75	3.6
	4m – 8m				3.8	3.2	3	3	4
	Over 8m				3.8	4	4	4	4

Table A.1.3 (continued)

Factors		Transportation Methods	Rubber wheel truck	Rail - Locomotive type			Conveyors
				Diesel – mechanical locomotive	Diesel - electric locomotive	High voltage locomotive	
Muck Particle Size & Water Content	Particle size	Less than 45cm	4	4	4	4	3.25
		More than 45cm	3.4	3.25	3.33	3.33	1
	Water content	Almost dry muck	4	3.75	3.67	3.67	4
		High water content	3.2	2.75	2.33	2	1.75
Health & Safety		Good health environment	2.71	2.43	3.5	3	3.13
Excavation Methods		Excavator / Front shovel / Backhoe	3.83	2.5	2.6	2.6	1.67
		Hand excavation	2.33	2.17	2.8	2	2.17
		Drill & Blasting	3.67	2.67	2.8	2.2	2.5
		Roadheader	3.67	2.67	2.8	2.8	3.17
		Micro-tunnelling	1	2	2.6	1	2.33
		Shield machine	2.6	3.67	3.8	3.4	3.33
		TBM machine	2	3.83	3.8	3.4	4

Table A.1.4 Controlling factors for support methods (Support methods matrix)

Factors \ Support Methods			Side wall & Crown support					Face support					Cut & cover		
			Rock bolts	Dowels	Steel arch	Shotcrete	Precast concrete	Forepoling	Pipe umbrella	Doorframe slab	Earth wedge	Shotcrete	Diaphragm wall	Sheet pile	Bored pile
Ground conditions	Ground is soil		1.5	1.2	2.5	3.6	4	2	3.5	2	3	4	4	3.6	3.8
	Rock Quality (RMR values)	0 - 20	2	2.2	3.4	3.6	3.2	3.8	3.6	2.67	3.6	3.6	4	3.6	3.8
		21 - 40	2.25	2.5	3.75	3.75	3.25	3	2.5	3.5	2.5	3	3	2.25	3.5
		41 - 60	3.25	3.25	2.75	3.75	2.75	2	1	1.5	1.75	2.25	2	1.5	2.75
		61 – 80	3	3.25	2	3.5	1.5	No need for support					1	1	2.5
		Over 80	No need for support										No need for support		
	Prevent Failure	Failure due to weathering	3	2.75	2.25	3.25	3.25	2.25	2	2.67	2.75	3.25	3	2.67	3
		Failure due to moving water	2	1.75	1.75	2.5	3.25	2.25	2.75	2.67	2.5	3.25	2.67	2.33	2.67
		Failure due to corrosion of support	2	2.5	2.25	3	3.25	2	2.33	2.67	2	2.67	4	3.67	4
		Failure due to squeezing & swelling	2	2.5	2.75	2.75	3	2.33	2.67	2.33	2.67	3.33	4	3.67	4
		Failure due to overstress	2.33	2.75	2.75	3	3	2.67	3.33	2.67	2.67	3.33	4	3.67	4
Tunnel Depth	Less than 30m		2.67	3.25	3.5	4	4	4	4	4	3.67	3.5	4	3.17	3.67
	30 – 50m		3.67	3.33	3.67	4	4	4	3	2.33	2.5	3.33	The model assumes that cut and cover method cannot be used with tunnel depth more than 30m		
	50 – 100m		3.67	3.33	4	4	3.33	3	2.5	2	2.5	3.33			
	100 – 500m		3.67	3.33	4	4	3	2	1	1	1.5	3.33			
	500 – 1000m		3.67	3	4	4	2.33	1	1	1	1.5	3			
	Over 1000m		3.67	3	3	3.67	1.67	1	1	1	1.5	2			

Table A.1.4 (continued)

Factors / Support Methods			Side wall & Crown support					Face support					Cut & cover		
			Rock bolts	Dowels	Steel arch	Shotcrete	Precast concrete	Forepoling	Pipe umbrella	Doorframe slab	Earth wedge	Shotcrete	Diaphragm wall	Sheet pile	Bored pile
Basic tunnelling & Excavation methods	Basic methods	Cut & Cover	1	1	1	1	1	1	1	1	1	1	4	3.4	4
		NATM - Full face	2.75	3	2.8	3.8	2.8	3.4	3	3	2.4	2.8	These support methods are used only with cut and cover method		
		NATM - Heading & Bench	2.75	3.4	3.6	4	1	3.8	4	2.67	3.2	3.6			
		NATM - Multiple drift	2.75	2.8	3.2	3.8	1	3	3.2	1.5	3	3.4			
		NATM - Pilot enlargement method	2	2.4	2.6	3.2	2.2	2.2	2.2	2.33	1.8	2.8			
	Excavation methods	Excavator / Front shovel / Backhoe	2.8	3.2	3.8	3.8	2.25	3.8	3.4	3	3	3.6	4	3.5	3.5
		Hand excavation	2.2	3	3.2	3.2	2	2	1.6	2	2.8	2.8	3	3	3
		Drill & Blasting	3.8	3.8	3.2	3.6	1	2.6	2.4	1	1	2.8	These excavation methods are not used with cut and cover method		
		Roadheader	3.2	3	2.4	3.6	2.25	1.8	2.4	2	1.8	2.8			
		Micro-tunnelling	1	1	1	1	3.6	These excavation methods do not need face support method							
		Shield machine	1.4	1	1.4	1	4								
		TBM machine	2.2	2.4	1.8	2.2	4								
Constructibility	Circular or mouth cross section		3.4	3.2	3	3.2	4	3	2.67	2	3	3.5	4	4	4
	Oval or Horseshoe cross section		4	3.8	3.6	4	1	3.75	3.33	2	3.25	3.5	4	4	4
	Other cross sections		4	3.8	3.6	4	1	3.75	3.33	2	3.25	3.5	4	4	4
	Tunnel span	Less than 1.5m	1.6	2	2.6	2.6	3	2.25	1.75	1	1.75	2.5	1	3	1
		1.5 – 4m	2.2	2.2	3	3.6	3.2	3.25	2.25	1	3	3.25	2	3	2
		4 – 6m	3.25	2.75	3.5	4	3.4	3.75	3.25	2	3	3.5	3	3	3
		6 – 10m	3.5	3.25	3.5	4	3	3.75	3.75	3.5	3.25	3.75	4	3	4
		Over 10m	3.5	3.75	3.25	3.75	2.4	3.5	3.75	3	2.75	3.5	4	2	3

Table A.1.5 Controlling factors for lining methods (Lining methods matrix)

Factors \ Lining Methods				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		1.1	1.1	1.1	1.1	1.75	4
		40 – 100		1.5	1.1	1.1	1.1	2	3.75
		10 – 40		1.75	1.75	2	1.75	3	2.875
		4 – 10		2.25	2.25	2.75	2.25	3.75	2.25
		1 – 4		2.75	3	3.25	3	4	1
		0.1 – 1		2.75	3.33	3	3	3.75	1
		0.01 – 0.1		4	4	3	3.5	3.25	1
		0.001 – 0.01		4	4	4	4	2.75	1
	Ground is soil			4	4	4	4	2.75	1
	Minimum reaction with ground mineral	Feldspars	Orthoclase	3	3	3	3	2	2
			Plagioclase	3	3	3	3	2	2
		Quartz	Silica	3	3	3	2.5	3	1.5
		Clay minerals	-----	3	3	3.5	3.5	2.5	1.5
		Micas	Muscovite	3	3	3	2.5	2	1.5
			Biotite	3	3	3	2.5	2	1.5
		Chlorite	-----	3	3.5	2.5	3	2.5	2.5
		Calcite	$CaCo_3$	3.5	3.5	3.5	3	3.5	1.5
		Iron Ores	Carbonates	2	3	2	3	2	1
			Pyrite	3	3	3	3	2	1
		Ferromagnesium minerals	Augite	4	3	3	3	3	2
			Olivine	4	2	3	3	3	2
Tunnel profile	Circular or Mouth profile			4	3.67	3.17	4 (1.85)	3.33	3.33
	Horseshoe profile			1	2.4	4	1	3.8	3.4
	Oval profile			1	2.4	3	1	4	3.25
	Nordic profile			1	2	3.33	1	4	3.5
	Basket Handel			1	2	3.25	1	3.75	2.25
	Rectangular profile			1	1	3.25	1	3	2.25
Tunnel Function	water conveyance			3.8	1.8	3.8	4	2.6	2
	road			4	2.4	4	1	2.4	2
	railway			4	3	4	2	3	2.5
	storage			3	2.8	3.2	2	3.2	3.2
	defense			3.17	3.5	3.83	2.33	3.5	2.83

Table A.1.5 (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	3.5	4	3.75	4	4	4
		10-25 L/min	3.75	3.5	3.67	3.5	4	2.5
		25-125 L/min	4	3.25	3.25	4	2.75	2
		> 125 L/min	3.75	3.25	2.75	4	2.25	1
Basic tunnelling & Excavation methods	Basic methods	Cut & Cover	1	1	4	2	1	1
		NATM - Full face	2.8	3	3	1.5	3.8	4
		NATM - Heading & Bench	1	2.75	3	1.75	4	2.5
		NATM - Multiple drift	1	2.75	3.5	3	3.8	2.25
		NATM - Pilot enlargement method	2.2	2.75	2.75	3	3.2	2
	Excavation methods	Excavator / Front shovel / Backhoe	2.25	2.25	3.75	2.5	3.8	2.25
		Hand excavation	2	2.5	3	2	3.2	2.25
		Drill & Blasting	1	2.5	3.5	1	3.6	4
		Roadheader	2.25	2.5	3.5	1.5	3.6	2.5
		Micro-tunnelling	3.6	2.5	1	3.25	1	2.5
		Shield machine	4	2.25	2	1.75	1	1
		TBM machine	4	4	1	1	2.2	2.75
Supporting methods	Rock bolts		1	2.25	3	3	4	3.67
	Dowels		1	2.25	3	4	4	3.67
	Steel arch		1	1	3	1.67	4	3.33
	Shotcrete		1.67	2.33	3	3.5	4	3.5
	Precast concrete segments		4	1	1	1	1	4

Table A.1.6 Controlling factors for groundwater control methods (Groundwater control methods matrix)

Factors	Groundwater control methods		Dewatering	Slurry wall	Compressed air	Freezing	Chemical & cement grouting	Jet grouting
Ground Conditions	GM (gravel – sand – silt mixtures)		3	4	1.5	2.5	3	1.2
	GC (gravel – sand – clay mixtures)		3	4	1.5	2.5	3	1.2
	SM (silty sands)		4	4	1.5	3	3	1.8
	SC (clayey sands)		2.75	3	4	3	1.5	2.5
	ML (inorganic silts)		3	3	2	3.3	1.2	2.5
	CL (inorganic clays)		2	3	3	3.5	1.1	2
	OL (organic silts)		1.1	2.75	2.8	4	1.1	1.6
	OH (organic clays)		1.1	2.5	2.3	4	1.1	1.3
	GWT ≤ 0.5D & GWT ≤ 7m		4	3.8	3.5	2.8	3	3
	GWT = D & GWT ≤ 14m		4	3.5	3	2.2	2.75	2.75
	14m < GWT ≤ 30m		3.5	3	1.5	2	2.5	2.5
	GWT > 30m		3	2.75	1	2	2	2
Groundwater inflow / 10m tunnel length		< 10 L/min	4	1.67	2	4	2.67	3.33
		10-25 L/min	4	2.67	2.67	2.33	2	3.33
		25-125 L/min	4	3.67	2.67	1	2.33	2.33
		> 125 L/min	4	3.67	2	1	2.33	2
Tunnel Depth	Less than 15m		3.6	3.4	3.4	3.6	3.6	3.8
	15m – 30m		3.4	3.6	3.4	3.8	3.4	3.4
	30m – 50m		3	3	2.6	3.4	2.6	3
	Over than 50m		2.4	2.2	1.8	3	2.4	3
Tunnel Position	Under urban areas		2.8	3.8	3	3.2	3.2	3.6
	Under water bodies		2.6	3	2.4	3.8	3.8	3.8

Table A.1.6 (continued)

Factors		Groundwater control methods	Dewatering	Slurry wall	Compressed air	Freezing	Chemical & cement grouting	Jet grouting
Working Length of the Tunnel (m/day)		Less than 4m	4	3.5	3.75	4	4	4
		4m – 8m	3.5	4	3.25	3.25	3.25	2.75
		8m – 15m	2.75	3.5	2.75	2.75	3	2.25
		15m – 25m	2	2.75	2.5	2.5	2.75	1.75
		Over 25m	2	2.5	2.5	2.5	2.25	1.25
Basic tunnelling & Excavation methods	Basic methods	Cut & Cover	4	4	1	1	2.75	2
		NATM - Full face	4	4	2.5	3	3.25	2.5
		NATM - Heading & Bench	4	4	2.5	3.33	3.5	3.5
		NATM - Multiple drift	3	4	2.5	3	3.75	3.5
		NATM - Pilot enlargement method	4	3	2.5	2.75	3	3.25
	Excavation methods	Excavator / Front shovel / Backhoe	3.75	4	3.25	2.5	3.75	3.75
		Hand excavation	4	4	2.25	2	1.75	2.25
		Drill & Blasting	4	2.75	1	1	1.75	1.75
		Roadheader	4	4	2.25	2.75	2.75	2.75
		Micro-tunnelling	3.5	2.75	2.25	1.75	2.5	1
		Shield machine	3.67	3	3.33	2.5	3.67	2.25
		TBM machine	3	2.75	1	2.25	3	2
Health & Safety		Good heath environment	3	3	2	2.2	2.4	3
		Few accidents	3.2	2.8	2.2	2.6	2.6	2.8
Environmental Conditions		Minimum bad effect on buildings	1.67	3.67	2.67	3.33	3	3
		Less contamination of groundwater	3	3	3.67	3.67	2.33	2.67
		Minimum effect on groundwater regime	1.33	1.67	3.67	3.33	2	2.33

PART II

Comparison of methods based on non-technical factors (Cost & Time)

Table A.2.1 Comparing between basic tunnelling methods and excavation methods based on cost

Factors \ Methods			Basic tunnelling methods						Excavation Methods						
				NATM											
			Cut & Cover	Full face	Heading & bench	Multiple drift	Pilot enlargement	Mechanical method	Excavator / Backhoe / Front shovel	Hand excavation	Drill & Blast	Roadheader	Micro-tunnelling	Shield Machine (Slurry / EPB)	TBM Machine (Open machine)
Running Cost / 1m of tunnel length	Ground Strength	Less than 0.4 MPa	4	1.5	2.5	2.5	2.5	4	3.8	3.4	1	1.5	4	4	1
		0.4 - 1.25 MPa	3.4	1.6	2.6	2.4	2.4	4	3.6	3.2	1.4	2	4	3.2	1.8
		1.25 – 5.00 MPa	3.2	2.6	3.2	2.8	2.4	3.4	3	1.8	1.8	2.8	3.4	3.4	2.4
		5.00 – 12.5 MPa	3.2	3.4	3.4	2.4	2.6	3.2	2.4	1.4	3	3.6	3.2	2.8	3
		12.50 – 50 MPa	3.2	3.6	3.2	2	2.8	3.6	1.8	1	3.2	3.2	3.2	2.4	3.6
		50 – 100 MPa	2.4	3.8	3.2	2	2.8	3.6	1.4	1	3.6	2.4	2.8	2	3.6
		100 – 200 MPa	2.2	4	3.2	1.8	2.4	3.4	1.6	1	3.6	1.6	2.4	1.6	3.4
		Over 200 MPa	2.2	4	3.2	1.8	2.2	2.8	1.6	1	4	1	2.2	1.6	2.8
	Tunnel length less than 3km		3.6	3.2	3.67	2.8	2.6	4	3.8	1.8 (3)	3.8	3.4	4	2.67	2.6
	Tunnel length more than 3km		3.4	3.6	3.17	2.2	2	4	3.6	1 (3)	3.6	3.2	3	4	4
Initial Cost			3.75	3.25	3.4	2.75	2.25	2.25	3.5	4	3.5	2.25	2.25	1.6	1.6

Table A.2.2 Comparing between mucking methods based on cost

Factors \ Mucking Methods	Rubber wheel loader	Tracked loader
Running Cost	3	2.67
Initial Cost	3.67	2.33

Table A.2.3 Comparing between transportation methods based on cost

Factors \ Transportation Methods			Rubber wheel truck	Rail - Locomotive type			Conveyors
				Diesel – mechanical locomotive	Diesel – electric locomotive	High voltage locomotive	
Running Cost	Transportation distance	Less than 0.5 km	3.8	2	2.5	1.25	2
		0.5 km – 1 km	3.4	2.6	2.75	2	3
		1km – 3km	3.2	2.8	3.25	2.75	3.6
		Over 3km	3	3	3.25	3.5	3.8
Initial Cost			3	3	3.5	2	2.67

Table A.2.4 Comparing between support methods based on cost

Factors \ Supporting Methods	Side wall & Crown support					Face support					For cut & cover		
	Rock bolts	Dowels	Steel arch	Shotcrete	Precast concrete segments	Forepoling	Pipe umbrella	Doorframe slab	Earth wedge	Shotcrete	Diaphragm wall	Sheet pile	Bored pile
Cost / 1m length of tunnel	3.2	3.4	2.6	3.4	2.6	3.2	2.2	2.33	3.8	3.2	1.8	3.2	2.6

Table A.2.5 Comparing between lining methods based on cost

Factors \ Lining Methods	Precast concrete segments (reinforced/not reinforced)	Cast steel segments	Cast-in-place concrete (reinforced/ not reinforced)	Pipe jacking	Shotcrete lining	No Final lining
Cost / 1m length of tunnel	2	2	2.6	2.2	3.25	4

Table A.2.6 Comparing between groundwater control methods based on cost

Factors \ Groundwater control methods			Dewatering	Slurry wall	Compressed air	Freezing	Chemical & cement grouting	Jet grouting
Running Cost / hour	Groundwater inflow / 10m tunnel length	< 10 L/min	3.42	2.4	2	1.33	2.8	2.4
		10-25 L/min	3.6	2.5	2	1.6	2.75	2.5
		25-125 L/min	3	2.75	2.4	1.6	2.75	2.5
		> 125 L/min	2.6	2.75	2.4	1.4	2.5	2.25
Initial Cost			3.08	2.25	2.08	1.5	2.9	2.8

Time

Table A.3.1 Comparing between basic tunnelling methods and excavation methods based on time

Factors \ Methods			Basic tunnelling methods						Excavation Methods						
				NATM											
			Cut & Cover	Full face	Heading & bench	Multiple drift	Pilot enlargement	Mechanical method	Excavator / Backhoe / Front shovel	Hand excavation	Drill & Blast	Roadheader	Micro-tunnelling	Shield Machine (Slurry / EPB)	TBM Machine (Open machine)
Advance rate = 75m / week	Ground Strength	Less than 0.4 MPa	3	2.5	2.5	3	2.7	4	3.5	3	1	3.5	4	4	1
		0.4 - 1.25 MPa	3.4	2.67	2.6	3	2.2	3.8	4	2.8	2.5	3.5	3.8	3.4	3
		1.25 – 5.00 MPa	3.6	2.75	3.2	3	2.6	4	3.6	2	2.75	3.75	4	3.6	3
		5.00 – 12.5 MPa	3.4	3	3.2	2.4	2.6	3.6	2.6	1.6	3.2	3.6	3.6	3.4	3.6
		12.50 – 50 MPa	3.2	3.6	3.2	2.2	2.6	3.8	1.6	1	3.4	3	3	3	3.8
		50 – 100 MPa	2.4	3.4	3	1.8	2	3.4	1.2	1	3.5	2.4	2.75	1.8	3.4
		100 – 200 MPa	2.2	3.2	2.8	1.6	1.6	2.8	1.2	1	3.6	1.6	2	1.4	2.8
		Over 200 MPa	1.8	3	2.8	1.6	1.6	2.6	1	1	3.6	1	1.8	1.4	2.6
Minimum preparation & Mobilization Time			3	3.4	3.33	2.4	2	2	4	4	3.25	2.25	2	1.25	1.25

Table A.3.2 Comparing between mucking methods based on time

Factors \ Mucking Methods	Rubber wheel loader	Tracked loader
Production rate = 20m^3/ hour	3.67	3.67

Table A.3.3 Comparing between transportation methods based on time

Factors \ Transportation Methods	Rubber wheel truck	Rail - Locomotive type			Conveyors
		Diesel – mechanical locomotive	Diesel – electric locomotive	High voltage locomotive	
Transportation time < 5min/km	3	2.8	2.5	2.75	3.6
Minimum preparation & Mobilization Time	3.4	2.6	3.25	2.25	2.6

Table A.3.4 Comparing between support methods based on time

Support Methods / Factors	Side wall & Crown support					Face support					For cut & cover		
	Rock bolts	Dowels	Steel arch	Shotcrete	Precast concrete segments	Forepoling	Pipe umbrella	Doorframe slab	Earth wedge	Shotcrete	Diaphragm wall	Sheet pile	Bored pile
Production rate = 75m/week	3	3.2	2.4	2.6	3.4	2.4	1.4	2.33	3.2	3	2	3	2.4

Table A.3.5 Comparing between lining methods based on time

Lining Methods / Factors	Precast concrete segments (reinforced/not reinforced)	Cast steel segments	Cast-in-place concrete (reinforced/ not reinforced)	Pipe jacking	Shotcrete lining	No Final lining
Production rate = 75m/week	3.67	3	2.17	3	2.33	4

Table A.3.6 Comparing between groundwater control methods based on time

Groundwater control methods / Factors	Dewatering	Slurry wall	Compressed air	Freezing	Chemical & cement grouting	Jet grouting
Minimum preparation & mobilization time	2.86	2.5	2.71	1.57	2.83	2.83

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (west section)

Owner: HL-AG

Basic Tunnelling Methods Report (9/5/2005)

Ranking of the Basic Tunnelling Methods

Basic Tunnelling Methods	Efficiency Percentages
Mechanical Method	84.4%
NATM - Head and Bench	82.6%
NATM - Multiple Drift	77.4%
NATM - Full Face	74%
NATM - Pilot Enlargement	71.5%
Cut and Cover	Excluded

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (west section)

Owner: HL-AG

Excavation Methods Report (9/5/2005)

Ranking of Excavation Methods

Excavation Methods	Efficiency Percentages
Excavator / Backhoe / Front Shovel	90.9%
Shield Machine	84.4%
Roadheader	73.2%
Hand Excavation	Excluded
Drill and Blast	Excluded
Micro-Tunneling	Excluded
TBM Machine	Excluded

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (west section)

Owner: HL-AG

Mucking Methods Report (9/5/2005)

Ranking of Mucking Methods

Mucking Methods	**Efficiency Percentages**
Rubber wheel loader	92.7%
Tracked loader	67.3%

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (west section)

Owner: HL-AG

Transportation Methods Report (9/5/2005)

Ranking of Transportation Methods

Transportation Methods	Efficiency Percentages
Conveyors	85%
Rail / Diesel - Electric locomotive	84.4%
Rubber wheel truck	82.7%
Rail / Diesel - Mechanical locomotive	82.6%
Rail / High voltage locomotive	78.2%

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (west section)

Owner: HL-AG

Side Wall and Crown Support Methods Report (9/5/2005)

Ranking of Support Methods

Support Methods	Efficiency Percentages
Shotcrete	83.4%
Steel Arch	76.7%
Precast Concrete Segments	76%
Dowels	75.5%
Rock Bolts	71.9%
In Case of Cut and Cover	
Diaphragm Wall	Excluded
Sheet Pile	Excluded
Bored Pile	Excluded

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (west section)

Owner: HL-AG

Face Support Methods Report (9/5/2005)

Ranking of Face Support Methods

Face Support Methods	Efficiency Percentages
Shotcrete	83.8%
Earth Wedge	71.3%
Forepoling	70.9%
Pipe Umbrella	Excluded
Doorframe Slab	Excluded

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (west section)

Owner: HL-AG

Lining Methods Report (9/5/2005)

Ranking of Lining Methods

Lining Methods	Efficiency Percentages
Precast concrete segments (reinf./not reinf.)	86.7%
Cast-in-place concrete (reinf./not reinf.)	81.6%
Cast segments (steel/iron)	76.9%
Shotcrete	72.7%
Pipe in tunnel	71.9%
No final lining	Excluded

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (west section)

Owner: HL-AG

Groundwater Control Methods Report (9/5/2005)

Ranking of Groundwater Control Methods

Groundwater Methods	Efficiency Percentages
Dewatering	89.7%
Slurry Wall	78.7%
Compressed air	78%
Chemical/Cement grouting	77.5%
Jet grouting	77.5%
Freezing	72.4%

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Wienerwald (west section)
Owner: HL-AG

Tunnel Construction Systems Report (9/5/2005)

Rank	Basics	Excavation	Mucking	Transportation	Side Wall Support	Face Support	Lining	Groundwater Control
1	C6	E6	M5	T3	S5	F8	L1	G1
2	C3	E1	M1	T1	S4	F5	L5	G1
3	C2	E1	M1	T1	S4	F1	L5	G1
4	C4	E1	M1	T1	S4	F5	L5	G2
5	C3	E4	M3	T1	S4	F5	L5	G1
6	C5	E1	M1	T1	S4	F5	L5	G1
7	C2	E4	M3	T1	S4	F5	L5	G1
8	C4	E4	M3	T1	S4	F5	L5	G2
9	C5	E4	M3	T1	S4	F5	L5	G1

Selecting Efficient Tunnelling System
(SETS - Version 1)

Code Definition

Code	Definition
C1	Cut and Cover
C2	NATM - Full Face
C3	NATM - Head & Bench
C4	NATM - Multiple Drift
C5	NATM - Pilot Enlargement
C6	Mechanical Method
E1	Excavator/Backhoe/Front Shovel
E2	Hand Excavation
E3	Drill and Blast
E4	Roadheader
E5	Micro-Tunneling Machine
E6	Shield Machine
E7	TBM Machine
M1	Rubber Wheel Loader
M2	Tracked Loader
M3	Roadheader
M4	Micro-Tunneling Machine
M5	Shield Machine
M6	TBM Machine
T1	Rubber Wheel Truck
T2	Rail (Diesel-mechanical Locomotive)
T3	Rail (Diesel-electric Accumulator Locomotive)
T4	Rail (Hight Voltage Locomotive)
T5	Conveyors
S1	Rock Bolts
S2	Dowels
S3	Steel Arch
S4	Shotcrete
S5	Precast Concrete Segments
S6	Diaphragm Wall

Selecting Efficient Tunnelling System (SETS - Version 1)

Code Definition

Code	Definition
S7	Sheet Piles
S8	Bored Piles
S9	No Support Neede
F1	Forepoling
F2	Pipe Umbrella
F3	Doorframe Slab
F4	Earth Wedge
F5	Shotcrete
F6	No Support Needed
F7	Micro-Tunneling Machine
F8	Shield Machine
F9	TBM Machine
L1	Precast Concrete Segments
L2	Cast Steel Segments
L3	Cast-In-Place Concrete
L4	Pipe in Tunnel
L5	Shotcrete
L6	No Final Lining
G1	Dewatering
G2	Slurry Wall
G3	Compressed Air
G4	Freezing
G5	Chemical/Cement Grouting
G6	Jet Grouting

**In case of Shield machine and Microtunneling it is optional to use groundwater controling method

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße

Owner: Wiener Linien

Basic Tunnelling Methods Report (9/6/2005)

Ranking of the Basic Tunnelling Methods

Basic Tunnelling Methods	Efficiency Percentages
NATM - Head and Bench	82.6%
Mechanical Method	80.8%
NATM - Multiple Drift	78.8%
NATM - Pilot Enlargement	74.7%
Cut and Cover	Excluded
NATM - Full Face	Excluded

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße

Owner: Wiener Linien

Excavation Methods Report (9/6/2005)

Ranking of Excavation Methods

Excavation Methods	Efficiency Percentages
Excavator / Backhoe / Front Shovel	91.1%
Shield Machine	80.8%
Roadheader	75.9%
Hand Excavation	Excluded
Drill and Blast	Excluded
Micro-Tunneling	Excluded
TBM Machine	Excluded

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße

Owner: Wiener Linien

Mucking Methods Report (9/6/2005)

Ranking of Mucking Methods

Mucking Methods	Efficiency Percentages
Rubber wheel loader	91.2%
Tracked loader	72.8%

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße

Owner: Wiener Linien

Transportation Methods Report (9/6/2005)

Ranking of Transportation Methods

Transportation Methods	Efficiency Percentages
Rubber wheel truck	86.6%
Conveyors	85.1%
Rail / Diesel - Electric locomotive	83.6%
Rail / Diesel - Mechanical locomotive	80.5%
Rail / High voltage locomotive	77.1%

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße

Owner: Wiener Linien

Side Wall and Crown Support Methods Report (9/6/2005)

Ranking of Support Methods

Support Methods	Efficiency Percentages
Shotcrete	89.6%
Steel Arch	74.1%
Rock Bolts	69.7%
Dowels	69.3%
Precast Concrete Segments	Excluded
In Case of Cut and Cover	
Sheet Pile	82.7%
Bored Pile	81.3%
Diaphragm Wall	79.3%

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße

Owner: Wiener Linien

Face Support Methods Report (9/6/2005)

Ranking of Face Support Methods

Face Support Methods	Efficiency Percentages
Shotcrete	87.1%
Earth Wedge	82.3%
Forepoling	77.1%
Pipe Umbrella	74.4%
Doorframe Slab	61.2%

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße

Owner: Wiener Linien

Lining Methods Report (9/6/2005)

Ranking of Lining Methods

Lining Methods	Efficiency Percentages
Cast-in-place concrete (reinf./not reinf.)	83.4%
Cast segments (steel/iron)	81.2%
Shotcrete	81.1%
Precast concrete segments (reinf./not reinf.)	Excluded
Pipe in tunnel	Excluded
No final lining	Excluded

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße

Owner: Wiener Linien

Groundwater Control Methods Report (9/6/2005)

Ranking of Groundwater Control Methods

Groundwater Methods	Efficiency Percentages
Dewatering	79.2%
Jet grouting	73.6%
Chemical/Cement grouting	72.7%
Freezing	72.4%
Slurry Wall	72.2%
Compressed air	68.9%

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: U2/2 Taborstraße
Owner: Wiener Linien

Tunnel Construction Systems Report (9/6/2005)

Rank	Basics	Excavation	Mucking	Transportation	Side Wall Support	Face Support	Lining	Groundwater Control
1	C3	E1	M1	T1	S4	F1	L5	G1
2	C4	E1	M1	T1	S4	F5	L5	G2
3	C3	E4	M3	T1	S4	F5	L5	G1
4	C5	E1	M1	T1	S4	F5	L5	G1
5	C4	E4	M3	T1	S4	F5	L5	G2
6	C5	E4	M3	T1	S4	F5	L5	G1
7	C6	E6	M5	T3	S3	F8	L3	G1

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)

Owner: Alptransit AG

Basic Tunnelling Methods Report (9/6/2005)

Ranking of the Basic Tunnelling Methods

Basic Tunnelling Methods	Efficiency Percentages
NATM - Full Face	87.4%
Mechanical Method	83.6%
NATM - Head and Bench	82%
Cut and Cover	Excluded
NATM - Multiple Drift	Excluded
NATM - Pilot Enlargement	Excluded

Selecting Efficient Tunnelling System (SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)

Owner: Alptransit AG

Excavation Methods Report (9/6/2005)

Ranking of Excavation Methods

Excavation Methods	Efficiency Percentages
Drill and Blast	88.2%
TBM Machine	83.6%
Excavator / Backhoe / Front Shovel	Excluded
Hand Excavation	Excluded
Roadheader	Excluded
Micro-Tunneling	Excluded
Shield Machine	Excluded

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)

Owner: Alptransit AG

Mucking Methods Report (9/6/2005)

Ranking of Mucking Methods

Mucking Methods	Efficiency Percentages
Rubber wheel loader	91.1%
Tracked loader	69.9%

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)

Owner: Alptransit AG

Transportation Methods Report (9/6/2005)

Ranking of Transportation Methods

Transportation Methods	Efficiency Percentages
Conveyors	82.6%
Rail / Diesel - Electric locomotive	81.8%
Rubber wheel truck	79.4%
Rail / Diesel - Mechanical locomotive	75.2%
Rail / High voltage locomotive	74.4%

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)

Owner: Alptransit AG

Side Wall and Crown Support Methods Report (9/6/2005)

Ranking of Support Methods

Support Methods	**Efficiency Percentages**
Shotcrete	81.2%
Dowels	77.8%
Rock Bolts	76.6%
Precast Concrete Segments	68.1%
Steel Arch	66.3%
In Case of Cut and Cover	
Diaphragm Wall	Excluded
Sheet Pile	Excluded
Bored Pile	Excluded

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)

Owner: Alptransit AG

Face Support Methods Report (9/6/2005)

Ranking of Face Support Methods

Face Support Methods	Efficiency Percentages
Forepoling	No Support Needed
Pipe Umbrella	No Support Needed
Doorframe Slab	No Support Needed
Earth Wedge	No Support Needed
Shotcrete	No Support Needed

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)

Owner: Alptransit AG

Lining Methods Report (9/6/2005)

Ranking of Lining Methods

Lining Methods	Efficiency Percentages
Precast concrete segments (reinf./not reinf.)	76.1%
Cast segments (steel/iron)	70.4%
No final lining	69.4%
Cast-in-place concrete (reinf./not reinf.)	67.5%
Pipe in tunnel	67.3%
Shotcrete	65.1%

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)

Owner: Alptransit AG

Groundwater Control Methods Report (9/6/2005)

Ranking of Groundwater Control Methods

Groundwater Methods	Efficiency Percentages
Dewatering	76.8%
Slurry Wall	69.1%
Jet grouting	67.5%
Chemical/Cement grouting	65.6%
Compressed air	60.1%
Freezing	Excluded

Selecting Efficient Tunnelling System
(SETS - Version 1)

Project: Gotthard base tunnel (Amsteg section lot 252)
Owner: Alptransit AG

Tunnel Construction Systems Report (9/6/2005)

Rank	Basics	Excavation	Mucking	Transportation	Side Wall Support	Face Support	Lining	Groundwater Control
1	C6	E7	M6	T5	S5	F6	L1	G1
2	C2	E3	M1	T1	S4	F6	L5	G1
3	C3	E3	M1	T1	S4	F6	L5	G1

Curriculum Vitae

M.Sc. Eng. Hossam Mohamed Toma

Personal Data

Date of Birth	23 / 08 / 1968
Place of Birth	Zagazig, Egypt
Nationality	Egyptian
Gender	Male
Address	Forsthausgasse 2-8 / 2304, A - 1200 Vienna, Austria
Telephone	+4369911095628
E-mail	hossam.toma@gmail.com

Languages

Arabic: Mother language

English (very good) and German

Education

November. 2001 till now

I was awarded a scholarship from the Österreichischer Austauschdienst (ÖAD) – the Austrian Exchange Service – in order to pursue doctoral studies in Vienna. Since November 2001, I have been conducting research under the supervision of Univ. Prof. Dr. Hans Georg Jodl, Fakultät für Bauingenieurwesen, Institut für Baubetrieb und Bauwirtschaft, Technische Universität Wien (Institute for Construction Operations and Construction Management, Vienna University of Technology) and Prof. Dr. Herbert Einstein, Massachusetts Institute of Technology, Boston, Massachusetts, USA.

In my Ph.D. research, I developed a computer model using Visual Basic to determine efficient tunnelling systems based on project conditions. My Ph.D. research is in its completion phase.

June 1997

I received a master's degree in Civil Engineering "Construction Engineering and Management"- Cairo University, Cairo, Egypt. My master's research focuses on the cash flow and the economic evaluation of construction projects. I developed a computer program using FORTRAN to determine the cash flow profile of construction projects. The program takes into consideration the differences between (cost and expenses) and (revenue and income). Price escalation and its effect on the project profitability are also included as a step of the program calculations. The title of my master's thesis is "Development of a Computer Model for Prediction of Construction Contracts Cash Flow".

July 1991

I graduated as a civil engineer. I received a bachelor's degree (with honours) in Civil Engineering from Zagazig University, Zagazig, Egypt. My graduation project was in the field of construction engineering and management. The application of my project was on "Al-Ameria pumping station". This project was a part of the "Greater Cairo Waste Water" project. The "Al-Ameria pumping station" project included constructing one of the largest shafts in the world (45m diameter and 35m depth).

Because I was in the first rank among students who specialized in construction project management, and at the same time I was in the third rank among students who were graduated that year from the civil engineering department, Faculty of Engineering, Zagazig University selected me to work as a demonstrator in the Construction Engineering department which is in the 23rd rank among the top 30 institutes that specialize in construction engineering and management according to *Journal of Construction Engineering and Management, ASCE, Vol. 130, No. 3, May/June 2004, pp 440-448.*

Publications

El-Dosouky, A. I., El-Said, M. I. and Toma, H.M., "A Proposed Model for Prediction of Contract Cash Flow", Alexandria Engineering Journal (AEJ), Vol. 37, No. 3, July 1997.

Professional Affiliations and Honoured Societies

- Member of American Society of Civil Engineers ASCE
- Egypt Engineers Syndicate
- Egyptian Society of Engineers (ESE)
- Egyptian Management Engineering Society (MES)

Experiences

11/2001 – Until now

Preparation for Doctoral degree at Vienna University of Technology.

2/98 – 11/2001

Assistant lecturer in the department of Construction Engineering, Faculty of Engineering, Zagazig University. I was teaching the following topics for undergraduate students:

- Estimating and tendering of construction projects
- Construction contracts and delivery systems
- Construction project planning and scheduling
- Project cost and time control
- Project financial management
- Construction equipment
- Formwork design
- Site layout
- Quality control
- Application of technology in construction

I shared in the supervision of the following graduation projects:

- San-Stifano Hotel in Alexandria, and Central Bank of Egypt
- El-Azhar Road Tunnels
- Mubarak project for Youth Housing, Domitta
- Suez canal suspension bridge

8/91 – 2/98

Demonstrator in Construction Engineering Dept., Faculty of Engineering, Zagazig University, Egypt. I was teaching the same topics mentioned before.

I shared in the supervision of the following graduation projects:

- Evaluation of using a flying shutter in the 6th October bridge, Cairo
- Underground construction of El-Ataba station (Cairo Underground Metro line 2)
- Sewer system between (Al Zahraa and Ain Shams) Cairo
- Underground construction of El-Khalafawi station (Cairo Underground Metro line 2)
- Ring road around Cairo

Part Time Job

9/97 – 11/2001

Head of projects' department "House of Consultancy – Construction Management Consultant". I worked in the following:

Training Courses:

- Modern methods for construction project Management
- Special course for planning using Primavera
- Quality improvement in construction projects
- Quality measurement of construction projects
- Quality control in construction projects
- Fundamentals of quality circles

Projects:

- Establishment and implementation of twenty quality circles in different branches and departments of Arab Contractors Company which is the biggest construction company in the Middle East

- Establishment of a performance evaluation system for Arab Contractors Company's Projects
- Performance evaluation and improvement of "El-Canal Branch – Arab Contractors Company"
- Measuring the quality and customer satisfaction of "Alexandria Branch's projects – Arab Contractors Company"
- Measuring the quality and customer satisfaction of "Helwan Branch's projects – Arab Contractors Company"
- Project management consultation for "Tanta hospital" project

The quality circles projects include preparation of engineers by training them in quality measurement and improvement tools and then selecting a problem from the construction sites to find a solution for it.

For the performance evaluation system project, 15 factors and their corresponding measurement methods were determined. The system evaluates the performance of the projects and ranks them. It is very efficient tool for multi-project management.

7/93 – 6/95

I worked in the project "Development of Construction Industry in Egypt"- The project was financed by World Bank. My tasks in this project included the following:

- Preparation of some materials about construction management
- Training engineers for management tools

Computer Knowledge

Visual Basic programming language, FORTRAN programming language, Primavera, MS project, Flac, Windows, and Microsoft office (Word, Excel, Front page, etc.), Internet, and some other programs

Referees

Name: Prof. Dr. Hans Georg JODL

Occupation: Head of Construction Management and Economics Institute

Address: Institute of Construction Management and Economics,
Vienna University of Technology
Karlsplatz 13/234, A-1040 Vienna
Austria

Name: Prof. Dr. Refaat ABDEL-RAZEK

Occupation: Head of Construction Engineering Department

Address: Construction Engineering Department,
Faculty of Engineering, Zagazig University
Zagazig, Egypt

Name: Prof. Dr. Ismail BASHA

Occupation: Professor of Construction Engineering and Management

Address: Construction Engineering Department,
Faculty of Engineering, Zagazig University
Zagazig, Egypt