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Tunnel and Station Cost Methodology

Mined Tunnels

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16. Abstract

This report describes a cost estimating methodology for subway tunnels. This methodology is for the use of planners and designers interested in evaluating a realistic range, within which the actual bid would fall, for the cost of subway tunnels. A similar methodology has been developed for cut-and-cover station construction and is reported in a separate publication.

The rationale behind this cost estimating methodology is the effort to parallel the estimating process of tunneling contractors. Extensive interviews were conducted with reputable subway tunnel contractors and designers to identify the basic framework for estimating costs.

A hierarchical cost estimating technique is developed whereby project-specific and contractor-specific factors are identified and structured; i.e., typical advance rates are developed for a variety of geological and geometrical conditions; crew sizes (by skill) for varying geological conditions and construction methods; type and size of equipment and their associated write-off values; type of materials; contractor overhead, taxes, interest costs, etc.

Finally, a data base of actual equipment, labor, materials, and lump sum costs has been compiled and may be updated as changes occur.

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PREFACE

This study has been undertaken to develop a working subway tunnel and station cost estimating methodology that can be used by planners, designers, owners, and government agencies. The best approach for developing a "usable" methodology was to analyze the actual subway contractors' techniques and try to formalize their cost estimating processes into a realistic model.

This study was prepared by M. Ziad Ramadan, Barbara M. Parness and Youssef E. Nassar of Multisystems, Inc. for the Office of Technology Development and Deployment, Office of Rail and Construction Technology, Urban Mass Transportation Administration, U.S. Department of Transportation, under contract to the Transportation Systems Center in Cambridge, Massachusetts.

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METRIC CONVERSION FACTORS

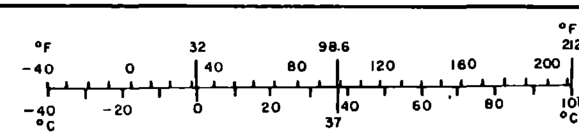
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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ADDITIONAL SYMBOLS AND ABBREVIATIONS

LF	linear foot
CL	center line
OD	outside diameter
CD	center diameter
CFM	cubic foot/minute
TBM	tunnel boring machine
GAL	gallon
SF	square foot
ID	inside diameter
L	length of tunnel
GPM	gallons per minute
CY	cubic yard
LBS	pounds
LHD	load-haul-dump
WF	weighting factor

1. INTRODUCTION

In January 1980, Multisystems was awarded a contract to develop a model for estimating the cost of subway station and tunnel construction. The basis for the award was the approach to the development and implementation of the cost estimating methodology. Multisystems' approach was to first identify those project-related characteristics that have an impact on cost, and then develop a model that parallels the estimating process of the contractors. To accomplish this, Multisystems had to gain insight and understanding of the method by which contractors go about estimating their costs. With this in mind, Multisystems solicited the help of five reputable contractors, namely: Grow Tunneling; Al Johnson Construction; Traylor Brothers, Inc.; Granite Construction; and Guy F. Atkinson & Company; as well as a major design firm; Parsons, Brinckerhoff, Quade, & Douglas, Inc.

The plan was to conduct an extensive interviewing process with each contractor to identify the construction method used by that firm in estimating the cost of tunnels under various conditions (project-related and contractor-related). This lead to the estimation of advance rates for several construction methods, given the geological conditions and other factors that impact the advance rate. Identified in the process were the crew sizes (by skill) under varying geological conditions and construction methods, and the type, quantity, and size of equipment to be used and their associated write-off values. All construction activities were defined, along with the contractor's method of determining their costs, plus any additional costs and markup provisions.

Admittedly, estimating the cost of subway tunnel construction is as much an art as it is a science. Recognizing this, Multisystems is not attempting to develop a model that would formalize all possible actions and decisions and come up with a precise cost estimate. The model user should understand that no matter how extensively he provides details characteristic of the job at hand, he will not be able to fully replicate the complexity and specificity of the actual job conditions. With this in mind, it was more realistic for the model to produce a cost range (instead of a single number) within which the actual bid would fall. This model is foreseen to be of immediate importance to designers, and at some future point, of importance to planners. It will help owners in planning, and also in understanding how and why contractors put out a particular bid, or decide on a particular construction method. Thus, everyone is likely to benefit from a more predictable and cooperative job environment.

2. THE MODEL

2.1 INTRODUCTION

The basic criterion used in the development of this model is that it must replicate the contractor's procedure for bid preparation. To ensure accurate model development, a step-by-step approach to this estimating process is followed. A parallel will be drawn between the actual estimating process and the cost model. Keep in mind that this study is limited to mined subway tunnels with an outside diameter of 18 to 24 feet, along with all necessary access and ventilation shafts. It is assumed that the contract package for the construction of the subway tunnel would require a minimum of one shaft at each end of the tunnel.

2.2 IDENTIFICATION AND MODELING OF PROJECT CHARACTERISTICS

The first step the contractor takes in estimating any project is to identify all project characteristics that have an impact on cost. At this stage the data available to the contractor may come from the following sources:

1. Designer's plans and specifications and bid items,

2. Designer's description of site and ground geology, past historical data on geological samplings,

3. Contractor's past experience in the area (or in a similar one), and

4. General economic climate.

In order for the model to attempt to replicate the contractor's cost estimating process it must have at its disposal the same type of information that is normally available to the contractor; namely, all of the project characteristics defined above. This information tends to be voluminous and is not available until the final design is complete. It also relates to a specific site or project and might not be useful to any other projects. Therefore, feeding it all to the system becomes prohibitively expensive and inefficient. So, all the information available to the contractor must be reviewed and, from it, those project characteristics that have a real impact on costs must be selected. Appendix B provides a list of the project characteristics that are considered important. They have been grouped under ten categories:

1. General
2. Community constraints
3. Construction site conditions
4. Utilities relocation
5. Building protection
6. Tunnel design
7. Shaft design
8. Tunnel and shaft geology
9. Temporary tunnel support system
10. Muck hauling from construction site to dump

The General project characteristics provide general information regarding the project and its environment. They include the following:

- Location of the city in which the subway tunnel is to be built. This variable is used when deciding labor rates, crew sizes (to reflect locational constraints due to union regulations), and level of productivity.
- The expected starting date of the project. This is used in the escalation of costs, reflecting the current inflation rates.
- The duration of the project. This is the owner's specified expected duration of the contract, not the actual or the contractor's estimate of duration.
- The cost bias. This is input to the model to request pessimistic, optimistic, or most likely estimates. By requesting all three values of this variable, one can arrive at the cost estimate range.
- The owner's attitude toward change orders (fair, unfair, unpredictable); the legal liability placed on the contractor through the designer's specifications and changed conditions clauses (low, medium, high); the owner's willingness to reimburse for partial completion of work (low, medium, high); the current state of the economic climate within the construction industry (poor, fair, good); the anticipated number of bidders; and the number and type of allowable workshifts. All of these variables are utilized in the determination of the markup factor in the model.
- The forecasted inflation rate and an average interest rate on construction loans (national prime rate) are used in inflating the cost estimate to the date of its expenditure and to help in determining the contractor's costs.

The Community Constraints variables describe those community stipulations that may affect the contractor's construction method, and ultimately, the cost of the project. These variables include whether surface equipment insulation would be required to minimize noise pollution (yes or no); accessibility of shafts when not in use (closed or open); restrictions on the number of hours of operation; limitations on drilling and blasting; and regulations for dynamite stockpiling.

The Construction Site Conditions variables include general site work (snow removal; rodent, insect, and odor control; street cleaning; etc.); congestion of the area surrounding the site; the availability of storage space (expressed as a distance in miles from the work area); the level of surveillance and security required (light, medium, heavy); the dimensions of the surface area provided by the owner for work at each access shaft (in sq. ft.); the extent of site clearing required; the amount of curbing, sidewalk, and pavement to be removed; the number of small, medium and large structures to be demolished; the amount and type of fencing to be installed; and the dimensions of the area to be restored and the type of restoration work. Also included are the level of traffic re-routing and problems, the number of trailers to be brought to the construction site, the number of employees to be relocated, and demolition required.

The Utilities Relocation variable indicates to the model the extent of utilities relocation performed by the contractor (none, little, moderate, or extensive) and the quality of utilities surveys showing locations.

The Building Protection variables take into account the level of effort required for underpinning adjacent properties. Also included in this section are the monitoring requirements for settlement, blasting damage, seismic activity, etc. (minimal, moderate, extensive) and the amount of special insurance.

The Tunnel Design characteristics reflect the main parameters given by the designers. They include the tunnel diameter; tunnel length; number and length of geological segments and subsegments; and horizontal curvature and vertical gradient within each subsegment. The type of lining is also considered (steel, precast concrete, or poured concrete). If the lining is precast or poured concrete, the thickness, strength (in psi), and amount of reinforcing steel (in lbs/cu yd) for each segment are specified. If a steel lining is used, the size of steel sets is specified. Other variables include the amount of caulking and grouting required for drainage purposes; the depth (inches) of the invert; the dimensions (cubic feet) of the safety walk; the strength of the concrete used in the invert and safety walk, and the associated amount of reinforcing steel; and finally, the thickness of the subgrade material.

Note on Geological Segments: In order to reflect varying geological conditions and design parameters throughout the tunnel, the user is requested to divide the tunnel into one, two, or three segments. The division of the tunnel into segments is based primarily on geological variations among rock, soft ground, and mixed face conditions. If a tunnel is all rock, then there would be only one segment (the same is true if it is all soft ground or all mixed face). If the tunnel is part rock, part mixed face, it consists of two segments, and so on. These segments can be further subdivided into subsegments. The subsegments are again based on geological variations, but also on design variations. The subsegmentation utilizes detailed geological data with regard to the soil or the rock. For example, a subsegment of a soft ground segment might be classified as one of the following:

uniformly soft silt, and gravel; cohesive sand, silt, and gravel; and so on, up to bouldery till. Please refer to Appendix A for the geological classifications within a tunnel for rock, soft ground, and mixed face conditions. Subsegmentation can also be defined in terms of design parameters such as curvature or vertical gradient. This subsegment representation was deemed necessary for accurate calculation of an average advance rate over the segment as a whole. The segment representation was, in turn, essential to the determination of the proper construction method to be used. This is necessary, for example, since a construction method for soft ground would not be applicable for tunneling in rock.

The Shaft Design variables cover the designer's plans for the ventilation/access shafts. They include the depth, length, width and purpose of each shaft; the number of fan units; the temporary support to be used when excavating each shaft, the type of shaft bracing; the pile size and spacing, the number of piles, their depths; and so on. Refer to Appendix B for a complete list of these variables.

The Tunnel and Shaft Geology variables provide a profile of the geological conditions for the tunnel and the shafts. Among the variables are soil, rock, and mixed face classifications, which are based on the system shown in Appendix A, groundwater inflow problems.

The Temporary Tunnel Support System variables reflect the designer's plans for supporting the tunnel excavation before the final lining is placed. This includes the type of ground control and solidification; the diameter and number of rock bolts to be used (if any); and the support requirements imposed by the designer.

The Muck Hauling from Construction Site to Dump variables reflect the cost of hauling the muck, maintaining the dump site, and paying any dumping fees.

All of the above information is contained in Appendix B.

2.3 CONTRACTOR DECISIONS

After the data-gathering phase of the cost-estimating process has been completed, the contractor is confronted with several decisions. The first decision the contractor must make concerns the construction method to be utilized in the subway tunneling process. This model considers five major construction methods, three of which relate to soft ground and two of which relate to rock. The construction methods considered for soft ground tunneling consist of shield with excavator, shield with conventional mining, and forepoling or floating crown bars with conventional mining. The construction methods considered for rock tunneling consist of tunnel boring machine and drill-and-blast. The contractor first determines which of the above methods to use, or in the event that geological variations are encountered, which combination of methods to use. Appendix C, Section 1, describes the logic and reasoning contractors employ in selecting a construction method or combination of methods. There are many factors that affect this choice, including the geology and length of each segment of the tunnel, the length of the entire tunnel, community constraints, and the type of support mandated by the designer. It is a fact that, under identical conditions, different contractors might select different construction methods. The principal reason for this variation is that one contractor might have access to a piece of equipment that another contractor would have difficulty obtaining. His ability to utilize this equipment in the tunnel construction process could conceivably render one construction method more desirable to him than it would be to another contractor.

Since the primary concern is to produce a cost-estimate range that reflects the known details of each tunnel construction project, the user of this model has the option of over-riding the construction method decision that is generated.

The second decision the contractor must make is regarding the initial support system implemented during the construction process. The options for soft ground tunneling include a temporary liner of ribs and lagging, permanent steel lining, and permanent precast concrete. For rock, ribs and lagging, rock bolts, shotcrete, ribs and shotcrete, rock bolts and shotcrete, or rock bolts and steel sets would be used. This decision is based partially on the construction method chosen by the contractor and partially on the designer's plans, specifications, and requirements. The logic employed by the model in determining the temporary support system is described in Appendix C, Section 2. While the temporary support method is usually decided by the designer, the model is flexible and allows the user to generate several costs using various support system options, thereby determining the most economical method.

The third decision the contractor must make deals with the number of construction headings to be used in mining the tunnel. The number of headings depends primarily on the selected construction method or methods, labor intensity and time constraints. The logic for determining the number of headings for subway tunnel construction is described in Appendix C, Section 3. This logic has been developed under the assumption that the contractor would not be willing to use more than one construction heading, except when drilling-and-blasting, to aviod investing large sums of money into equipment.

The fourth decision to be made by the contractor concerns the advance rate to be assumed when estimating costs. The advance rate represents the average number of feet excavated per day and is dependent on the construction method; the temporary support system; the geological and water conditions of the region; the number and length of each shift; the shape, curvature, and slope of the tunnel. Since the advance rate is a key factor in cost calculations, the model has been designed to compute the advance rate in the same manner that the contractor would. Given the above information, the model obtains an advance rate for each subsegment of a segment from pre-established tables of advance rates. The advance rate varies from one subsegment to the next, simply because each subsegment possesses different geological characteristics and possibly different design specifications with regard to tunnel curvature or slope. Appendix J contains advance rate tables for various combinations of geological conditions, tunnel curvature and slope, level of water inflow, excavation in free air versus compressed air, number of work shifts, construction method, and temporary support system. For each of these parameters, the tables provide an estimate of the most likely advance rate. The assumption is made that the best possible advance rate and the worst possible advance rate under each specified set of conditions are represented by +25 percent and -25 percent of the most likely advance rate figure, respectively. The rate used by the model in calculating the cost estimate depends on the user's request in the form of required input of a pessimistic, optimistic, or most likely cost estimate. Note that the hauling system is not included as a parameter that impacts advance rates. This is because the hauling system would never constrain the advance rate; rather, the contractor would always design a hauling system that is capable of handling the anticipated advance rate. In addition, note that the advance rate does not reflect time lost due to the learning curve process and the ironing out of any wrinkles before smooth operations are achieved. This time is incorporated elsewhere in the model. Appendix C, Section 4, explains how the advance rate tables are utilized in conjunction with detailed geological data for each subsegment as well as tunnel design specifications to arrive at an average advance rate for the tunnel as a whole.

Once the construction method, the temporary support system, the number of construction headings, and the average advance rate for the tunnel have been determined, the contractor must design the hauling system to be used for muck removal. The fundamental criteria for the hauling system are that it be capable of handling all generated muck, that it not delay progress, and that it be efficient, reliable, and cost-effective.

The first decision the contractor makes in designing the hauling system is whether to use a system that travels on rails or rubber tires. The decision is based on two factors: the length of the tunnel, and the grade of the tunnel; the shape of the tunnel being assumed noncritical.

The second decision the contractor makes is based on the amount of muck to be hauled in each load. When the shield with digger or shield with conventional mining excavation method is used, the load of muck to be hauled is equal to the volume of muck generated during each advance cycle. For example, if the shield is advanced 4 ft/cy and if segmental supports are placed during each cycle, the contractor would favor a hauling system that is capable of carrying all the muck generated in one 4-ft cycle. During the time the shield is being advanced, the muck load can be transported to the shaft and an empty train can be sent to the shield. This tactic takes advantage of the time during which no muck is being generated.

Once the hauling capacity per cycle is determined, then the muck removal cycle must be calculated. This cycle is the time required for a fully loaded train to leave the site and an empty one to take its place. This cycle time must not be greater than the time consumed in advancing the shield and starting the generation of additional muck. The muck removal cycle is a function of the length of the tunnel, the distance between the fully loaded train and the empty train awaiting to be loaded, the speed with which trains can be unloaded and again made ready for loading, and the number of trains utilized in the operation. The number of trains utilized is a function of the length of the tunnel. For a tunnel length of less than 5000 feet, two trains are used in the operation. Normally, while one train is being loaded, the other train is being unloaded. For a tunnel length of greater than 5000 feet, a third train is utilized and is placed in a turnout close to the tunnel face in order to minimize the time interval between the departure of a fully loaded train from the face and the arrival of an empty train. When the number of trains has been established, the contractor designs the make-up of each train in terms of the number of cars and the size of each car.

Next, the contractor must design the muck lifting system. If the depth of the shaft is less than 100 feet and the rate of muck generation is low to medium, the contractor tends to favor a crane as the mechanism for muck lifting, rather than a headframe and hoist, bucket elevator, or conveyor. A headframe and hoist can handle a higher rate of muck generation and perform at a greater depth than a crane; however, it requires a set-up time of approximately two months and is not versatile. The reason is that cranes tend to be more versatile, require minimal set-up time, and can be used prior to the muck lifting operation in the excavation of the shaft.

When using a crane, a contractor must provide a separate means of access to the face for his employees. This is normally accomplished by constructing a stairway or man elevator adjacent to the crane operation. The required capacity of the crane is determined by the contractor as a function of the rate of muck generation and the availability of certain sizes of cranes. In designing a hauling system, the contractor tends to design a system capable of handling a higher excavation rate than he estimates will be attained. The rationale here is that the contractor can then maintain flexibility in the construction process by increasing the advance rate whenever possible without being constrained by the hauling system capacity. The logic used in the model for making all of these decisions is detailed in Appendix C, Section 5.

The contractor's next step is to estimate the duration of the job. Prior to establishing job duration, the contractor must develop a schedule that shows the duration of activities and interrelationships of activities within the job. For the model, the following activities have been defined:

1. Site preparation and mobilization
2. Shaft excavation and fittings
3. Utilities relocation
4. Tunnel setup operation
5. Tunnel excavation, support, and lining
6. Tunnel construction equipment removal
7. Tunnel concrete and grout
8. Shaft finishings
9. Underpinning and building protection
10. Ground control

11. Tunnel cleanup
12. Demobilization and site cleanup

The order in which these activities occur has also been defined. The following nine activities are listed chronologically. The remaining three activities (utilities relocation, underpinning and building protection, and ground control) are assumed to occur in tandem with these nine:

1. Site preparation and mobilization
2. Shaft excavation and fittings
3. Tunnel setup operation
4. Tunnel excavation, support, and lining
5. Tunnel construction equipment removal
6. Tunnel concrete and grout
7. Shaft finishings
8. Tunnel cleanup
9. Demobilization and site cleanup

The duration of each of the nine activities must first be determined, and the summation of these activity durations equals the job duration. Statistics indicate that the duration of the site preparation and mobilization activity is approximately two months, provided that no complicated work is entailed. The duration of the shaft excavation and fittings activity equals the time required to excavate and fit the main access shaft. This duration is a function of the shaft depth, length, and width; geological conditions; and the temporary support system to be utilized for the shaft. The tunnel setup operation duration is based on the muck hauling system, the muck lifting system, and the construction method. For example, if a shield with digger or a tunnel boring machine is used, then the tunnel setup operation duration must include the time required to assemble the machine at the bottom of the shaft. The duration of the tunnel excavation, support, and lining activity depends on the number of construc tion headings, the length of the tunnel, the previously established advance rate, and the temporary support system. The duration of the tunnel construction equipment removal activity is a function of the type of equipment to be utilized and the time needed to disassemble and remove such equipment. The duration of the tunnel concrete and grout activity depends primarily on the shape of the tunnel and its length. The duration of the shaft finishings activity is based on the number of ventilation systems to be installed in the shaft and the complexity of the shaft's mechanical and electrical equipment. The duration of the tunnel cleanup activity is a function of the tunnel length. The duration of the demobilization and site cleanup activity depends on the amount of site work needed as the job nears completion. The logic for calculating the job duration is described in detail in Appendix C, Section 6.

Calculation of the job duration is an important step in the procedure of determining job overhead cost. Hence, any miscalculation of this duration will produce an error in the job overhead cost calculation. For purposes of computing labor overhead, the model reduces the job duration by two months before proceeding with the calculation. The rationale for such a reduction is that, under normal circumstances, the contractor does not initially maintain a full-size overhead staff, but rather increases the size of the staff as the job progresses and decreases it prior to job completion. The model assumes a standard overhead crew size. The composition of the standard overhead crew is depicted in Table E-1.

The final decision the contractor must make pertains to the write-off value of the excavation equipment at the tunnel face. This write-off value comes to bear when a shield with digger or a tunnel boring machine is used. The write-off is a percentage of the current cost of a new piece of equipment. This percentage varies depending on the tunnel length. Appendix D delineates the write-off values which the model assumes for shields with diggers and for tunnel boring machines for different tunnel lengths. The original value of the equipment times the write-off value (in percent) represents the cost of equipment ownership. In addition to this cost, the model calculates an equipment operating cost that is directly related to the number of cubic yards excavated. This operating cost represents the cost of replacement parts and repair materials for the equipment.

2.4 MODEL BREAKDOWN

Once the contractor has made all of the above decisions, he computes the cost of each individual activity in terms of labor, material, and equipment expenses. The model, in an attempt to replicate the contractor's estimating process, calculates detailed costs for each of the 12 activities mentioned above.

Those costs that are directly incurred in completing each activity are included in that activity's cost. After the cost of each activity has been determined, the model calculates the labor, material, and equipment costs that do not relate to any particular activity but rather to the job as a whole. These costs encompass overhead, miscellaneous small tools, bonds, property taxes, license permits, dues, contributions, legal work, accounting, entertainment, progress photographs, employee expenses, travel, relocation, and the borrowing of capital invested in the project. In addition, the model calculates a cost markup or profit margin for the contractor. This cost markup is based on the general state of the economy, the cost of the job, and the expected duration of the job. The following sections explain in detail how the model derives the labor, material, and equipment costs of work not directly related to the major activities; and the contractor's profit margin for the job. Together these costs comprise the bid estimate.

3. SITE PREPARATION AND MOBILIZATION

3.1 INTRODUCTION

This component comprises all efforts needed to prepare the site so that construction can begin, as well as all expenses of equipment mobilization, freight in and out, and expenses of setting up field offices. Site preparation includes such activities as tree removal, pavement removal, building demolition, fencing of the site, traffic maintenance, and security measures. Mobilization includes such activities as the setting up of equipment and field offices. In order to determine the cost of the site preparation and mobilization activity, it must be divided into the following subactivities:

1. Site clearing
2. General site preparation
3. Site fencing
4. Traffic maintenance
5. Trailer setup
6. Equipment setup
7. Utilities setup
8. Security

The method for calculating the cost of each of these subactivities is described in this chapter.

3.2 SITE CLEARING

This activity includes all work required to clear the site of any existing obstructions, such as trees, pavement, or buildings. It is subdivided into: 1) tree removal, 2) pavement removal, 3) small building demolition, 4) medium building demolition, and 5) large building demolition.

3.2.1 Tree Removal

This activity consists of all foliage and tree removal work on the construction site. The cost of this activity is based on the square footage of the area to be cleared and the extent of tree congestion. The area to be cleared and the congestion of trees (light, moderate, or heavy) are given to the model as input. The model calculates the cost of this activity by extracting from the unit cost data file (detailed in Appendix I) the cost per square foot of clearing few trees, some trees, or heavy foliage and trees. That unit cost is then multiplied by the square footage of the area to be cleared to produce the cost of tree removal.

3.2.2 Pavement, Curbing, and Sidewalk Removal

This activity consists of all asphalt or concrete pavement, curbing, and sidewalk removal work done on the construction site. The model calculates the cost of this activity by extracting the cost per square foot of pavement, curbing, and sidewalk removal from the unit cost data file in Appendix I and then multiplying it by the square footage of pavement, curbing, and sidewalk which has been input to the model.

3.2.3 Small Building Demolition

This activity consists of the demolition of one or two-story wood-framed buildings on the construction site. The cost of this activity is calculated by extracting the unit cost of small building demolition from the unit cost data file in Appendix I and then multiplying it by the number of cubic feet of small buildings to be demolished. The number of cubic feet of small buildings to be demolished is derived from data previously input to the model.

3.2.4 Medium Building Demolition

This activity consists of the demolition of small masonry structures and light commercial buildings on the construction site. Its cost is calculated by extracting the unit cost of medium building demolition from the unit cost data file in Appendix I and then multiplying it by the number of cubic feet of medium buildings to be demolished. The number of cubic feet of medium buildings to be demolished is derived from data already supplied to the model.

3.2.5 Large Building Demolition

This activity consists of the demolition of large masonry structures, multi-story buildings, and bridges on the construction site. Its cost is calculated by extracting from the unit cost data file in Appendix I the unit cost of large building demolition and then multiplying it by the number of cubic feet of large buildings to be demolished. The number of cubic feet of large buildings to be demolished is derived from data previously input to the model.

3.3 GENERAL SITE PREPARATION

This activity comprises general site work requirements such as snow removal; rodent, insect, and odor control; street cleaning; etc. The cost of this activity is calculated by extracting a unit price from the lump sum cost data file for minimal, moderate, or extensive general site work. The particular unit cost extracted depends on the user's input to the model regarding general site work requirements.

3.4 SITE FENCING

This activity consists of all fencing requirements for the construction site and the area around each access shaft. The model is supplied with the lineal footage of fencing needed for the site and the type of fencing. The model considers three types of fencing: 1) 6-foot high chain link fence, 2) wire mesh on 4-inch by 4-inch posts and 8-foot high, and 3) painted plywood (sound barrier type). If type one fencing is specified to the model, then the costing of this activity is done by extracting from the lump sum cost data file the price per lineal foot of type one fencing installation and then multiplying that unit price by the fence length. Similarly, if type two or three is specified to the model, then the unit cost of type two or three fencing installation is extracted from the lump sum cost data file and used in the calculation of the cost of site fencing.

3.5 TRAFFIC MAINTENANCE

This activity covers all traffic maintenance, including rerouting, traffic officers, and signal installation. The user gives the model one of four possible traffic alternatives. These include: 1) no traffic maintenance, 2) closing off traffic completely, 3) limited two-way traffic, and 4) one lane with an officer controlling traffic direction. The cost for traffic maintenance is calculated by extracting a unit price for the level of traffic maintenance required from the lump sum cost data file. This unit cost is represented as dollars per month of traffic maintenance. In order to calculate the total cost of traffic maintenance, the unit cost is then multiplied by the job duration (in months) which has been previously calculated by the contractor.

3.6 TRAILER SETUP

This activity includes the setting up of site offices, change houses, maintenance shops, and sanitary facilities. Because this activity can vary greatly from one job to the next, it is difficult to accurately estimate its cost. For example, in one situation the contractor might desire to lease or purchase an adjacent building, remodel that building, and use it as his office during construction. In another situation, the contractor might install temporary trailers on site which would serve as an office and change house, and provide the necessary sanitary facilities. This model assumes that the contractor would employ the latter option and therefore calculates the cost of this activity by extracting the cost per trailer from the equipment cost data file (Appendix F) and multiplying it by the number of trailers previously determined by the model.

3.7 UTILITIES SETUP

This activity consists of the setting up of all utilities for field offices on the construction site. It includes the installation of electric, telephone, water, and sewage systems. The model calculates the cost of utilities setup by extracting a lump sum cost for this activity from the lump sum cost data file.

3.8 SECURITY

This activity covers all the security and surveillance requirements for the construction site. Its cost is based on the level of surveillance stipulated by the user. The cost of this activity is derived by extracting from the lump sum cost data file a monthly cost for surveillance activities under light, medium, or heavy surveillance requirement conditions. This unit cost is then multiplied by the job duration (in months) to arrive at a total cost for security.

4. SHAFT EXCAVATION AND FITTINGS

4.1 INTRODUCTION

This activity consists of the excavation and fittings for all shafts. It does not include shaft finishings and installation of ventilation systems. For each shaft this activity is divided into four subactivities: shaft support, shaft excavation, shaft fittings, and muck disposal. The number of shafts, the temporary support system to be utilized for each shaft, the geometric configuration of each shaft, and the existing geological conditions in each shaft have been previously specified by the user.

4.2 SHAFT SUPPORT

This activity consists of all temporary shaft support requirements. It is broken down into two elements, shaft support wall and shaft bracing. The shaft wall support can be slurry wall, soldier piles and lagging, or steel sheet piling. The type of support to be used is supplied by the user. The only type of shaft bracing considered by the model is cross bracing and tiebacks.

4.2.1 Slurry Wall Shaft Support

This activity covers slurry wall placement as the means of temporary support for the shaft. The model calculates the cost of the slurry wall by extracting from the unit cost data file in Appendix I the price per cubic yard of slurry wall placement and then multiplying that unit price by the volume of slurry wall to be installed. If there is a water or boulder problem, the cost of slurry wall will be much higher, but there is no way of predicting this at the estimating stage. This uncertainty is reflected in the contingency allowance.

4.2.2 Soldier Piles and Lagging Shaft Support

This activity consists of the installation of soldier piles and lagging as the means of temporary support for the shaft and does not include tie backs or cross bracing. It is subdivided into the placement of soldier piles and the placement of wood lagging.

4.2.2.1 Soldier Piles for Shaft - This activity covers the cost of installing soldier piles prior to shaft excavation. There are two methods of placing soldier piles: 1) pounding, or 2) augering, which is drilling a hole and lowering the soldier pile into it, then filling the excess space with poured concrete. The number of piles needed is calculated by dividing the perimeter of the shaft by the distance between piles. This distance is supplied as input by the user. The depth at which the piles are placed is assumed to be 5 feet greater than the depth of the soft ground (if any) surrounding the shaft.

To install piles by drilling, two major pieces of equipment are needed: an auger and a pile driver. The unit prices of these items are found in the equipment cost data file. The principal materials needed for this effort consist of soldier piles and concrete. The piles vary in size according to their weight per lineal foot, therefore, the user must supply the model with a specific pile size. The model computes the cost of piles by extracting the unit cost for the given pile size from the material cost data file and multiplying it by the number of piles calculated above. The volume of concrete per pile is ascertained by multiplying 0.5 square feet by the depth of the pile. This figure is multiplied by the number of piles to yield the total volume of concrete in cubic feet. The unit prices for these items are found in the material cost data file. The cost of labor is determined by obtaining the appropriate crew configuration from Appendix E, and from it deriving the number of man-hours required daily of each labor type. The model extracts from the labor cost data file in Appendix G the cost per man-hour of each labor type and the cost per man-hour of fringe benefits for the appropriate city. The model then adds 34.88 percent of the hourly wage rate to the hourly fringe benefits rate figure to account for the government-mandated benefits of social security (6.13 percent), workers' compensation (24.00 percent), and unemployment taxes and insurance (4.75 percent)*. The sum of the hourly wage rate and the hourly benefit rate (including both union-stipulated and government-stipulated benefits) equals the total cost per man-hour for a specific labor type. The model multiplies the total cost per man-hour by the number of man-hours required to produce the daily labor cost for each labor type. Summing the daily cost for each labor type yields the total daily labor cost for soldier pile installation. Once the labor cost per day is computed, it is multiplied by the number of days required to complete soldier pile installation in order to arrive at the total labor cost for this part of the job.

The procedure for costing soldier pile installation by driving the piles is similar to the procedure just described. The equipment and materials differ in that a pile driver is used, rather than an auger, and no concrete is needed. The labor crew differs in that one less crane operator is needed. After eliminating these items, the model costs soldier pile installation by driving in the same manner as delineated above.

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*These figures represent national averages. Benefit rates vary greatly from city to city, and these figures should be examined and modified accordingly for each project location.

4.2.2.2 Wood Lagging for Shaft - This activity comprises the cost of placing wood lagging between soldier piles as a means of temporary support for the walls of the shaft. The amount of lagging needed is calculated by multiplying the perimeter of the shaft by the depth of the lagging (assumed to be the same as the depth of the shaft). The resulting figure represents the total square footage of lagging. The surface area of one piece of lagging is 0.5 ft x 4 ft, or 2 square feet (assuming 4-foot long wood lags). Hence, total square footage of lagging is divided by 2 to obtain the number of pieces of lagging needed. The equipment used for this operation consists of a small (25-ton) crane for transporting the wood lagging. The actual erection of the wood supports is done by hand. The crew configuration for this effort is shown in Appendix E.

The total cost of installing lagging is equal to the cost of materials (the number of pieces of lagging multiplied by the unit cost from Appendix H), plus the cost of a 25-ton crane from Appendix F, plus the cost of labor (computed using the same procedure as described for soldier piles).

4.2.3 Steel Sheeting Shaft Support

In the event that steel sheeting is utilized for the shaft support system, the model estimates its cost as follows. The cost of materials is the weight of steel multiplied by the cost of steel per pound from Appendix H. The equipment needed to install steel sheet piling includes a vibratory pile driver (if the soil is soft) or a double-acting pile hammer (if the soil is hard). A medium-size (50-ton) crane is used to transport the sheet piling, and welding machines and compressors are also needed. The costs of these pieces of equipment are listed in Appendix F. The configuration of the crew working on this operation is depicted in Appendix E. The procedure for calculating the labor cost is the same as described previously.

4.2.4 Cross Bracing and Tiebacks

The number and size (lbs/ft) of cross braces are input to the model by the user. The size of cross braces is multiplied by the length of each brace to give the weight. This figure is multiplied by the number of braces, resulting in the total weight. Finally, the total weight of the braces is multiplied by the unit cost of steel (dollars/lb) to produce the total cost of materials for the shaft bracing operation. The equipment required consists of a crane, welders, and compressors. However, the same equipment that was used for installation of the shaft wall support can be used for the installation of shaft bracing; therefore, its cost is not included here. The cost of labor is derived by selecting the appropriate crew composition table from Appendix E and utilizing it in the standard procedure for costing labor. In the case of tiebacks, the total number of tiebacks is multiplied by a lump sum cost from Appendix I for tiebacks (installed).

4.3 SHAFT EXCAVATION

The cost of shaft excavation varies widely, depending on the geological conditions of the area in which the shaft is to be dug. The model examines this cost for two geological conditions: soft ground and rock.

4.3.1 Shaft Excavation in Soft Ground

The equipment used here is a clamshell, an excavator (CAT 955TM) and a crane (with muck skip). Their costs can be found in Appendix F. The appropriate crew composition table in Appendix E is used in conjunction with the labor rates in Appendix G to determine the daily labor cost for shaft excavation in soft ground. In addition, the depth of the shaft is divided by an assumed advance rate of 1 ft/day to produce the duration of this activity. Multiplying the duration by the daily labor cost yields the total labor cost. For muck disposal, see page 55.

4.3.2 Shaft Excavation in Rock

The equipment used here includes air tracs or a shaft vertical jumbo with 4 drills, a crane, a loader, and a bulldozer. Their costs are found in Appendix F.

For the drill-and-blast operation, dynamite, caps, and wire are needed. See Section 7.3.2 of this report for the procedure for costing these materials. The crew configuration for shaft excavation in rock is obtained from Appendix E, and the cost of labor is computed as it is in Section 7.3.2. The advance rate is again assumed to be 1 ft/day for job duration calculations. For muck disposal, see page 55.

4.4 SHAFT FITTINGS

This activity comprises the fan system required during the construction and excavation process, the stairways needed by the labor crews for access to and exit from the shaft, and the power, telephone, ventilation, and electric lines in the shaft. All of these items are included in a lump sum cost per lineal foot of shaft in the unit cost data file (Appendix I).

4.5 MUCK DISPOSAL

See Section 7.8, Page 55.

5. UTILITIES RELOCATION

This activity consists of the maintenance, support, restoration, and relocation of utilities. Utilities may be handled in a variety of ways: 1) they may be supported and maintained in place during construction, 2) they may be temporarily relocated and maintained during construction, and replaced and restored to service following the completion of construction, or 3) they may be permanently relocated to a new location beyond the immediate limits of transit construction. Since the circumstances surrounding utility relocation vary so greatly from job to job and the methods for handling utilities are so diverse, it is difficult to cost this activity in a detailed fashion. The approach that the model uses is to request as input from the user the extent of utility relocation work required (none, little, moderate, extensive). For each of these four levels of effort there exists a lump sum cost in the unit cost data file, Appendix I. Based on the user's input, the model selects the appropriate cost from the file and assumes that it represents the total cost for the utility relocation activity. If utility relocation is expected to be very extensive, cost estimates should be more detailed. It is suggested to cost utility relocation by the linear foot for water, sewer, gas, and electrical lines, and by the size of each utility pipe. This model will adopt the less sophisticated approach.

6. TUNNEL SETUP OPERATION

6.1 INTRODUCTION

This activity encompasses all efforts to prepare the tunnel for excavation. The activity includes back drift and forward drift mining when needed to provide enough space for shield or tunnel boring machine assembly at the bottom of the shaft. It includes the assembly and disassembly of all excavation equipment as well. The activity is broken down into four subactivities: 1) lowering equipment into the first parallel tube and assembling it, 2) disassembling and removing equipment from the first parallel tube, 3) lowering equipment into the second parallel tube and assembling it, and 4) disassembling and removing equipment from the tunnel after the second tube has been excavated.

6.2 COSTING OF THE TUNNEL SETUP OPERATION

The activity is comprised of the cost of labor only. It is assumed that the amount of labor required for each of the four subactivities, including the labor consumed in the learning curve process, is as follows:

	Subactivity	Number of Work Shifts
1.	Lowering and assembling equipment in first tube	67
2.	Disassembling and lifting equipment from first tube	35
3.	Lowering and assembling equipment in second tube	46
4.	Disassembling and lifting equipment from second tube	35
	TOTAL TUNNEL SETUP OPERATION	183

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Appendix E contains a table of the crew composition for equipment assembly/disassembly underground. From this table, the model derives the number of man-hours per shift required of each type of labor skill. Next, the model extracts from the labor cost data file in Appendix G the cost per man-hour for each skill and the cost per man-hour of fringe benefits for the appropriate city. The model then adds 34.88 percent of the hourly wage rate to the hourly fringe benefits rate figure to account for the government-mandated benefits of social security (6.13 percent), workers' compensation (24.00 percent), and unemployment taxes and insurance (4.75 percent)*. The sum of the hourly wage rate and the hourly benefit rate (including both union-stipulated and government-stipulated benefits) equals the total cost per man-hour for a specific labor skill. The model multiplies the total cost per man-hour by the number of man-hours per shift required to produce the labor cost per shift for each skill. Summing the labor cost for each skill yields the total labor cost per shift for the tunnel setup operation. Once the labor cost per shift is computed, it is multiplied by the total number of shifts required for the tunnel setup operation (from the table above) in order to arrive at the total labor cost for this part of the job.

*See note, page 26.

7. TUNNEL EXCAVATION, SUPPORT, AND LINING

7.1 INTRODUCTION

This activity comprises the bulk of the cost of tunneling construction. Consequently, its accurate estimation is of primary importance to designers, planners, and contractors. The model estimates the cost of this activity at a greater level of detail than it does for the other activities. The cost includes all expenses that are incurred from the time shaft construction has been completed and tunnel excavation has begun, until such time as excavation of the tunnel is complete. These expenses consist of all labor, material, and equipment costs incurred both underground and above ground (with the exception of overhead labor costs) to accomplish the activity. This activity does encompass the placement of the permanent lining but does not encompass the cost of laying subgrade along the tunnel invert or constructing the walkway. These latter costs are incorporated in the subsequent tunnel invert pour and finishings activity.

In order to estimate the cost of the tunnel excavation, support and lining activity, it must first be redefined as a sequence of smaller activities whose labor, material, and equipment costs are individually determined. These smaller activities, or subactivities, vary greatly depending on the geological conditions, the construction method, and the temporary support system. Therefore, in order for this model to generate costs for the subactivities accurately, it must develop them based on the following parameters.

When a tunnel is constructed through soft ground, the contractor ordinarily chooses to use either a shield with digger or a shield with conventional mining as the construction method. This decision is made earlier in the course of the model.

Refer to Section 2.3 of this report (Contractor Decisions) for a synopsis of the mechanism by which the model chooses between these two methods and the less often used alternatives of forepoling and floating crown bars. The contractor's possible choices, if not limited by the owner, for the temporary support system are ribs and lagging, steel sets, or precast concrete. Therefore the following six options apply in excavating and supporting a tunnel in soft ground: 1) shield with digger and ribs and lagging as temporary support, 2) shield with digger and steel sets as temporary support, 3) shield with digger and precast concrete as temporary support, 4) shield with conventional mining and ribs and lagging as temporary support, 5) shield with conventional mining and steel sets as temporary support, and 6) shield with conventional mining and precast concrete as temporary support.

When the subway tunnel is constructed through rock, the contractor ordinarily chooses to use either drilling-and-blasting or a tunnel boring machine as the construction method. Once again, this decision is delineated in the Contractor Decisions section of the report. The contractor's possible choices for the temporary support system are rock bolts, rock bolts and shotcrete, rock bolts and steel sets, shotcrete, ribs and shotcrete, and ribs and lagging. Twelve options are available in excavating and supporting a tunnel in rock, since either excavation method can be linked with any of the six support methods.

In mixed face conditions, combinations of the excavation and support techniques for soft ground and rock are utilized in accordance with the specifications detailed in Appendix C.

The hauling system, underground support system, above ground support system, permanent lining, and muck disposal are independent of the construction method and temporary support system. Hence, the cost of the tunnel excavation, support, and lining activity can be defined in terms of the following subactivities: 1) excavation and temporary support at the face, 2) hauling system, 3) underground support, 4) above ground support, 5) permanent lining, and 6) muck disposal. The fifth subactivity is included only when the tunnel's temporary support system does not serve as the final support system, that is, when the temporary support is ribs and lagging and the permanent support is poured concrete.

7.2 EXCAVATION AND TEMPORARY SUPPORT AT THE FACE OF SOFT GROUND TUNNELS

This subactivity consists of all labor, equipment, and material costs incurred in excavation and temporary support at the face of soft ground tunnels.

7.2.1 Shield with Digger, and Ribs and Lagging as Temporary Support

If the construction method is shield with digger and the temporary support system is ribs and lagging, then the cost of excavation and temporary support at the tunnel face is determined in the following manner. The labor cost is calculated by extracting from Appendix E the crew composition figures for excavation of soft ground using a shield with digger, ribs and lagging, and the specific number of work shifts previously determined in the model. Given the number of workers within each skill category, the model calculates the number of man-hours required of each skill on a daily basis. Next, the model extracts from the labor cost data file in Appendix G the cost per man-hour for each skill and the cost per man-hour of fringe benefits for the appropriate city. The model then adds 34.88 percent of the hourly wage rate to the hourly fringe benefits rate figure to account for the government-mandated benefits of social security (6.13 percent), workers' compensation (24.00 percent), and unemployment taxes and insurance (4.75 percent)*. The sum of the hourly wage rate and the hourly benefit rate (including both union-stipulated and government-stipulated benefits) equals the cost per man-hour for a specific labor skill. The model multiplies the total cost per man-hour by the number of man-hours required to produce the daily labor cost for each skill. Summing the daily labor cost for each skill yields the total daily labor cost for excavation and temporary support at the face. Note that if grouting is done, the crew composition is increased to account for the additional workers needed to place the grouting. These figures are included in the crew composition table in Appendix E. Once the labor cost per day is computed, it is multiplied by the number of days required to complete the excavation and support of the tunnel in order to arrive at the total labor cost for this part of the job. The number of days is calculated by dividing the length of the tunnel segment by the average advance rate, which has been previously determined in the model. Note that in the procedure for computing labor costs there is an implicit assumption that the second parallel tube is constructed after the first one is complete rather than concurrently with the first one. If the contractor does decide to excavate the two tubes simultaneously, then the model multiplies the labor cost associated with the first tube by two to produce the actual total labor cost.

The equipment costs vary depending on the contractor's decision of constructing the two tubes concurrently or sequentially. When constructing the two tubes sequentially, the contractor utilizes the same shield with digger for both tubes. The write-off value for the shield with digger is then based on the diameter

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*See note, page 26.

of the tubes and the combined length of both tubes, which have been determined previously by the model. The equipment cost is calculated by multiplying the write-off value (percent) by the original cost of the shield and digger, and adding the cost of breasting (if it is needed), the cost of a poling hood (in the event of running sand, silt, or gravel), the cost of a rib expander, the cost of a laser guidance system, the cost of insurance spare parts for equipment (approximately 8 percent of the current shield and digger value), and the cost of working spare parts (which is assumed to be $1.25 times the number of cubic yards to be excavated). Note that backup equipment for the shield and digger is not included here, because its cost is incorporated into the cost of the shield and digger unit. Grouting equipment (including two grout pumps, a batch plant, and four cars), is added at this point if grouting is required.

The cost of materials used in excavating the tunnel and placing the temporary supports is calculated as follows. The cost per pound of ribs for a given tunnel diameter is obtained from the material cost data file in Appendix H. This cost is multiplied by the weight per foot specified and by the circumference of the tunnel to obtain the cost per rib. This cost is then multiplied by the number of ribs required. The number of ribs is determined by dividing the length of the tunnel by the distance between each rib. The model assumes a standard distance of 48 inches between ribs. The cost of wood lagging is calculated by extracting from the material cost data file the cost of a 6-inch x 6-inch x 4-foot piece of lagging (12 board feet). This unit cost is multiplied by the number of pieces of lagging needed for the tunnel, which is calculated by dividing the tunnel circumference by 6 inches to determine the number of pieces of lagging per rib and multiplying that number by the number of ribs. Additional materials to be totalled here include materials for grouting (if grouting is required) and electrical power.

The cost of grouting is calculated by extracting the cost per cubic foot of grout from the material cost data file and multiplying that figure by the number of cubic yards of grout needed. The number of cubic yards of grout is determined by assuming a 2-inch thickness of grout around the perimeter of the tunnel for the entire tunnel length.

The cost of power is calculated by extracting the cost of power per kilowatt hour from the material cost data file and multiplying it by the number of kilowatt hours required. The number of kilowatt hours is calculated by multiplying the horsepower of the shield and digger by 1.1 and multiplying that figure by 0.75 (the assumed operating capacity of the shield and digger). The result is the kilowatt usage per hour. This number is multiplied by the number of hours of operation per day (8, 16, 20, or 24, depending on the number and length of work shifts) and then multiplied by the number of days required to complete the excavation and support of the tunnel. The sum of these various material costs equals the total material cost for this part of the job.

7.2.2 Shield with Digger and Steel Sets as Temporary Support

The labor cost for this excavation and support method is calculated in the same manner as for shield with digger and ribs and lagging. The only disparity is that a different crew composition is extracted from Appendix E for use in these calculations.

The equipment cost is also calculated in the same manner as for shield with digger and ribs and lagging, with the exception that the cost of a steel sets installer, rather than a rib expander, is incorporated into the calculations. The cost of a steel set installer is obtained from the equipment cost data file in Appendix F.

The material cost is calculated by multiplying the segment length by the unit cost of steel sets per foot, which is extracted from the material cost data file in Appendix H. Additional material cost considerations include grouting, if required, and power consumption. These two costs are calculated in the same manner as described previously.

7.2.3 Shield with Digger and Precast Concrete as Temporary Support

The labor cost is calculated as delineated above (Section 7.2.1), except that a different crew composition table is used.

The equipment cost is also calculated in the same manner as before, save that the cost of precast concrete installation equipment, rather than the cost of a rib expander, is included. The cost of a precast concrete segment installer for a given tunnel diameter is extracted from the equipment cost data file.

The material cost is calculated by multiplying the surface area of the tunnel by the cost per square foot of precast concrete, which is extracted from the material cost data file. The choice of using precast concrete segments is dependent on the length of the tunnel. Grouting and power costs are also calculated in the same manner as described in Section 7.2.1.

7.2.4 Shield with Conventional Mining and All Types of Temporary Support

When a shield with conventional mining is used to excavate the tunnel face, the shield is advanced via its hydraulics. Excavation is then accomplished with a mucker and pneumatic spaders. Calculation of the labor cost is done as before, using the appropriate crew composition table in Appendix E.

The cost of equipment is computed by first extracting the costs of a shield with its hydraulics for a given tunnel diameter, a mucker, and a pneumatic spader from the equipment cost data file. The unit cost of a pneumatic spader is multiplied by five to arrive at the total cost of pneumatic spaders for the job. The cost of shield peripherals such as a poling hood are obtained if needed. The cost of the temporary support system installer, be it a rib expander, a steel set installer, or a precast concrete segment installer, is also ascertained. The summation of all these costs equals the total equipment cost. The costing procedure for materials is identical to the procedure explained previously for the applicable temporary support system.

7.3 EXCAVATION AND TEMPORARY SUPPORT FOR ROCK TUNNELS

This subactivity consists of all labor, equipment, and material costs incurred in the excavation and temporary support at the face for rock tunnels.

7.3.1 Tunnel Boring Machine (TBM) Excavation

The cost of excavation at the face using a tunnel boring machine is calculated by summing the costs of equipment, labor and materials and for this effort.

The equipment cost is comprised of the following items:

1. The cost of the tunnel boring machine. This cost has been previously determined (Contractor Decisions) by extracting from the equipment

cost data file the cost of a tunnel boring machine for a given tunnel diameter and multiplying it by the write-off value (percent). The write-off value is a function of the tunnel length and is found in Appendix D.

2. The cost of cutters and rings. This cost is computed by extracting the price of rings per cubic yard of excavation from the equipment cost data file and multiplying it by the number of cubic yards to be excavated. The cost of rings ranges from 5 to 9 dollars per cubic yard, depending on the strength of the rock. The cost of cutters is included in the cost of the TBM. Additional equipment needed for excavation at the face includes a laser guidance system, a rib expander, a shotcrete pump, a drill jumbo for installation of rock bolts, a steel set installer, and spare parts. The cost for each of these items, except for the drill jumbo, is calculated in a manner identical to the equipment costing procedures for soft ground tunneling (see Appendix F). The costing procedure for drill jumbos is described in the next section.

The labor cost is calculated by extracting the number and type of workers from the appropriate crew composition table and then, for each labor category, multiplying the cost per hour (Appendix G) by the number of man-hours required daily. The sum of these costs is multiplied by the duration of excavation to yield the total labor cost for excavation.

The material cost is calculated in the same manner as for a shield and digger.

7.3.2 Drill-and-Blast Excavation

The cost of excavation at the face via drilling-and-blasting is calculated by summing the costs of equipment, materials and labor for this effort.

The major piece of equipment needed is a drill jumbo, the cost of which is obtained from the equipment cost data file in Appendix F. The particular jumbo selected depends on the jumbo's mounting (wheels or rail), the tunnel diameter, the number of face drills, and the number of rock bolt drills. If rock bolts are used as part of the tunnel's temporary support system, it is assumed that there are five face drills and two rock bolt drills on the jumbo. If rock bolts are not used, it is assumed that there are four face drills on the jumbo. The original cost of the drill jumbo selected is multiplied by its write-off value, which is listed in Appendix D. Added to this value is the cost of one or two spare drills (one spare if there are four drills on the jumbo, two spares if there are seven drills total on the jumbo). The cost of drills is obtained from the equipment cost data file. Other equipment that may be required includes a rib expander, a shotcrete pump, a steel set installer and spare parts. The cost for each of these items is calculated in a manner identical to the equipment costing procedures for soft ground tunneling.

The materials needed for drill-and-blast excavation are, in part, a function of the type of tunnel support system. Such materials include rock bolts, shotcrete, steel sets, and ribs and wood lagging. The costing procedures for steel sets, ribs and lagging, as well as for electrical power, are delineated in the sections of this chapter dealing with soft ground tunnels. The only modification made to the procedure is that a larger tunnel size is incorporated in the calculations, which reflects an estimated blasting overbreakage rate of 11 percent.

To cost rock bolts, the number of rock bolts needed to form a four-foot by four-foot grid pattern along the tunnel walls is calculated and multiplied by the unit cost of rock bolts obtained from the material cost data file.

To cost shotcrete, the square footage of shotcrete required to cover the surface area of the tunnel, after overbreakage is accounted for, is determined. The square footage of shotcrete is multiplied by the unit cost of shotcrete, found in the material cost data file, to arrive at the total cost for this item.

Other materials required for the drill-and-blast operation include dynamite, prills, caps, wire, drill bits, and drill steel. The cost of dynamite is dependent on the predominant strength of the rock being blasted. If the rock is decomposed or soft, blasting entails 2.8 pounds of dynamite per cubic yard of excavation. For medium rock, 4.3 pounds of dynamite per cubic yard of excavation is required, and for hard rock the figure is 6.4 pounds. The appropriate figure is multiplied first by the number of cubic yards to be excavated and then by the cost per pound of dynamite (from the material cost data file) to produce the total cost of dynamite. The cost of prills is assumed to equal 25 percent of the cost of dynamite.

The cost of caps and wire is ascertained as follows. The number of holes to be drilled in the tunnel face for each blasting round is calculated by dividing the area of the face square feet, by 3.7. The total number of blasting rounds to be executed is calculated by dividing the segment length by the depth of each round, which has been previously defined in the model. The number of cap and wire assemblies needed equals the number of holes per round, times the number of blasting rounds. The number of assemblies is multiplied by the cost per assembly (from the material cost data file) to yield the total cost of caps and wire.

To determine the cost of drill bits and drill steel, the amount of drilling to be done in the course of excavating and supporting the tunnel must be calculated. The amount of drilling required for rock bolts equals the number of rock bolts times 10 feet. The amount of drilling required for blasting equals the number of holes per round times the segment length. The total amount of drilling required is equal to the amount of drilling for rock bolts plus the amount of drilling for blasting. The total amount of drilling is divided by a 1500-foot-life per drill bit to obtain the total number of drill bits used in the tunnel excavation and support process. The number of pieces of drill steel is similarly determined by dividing the total amount of drilling by a 2000-foot-life per piece of drill steel. The number of drill bits is multiplied by the unit cost of drill bits to produce the total cost of drill bits. Likewise the number of pieces of drill steel is multiplied by the unit cost of drill steel to produce the total cost. The unit costs for both items are listed in the material cost data file.

The labor cost for drill-and-blast excavation is calculated by extracting the number of workers within each labor category from the appropriate crew composition table in Appendix E. For each labor category, the number of man-hours required daily is projected from the crew composition data and multiplied by the hourly cost, consisting of wages, union-stipulated benefits, and government-stipulated benefits for that city. The resulting figures represent the daily cost for each labor category. The sum of these figures is multiplied by the number of days of excavation to yield the total labor cost for excavation of one tube. Note that with the drill-and-blast technique, excavation in the two parallel tubes proceeds simultaneously. In other words, while drilling and blasting activities proceed in one tube, mucking activities are carried out in the other tube, and vice versa.

Accordingly, the model divides the advance rate by two for purposes of determining the number of days required to complete tunnel excavation.

7.4 HAULING SYSTEM

The capacity of the hauling system is dependent on the rate of muck generation. The hauling system can be either rail mounted or rubber tire mounted. The decision concerning whether to use rail or rubber is discussed in Section 2.3. When rail is utilized, the cost of the hauling system is a function of the number of locomotives, the number of cars per train, the size of each car, the length of the tunnel, and the type of muck lifting system adopted. Values for all of these parameters have been determined at a prior point in the model.

The labor cost for muck hauling is computed by extracting the number of workers required under each skill category from the crew composition tables in Appendix E. The labor cost per day is calculated by multiplying the hourly cost, consisting of wages and benefits, for each skill category by the number of man-hours required, as derived from the crew composition tables. The resulting figures, representing the daily labor cost for each skill category, are then summed. The labor cost per day is multiplied by the duration of excavation to produce the total labor cost for muck hauling. The equipment and material costs for a rail system are calculated by summing the following items:

1. <u>MUCK CARS</u> This cost is determined by first extracting the cost per car for a previously defined car size from the equipment cost data file. Car sizes can range from 5 to 18 cubic yards. This unit cost is then multiplied by the number of cars in the hauling system, which has also been previously defined, to yield a total cost for muck cars.

2. LOCOMOTIVES This cost is calculated by extracting the unit cost of a diesel locomotive or a battery-powered locomotive from the equipment cost data file and multiplying it by the number of locomotives required. The type and number of locomotives have been previously defined in the model.

3. BATTERIES (if locomotive is battery-powered), electric generators (if locomotive is diesel-powered), and other support equipment for each locomotive. This cost is extracted from the equipment cost data file.

4. FLAT CARS FOR HAULING THE TEMPORARY SUPPORTS TO THE TUNNEL FACE This cost is calculated by extracting the unit cost of a flat car from the equipment cost data file and multiplying it by the number of flat cars required. The number of flat cars is assumed to equal six.

5. RAIL This cost is calculated by extracting from the material cost data file the cost per lineal foot of eighty pound rail. This unit cost is multiplied by the length of the rail to arrive at its total cost. Unlike other material costs, rail is not fully depreciated but has a write-off value of only 40 percent. Therefore, its cost is multiplied by a factor of 0.4 to produce its bid cost.

6. CALIFORNIA SWITCH If the tunnel is long, an intermediate turnout may be necessary to allow trains to bypass one another. If more than two locomotive trains are used, this switch would be required. The cost

of the switch is extracted from the equipment cost data file. This cost includes the cost of labor to install the switch.

7. <u>TIES FOR THE RAIL</u> This cost is calculated by extracting the cost per tie from the material cost data file and multiplying it by the number of ties required. The number of ties is obtained by dividing the length of the tunnel by two. This number allows for placing two ties every 4 feet, one on each rail. The ties are either wood or metal, depending on the type of temporary support system. If the temporary support system is ribs and wood lagging or steel sets, then the rail is tied directly to the temporary support system by means of metal ties. If the temporary support system is precast concrete, then wood ties are used.

8. <u>MUCK LIFTING SYSTEM</u> If the muck lifting system consists of a crane, then the cost of the crane is calculated by extracting the unit cost for the appropriate crane size (previously defined in the model) from the equipment cost data file, multiplying it by a write-off factor (percent) to determine the monthly cost of the crane, and multiplying again by the number of months of excavation. A similar procedure is used for headframes and hoists.

7.5 UNDERGROUND SUPPORT SYSTEM

The materials and equipment needed for the underground support system include the following items: ventilation lines, compressed air lines for pneumatic tools, power lines, tunnel lighting, grout mixing plants, and dewatering pumps and lines.

The cost of ventilation lines is calculated by extracting from the material cost data file the cost per lineal foot of a 24-inch, 36-inch, or 48-inch diameter ventilation line. The diameter of the ventilation line selected by the model depends on the type of hauling system instituted and the type of equipment used at the tunnel face. If the equipment is electrically operated, then the ventilation line chosen is 24-inches in diameter. If the hauling system comprises rubber tire vehicles, then the ventilation line used is 36 inches in diameter. If the hauling system is as just described, and additionally, the equipment used at the tunnel face is gas-powered or diesel-powered, then the ventilation line required is 48 inches in diameter. The unit cost of the appropriate ventilation line is multiplied by the tunnel length to determine the total cost of the ventilation lines. The model assumes a 100 percent write-off on the ventilation lines.

The cost of compressed air lines for pneumatic tools utilized at the tunnel face is calculated by extracting the cost per lineal foot of a compressed air line from the material cost data file and multiplying that cost by the length of the tunnel. The model assumes 4-inch diameter compressed air lines for shield or TBM excavation, and 8-inch diameter compressed air lines for drill-and-blast excavation.

The cost of power lines is calculated by extracting from the material cost data file the cost per lineal foot of a copper wire power line (5000 volts for a TBM or a shield with digger and 600 volts for a shield alone) and then multiplying it by the tunnel length. Since the write-off value for power line is 60 percent rather than 100 percent, its bid cost is derived by multiplying the original cost by 0.6.

The cost of a transformer with the appropriate volt-amperage is then obtained from the equipment cost data file and added to the power line cost.

The cost of tunnel lighting is calculated by extracting the cost per linear foot of lighting from the material cost data file and multiplying it by the tunnel length. The unit cost in the file reflects the assumption that lights are installed at 40-foot intervals.

The cost of the grout mixing plant at the bottom of the shaft, if required, is calculated by extracting the unit price of a grout mixing plant from the equipment cost data file. The model assumes the grout mixing plant is depreciated 80 percent.

The cost of dewatering pumps is calculated by extracting from the equipment cost data file the cost of a 2-inch, 4-inch, or 6-inch pump, and multiplying it by the number of pumps. The size of the pump is determined by the water condition in the tunnel (none, slight, moderate, or heavy groundwater inflow) as given to the model. The number of pumps is assumed to be three. The cost of dewatering lines is calculated by extracting from the material cost data file the cost per linear foot of a 2-inch, 4-inch, or 6-inch water line. The water line selected depends on the pump size to be utilized. This cost is multiplied by the length of the tunnel to determine the bid cost. The model assumes that dewatering pumps and lines are depreciated 80 percent.

Most of the labor cost for underground support is covered by the labor cost for excavation and temporary support at the tunnel face. Underground laborers are able to perform excavation and temporary support work only 55 percent to 60 percent of the time. This figure represents system availability and is the underlying basis for the determination of advance rates. The laborers' remaining time is then utilized for the underground support function. This function includes the extension of rail lines, power lines, ventilation lines, and tunnel lighting. The model costs this work by assuming that it entails the use of a dewatering crew. These laborers are responsible for the support activities listed above, and are also responsible for miscellaneous activities, tunnel cleanup, and monitoring the dewatering pump.

7.6 ABOVE GROUND SUPPORT (LABOR AND EQUIPMENT)

The labor cost for above ground support is calculated by obtaining the crew composition for above ground support from Appendix E. These data identify the number of workers within each skill category that are needed to provide above ground support. For each skill category, the model computes the cost per hour for wages, union benefits, and government benefits using the labor cost data file and multiplies it by the number of man-hours required on a daily basis. The summation of these costs equals the labor cost per day for above ground support. This cost figure is then multiplied by the duration of excavation, support, and permanent lining work to arrive at the total labor cost.

The equipment cost is calculated by adding the costs of the following items: a compressor, a 25,000-pound forklift, a CAT 950TM loader, and a fan system. The cost of a compressor is calculated by extracting from the equipment cost data file the unit cost for the appropriately sized compressor. The particular compressor chosen by the model depends on the methods of construction and ground control used. If many pneumatic tools are used, then the 1600 CFM portable compressor is selected. If compressed air requirements are minimal, then the 1100 CFM portable compressor is selected. The bid cost of a compressor is adjusted by a write-off factor times its original value per month of usage. The bid cost of a 25,000-pound forklift is equal to 3 percent of its original value per month of use, which is calculated by extracting the unit cost of the forklift from the equipment cost data file and multiplying it by 0.03 and then by the number of months of usage. The bid cost of a CAT 950 loader is also equal to 3 percent of its original value per month of usage, and is calculated similarly. The cost of fan equipment for tunnel ventilation is calculated by extracting from the equipment cost data file the cost of a 24-inch, 36-inch, or 48-inch size fan system. The fan size chosen depends on the size of the ventilation line, which has been previously determined. The model assumes that two or three fan systems are present during tunnel excavation, one of which serves in a backup mode.

7.7 PERMANENT TUNNEL LINING

The cost of permanent tunnel lining is zero when the temporary support system consists of either steel sets or precast concrete, because such temporary supports also serve as the permanent lining for the tunnel. When the temporary supports system consists of ribs and lagging, then the permanent lining must be poured concrete. The cost of poured concrete for the permanent lining of the tunnel is computed by summing the cost of buying and placing reinforcing steel, the cost of formwork, and the cost of buying and placing poured concrete.

The materials needed for the poured concrete operation consist primarily of concrete, reinforcing steel, steel forms, vibrator forms, and curing compound. The volume of concrete is computed by means of the following formula:

$$\text{Concrete (CF)} = 2/3 \times \pi \times \frac{(\text{inside diameter} + \sqrt{1.11}\ \text{outside diameter})}{2} \times 1 \times \text{tunnel length}$$

In other words, two-thirds of the circumference of the tunnel multiplied by a concrete thickness of 1 foot, multiplied by the tunnel length equals the volume of concrete for the tunnel's permanent lining. The assumption is made here that two-thirds of the circumference constitutes the tunnel arch and is, therefore, lined with 1 foot of poured concrete, while one-third of the circumference constitutes the tunnel invert and is treated separately. In addition, the assumption is made here that a reasonable figure for the circumference may be obtained by averaging the tunnel's inside diameter and outside diameter (increased by the overbreakage factor). The volume of reinforcing steel is approximately 0.7 percent of the volume of concrete. Hence,

$$\text{Weight (pounds) of reinforcing steel} = 0.007 \times \text{cubic feet of concrete} \times 490 \text{ lb/cu ft}$$

The price per cubic foot of concrete is obtained from the material cost data file and multiplied by the number of cubic feet of concrete calculated above in order to determine the total cost of concrete. Similarly, the price per pound of reinforcing steel in the material cost data file is multiplied by the number of pounds of reinforcing steel in order to derive the total cost of reinforcing steel. To determine the amount of curing compound needed, the surface area of the permanent lining must first be calculated by multiplying two-thirds of the tunnel circumference by the tunnel length:

$$\text{square feet of concrete to be treated with curing compound} = 2/3 \times \pi \times \text{inside diameter} \times \text{tunnel length}$$

Approximately 1 gallon of curing compound is used to treat 300 square feet of concrete. The square footage of concrete calculated above is divided by 300, in order to determine the total amount of curing compound required for the tunnel lining. This amount is multiplied by the cost per gallon of curing compound in the material cost data file to produce the total cost of curing compound. As concerns steel forms and vibrator forms, a standard length of 320 lineal feet, divided into ten 32-foot sections, is assumed. The cost of both steel forms (per sq. ft.) and vibrator forms (linear ft.) is in the material cost data file. In both cases, the cost is multiplied by 320 for the total cost of steel forms and vibrator forms.

The principal pieces of equipment utilized in the poured concrete operation are a hydraulic form traveler, a locomotive, two agitator cars, two conveyors, a concrete pump, and six vibrators. The costs of these items are extracted from the equipment cost data file.

The cost of labor is determined by extracting the crew composition for poured concrete operations from the appropriate table in Appendix E. From these data, the number of man-hours required daily of each type of labor can be derived. For each labor classification, the number of man-hours is multiplied by the hourly cost of wages and benefits as derived from data in Appendix G. These figures represent the daily cost of each type of labor. These figures are summed and the result is multiplied by the duration of permanent lining work to produce the total labor cost.

7.8 MUCK HANDLING

There are four parts to the muck handling process: lifting the muck from the bottom of the excavation to the surface, hauling the muck from the construction site to the dump, dumping and reworking muck at the dump site, and the dumping fee.

Lifting can be accomplished by: a vertical lift system (i.e., either a crane, headframe and hoist, bucket elevator or conveyor). The model selects the method by means of the input variable provided by the user.

The cost of lifting via a crane or other method consists of an equipment component and a labor component. The costs of a 100-ton crane, muck car, and such are extracted from Appendix F. The labor cost is derived using the same procedure as described earlier; the crew composition for muck lifting is located in Appendix E and the duration of the muck lifting activity is assumed equal to the duration of the excavation.

The cost of hauling muck is the cost per mile of transporting one cubic yard of muck (see Appendix I) multiplied by the effective volume of muck generated, then multiplied by the mileage between the dump site and the construction site. The distance between the dump site and the construction site is provided by the user.

The cost per cubic yard of dumping and reworking muck at the dump site is also found in Appendix I. It is multiplied by the effective volume of muck to provide the total cost of dumping and reworking. The user inputs whether the dumping fee is small, medium, or large (see Appendix B, Section 10). The corresponding cost per cubic yard is extracted from the file and multiplied by the effective volume of muck.

8. TUNNEL CONSTRUCTION EQUIPMENT REMOVAL

This section describes the activity of disassembly and removal of major pieces of equipment from the excavation area. Since tunnel excavation machinery can be very large and difficult to remove from the site, the associated impact on cost and schedule may be significant. The costs involved in this activity are considered in conjunction with tunnel setup, where the cost of tunnel construction equipment removal is computed as follows:

1. The crew composition for equipment assembly/disassembly underground is obtained from Appendix E.

2. The daily labor cost is computed using the crew composition table and the labor cost data file. The computation procedure is the same as described in previous chapters. This daily cost is then multiplied by 30 days (for a TBM) or by 20 days (for a shield with digger) to arrive at the total cost of the activity.

9. TUNNEL INVERT POUR AND FINISHINGS

This section analyzes tunnel invert pouring, subgrade installation, drainage piping within the subgrade, safety walk pouring, curing of all concrete, and concrete treatment and finishings.

A typical tunnel cross-section as depicted in Figure 9-1 is used to calculate the volume of concrete, the weight of reinforcing steel, and the amount of formwork needed for this activity.

Safety Walk:	width depth	10 percent of OD 15 percent of OD
Subgrade and Invert:	max CL depth width of invert	20 percent of OD 60 percent of OD
Lining:	thickness invert section	T ft 1/3 of tunnel circumference = 1/3 CD

where, OD = Outside Diameter x $\sqrt{1.11}$ (to account for over breakage)

ID = Inside Diameter

CD = Center Diameter = (OD + ID)/2

CL = Center Line

<u>Volume of Concrete (CF) per Tunnel Foot:</u>

Safety Walk:

$$V_1 = 2/3\,(0.1\text{ OD})\,(0.15\text{ OD}) \times 1\text{ ft}$$

$$V_1 = 0.01\text{ OD}^2$$

Subgrade and Invert:

$$V_2 = 2/3\,(0.2\text{ OD})\,(0.6\text{ OD}) \times 1\text{ ft}$$

$$V_2 = 0.08\text{ OD}^2$$

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Lining (invert part):

$$V_3 = 1/3 \times \pi \times \sqrt{\frac{OD + ID}{2}} \times 1 \text{ ft} \times 1 \text{ ft}$$

$$V_3 = 0.524\,(OD + ID)$$

Total Volume of Concrete (CF) per Lineal Foot of Tunnel (LF): $V_t = 0.09\,OD^2 + 0.524\,(OD + ID)$ CF/LF

Example: What is the total volume of concrete (CF) required for the tunnel invert, subgrade, safety walk, and invert lining, if the tunnel is 3000 feet long and has an outside diameter of 20 feet?

$V_1 = 0.01\,OD^2 = 0.01\,(20)^2 = 4$ CF/LF

$V_2 = 0.08\,OD^2 = 0.08\,(20)^2 = 32$ CF/LF

$V_3 = 0.524\,(OD + ID) = 0.524\,(20 + 18) = 19.912$ CF/LF

$V_t = 55.912$ CF/LF

$V_T = V_t \times$ length of tunnel $= 55.912 \times 3000 = 167{,}736$ CF $= 6{,}212$ CY

The cost of concrete is then equal to the total volume of concrete (in cubic yards) times the unit cost of concrete from the material cost data file.

Weight of Reinforcing Steel (LBS):

Since most of the loading in a tunnel is of a compressive nature (thereby being borne efficiently by the concrete), the amount of reinforcing steel required is rather small. After analyzing several tunnel designs, it was noted that the volume of steel typically ranges from 0.6 percent to 1.0 percent of the volume of concrete for the invert and subgrade. The model therefore assumes a volume of steel equal to 0.7 percent of the volume of concrete:

$$V_s(CF) = (0.7/100)\,V_t$$

Multiplying this volume of steel by 490 LBS/CF yields the weight of steel:

$$W_s = 490\ V_s\ \text{(LBS)}$$

The cost of the reinforcing steel equals the weight W_s of steel multiplied by the cost per pound of rebar from the material cost data file.

Formwork:

For underground concrete applications, only one specific type of formwork is considered, namely, steel forms. These forms are reusable and have a long life. The model assumes that the contractor buys 320 linear feet of forms and uses them for the entire duration of the project. The forms travel across the length of the tunnel (in 32-foot sections), thereby entailing the use of a hydraulic traveler. Ten 32-foot vibrating forms are used to attain a better quality of concrete. Six hand-held concrete vibrators are also used to achieve a void-free concrete mix. The costs of the hydraulic traveler and the concrete vibrators are found in the equipment cost data file, while the costs of forms are found in the material cost data file.

Labor for Concrete Placement:

The crew composition for poured concrete operations is found in Appendix E. To obtain the cost of labor, the hourly rate per labor trade from the data in Appendix G must first be derived. Next, the rate for each trade is multiplied by the number of man-hours required daily (derived from the table in Appendix E). The sum of these figures equals the daily labor cost. Multiplying this cost by the duration of the concrete placement work produces the total labor cost for this activity.

Curing:

The model assumes that curing compound is used at a rate of 300 SF/GAL. Using this figure, the total volume of curing compound can be obtained by multiplying the surface area of concrete to be treated by one gallon of curing compound per 300 square feet. This volume is then multiplied by the cost of curing compound per unit volume to yield the total cost of curing compound.

$$\text{Cost of Curing Compound} = \begin{array}{l}\text{Surface Area (SF)} \\ \text{to be treated}\end{array} \times \frac{1\ \text{GAL}}{300\ \text{SF}} \times 3.40 \frac{\$}{\text{GAL}}$$

Note that:

Surface Area of Invert = .75 OD x L;

where:

L = Length of Tunnel

OD = Outside Diameter.

Mechanical and Drainage:

For drainage purposes, porous wall concrete pipes are used. The diameter of the pipes is a function of the level of groundwater inflow. The model selects 4-inch, 6-inch, 10-inch, or 18-inch diameter pipes depending on whether the groundwater inflow is nil, slight, moderate, or heavy. The cost per linear foot for various diameter pipes is found in the material cost data file. By multiplying the appropriate unit cost by the length of piping required, the total cost of invert drainage pipe is obtained.

Finishings:

For concrete finishings, the model makes the following assumptions:

- o form finishing for walls and roof
- o wood float finishing for invert slabs
- o broom finishing for safety walk.

A lump sum cost (labor, material, and equipment costs combined) for each type of finishing is contained in the unit cost data file in Appendix I. The costs are expressed in dollars/sq ft of concrete. Multiplying the surface area of concrete by the unit cost of the appropriate type of concrete finishing yields the total cost of concrete finishing for a specific part of the tunnel.

10. SHAFT FINISHINGS

The shaft finishing activity is comprised of installation of the ventilation system and concrete finishings, and is usually accomplished at the same time that the tunnel finishing activity is carried out. As concerns the ventilation system, the model assumes that natural ventilation suffices. As concerns concrete finishings, the model assumes form finishing for the shafts. A lump sum cost for form finishing, comprising labor, material, and equipment, is found in the unit cost data file in Appendix I. This cost is defined per square foot of concrete. The model calculates the square footage of concrete via the expression 2 x (shaft length + shaft width) x shaft depth. Multiplying this figure by the lump sum unit cost of form finishing results in the total cost of concrete finishing for a particular shaft. The mechanical and electrical systems for the shafts are covered in the stations model, as well as all architectural work, waterproofing, structural steel, etc.

11. UNDERPINNING AND BUILDING PROTECTION

11.1 INTRODUCTION

This chapter presents a simplified description of the underpinning methods commonly used in subway tunnel construction. It is understood that the cost of this activity is very much site-dependent. For planning purposes, the model bases its cost figures on the type of underpinning method used and the number of structures affected by tunnel construction. The assumptions made in computing these costs are explained in this chapter.

11.2 PIT PIERS

This method of underpinning is used for heavy buildings with large spread footings and involves placing several pit piers under each footing. Each pier is installed in the following manner: 1) an approach pit is excavated from the ground surface down to a level a few feet below the footing, 2) the underpinning pit is excavated directly underneath the footing, and 3) the underpinning pit is backfilled with concrete. Wood lagging is installed continuously between pits. A typical pit pier is 3 feet by 4 feet in plan, with an average depth of 40 feet (the depth usually ranges from 25 to 60 feet). Excavation is done by hand, using a three-man crew, one 8-hour shift, and an advance rate of 4 feet per shift (1 foot per shift in geological conditions of running sand). The cost of hand-excavated pits will increase sharply if running sand is encountered.

11.3 JACKED PILES

This method of underpinning is also used for heavy buildings with large spread footings and requires several jacked piles for each footing. Spread footings are converted into piled foundations by means of the following procedure: 1) an approach pit is excavated from the ground surface down to a level about 6 feet below the footing, 2) the jack pit is excavated directly underneath the footing, and 3) the jack piles are forced into the ground in short sections by high capacity hydraulic jacks that thrust against the footing. Most jack piles consist of 12-inch diameter pipe in sections 3 feet to 5 feet long. The pile is advanced to the required depth through a jacking and cleaning-out process. It is then filled with concrete. A typical pile is 50 feet long on the average, with a range of 30 to 60 feet. It takes a two-man crew approximately six 8-hour shifts to install a 50-foot long pile. The installation rate can increase dramatically if a small boulder is encountered. The model cost of jacked piles assumes that boulders are not encountered.

11.4 PICK-UPS

This method of underpinning entails supporting a column independently of its footing. It is usually accomplished by attaching wide-flanged steel members to each side of the column. Pads are placed under each end of these needle beams, and high capacity jacks thrust against the pads and the needle beams to raise the column load off its footing. This method is frequently used in conjunction with pit piers. Installation time is 2 to 3 weeks.

11.5 ESTIMATING THE COST OF UNDERPINNING

In estimating the cost of underpinning, the model assumes that the user provides the following information: 1) the number of one or two-story wood frame structures to be protected, 2) the number of small masonry structures and light commercial buildings to be protected, and 3) the number of large masonry structures, multi-story buildings, etc. to be protected. For each type of structure, the model assumes a specific method of underpinning and the quantities of materials required:

Structure Description	One or two-story wood frame buildings	Small masonry and light commercial buildings	Large masonry and multi-story buildings, and bridges
Underpinning Method	No underpinning required	18 jacked piles	14 pick-ups and 15 pit piers

The cost of underpinning is then equal to a lump sum cost per pier or pile, multiplied by the number of piers or piles.

11.6 ESTIMATING THE COST OF BUILDING PROTECTION

The user inputs the extent of the monitoring requirements for building settlement, blasting damage, seismic controls, etc., and an indication of the amount of special building protection insurance required. Based on this input, the model selects appropriate lump sum costs for these items from the unit cost data file in Appendix I. The sum of the cost of each item represents the total cost for the building protection activity.

12. GROUNDWATER CONTROL

12.1 INTRODUCTION

Groundwater control is not always needed in tunnel construction, but if water conditions are poor, construction costs increase at a remarkable rate, thereby imposing the need for an effective groundwater control program. There are many techniques presently available to prevent costly delays due to groundwater problems during construction; all of them entail a thorough geotechnical investigation of the site.

The most important factor affecting groundwater control is the elevation of the water table. Other significant factors are the permeability of the soil, the proximity of large water bodies (i.e., lakes, rivers, etc.), the uniformity of the soil, and the effect of dewatering on the settlement of neighboring buildings.

12.2 TYPES OF DEWATERING SYSTEMS

a. <u>Trenching and Pumping:</u> This method is conventional for draining soils with little or moderate groundwater inflow. Trenches are typically 2 feet wide by 3 feet deep, and are excavated with a backhoe loader. Pumping is generally conducted 24 hours a day using a 2-inch pump if the water inflow is slight (less than 200 gal/min/1000 ft), a 4-inch pump if the water inflow is moderate (200-1000 gal/min/1000 ft), and a 6-inch pump if the water inflow is heavy (more than 1000 gal/min/1000 ft). The crew configuration for dewatering is included in Appendix E.

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b. <u>Deep Wells:</u> Deep wells are used to lower the water table. Costs for each well include the cost of: excavation, a submersible pump, a pipe, a water line, and operation. The size of each item depends on the anticipated water inflow. Wells are placed adjacent to the tunnel, every 100 feet along the longitudinal tunnel axis. Each well is excavated 20 feet deeper than the deepest shaft. Excavation costs are calculated on a lump sum basis (Appendix I). Pump operation is overseen by a dewatering crew, as specified in the crew composition table. The dewatering cost (per well) is calculated by adding the results of the following equations:

1) Cost of excavation = depth of well (feet) x cost of excavation per linear foot (Appendix I)
= (depth of deepest well + 20 feet) x cost of excavation per linear foot

2) Cost of pump = cost of a 2-inch, 4-inch or 6-inch submersible pump (Appendix H), respectively, for slight, moderate or heavy water inflow.

3) Cost of pipe = cost of 6-inch, 10-inch or 18-inch pipe per linear foot (for slight, moderate or heavy water inflow) x depth of well.

4) Cost of water line = cost of 2-inch, 4-inch or 6-inch water line per linear foot (corresponds to pump size) x depth of well.

5) Operating Cost = (cost of labor + cost of power in kW-hrs) x number of hours of operation.

12.3 GROUND IMPROVEMENT

This classification covers all techniques used to modify some characteristic of the soil (strength, permeability, etc.). These methods are very site-specific, and are used to facilitate the excavation and support process, minimize the need for underpinning, and improve groundwater conditions. Three techniques are commonly utilized: chemical grouting, cement grouting, and to a limited extent, freezing. Grout is used to reduce the permeability of the soil or when the soil needs to be strengthened. Grout in the form of cement, bentonite, or chemical gel is injected into a soil mass under high pressure. The grout then spreads through the soil mass and hardens, filling the voids between the soil particles by displacing water and air. The lump sum cost of grouting is expressed per cubic yard of soil mass to be treated (see Appendix I). Freezing of the ground is a little-used technique that involves placing a network of pipes throughout the soil mass and circulating a refrigerant. As the water in the soil freezes, the soil becomes a cohesive, icy mass. Freezing does not usually work as well as other ground control methods for coarse-grained soils that are below the water table. The cost of freezing the groundwater is determined in the same manner for grouting.

12.4 COMPRESSED AIR

Tunneling under compressed air conditions results in substantial increases in labor and equipment costs. The model only considers compressed air tunneling for air pressures of 12 lb/sq in or less. As indicated in Appendix J, the advance rate is reduced by 50 percent when compressed air is used, which means that the job duration is twice what it would be under free air conditions. (Note: Under compressed air conditions, groundwater does not flow into the work area; therefore the user must input either 1, no inflow, or 2, slight inflow, for the GROUNDWATER input in Appendix B, p. 98). The labor costs increase accordingly, due to the decreased advance rate and due to the hazardous working environment. In addition, the labor crew is expanded to include two lock tenders, one for the outside and one for the pressure side of the air lock. The wage rates for these laborers are found in Appendix G. The unit price of an air lock (including the compression chamber) is extracted from the equipment cost data file in Appendix F and added to the total equipment cost. Because of the time and expense involved in compressed air operations, a contractor ordinarily chooses this option only when grouting and/or dewatering would provide insufficient groundwater control.

13. CLEANUP AND DEMOBILIZATION

This section describes the activities that occur after construction is complete. Cleanup activities are two-fold: tunnel cleanup and site cleanup.

The cost of tunnel cleanup is computed by extracting the lump sum cost per linear foot of tunnel for this activity from Appendix I, and multiplying by the length of the tunnel. This activity includes removal of tracks and utilities, general cleanup, and so forth.

The cost of site cleanup is estimated via a lump sum figure and can be found in the unit cost data file in Appendix I. The cost of demobilization depends on the number and type of pieces of equipment on the job site. The model specifies three levels of demobilization: light, moderate and extensive, and provides lump sum costs for each in Appendix I.

14. MISCELLANEOUS COSTS, OVERHEAD, INTEREST, AND PROFIT MARGIN

14.1 MISCELLANEOUS COSTS

Miscellaneous costs include certain fixed items that the contractor incorporates into his bid, such as taxes and insurance. These items, together with their approximate dollar values, are listed in Appendix K.

14.2 OVERHEAD

To compute the cost of overhead, the contractor's estimate of the total project duration, as well as the crew composition for overhead activities and the associated labor rates must be determined. The following notation is used:

D_w = the contractor's estimate of the total project duration in working days =

total number of calendar days for project x $\frac{\text{22 workingdays/month}}{\text{30.4 calendar days/month}}$,

where 1 month = 22 working days

N_i = (number of overhead crew members in each job category)$_i$, e.g., project manager, secretary, etc.

L_i = (daily labor rate, including wages and benefits, for each overhead crew member)$_i$

The contractor does not maintain a full-size staff at the beginning or the end of a project. Accordingly, the model assumes an effective total duration of overhead activities equal to two months less than the total duration of the project.

$D_o = D_w - 44$ (1 month = 22 working days)

The total overhead cost is then computed in the following manner:

Overhead Cost (OC) = $D_o \times \sum_i L_i$

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In other words, the overhead cost is equal to the effective duration of overhead activities, in days, multiplied by the daily cost of the entire overhead crew.

14.3 INTEREST

Many factors affect the interest expense that the contractor incorporates in his bid. Such factors include the cost of major pieces of equipment, the payment schedule (i.e., the amount of money retained by the owner during the project, and the time differential between the contractor's expenses and the associated payment by the owner), the owner's willingness to reimburse the contractor for mobilization expenses and the amount of such expenses, the project duration, and the current prevailing interest rates. The model defines the monthly interest expense as follows:

Interest Cost = (cost of each item or activity) x (number of months for reimbursement) x (prime rate + 1%);

where the number of months for reimbursement = 0, 1, or 2, corresponding to high, medium or low owner willingness for prompt reimbursement, respectively.

14.4 CONTINGENCY AND PROFIT

The margin incorporated in a bid for contingency and profit is a function of the general state of the economy, the anticipated number of bidders on the project, the number of tunneling projects expected to arise in the future, the owner's attitude toward contractors (Is he fair? Does he grant change orders when necessary?), and the risk entailed in the project (Is the geology of the area well-known? Are union contracts expected to expire soon? Is the design of the tunnel well-detailed?). The model provides allowances for the above and calculates the contractor's profit allowance according to the following procedure:

Profit Allowance

= 4 percent x Total Construction Cost (if user specifies an optimistic cost estimate)

= 7 percent x Total Construction Cost (if user specifies a most likely cost estimate

= 10 percent x Total Construction Cost (if user specifies a pessimistic cost estimate)

By determining the project cost using each of the above options, a range within which the actual project cost should occur can be determined.

GLOSSARY OF TERMS

backfill	refilling of a trench, excavation, or space around foundations and walls.
bouldery till	drift deposited by a glacier and consisting of clay, sand, gravel, and boulders.
breasting	mechanism at the front of a TBM or shield to hold the face of the excavation.
caulking	the process of stopping up and making tight against leakage by forcing in a sealing substance (caulk).
conduit	pipe or tube for receiving and protecting electric wires or cables (telephone, etc.)
cut-and-cover	station or tunnel constructed in a cut or excavation and covered with material (e.g., earth, paving) after completion.
decking	installation or materials used in installing a surface to move on, or work under (under-the-roof construction).
drill jumbo	a traveling carriage, rail- or wheel-mounted, for mounting drills for tunnel driving.
faulted rock	rock with faults or fractures accompanied by a displacement of one side of the fracture with respect to the other in a direction parallel to the fracture.
floating crown	same as forepoling, but driving sheathing into the ground.
folded rock	rock patterned in folded layers.
forepoling	excavating the ground by driving poles into the ground ahead of the excavation face.
forklift	machine for lifting heavy objects by inserting a row of steel fingers under the load and lifting vertically.
formwork	a set of wooden or metallic forms for placing concrete.
grouting	the process of applying or using grout, a thin mortar fluid poured or sprayed under pressure. Grout is used mainly to fill spaces between the tunnel lining and the surrounding earth.
heading engineer	an engineer/surveyor directing the tunnel heading direction.
jointed rock	rock with fractures or cracks that are not accompanied by dislocation, but are generally arranged in a systematic pattern.

lagging	planking erected to prevent cave-ins in excavations by supporting the soil.
load-haul-dump	truck/loader especially designed for mucking operations.
massive rock	rock having no regular form but may have a crystalline structure (e.g., sandstone).
muck	material generated and removed in the process of excavating or mining.
poling hood	mechanism used to support the face/sides of an excavation when digging by sections; also protects workers.
powderman	sets the dynamite (powder) charge and blast.
shotcrete	a mixture of cement, sand, and water applied under pneumatic pressure.
skip-cage	caged car mounted on wheels, rails, or vertical shafts for carrying men or materials.
slurry	a stable suspension of powdered bentonite in water used to keep an open excavation stable.
soil-grouting	grouting a soil mass to improve its physical characteristics.
soldier piles	long slender members of timber, steel or concrete driven into the ground to resist lateral forces or to carry vertical loads.
steel sheet piles	steel boards driven into the ground to form a wall to retain the side of an excavation.
tiebacks	metallic bars/rods tied to the back of the retaining wall of an excavation, and anchored into the surrounding soil.
track mucker	rail-mounted machine that removes soil from the face of the tunnel and dumps it onto trucks, conveyor belts, etc., for final muck hauling out of the excavation.
trenching	excavating a long narrow cut in the ground.
underpinning	the material and process used to support structures adjacent to the construction site.

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APPENDIX A

GEOLOGICAL CLASSIFICATIONS WITHIN A TUNNEL

A tunnel can be broken down into one, two, or three segments to denote its macro-geology:

1 = Rock

2 = Soft Ground

3 = Mixed Face

If a tunnel were constructed in its entirety through rock, then it would have only one segment (rock). Similarly, if the general geology along the length of the tunnel were either all soft ground or all mixed face, there would also exist only one segment. If the geology along the length of the tunnel were to evolve from soft ground to mixed face, then there would be two segments (soft ground, mixed face), and so on.

Each segment of the tunnel is further divided into geological subsegments, with a maximum of 5 subsegments per segment. Each subsegment is defined in terms of the detailed geological classifications into which it falls. The possible geological classifications within each segment type are as follows:

<u>Segment Type</u>:

1) <u>Rock</u>

Rock strength	1 = decomposed 2 = soft 3 = medium 4 = hard
Geological structure	1 = massive 2 = slightly faulted or folded 3 = moderately faulted or folded 4 = intensely faulted or folded

Joint pattern	1 = very closely jointed	
	2 = closely jointed	
	3 = moderately jointed	
	4 = moderate to blocky	
	5 = blocky to massive	
	6 = massive	
Joint condition	1 = tight or cemented	
	2 = slightly weathered or altered	
	3 = severely weathered, altered, or open	
Abrasiveness	1 = low	
	2 = medium	
	3 = high	

2) Soft Ground

1 = Uniformly soft and compact ground

2 = Soft clay

3 = Firm clay

4 = Stiff, cohesive clay

5 = Running sand, silt, and gravel

6 = Cohesive sand, silt, and gravel

7 = Cemented sand, silt, and gravel

8 = Uncemented sand, silt, and gravel below water

9 = Bouldery till

3) Mixed Face

Vector containing 2 elements (x, y),

where x = soft ground classification (1-9)

and y = rock strength classification (1-4)

Several items of data are delineated on a subsegment-by-subsegment basis. These items include horizontal curvature of tunnel, vertical gradient of tunnel, groundwater inflow, and methane gas problems. The model evaluates the user input data and determines an appropriate construction method for each geological segment. The data that exist on a subsegment level are used to calculate variations in the advance rate within each geological segment.

APPENDIX B

COMPUTER INPUT TERMS

This glossary of computer terms contains the input data points that are required of the user, or computed by the model in its evaluation of mined tunnel operations. It covers all relevant factors affecting mined tunneling costs. Refer to Section 2 for a full explanation of this appendix.

COMPUTER INPUT TERMS
1. General

Key: GENERAL
Array: GENERL

Field Name	Unit of Measure	Description
LOCATION	city (1-22) SR	A number representing a city: 1 = Atlanta, 2 = Baltimore, 3 = Boston, 4 = Chicago, 5 = Cleveland, 6 = Denver, 7 = Detroit, 8 = Houston, 9 = Los Angeles, 10 = Miami, 11 = Milwaukee, 12 = Minneapolis, 13 = New Orleans, 14 = New York, 15 = Oakland, 16 = Philadelphia, 17 = Pittsburgh, 18 = Portland, 19 = San Francisco, 20 = Seattle, 21 = St. Louis, 22 = Washington,D.C.
START	Julian date CN	Start date of construction
DURATION	days SR	Duration of contract (calendar days) (This is used as a constraint, not as an estimate.)
(COST) BIAS	1-3 SR	Bias of cost estimate: 1 = pessimistic, 2 = optimistic, 3 = most likely
ATTITUDE	1-3 SR	Owner attitude towards change orders: 1 = fair (owner grants justifiable change orders), 2 = unpredictable (owner vacillates between being fair and unfair), 3 = unfair (owner refuses to grant justifiable change orders, thereby forcing contractor to resort to filing a claim in court)
LIABILITY	1-3 SR	Amount of legal liability placed on contractor through designer's specifications and changed condition clauses: 1 = low (contract stipulates that owner will pay additional expenses arising from unexpected geologic conditions or other unforseen circumstances), 2 = medium (contract stipulates that owner will pay some of the additional expenses arising from unforseen circumstances), 3 = high (contract places the financial responsibity for unforeseen circumstances upon the contractor)
REIMBURSE	1-3 SR	Owner willingness to reimburse contractor for mobilization costs, partial progress, materials on site, and retainages: 1 = low (owner is unwilling to pay contractor anything for work activities until they have been completed), 2 = medium (owner is sometimes willing to make partial payments to contractor for work activities that are partially complete), 3 = high (owner is willing to make partial payments to contractor for work activities that are partially complete, recognizing the fact that the contractor incurs expenses at the outset of an activity for which he deserves to be reimbursed at that point in time)

COMPUTER INPUT TERMS
1. General (continued)

Field Name	Unit of Measure	Description
INFLATION	percent per year SR	Inflation rate
INTEREST	percent per year SR	Interest rate on construction loans (national prime rate)
ECONOMY	1-3 SR	Economic climate within tunnel construction industry: 1 = poor (there are few current or anticipated tunneling jobs in the U.S.), 2 = fair (there are some current and/or anticipated tunneling jobs in the U.S.), 3 = good (there is a good number of current and anticipated tunneling jobs in the U.S.)
(NUMBER) BIDDERS	bids SR	Anticipated number of bidders
(NUMBER) SHIFTS (3)	1-4 VR	Number of work shifts per day (by segment): 1 = one 8-hour shift 2 = two 8-hour shifts 3 = two 10-hour shifts 4 = three 8-hour shifts

Note:

S = Scalar
C = Character string
V = Vector
M = Matrix

R = Required of user
N = Not required of user
O = Optional

COMPUTER INPUT TERMS
2. Community Constraints Key: COMUNITY

Field Name	Unit of Measure	Description
HOURS	1-3 SR	Hours of operation 1 = always prohibit operation between 10 p.m. and 7 a.m., 2= prohibit operation between 10 p.m. and 7 a.m. when drilling-and-blasting, 3 = allow operation between 10 p.m. and 7 a.m. without restriction
DRILLNBLAST	1-5 SR	Limitations on drill-and-blast: 1 = drill-and-blast not allowed, 2 = drill-and-blast allowed daytimes only, and limited to 4-foot cycles, 3 = drill-and-blast allowed daytimes only and limited to 10-foot cycles, 4 = drill-and-blast allowed day and night and limited to 4-foot cycles, 5 = drill-and-blast allowed day and night and limited to 10-foot cycles

Note: S = Scalar, C = Character string, V = Vector, M = Matrix; R = Required of user, N = Not required of user, O = Optional

COMPUTER INPUT TERMS
3. Construction Site Conditions   Key: SITECOND

Field Name	Unit of Measure	Description
GENERAL (WORK)	1-3 SR	General requirements for snow removal; rodent, insect and odor control; street cleaning; etc.: 1 = minimal, 2 = moderate, 3 = extensive
SECURITY	1-3 SR	Level of surveillance/security: 1 = light, 2 = medium, 3 = heavy
WORK (AREA)	sq ft SR	Dimensions of surface area provided by the owner for contractor work area and around each access shaft
(SITE) CLEARING	1-3 SR	Extent of site clearing required: 1 = grass, topsoil, few trees, 2 = some trees, 3 = heavy foliage and trees
PAVEMENT (REMOVAL)	sq ft SR	Asphalt or concrete pavement, curbing and sidewalk to be removed
SMALL (DEMOLITION)	cu ft SR	Volume of 1- or 2-story buildings to be demolished and removed from site
MEDIUM (DEMOLITION)	cu ft SR	Volume of small masonry structures and light commercial buildings to be demolished and removed from site
LARGE (DEMOLITION)	cu ft SR	Volume of large masonry structures, multi-story buildings, and bridges to be demolished and removed from site
FENCE LENGTH	linear ft SR	Linear footage of fencing required
FENCE TYPE	1-3 SR	Type of fencing: 1 = 6-foot high chain link fence, 2 = wire mesh on 4-inch by 4-inch posts and 8-foot high, 3 = painted plywood (sound barrier type), 4-inch by 4-inch frame and 8-foot high
(TRAFFIC) MAINTEN-ANCE	1-4 SR	Traffic maintenance: 1 = none, 2 = closing off traffic completely, 3 = limited two-way traffic, 4 = one lane with an officer controlling traffic direction
(NUMBER) TRAILERS	trailer SO	Number of trailers to be established on construction site
DEMOBILIZA-TION	1-3 SO	Demobilization required (depends on number and type of pieces of equipment on the job site): 1 = light, 2 = moderate, 3 = extensive

Note:

S = Scalar
C = Character string
V = Vector O = Optional
M = Matrix

R = Required of user
N = Not required of user

COMPUTER INPUT TERMS
4. Utilities Relocation Key: UTLRELOC

Field Name	Unit of Measure	Description
EXTENT	1-4 SR	Extent of utilities relocation: 1 = none, 2 = little, 3 = moderate, 4 = extensive

Note:

S = Scalar
C = Character string
V = Vector
M = Matrix

R = Required of user
N = Not required of user
O = Optional

COMPUTER INPUT TERMS

5. Building Protection — Key: BLDPROTC

Field Name	Unit of Measure	Description
MINIMUM (UNDER-PINNING)	buildings SR	Number of 1- or 2-story wood frame buildings requiring underpinning
MODERATE (UNDER-PINNING)	buildings SR	Number of small masonry structures and light commercial buildings requiring underpinning
EXTENSIVE (UNDER-PINNING)	buildings SR	Number of large masonry structures, multi-story buildings, and bridges requiring underpinning
MONITORING	1-3 SR	Monitoring of settlement, blasting damage, seismic controls, etc.: 1 = minimal, 2 = moderate, 3 = extensive
INSURANCE	1-4 SR	Amount of special insurance for building protection 1 = none, 2 = small, 3 = medium, 4 = large

Note:

S = Scalar
C = Character string
V = Vector
M = Matrix

R = Required of user
N = Not required of user
O = Optional

COMPUTER INPUT TERMS

6. Tunnel Design

Key: TUNLDSGN

Field Name	Unit of Measure	Description
(EXCAVATED) DIAMETER	ft SR	Excavated diameter of tunnel
TUNNEL LENGTH	ft SR	Length of tunnel (twin tubes are assumed; give length of only one)
NUMBER SEGMENTS	segments SR	Number of geological segments (1, 2 or 3)
SEGMENT LENGTH (3)	ft VR	Length of each geological segment
NUMBER SUBSEGMENTS (3)	sub-segment VR	Number of geologic subsegments within each segment (1, 2, 3, 4 or 5)
SUBSEGMENT LENGTH (3, 5)	ft MR	Length of each geologic subsegment within each segment
HORIZONTAL (CURVATURE) (3, 5)	ft of radius MR	Horizontal curvature of tunnel within each subsegment (Omit or give zero for a straight tunnel)
VERTICAL (GRADIENT) (3, 5)	percent MR	Vertical gradient of tunnel within each subsegment (A gradient less than 3% will be considered level)
LINING (TYPE)	1-3 SR	Type of lining: 1 = steel sets, 2 = precast concrete, 3 = poured concrete
POURED THICKNESS	in SO	If poured concrete lining used, thickness of lining (default: 12 inches)
POURED STRENGTH	lbs per sq in SO	If poured concrete lining used, strength of concrete in psi (table currently has only 4000 psi which is the default)
POURED REINFORCE-MENT	lbs per cu ft VO	If poured concrete lining used, amount of reinforcing steel for each segment (lbs steel/cu ft concrete)
SIZE STEEL (SETS)	lbs/ft SR	If steel lining used, size of steel sets

COMPUTER INPUT TERMS
6. Tunnel Design (continued)

Field Name	Unit of Measure	Description
RIBS	lbs/ft SR	If ribs and lagging used, weight per linear foot for ribs
CAULKING	y or n SR	Caulking and grouting required for drainage purposes (yes or no)
BREASTING (3)	y or n VO	Breasting used within each segment (yes or no)
INVERT DEPTH	in. SO	Depth of invert
WALK SIZE	cu ft per ft SO	Volume of concrete in the safety walk
INVERT REINFORCE-MENT (3)	lbs per cu ft VR	Amount of reinforcing steel used for invert and safety walk for each segment
SUBGRADE (THICKNESS)	in SO	Thickness of sub-grade material

Note:

S = Scalar
C = Character string
V = Vector
M = Matrix

R = Required of user
N = Not required of user
O = Optional

COMPUTER INPUT TERMS
7. Shaft Design — Key: SHFTDSGN

Field Name	Unit of Measure	Description
DEPTH (3)	ft VR	Depth of each shaft
LENGTH (3)	ft VR	Length of each shaft opening
WIDTH (3)	ft VR	Width of each shaft opening
PURPOSE (3)	1-4 VR	Purpose of each shaft: 1 = access, 2 = fan, 3 = vent, 4 = access and vent
NUMBER FANS (3)	fans VO	Number of fans in each fan shaft
SUPPORT (3)	1-4 VR	Type of support: 1 = slurry walls, 2 = soldier piles and lagging, 3 = steel sheeting, 4 = none
BRACING (3)	1-3 VO	Type of bracing used with soldier piles and lagging: 1 = tiebacks, 2 = cross bracing, 3 = none
PILE SIZE (3)	lbs/ft VR	If soldier piles and lagging used for support, size of piles
PILE DISTANCE (3)	ft VR	If soldier piles and lagging used for support, distance between piles
NUMBER PILES (3)	piles VO	If soldier piles and lagging used for support, number of piles
PILE DEPTH (3)	ft VO	If soldier piles and lagging used for support, depth of piles
METHOD (OF) INSTALLATION	1-2 SR	Method used to install soldier piles: 1 = pounding or driving, 2 = augering or drilling
WOOD (LAGGING) AREA (3)	sq ft VN	If soldier piles and lagging used for support, area covered by wood lagging

COMPUTER INPUT TERMS
7. Shaft Design (continued)

Field Name	Unit of Measure	Description
WOOD (LAGGING) DEPTH (3)	ft VO	If soldier piles and lagging used for support, depth of wood lagging
STEEL (SHEET) AREA (3)	sq ft VN	If steel sheeting used for support, area covered by sheet piling
NUMBER TIEBACKS (3)	tiebacks VO	If tiebacks used for bracing the support, number of tiebacks
NUMBER CROSS (BRACINGS) (3)	bracings VO	If cross bracings used for bracing the support, number of cross bracings
CROSS (BRACINGS) SIZE (3)	lbs/ft VR	If cross bracings used for bracing the support, size of cross bracings
SLURRY (WALL) SIZE (3)	cu ft VR	If slurry walls used for support, volume of slurry walls
DEWATERING (3)	1-4 VR	Extent of dewatering: 1 = none, 2 = minimal, 3 = moderate, 4 = extensive
NUMBER SHAFTS	shafts SR	Number of shafts in tunnel
NUMBER SEGMENTS (3)	segment VR	Number of geological segments in each shaft (1 or 2)
SEGMENT DEPTH (3, 2)	ft MR	Depth of each geological segment in each shaft, starting with segment at surface

Note:

S = Scalar
C = Character string
V = Vector
M = Matrix

R = Required of user
N = Not required of user
O = Optional

Field Name	Unit of Measure	Description
SEGMENT (CLASSIFI- CATION) (3)	1-3 VR	Classification of each geological segment 1 = rock, 2 = soft ground, 3 = mixed face
SOIL (CLASSIFI- CATION) (3, 5)	1-9 MR	Soil classification of subsegments in soft ground: 1 = uniformly soft and compact ground, 2 = soft clay, 3 = firm clay, 4 = stiff, cohesive clay, 5 = running sand, silt and gravel, 6 = cohesive sand, silt and gravel, 7 = cemented sand, silt and gravel, 8 = uncemented sand silt and gravel below water, 9 = bouldery till
(ROCK) STRENGTH (3, 5)	1-4 MR	Strength of subsegments in rock: 1 = decomposed, 2 = soft, 3 = medium, 4 = hard
(ROCK) FAULTS (3, 5)	1-4 MR	Geological structure of subsegmentys in rock: 1 = massive, 2 = slightly faulted or folded, 3 = moderately faulted or folded, 4 = intensely faulted or folded
(JOINT) PATTERN (3, 5)	1-6 MR	Joint patterns in subsegments of rock: 1 = very closely jointed, 2 = closely jointed, 3 = moderaely jointed, 4 = moderate to blocky 5 = blocky to massive, 6 = massive
(JOINT) CONDITION (3, 5)	1-3 MR	Joint condition of subsegments in rock: 1 = tight or cemented, 2 = slightly weathered or altered, 3 = severely weathered, altered or open
ABRASIVENESS (3, 5)	1-3 MR	Abrasiveness of subsegments in rock: 1 = low, 2 = medium, 3 = high
MIXED (FACE) (CLASSIFI- CATION) (3, 5, 2)	(1-9, 1-4) MR	Classification of subsegments in mixed face ground: a 2-element vector (x,y) where x = soil classification of soft ground portin of face and Y = strength classification of rock portion of face
GROUND- WATER (3, 5)	1-4 MR	Anticipated water inflow within each segment*: 1 = none, 2 = slight (200 gpm/1000 ft), 3 = moderate (200-1000 gpm/1000 ft), 4 = heavy (1000 gpm/1000 ft) *NOTE: Select water inflow 1 = none, if working under compressed air conditions.
SHAFT (CLASSIFI- CATION) (3, 2)	1-2 MR	Classification of each geologic segment in each shaft, from the surface down: 1 = rock, 2 = soft ground

Note:

S = Scalar
C = Character string
V = Vector
M = Matrix

R = Required of user
N = Not required of user
O = Optional

COMPUTER INPUT TERMS
9. Temporary Tunnel Support System Key: TMPSUPRT

Field Name	Unit of Measure	Description
GROUND (CONTROL)	1-4 SR	Ground control method used under ground: 1 = none, 2 = dewatering, 3 = compressed air, 4 = deep wells
SOLIDIFI-CATION	1-4 SR	Ground solidification technique used at surface: 1 = none, 2 = chemical grouting, 3 = cement grouting, 4 = freezing the groundwater
(SOIL) MASS	cu yd SO	If grouting used for ground solidification, volume of soil mass to be treated
ROCK (BOLTS)	y or n CO	Rock bolts used for temporary support (yes or no)
(ROCK) (BOLTS) DIAMETER	in SO	If rock bolts used for support, diameter of rock bolts
NUMBER (ROCK) (BOLTS)	rock bolts SO	If rock bolts used for support, quantity of rock bolts
SUPPORT (REQUIRE-MENTS) (3)	1-9 VR	Type of support imposed by designer for each segment: 1 = ribs and lagging, 2 = steel sets, 3 = precast concrete, 4 = rock bolts, 5 = rock bolts and shotcrete, 6 = rock bolts and steel sets, 8 = shotcrete, 9 = none

Note:

S = Scalar
C = Character string
V = Vector
M = Matrix

R = Required of user
N = Not required of user
O = Optional

COMPUTER INPUT TERMS
10. Muck Hauling from Construction Site to Dump

Key: MUCKHAUL

Field Name	Unit of Measure	Description
RAIL VEHICLE	1-3 SR	Muck hauling vehicle (in the tunnel): 1 = rubber tire, 2 = diesel-powered rail, 3 = battery-powered rail
DISTANCE	miles SR	Distance from dump site to access shaft
FEE	1-3 SR	Amount of dump fee: 1 = small, 2 = medium, 3 = large

Note:

S = Scalar
C = Character string
V = Vector
M = Matrix

R = Required of user
N = Not required of user
O = Optional

APPENDIX C

CONTRACTOR DECISIONS

The purpose of this appendix is to describe those variables of the mined tunneling process that are determined by the individual contractor. For each variable a verbal description plus flow charts or tables have been provided where needed to show what factors influence the contractor's decision about a variable and what his train of thought is.

C.1 TUNNEL CONSTRUCTION METHOD

This first section describes the logic and reasoning contractors follow in selecting a construction method.

The contractor's selection of a tunnel construction method (if not limited by the owner) is impacted by geology, community constraints, tunnel length, and equipment availability. In addition, the contractor must weigh the high capital cost and set-up time associated with high speed excavation machines against the savings derived from a faster rate of tunnel construction. He must also evaluate the costs arising from design specifications that the designer might stipulate for certain construction methods, but not mandate for others.

By far the most important of these considerations is the geological makeup of the ground through which the tunnel is to be constructed. Appendix A, "Geological Classifications within a Tunnel," delineates the scheme by which the length of a tunnel is broken down into one, two, or three geological segments. This scheme allows for six different possible combinations of geological segments within a tunnel:

1. Rock
2. Soft Ground
3. Mixed Face
4. Rock and Mixed Face
5. Soft Ground and Mixed Face
6. Rock, Mixed Face, and Soft Ground

The logic by which the cost estimating model determines the construction method is dependent on which of the six combinations apply. A logic flowchart is shown as Figure C-1. The flowchart makes reference to a rock evaluation algorithm and a soft ground evaluation algorithm. Tables depicting these two algorithms are found in Tables C-1 and C-2. For a better understanding of the flowchart and geological evaluation algorithms shown in the figures and tables, refer to the following examples.

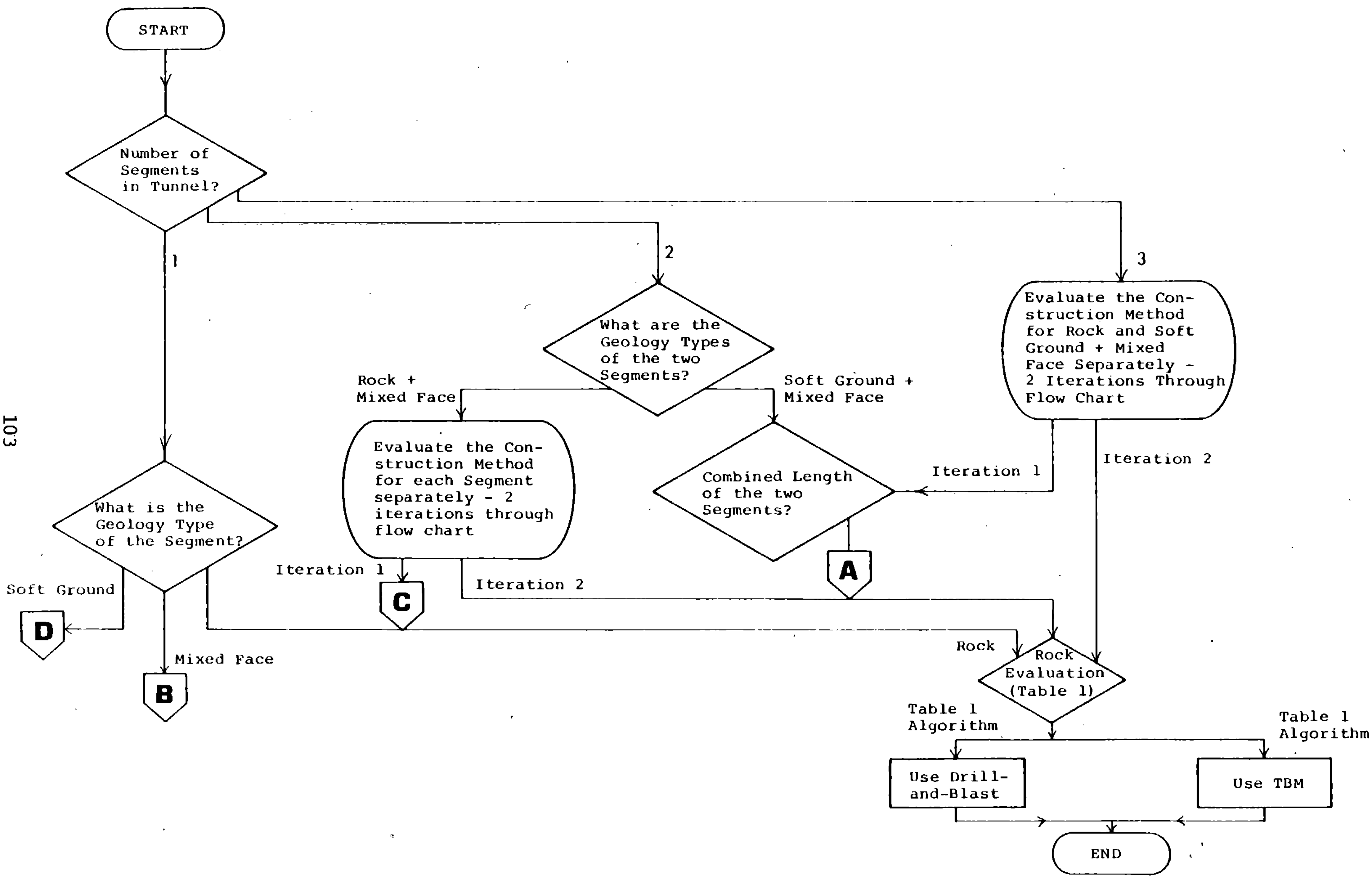

FIGURE C-1. DETERMINATION OF CONSTRUCTION METHOD

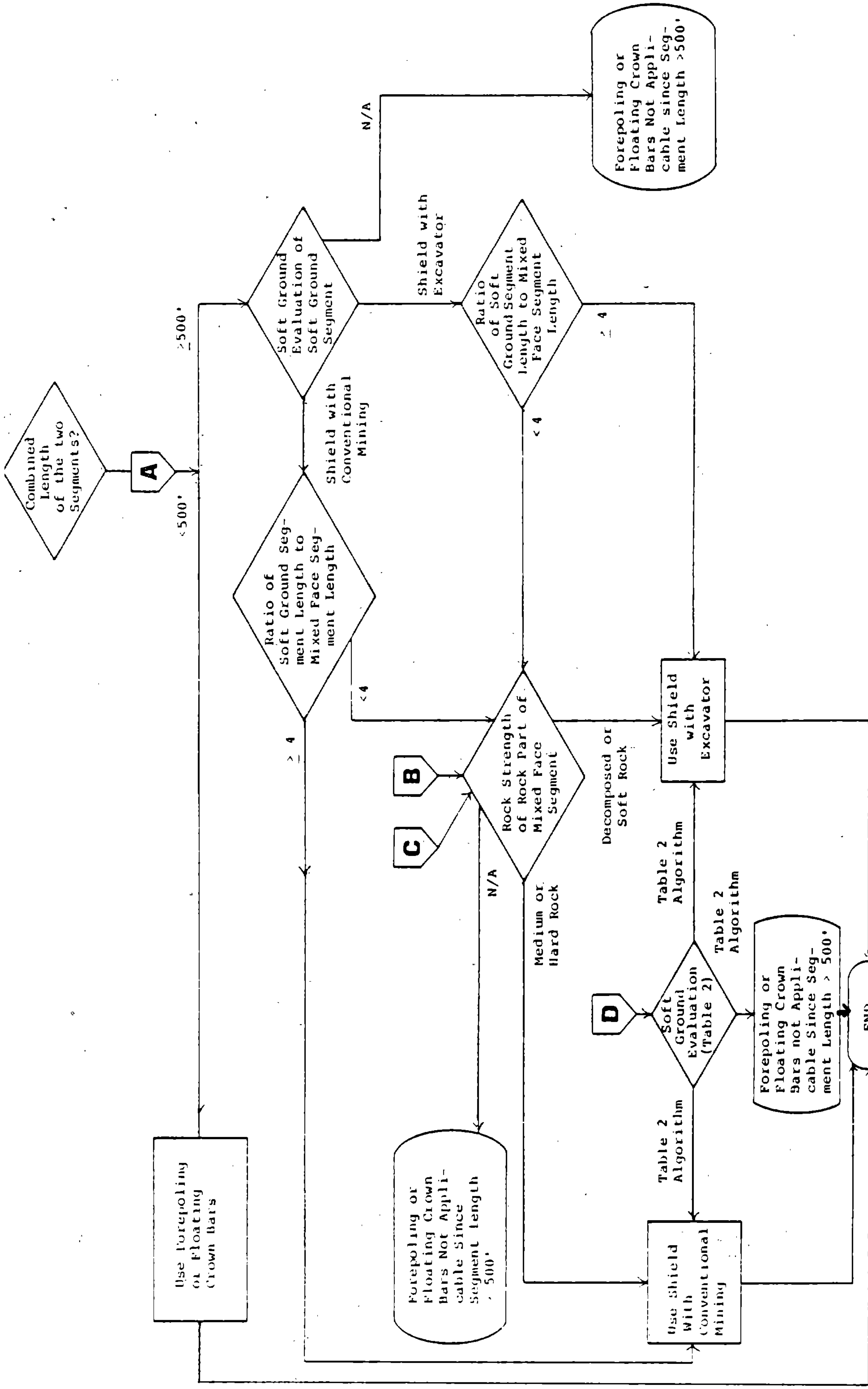

FIGURE C-1. DETEPMINATION OF CONSTRUCTION METHOD (CONT'D)

TABLE C-1. EVALUATION OF ROCK SEGMENTS

I. Assignment of Weighting Factors

	Parameter	Values	Weighting Factor
1.	Segment length	< 2500 ft	-10
		2500'-3000'	1
		3000'-3500'	2
		3500'-4000'	3
		4000'-4500'	5
		4500'-5000'	7
		5000'-7000'	9
		> 7000'	10
2.	Drill-and-blast restrictions imposed by community	Drill-and-blast allowed day and night, and limited to 10' cycles	0
		Drill-and-blast allowed day and night, and limited to 4' cycles	4
		Drill-and-blast allowed daytimes only, and limited to 10' cycles	5
		Drill-and-blast allowed daytimes only, and limited to 4' cycles	8
		Drill-and-blast not allowed	50
3.	Support requirements imposed by designer	Permanent support required	5
		Permanent support not required	10
4.	Rock strength of longest sub-segment	Decomposed	10
		Soft	8
		Medium	5
		Hard	0
5.	Geological structure of longest sub-segment	Massive	10
		Slightly faulted or folded	7
		Moderately faulted or folded	3
		Intensely faulted or folded	-40
6.	Joint Pattern of longest sub-segment	Very closely jointed	5
		Closely jointed	5
		Moderately jointed	5
		Moderate to blocky	5
		Blocky to massive	5
		Massive	5
7.	Joint condition of longest sub-segment	Tight or Cemented	5
		Slightly weathered or altered	5
		Severely weathered, altered or open	5
8.	Abrasiveness of longest subsegment	Low	8
		Medium	5
		High	2

TABLE C-1. EVALUATION OF ROCK SEGMENTS (CONTINUED)

I. Assignment of Weighting Factors (cont'd)

	Parameter	Values	Weighting Factor
9.	Water inflow of longest subsegment	None	10
		Slight	8
		Moderate	4
		Heavy	0
10.	Number of segments in tunnel	1	5
		2	0
		3	-20

II. Computation of Construction Method

If Σ weighting factors ≥ 50, use TBM; otherwise, use Drill-and-Blast.

TABLE C-2. EVALUATION OF SOFT GROUND SEGMENTS

I. Assignment of Weighting Factors

	Parameter	Values	Weighting Factor
1.	Segment Length	< 1000'	0
		1000'-1500'	4
		1500'-2000'	6
		2000'-2500'	8
		> 2500'	10
2.	Soil classification of longest sub-segment	Bouldery till	1
		Soft clay	3
		Cemented sand, silt, gravel	3
		Firm clay	5
		Cohesive sand, silt, gravel	5
		Uncemented sand, silt, gravel below water table	5
		Stiff, cohesive clay	7
		Running sand, silt, gravel	7
		Uniformly soft and compact ground	10

II. Computation of Construction Method

If segment length < 500',
use forepoling or floating crown bars with conventional mining

If segment length $\geq$500' and
if Σ weighting factors $\geq$ 10,
use shield with excavator;
otherwise, use shield with conventional mining.

Example 1

Problem:

Determine the construction method(s) for the tunnel described below. The relevant variables are as follows:

- o The tunnel consists of one geological segment.
- o This segment is known to be rock.
- o The length of the segment is 10,000 feet.
- o The community regulations stipulate that no drilling-and-blasting is allowed at night. The drill-and-blast cycles can be as great as 10 feet in length.
- o Permanent support is mandated by the designer.
- o The rock is primarily decomposed, intensely faulted, moderately jointed, slightly weathered, and of medium abrasiveness.
- o The water inflow is heavy.

Solution:

To solve this problem, the flowchart in Figure C-1 is followed. The diamond-shaped nodes on the flowchart signify conditional situations (i.e., a question that must be answered), and the branch followed from each node depends on the answer to the question. The process follows:

Question 1:	Number of segments in tunnel?
Answer:	One
Question 2:	What is the type of geology in this segment?
Answer:	Rock
Question 3:	What is the result of the rock evaluation procedure (Table C-1)?

Answer: To arrive at this answer, one must evaluate the detailed geological characteristics of the rock and assign values (weighting factors) to each one. The greater the value of the weighting factor, the more attractive the TBM alternative becomes versus drill-and-blast.

1. Segment length = 10,000 feet.
   WF = 10. The longer the segment, the more attractive a TBM becomes, because it is an expensive piece of equipment and its write-off value is directly proportional to the tunnel length.

2. Drill-and-blast restrictions: 10-foot cycles, daytime only.
   WF = 5. Restricting the work to daytime hours only is somewhat inconvenient.

3. Support requirement = yes, permanent support is required.
   WF = 5. If using a TBM, the need for permanent support might impede the advance rate.

4. Rock is decomposed.
   WF = 10. It is very difficult to drill-and-blast in decomposed rock.

5. Rock is intensely faulted.
   WF = -40. The use of a TBM is precluded when the ground is very faulted.

6 Rock is moderately jointed.
   WF = 5. This factor has little impact on the decision.

7. Rock is slightly weathered.
   WF = 5. Likewise, this factor has negligible impact.

8. Rock is of medium abrasiveness.
   WF = 5. The TBM becomes less desirable as rock abrasiveness increases.

9. Water inflow is heavy.
   WF = 0. The TBM becomes less desirable as water conditions worsen.

10. Number of segments = 1.
    WF = 5. Constructing a tunnel entirely through rock makes usage of a TBM more attractive, for the same reasons indicated for parameter 1 above.

Adding all the values of the weighting factors yields:

$$WF = 10 + 5 + 5 + 10 - 40 + 5 + 5 + 5 + 0 + 5 = 10$$

Conclusion: If WF is greater than 50, we choose to use a TBM. In this case it is not, so we choose the drill-and-blast method of excavation.

Example 2

Problem:

Determine the construction method(s) for a tunnel given the following relevant variables:

- o The tunnel consists of three segments.
- o The length of the rock segment is 3000 feet. The length of the mixed face segment is 2000 feet. The length of the soft ground segment is 5000 feet.
- o Drilling-and-blasting at night is not permitted. The cycle depth is 10 feet maximum.
- o Permanent support is stipulated by the designer.
- o The rock is of medium strength, slightly faulted, moderately jointed, slightly weathered, and of medium abrasiveness.
- o The water inflow is moderate.
- o The soft ground segment consists primarily of soft clay.

Solution:

Question 1: Number of segments in tunnel?

Answer: Three

Proceed through the flow chart (Figure C-1) for two iterations: one for the rock segment, and one for the soft ground and mixed face segments.

Iteration 1: Soft Ground and Mixed Face Segments

Question 2: Combined length of the two segments?

Answer: 2000 + 5000 = 7000 feet, which is greater than 500 feet.

Question 3: What is the result of the soft ground evaluation (Table C-2)?

Answer:

+10 (segment length greater than 2500 feet)

+3 (soft clay in longest subsegment)

WF = 13

Since WF is greater than or equal to 10 and the length of the soft ground segment is greater than 500 feet, the use of a shield with excavator is recommended at this point.

Question 4: What is the ratio of the soft ground segment length to the mixed face segment length? (Figure C-1)

Answer: 5000/2000 = 2.5 (less than 4)

In other words, the mixed face segment is of significant length and since it contains some rock, it is considered uneconomical to use a shield with excavator unless the rock is decomposed or soft.

Question 5: What is the strength of the rock in the mixed face segment?

Answer: The rock is of medium strength. Therefore, the use of a shield with excavator is not recommended. It is preferable to use a shield with conventional mining.

Iteration 2: Rock Segment

Question 6: What is the result of the rock evaluation (Table C-1)?

Answer:

+5 (segment length = 3000 feet)

+5 (drill-and-blast daytime only, 10-foot cycles permitted

+5 (permanent support required)

+27 (+5 - medium strength rock, +7 - slightly faulted, +5 - moderately jointed, +5 - slightly weathered, +5 - medium abrasiveness)

+4 (moderate water inflow)

<u>-20</u> (3 segments in tunnel)

WF = 26, which is less than 50, so drill-and-blast is recommended.

Conclusion: <u>Use a combination of the drill-and-blast and shield with conventional mining techniques to excavate the tunnel.</u>

C.2 TUNNEL TEMPORARY SUPPORT SYSTEM

Generally, the temporary support system is specified by the designer and the contractor does not have much input in the decision. However, in the event the designer is lenient in this regard (e.g., he specifies merely that poured concrete should be used for the permanent lining), the contractor can maneuver with these guidelines in mind and choose an optimal support system for the given geology. In the case of poured concrete lining, the contractor can choose from among rock bolts and shotcrete, shotcrete only, etc.

For soft ground, the temporary support system alternatives are as follows:

1. Ribs and lagging (if the designer specifies poured concrete lining).
2. Permanent steel lining.
3. Permanent precast concrete lining.

For rock, the temporary support system alternatives are as follows:

A. If rock bolts are mandated by the designer:

   1. Rock bolts only (cannot be used if the rock is intensely faulted, soft, or decomposed).
   2. Rock bolts and shotcrete (used when the rock is intensely faulted).
   3. Rock bolts and steel sets (used when the rock cover above the tunnel is very shallow, that is, less than the tunnel diameter).

B. If rock bolts are not mandated by the designer, we shall assume that the contractor does not use them (the user may override this assumption). The alternatives then are:

   1. Ribs and shotcrete (used when the rock is decomposed or soft, and has a moderately faulted structure).
   2. Shotcrete only (used when the rock is decomposed or soft, and has a massive or slightly faulted structure).
   3. Ribs and lagging (used when the rock is decomposed or soft, and has an intensely faulted structure).

C.3 NUMBER OF CONSTRUCTION HEADINGS

The third decision made by the contractor deals with the number of construction headings utilized during tunnel excavation. This number depends primarily on the construction method chosen, and secondly, on the owner's schedule.

It is assumed that one heading is utilized if excavation is carried out with a TBM, a shield with digger, or a shield with conventional mining. The implication here is that the contractor excavates one of the twin tunnels completely before commencing excavation of the other twin tunnel. The user can override the model's decision at this point. The model assumes that the high cost of mining machines precludes using more than one heading for these types of excavation methods. If the tunnel has more than one geological segment, then one heading only is also automatically utilized.

Two headings are utilized for drilling-and-blasting. Here, the model assumes that both twin tunnels are excavated simultaneously and in the same direction (drilling at one heading while blasting and mucking at the other), provided each heading is not longer than 5000 feet. The model assumes that the two headings are mined from the same shaft for this method and for forepoling or floating crown bars.

C.4 ADVANCE RATE

The fourth decision to be made by the contractor concerns the average advance rate for each segment of the tunnel. Given the geological conditions, the construction method, the temporary support system, and the number and length of work shifts, the model determines the advance rate for each subsegment within each segment of the tunnel. Appendix J contains a detailed description of the procedure, as well as tables of advance rates. Each subsegment advance rate is then divided into the length of the subsegment to obtain the number of days needed to excavate it. Summing the number of days for each subsegment within a particular segment yields the total time duration needed to excavate that segment. Dividing the segment duration into the segment length results in the average advance rate for the segment. This algorithm is performed for every geological segment of the tunnel. By taking a weighted average (weighted by segment length) of the advance rate for each geological segment, the average advance rate for the tunnel as a whole is obtained.

C.5 HAULING SYSTEM

The fifth decision to be made by the contractor pertains to the design of the hauling system for muck disposal.

The decision of using a rubber tire system versus a rail system depends on the tunnel length and grade. A rubber tire system is used if the tunnel length is less than 2000 feet or the grade is more than 5 percent. If the length is greater than 2000 feet and the grade is less than 5 percent, a rail system is used.

1. For a rail system, three locomotives are used if the tunnel length is greater than 5000 feet (as the hauling cycle increases, more trains are needed). Otherwise, two locomotives are used. To determine the number and size of the cars, one must first consider the muck generation rate:

   For a shield, we assume 4 feet/penetration cycle. Thus, the volume of muck generated with each advance of the shield is:

   4 ft x π (tunnel diameter/2)^2 x 1.5,

   where 1.5 = the expansion coefficient for soft ground.

   This volume should equal the number of cars per train times the volume of each car. Typical volumes for muck cars range from 6 to 18 cubic yards. The number of cars per train ranges from 4 to 8 cars. The following table depicts the train configuration for different tunnel diameters.

Tunnel Diam. (ft)	Volume of Muck (cy/cycle)	Rail System Configuration
18	57	1 train x 5 cars x 12 cy/car = 60 cy
19	63	1 train x 6 cars x 12 cy/car = 72 cy
20	70	1 train x 6 cars x 12 cy/car = 72 cy
21	77	1 train x 7 cars x 12 cy/car = 84 cy
22	85	2 train x 5 cars x 12 cy/car = 120 cy
23	92	2 train x 5 cars x 12 cy/car = 120 cy
24	101	2 train x 5 cars x 12 cy/car = 120 cy

For muck cars of 12 cubic yard capacity and over, 80 lbs/ft sections of rail should be used (otherwise, 40 lbs/ft sections should be used). For two or more trains, a California Switch should be installed.

For a TBM, a constant penetration rate of 6 ft/hr (2 feet every 20 minutes) is assumed. Thus, the volume of muck generated in a 20-min haul/dump cycle is:

2 ft x π (tunnel diameter/2)^2 x 1.8,

where 1.8 = the expansion coefficient for rock.

Since muck generation is continuous, it is advisable to have two trains and one spare locomotive.

Tunnel Diam. (ft)	Volume of Muck (cy/ 20 min. cycle)	Rail System Configuration
18	34	2 trains x 2 cars x 12 cy/car = 48 cy
19	38	2 trains x 2 cars x 12 cy/car = 48 cy
20	42	2 trains x 2 cars x 12 cy/car = 48 cy
21	46	2 trains x 2 cars x 12 cy/car = 48 cy
22	51	2 trains x 3 cars x 12 cy/car = 72 cy
23	55	2 trains x 3 cars x 12 cy/car = 72 cy
24	60	2 trains x 3 cars x 12 cy/car = 72 cy

2. For a rubber tire system, the number and capacity of LHD's are calculated as follows:

For a shield, assume the following:

a. The distance from the tunnel face to the shaft is no more than 2000 feet.

b. The speed of an LHD is 10 mph when loaded and 15 mph when empty.

The load-haul-dump cycle time for a 2000-foot distance is:

load time	2	min
haul time to shaft @ 10 mph	2	min
dump time	1	min
return time from shaft @ 15 mph	1.5	min
spot time	0.5	min
lost time	3	min
	10	min

It takes 10 minutes for the LHD to load, haul, dump, and return to the face.

In order to determine the number and capacity of the LHD's, the peak excavation rate must first be calculated, so that the hauling system will never constrain the excavation rate. For a shield, the advance rate tables note that the maximum advance rate is 90 ft/day. However, rubber tire systems are normally used when the distance is short and the advance rate is low. Hence, 60 ft/day is adopted as a maximum. This advance rate represents an average number of feet per day and is based on 55-percent system availability. Thus, the peak penetration rate (i.e., with 100-percent system availability) is 60/0.55 = 109 ft/day. This figure translates into 0.8 ft/10-min cycle. Using a soil expansion coefficient of 1.5, the volume of muck generated per load-haul-dump cycle can be calculated and the recommended rubber tire system configuration can then be devised:

Tunnel Diam. (ft)	Volume of Muck (cy)	Rubber Tire System Configuration
18	11	3 x 5-cy LHD's = 15 cy
19	13	3 x 5-cy LHD's = 15 cy
20	14	3 x 5-cy LHD's = 15 cy
21	15	3 x 6-cy LHD's = 18 cy
22	17	3 x 6-cy LHD's = 18 cy
23	18	3 x 8-cy LHD's = 24 cy
24	20	3 x 8-cy LHD's = 24 cy

(Note that, as a rule, three LHD's are used.)

For a TBM, a rubber tire hauling system is rarely used because it is uneconomical on longer distances, while the TBM itself is uneconomical on shorter distances.

If a rubber tire system is used, however, the determination of the number and capacity of LHD's proceeds as follows:

The LHD cycle time is determined in the same way as for a shield.

From the advance rate table for TBM excavation in Appendix J, it is found that 90 ft/day is the maximum advance rate. For the same reason given before (rubber normally used with lower advance rates), 60 ft/day is again adopted as the maximum advance rate, given a system availability rate of 55 percent. This figure once again translates into an advance rate of 0.8 ft/10-min cycle. Using a rock expansion coefficient of 1.8, the muck generated and the corresponding rubber tire system configuration are:

Tunnel Diam. (ft)	Volume of Muck (cy)	Rubber Tire System Configuration
18	14	3 x 5-cy LHD's = 15 cy
19	15	3 x 6-cy LHD's = 18 cy
20	17	3 x 6-cy LHD's = 18 cy
21	18	3 x 8-cy LHD's = 24 cy
22	20	3 x 8-cy LHD's = 24 cy
23	22	3 x 8-cy LHD's = 24 cy
24	24	3 x 10-cy LHD's = 30 cy

3. Drill-and-Blast

For a rail system, the hauling cycle is constrained by the speed of muck removal, and more specifically, by the speed of the mucker used. The cycle time is a function of the hauling distance in feet, d, and the number of cars per train, n.

The following assumptions are made:

a. A 1.5-cy mucker can load a car at a rate of 2.5 cu yd/min
b. The speed of a train is 8 mph, which equals 700 ft/min
c. The time required to dump a 12-cy car is 3 min/car.

The cycle time is calculated as follows:

CYCLE TIME (min) = load + haul + dump + return + spot + lost

$$= \frac{\text{12-cy car}}{2.5} \times n + \frac{d}{700} + 3n + \frac{d}{700} + 0.5n + 3$$

If the hauling distance is less than 5000 feet, two trains are used; otherwise, three trains are used.

For a rubber tire system, the cycle time is a function of the hauling distance in feet, d. The speed of an LHD is assumed to be 10 mph (880 ft/min) when loaded and 15 mph (1320 ft/min) when empty.

CYCLE TIME (min) = load + haul + dump + return + spot + lost

$$= 2 + \frac{d}{880} + 1 + \frac{d}{1320} + 0.5 + 3$$

4. Muck Lifting

The contractor's decision concerning the type of equipment to be used in the muck lifting operation depends primarily on the depth of the shaft, the rate of muck generation, and the type of muck hauling equipment.

Case 1 - The shaft is more than 100 feet deep and rail is used for the muck hauling system: regardless of the muck generation rate, a headframe and hoist system is used to lift the muck.

Case 2 - The shaft is less than 100 feet deep and rail is used for the muck hauling system: if the muck generation rate is greater than 150 cy/hour, a 160-ton crane is used to lift the muck; if the muck generation rate is less than 150 cy/hour, a 100-ton crane is used to lift the muck.

Case 3 - The shaft is more than 150 feet deep and rubber tire is used for the muck hauling system: regardless of the muck generation rate, a bucket elevator system is used to lift the muck.

Case 4 - The shaft is less than 150 feet deep and rubber tire is used for the muck hauling system: if the muck generation rate is greater than 150 cy/hour, a 160-ton crane with a muck skip is used; if the muck generation rate is less than 150 cy/hour, a 100-ton crane with a muck skip is used.

C.6 CONTRACTOR'S ESTIMATE OF JOB DURATION

As mentioned earlier, the contractor's estimate of the job duration is an important step in the determination of the overhead cost for the job. To calculate this duration, it is assumed that the project schedule is basically a sequence of nine activities (critical path):

1. Site preparation and mobilization
2. Shaft excavation and fittings
3. Tunnel setup operation
4. Tunnel excavation, support, and lining
5. Tunnel construction equipment removal
6. Tunnel invert pour and finishings
7. Shaft finishings
8. Tunnel cleanup
9. Demobilization and site cleanup

Three non-critical activities occur in tandem with these nine: utilities relocation, underpinning and building protection, and ground control.

One Heading:

The following steps demonstrate the procedure for calculating the job duration if the contractor uses only one heading to excavate the tunnel:

1. Site preparation and mobilization	2.5 months.
2. Shaft excavation and fittings	Duration depends on shaft depth, shaft support, and difficulties encountered: excavation rate ranges from 0.5 foot/day to 2 ft/day, with an average rate of 1 ft/day. 1 month to install fittings.
3. Tunnel setup operation	12 months for equipment delivery (activities 1 and 2 occur during this period). Setup time depends on type of equipment: 50 days to set up TBM

	or shield with digger and 40 days to set up shield alone if two 8-hour shifts per day are employed. This time must be doubled to account for the fact that this activity is conducted in both twin tubes. Lead times for delivery of equipment are included.
4. Tunnel excavation	Duration depends on advance rate: duration = sum of segment durations, where each segment duration = segment length / average advance rate for segment. Again, this time must be doubled to reflect the fact that excavation is carried out in both twin tubes.
Tunnel support and lining	If permanent lining is poured concrete, duration depends on length of tunnel: 60 ft/day is the rate for the steel installation, forming, and concrete pouring sequence for both the invert and arch. For temporary supports, whether or not they also serve as the permanent lining, duration is zero, because time requirements for supports are reflected in advance rates (excavation and support activities go hand in hand).
5. Tunnel construction equipment removal	1 month for each twin tube.
6. Tunnel invert pour and finishings	Duration depends on length of tunnel: 80 ft/day rate for subgrade, invert laying, and safety walk using two 8-hour shifts. 1 month for tunnel finishings. The invert pouring and finishing of one tube can be done simultaneously with the excavation of the other tube (it is assumed that invert pouring and finishing is less time-consuming than excavation). Thus, only the pouring and finishing of the second tube contributes to the total job duration.
7. Shaft finishings	3.5 months.
8. Tunnel cleanup	Duration depends on length of tunnel: 200 ft/day rate. It is assumed that cleanup of only the second tube contributes to the total job duration,

	as the first tube can be cleaned during excavation of the second tube.
9. Demobilization and site cleanup	1.5 month.

Two Headings:

The duration of all nine activities must still be estimated for 2 headings. The duration of the tunnel setup operation for two headings is half again as long as it is for one (the time required to set up two machines is only 50 percent more than the time required to set up one machine, due to economies of labor crew and an overlap of supervision). Tunnel excavation varies somewhat, however. Instead of excavating one tube, removing the equipment, setting it up again, and then excavating the second tube, the contractor excavates both tubes simultaneously. When he does so by means of two complete sets of equipment, the excavation time is calculated by first summing the segment durations for one tube (it is assumed that the two tubes are very close and transect the same geological segments), and increasing this figure by 20 to 30 percent. If the headings for the two tubes are mined from the same shaft, the excavation time is increased by 30 percent to account for the resulting conflicts and logistic problems. If the headings are mined from different shafts, the excavation time is increased by 20 percent to account for time lost in staggering the operations.

APPENDIX D

EQUIPMENT WRITE-OFF VALUES

Shield with Excavator and Shield with Conventional Mining

Tunnel Length (feet)	Write-Off Value (Percent)
<2000	35
2000-2999	40
3000-3999	50
4000-4999	60
5000-5999	65
6000-7999	70
≥8000	75

Tunnel Boring Machine

Tunnel Length (feet)	Write-Off Value (Percent)
<5000	60
5000-9999	65
10,000-19,999	70
≥20,000	75

Hauling Equipment

Type of Equipment	Write-Off Value (Percent)
rail muck cars	50
rubber muck cars	75
rail	40
ties	100

Other Equipment

Type of Equipment	Write-Off Value (Percent)
main cables	60
telephone lines	100
pipes, copper	70
ventilation lines, hydraulic lines	100
man cars	100

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EQUIPMENT WRITE-OFF VALUES

Type of Equipment	Write-Off Value (Percent)
Jumbo	80%
Breasting	80%
Steel Installer	80%
Precast Concrete Installer	80%
Rib Expander	80%
Poling Hood	80%
Laser System	80%
Drill	80%
Magic Carpet	60%
Locomotive & Support	3% per month
Load Haul Dump	3% per month
Track Mucker	3% per month
Loader	3% per month
Tractor	3% per month
Forklift	3% per month
Compressor (electric)	3% per month
Headframe	3% per month
Hoist	3% per month
Skip Cage System	100%
Crane	3% per month
Trucks & Autos	3% per month
Forming Equipment	100%
Vibrator	100%
Concrete Conveyor	100%
Agitator Car	6% per month
Pile Driver	6% per month
Clam Bucket	6% per month
Backhoe	3% per month
Shotcrete Pump	80%
Grout Batcher	80%
Grout Pump	80%
Grout Bin	80%
Water Pump	80%
Concrete Pump	80%
Concrete Batch Plant	3% per month
Pneumatic Breaker	80%
Clay Spader	80%
Signaling Equipment	50%
California Switch	60%
Fan	3% per month
Air Lock	80%
Stairs & Ladders	80%
Radio Equipment	50%
Surface Generator	3% per month
Trailer	3% per month
Change House	3% per month
Repair Shop	3% per month
Toilet	3% per month

APPENDIX E

CREW COMPOSITIONS

The types and numbers of laborers required for mined tunneling operations have been defined in the attached tables. The data in these tables presuppose that construction has reached the point at which tunnel excavation is in full swing.

Overhead is listed in Table E-1. It is assumed that the overhead crew works during the day shift only and is constant in number. The labor crew for above-ground support portrayed in Table E-2 varies only as a function of the work shift. The labor for the hauling system is delineated in Table E-3. It is classified according to the work shift, the hauling distance, and the type of hauling vehicle (rail or rubber tire). Table E-4 contains the crew composition for equipment assembly/disassembly underground. It is assumed that this crew works during the day shift only and is constant in number. Table E-5 details the labor needed for soft ground excavation at the tunnel face. Labor here is categorized according to the excavation method, the work shift, and the temporary support system. Table E-6 lists the labor needed for drill-and-blast excavation at the face, categorized according to the type of labor and the work shift. Table E-7 contains the labor needed for TBM excavation at the face and is arranged in a format similar to the that of Table E-5. The labor crew for poured concrete operations is listed in Table E-8. This crew is used to install the tunnel's permanent lining, if required, and to lay the invert. The crew composition is categorized by work shift only. The labor crew for dewatering operations is depicted in Table E-9. The crew size varies only as a function of the work shift. Table E-10 delineates the crew configurations for the various operations included in the shaft excavation and fittings activity. It is assumed that each of the crews shown here works during the day shift only. Table E-11 contains labor needed for compressed air operations.

TABLE E-1. CREW COMPOSITION FOR OVERHEAD

Day Shift Only	
project manager	1
project engineer	1
field engineer	1
office engineer	1
junior engineer	1
party chief	1
general superintendent	1
surveyor	2
office manager	1
purchasing agent	1
EEO officer	1
safety engineer	1
secretary	3

TABLE E-2. CREW COMPOSITION FOR ABOVE-GROUND SUPPORT

Number of Shifts	1	2	3
oiler	2	2	2
fork lift operator	1	1	1
miscellaneous laborer	2	2	2
signal man	1	1	1
shop mechanic	1	0	0
superintendent	1	1	1
master mechanic	1	1	1
electrician	2	1	1
compressor operator	1	1	1
change house attendant	1	1	1
dewatering laborer	1	1	1

TABLE E-3. CREW COMPOSITION FOR HAULING SYSTEM

	Rail to Shaft (<1000 feet)			Rail to Shaft (≥1000 feet)			Rubber to Shaft			Shaft		
Number of Shifts	1	2	3	1	2	3	1	2	3	1	2	3
locomotive operator	1	1	1	2	2	2	1*	1*	1*			
brakeman (optional)	1	1	1	2	2	2						
bottom of shaft laborers	2	2	2	2	2	2	2	2	2			
crane operator										1	1	1
spotter										2	2	2
truck driver for hauling muck to dump										1*	1*	1*

*per vehicle.

TABLE E-4. CREW COMPOSITION FOR EQUIPMENT ASSEMBLY/DISASSEMBLY UNDERGROUND

Shift Number	1	2	3
mechanic	3	3	0
welder	2	2	0
electrician	2	2	0
laborer	4	4	0
crane operator	1	1	0
foreman	1	1	0
oiler	1	1	0

TABLE E-5. CREW COMPOSITION FOR EXCAVATION AT FACE

	Ribs and Lagging			Pre-cast Concrete			Steel Lining		
Number of Shifts	1	2	3	1	2	3	1	2	3
<u>Tunnel Excavation Using Shield with Digger</u>									
shifter (walking boss)	1	1	1	1	1	1	1	1	1
miner (installing support)	4	4	4	5	5	5	5	5	5
operator (shield digger & conveyor)	3	3	3	3	3	3	3	3	3
mechanic	1	1	0	1	1	0	1	1	0
foreman	1	1	1	1	1	1	1	1	1
heading engineer	1	1	0	1	1	0	1	1	0
if grouting is done:									
grout pump operator	1	1	1	1	1	1	1	1	1
grout laborer	2	2	2	2	2	2	2	2	2
grout mixer	1	1	1	1	1	1	1	1	1
<u>Tunnel Excavation Using Shield with Conventional Mining</u>									
shifter (walking boss)	1	1	1	1	1	1	1	1	1
miner (installing support)	6	6	6	7	7	7	7	7	7
operator (shield and mucker)	2	2	2	2	2	2	2	2	2
mechanic	1	1	0	1	1	0	1	1	0
foreman	1	1	1	1	1	1	1	1	1
heading engineer	1	1	0	1	1	0	1	1	0
if grouting is done:									
grout pump operator	1	1	1	1	1	1	1	1	1
grout laborer	2	2	2	2	2	2	2	2	2
grout mixer	1	1	1	1	1	1	1	1	1

TABLE E-5. CREW COMPOSITION FOR EXCAVATION AT FACE (CONTINUED)

	Ribs and Lagging			Pre-cast Concrete			Steel Lining		
Number of Shifts	1	2	3	1	2	3	1	2	3
<u>Tunnel Excavation Using Forepoling or Floating Crown Bars with Conventional Mining</u>									
shifter (walking boss)	1	1	1						
miner (installing support)	6	6	6						
operator (mucker)	1	1	1						
mechanic	1	1	1						
foreman	1	1	1						
heading engineer	1	1	1						
bull gang	1	0	0						
bull gang foreman	1	0	0						
if grouting is done:									
grout pump operator	0	0	0	(Since forepoling or floating crown bar operations are slow-moving, miners perform grouting functions.)					
grout laborer	0	0	0						
grout mixer	0	0	0						

TABLE E-6. CREW COMPOSITION FOR DRILL-AND-BLAST TUNNELING

Number of Shifts	1	2	3
Supervisors:			
shifter	1	1	1
walker	1	1	1
Laborers:			
miner	6	6	6
chucktender	2	2	2
nipper	1	1	1
bull gang	2	0	0
bull gang foreman	1	0	0
dumpman	1	1	1
powderman	1	1	1
Operating Engineers:			
mucker operator	1	1	1
mechanic foreman	1	0	0
mechanic above-ground	3	0	0
mechanic in tunnel	1	1	1
oiler in tunnel	1	0	0
brakeman	2	2	2
locomotive operator	3	2	2
compressor operator	1	1	1
dozer operator	1	0	0
drill repairman	1	0	0
Electricians:			
electrical foreman	1	0	0
electrician	1	1	1
Other:			
suppliers	1	0	0
bit repairman	1	0	0

TABLE E-7. CREW COMPOSITION FOR TBM EXCAVATION AT FACE OF TUNNEL

	Rock bolts			Rock bolts & Shotcrete			Rock bolts & Steel Sets		
Number of Shifts	1	2	3	1	2	3	1	2	3
shifter (walking boss)	1	1	1	1	1	1	1	1	1
miner (installing support)	4	4	4	5	5	5	5	5	5
operator (TBM, oiler & conveyor)	3	3	3	3	3	3	3	3	3
mechanic	2	2	2	2	2	2	2	2	2
foreman	1	1	1	1	1	1	1	1	1
electrician	2	2	2	2	2	2	2	2	2
heading engineer	1	1	1	1	1	1	1	1	1
if grouting is done:									
grout pump operator	0	0	0	1	1	1	1	1	1
grout laborer	0	0	0	2	2	2	2	2	2
grout mixer	0	0	0	1	1	1	1	1	1
bull gang	1	0	0	1	0	0	1	0	0
bull gang foreman	1	0	0	1	0	0	1	0	0

	Shotcrete			Ribs & Shotcrete			Ribs & Lagging		
Number of Shifts	1	2	3	1	2	3	1	2	3
shifter (walking boss)	1	1	1	1	1	1	1	1	1
miner (installing support)	5	5	5	4	4	4	5	5	5
operator (TMB, oiler & conveyor)	3	3	3	3	3	3	3	3	3
mechanic	2	2	1	2	2	1	2	2	1
foreman	1	1	1	1	1	1	1	1	1
electrician	2	2	2	2	2	2	2	2	2
heading engineer	1	1	1	1	1	1	1	1	1
if grouting is done:									
grout pump operator	1	1	1	1	1	1	1	1	1
grout laborer	2	2	2	2	2	2	2	2	2
grout mixer	1	1	1	1	1	1	1	1	1

TABLE E-8. CREW COMPOSITION FOR POURED CONCRETE OPERATIONS

Number of Shifts	1	2	3
shifter	2	2	1
foreman	2	2	2
miner (installing cast-in-place concrete)	16	16	10
pumpman (concrete)	1	1	0
oiler	1	1	0
operator (hydraulic form traveler)	1	1	0
rodman	4	4	4

TABLE E-9. CREW COMPOSITION FOR DEWATERING OPERATIONS

Number of Shifts	1	2	3
pump operator	1	1	1
mechanic	1	1	0

TABLE E-10. CREW COMPOSITION FOR SHAFT EXCAVATION AND FITTINGS

Day Shift Only

Soldier Piles and Lagging:	
foreman	1
pile driver	4
crane operator	2
oiler	1
Steel Sheet Piles:	
foreman	1
pile driver	4
crane operator	1
oiler	1
Cross Bracing:	
foreman	1
ironworker	4
crane operator	2
Shaft Excavation in Soft Ground:	
foreman	1
top laborer	2
clamshell operator	1
excavator operator	1
crane operator	1
spotter	4
top lander	1
oiler	1
mechanic	1
Shaft Excavation in Rock:	
foreman	1
miner	4
backhoe loader operator	1
bulldozer operator	1
jumbo operator	1
crane operator	1
top lander	1
oiler	1
mechanic	1

TABLE E-11. CREW COMPOSITION FOR COMPRESSED AIR OPERATIONS

Shift Number	1	2	3
lock tender	2	2	2

APPENDIX F

EQUIPMENT COSTS DATA FILE

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EQUIPMENT COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
JUMBOWIL1652	16-foot diameter jumbo on wheels, electric/hydraulic drilling. Includes 5 face drills, 2 rock bolt drills, power packs, controls, platform decking, ...	LS	4/82	$1,179,800	Atlas Copco (303)277-0110 (Denver)	+6
JUMBOWIL1640	Same as above, but 4 face drills, & no rock bolt drills.	LS	4/82	$674,200	Atlas Copco	+6
JUMBOWIL2052	Same as above, but 20-foot diam., 5 face drills, and 2 rock bolt drills.	LS	4/82	$1,258,400	Atlas Copco	+6
JUMBOWIL2040	Same as above, but 4 face drills, and no rock bolt drills.	LS	4/82	$719,100	Atlas Copco	+6
JUMBORIL1652	Rail mounted jumbo, 16-foot diam., 5 face drills, and 2 rock bolt drills. Includes all backup hydraulics, ...	LS	4/82	$983,150	Atlas Copco	+6
JUMBORIL1640	Same as above, but 4 face drills, and no rock bolt drills.	LS	4/82	$561,800	Atlas Copco	+6
JUMBORIL2052	Same as above, but 20-foot diam., 5 face drills, and 2 rock bolt drills.	LS	4/82	$1,061,800	Atlas Copco	+6

EQUIPMENT COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
JUMBORIL2040	Rail-mounted jumbo 20-ft. diameter, 4 face drills, and no rock bolt drills. Includes all backup hydraulics.	LS	4/82	$606,750	Atlas Copco (303)277-0110 (Denver)	+6
JUMBOWIL1602	16-ft. diameter jumbo on wheels, electric/hydraulic drilling, includes no face drills, 2 rock bolt drills, powerpacks, controls, platform decking.	LS	4/82	$337,200	Atlas Copco	+6
JUMBOWIL2002	Same as above, but 20-ft. diameter.	LS	4/82	$359,680	Atlas Copco	+6
JUMBORIL1602	Rail-mounted jumbo, 16-ft. diameter, no face drills, 2 rock bolt drills. Includes all backup hydraulics.	LS	4/82	$281,000	Atlas Copco	+6
JUMBORIL2002	Same as above, but 20-ft. diameter	LS	4/82	$303,480	Atlas Copco	+6
VERTIJUMBO	Vertical jumbo used for shaft excavation.	LS	4/82	$562,000	Atlas Copco	+6
WELDER300	300 amp welder	EA	4/82	$6,200	Contractors	+8.5
CONVEYER	Muck conveyer system.	LS	4/82	$27,495	Contractors	+8.5
AUGER	Auger used for placement of piles	MN	4/82	$1,638	Contractors	+8.5

EQUIPMENT COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
HYDRODRILL	Hydraulic rock drill, 3000-5000 PSIG, 1 5/8" diam., 10 ft. round, includes arm, feed unit, power, controls, ...	EA	4/82	$168,540	Atlas Copco (201)696-0554	+6
PNEUDRILL	Pneumatic drill, 1 5/8" diam., 500 CPM, 100 PSIG, 10 ft. round, includes feed, boom, drill, mounting. Model PR55	EA	4/82	$40,000	Gardner/ Denver/Cooper (303)243-0311 NJ Allis (201)478-3607	+7
LSRGUIDEZ	Zed laser guidance system.	LS	4/82	$62,010	Contractors	+8.5
MAGICCARPET	Articulated steel floor used with rail jumbo.	LS	4/82	$409,500	Contractors	+8.5
BLASTEQMT	Miscellaneous blasting equipment, magazines, warning system, gas detector, etc.	LS	4/82	$5,265	Contractors	+8.5
TBM1820	18 to 20 ft. diam. TBM, 200-225 tons, 1.75 M lbs. thrust force, 56 cutters, 550 HP. Model Mark 18.	EA	4/82	$4,355,000	Jarva (216)248-0166	+8.5
TBM2024	20 to 24 ft. diam. TBM, 250-350 tons, 2.25 M lbs. thrust force, 62 cutters, 1000 HP. Model Mark 22	EA	4/82	$5,312,000	Jarva (216)248-0166	+8.5
RINGDECOM	TBM rings per cubic yard of excavation in decomposed rock.	CUY	4/82	$5.75	Jarva (216)248-0166	+8.5

EQUIPMENT COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
RINGSOFT	TBM rings per cubic yard of excavation in soft rock.	CUY	4/82	$6.90	Jarva (216)248-0166	+8.5
RINGMEDIUM	TBM rings per cubic yard of excavation in medium rock.	CUY	4/82	$8.05	Jarva (216)248-0166	+8.5
RINGHARD	TBM rings per cubic yard of excavation in hard rock.	CUY	4/82	$10.35	Jarva (216)248-0166	+8.5
HEADFRAME	Headframe used in hauling system, 1.50/lb.	EA	4/82	$150,000	Card Corp. (303)922-7511	+8.5
HOIST	Hydrostatic drive, 200 HP hoist.	EA	4/82	$180,000	Card Corp. (303)922-7511	+50
SKIPCAGE	Skip & cage system for men & materials, 4.5 by 5 ft., Kimberley type with dump scroll	EA	4/82	$47,400	Card Corp. (303)922-7511	+17
CRANE25W	25-ton crane on wheels. TMS 250	EA	4/82	$189,500	Grove (617)969-7050	+2.5
CRANE50W	50-ton crane on wheels (116 ft. boom). TMS 475	EA	4/82	$267,700	Grove (617)969-7050	+4.5
CRANE100C	100-ton hydraulic crawler crane.	EA	4/82	$438,750	Contractors	+8.5
CRANE160W	160-ton crane on wheels.	EA	4/82	$800,000	Manitowoc (414)684-6621	+22

EQUIPMENT COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
LHD1	Front end loader 2.25 cu. yd., wheel-mounted, load-haul-dump, 4 tons payload, 10700 CFM ventilation, 85 HP, diesel Model 912	EA	4/82	$110,000	EIMCO (801)531-6000	+17
LHD2	5 cu. yd., LHD, 9 tons, 20000 CFM, 180 HP. Model 915	EA	4/82	$175,000	EIMCO (801)531-6000	+14
LHD3	6 cu. yd., LHD. Model 915 with bigger bucket.	EA	4/82	$180,000	EIMCO (801)531-6000	+4.5
LHD4	8 cu. yd., LHD. Model 918	EA	4/82	$250,000	EIMCO (801)531-6000	+5
LHD5	10 cu. yd., LHD, 18 tons, 48700 CFM, 400 HP. Model 920	EA	4/82	$350,000	EIMCO (801)531-6000	+10
TRACKMUCKER1	Track-mounted mucker, opertg. height 11 ft. 8 in., 240 CFM, 1.5 cu. yd. dipper, includes 15 ft. conveyor, no cables. Model 100-2	EA	4/82	$350,000	Goodman Equipment Corp. (312)927-7420	+28
TRACKMUCKER2	Same as above, 9 ft. 7 in. opertg. height, 120 CFM, 0.75 cu. yd. dipper, 13 ft. conveyor. Model 75-1	EA	4/82	$297,500	Goodman Equipment Corp. (312)927-7420	+24

EQUIPMENT COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
LOCOMO12BAT	12-ton locomotive for muck hauling, battery-powered.	EA	4/82	$80,000	National Mine Service (412)281-0688	+10
LOCOMO12DSL	12-ton locomotive for muck hauling, diesel.	EA	4/82	$84,000	National Mine Service (412)281-0688	-
LOCOMOBATSPT	Support equipment for battery-powered locomotive includes 2 batteries & 2 boxes, 1 charger, brakes, dead man control switch, couplers, ...	LS	4/82	$63,900	National Mine Service (412)281-0688	+3
LOCOMODSLSPT	Support equipment for diesel locomotive.	LS	4/82	$8,000	National Mine Service (412)281-0688	-
LIFTCAR25	Lift-off car, used with TBM, 25 cu. yd., used as muck bin.	EA	4/82	$20,675	Card Corp. (303)922-7511	+18
LIFTCAR18	Lift-off car, 18 cu. yd.	EA	4/82	$13,950	Card Corp. (303)922-7511	-
LIFTCAR10	Lift-off car, 10 cu. yd.	EA	4/82	$11,500	Card Corp. (303)922-7511	-
LIFTCAR8	Lift-off car, 8 cu. yd.	EA	4/82	$9,800	Card Corp. (303)922-7511	-
LIFTCAR5	Lift-off car, 5 cu. yd.	EA	4/82	$8,000	Card Corp. (303)922-7511	-

EQUIPMENT COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
GRANBYCAR12	Granby type car (side door), 12 cu. yd.	EA	4/82	$26,000	Card Corp. (303)922-7511	+24
ROTARYCAR	Rotary dumper system.	LS	4/82	$90,000	Card Corp. (303)922-7511	-
FLATCAR	10-ton flat cars.	EA	4/82	$8,500	Card Corp. (303)922-7511	+3
SHOTPUMP	Shotcrete pump with 45 HP electric motor, accelerator, on a trailer, covered. Model Transcrete, Western American Multipump	EA	4/82	40,000	QUIPCO (617)926-4500	+14
GROUTBATCHER	Grout batch plant.	LS	4/82	$29,250	Contractors	+8.5
GROUTPUMP	Grout pump.	EA	4/82	$2,925	Contractors	+8.5
GROUTBIN	Grout cars.	EA	4/82	$2,340	Contractors	+8.5
PUMPW2	2" submersible water pump. BS2050	EA	4/82	$1,107	Flygt Corp. (617)935-6515	+5
PUMPW4	4" submersible water pump. BS2125	EA	4/82	$3,640	Flygt Corp. (617)935-6515	+8
PUMPW6	6" submersible water pump. BS2400	EA	4/82	$27,582	Flygt Corp. (617)935-6515	+19
CONCPUMP1	Concrete pump, portable. Mayco	EA	4/82	$9,800	Logan Equipment (617)567-8700	-

EQUIPMENT COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
CONCPUMP2	Truck-mounted concrete pump.	EA	4/82	$140,400	Contractors	+8.5
CONCPUMP3	Trailer-mounted concrete pump.	EA	4/82	$93,600	Contractors	+8.5
CONCPLANT	Concrete batch plant.	LS	4/82	$117,000	Contractors	+8.5
PAVEBREAKER	65 lb. pneumatic breaker, 60 CFM, 87 PSI. Model TEX31S	EA	4/82	$1,300	Atlas Copco (201)696-0554	+4
CLAYSPADER	Hand-held pneumatic clay cutters. Model M2	EA	4/82	$995	Joy Mnftg. Co. Contractors	+33
COMPRESSOR1	800 CFM portable compressor.	EA	4/82	$69,000	Joy Mnftg. Co. (617)536-9207	+8.5
COMPRESSOR2	1100 CFM portable compressor.	EA	4/82	$92,200	Joy Mnftg. Co. (617)536-9207	+17
COMPRESSOR3	1600 CFM portable compressor.	EA	4/82	$102,375	Contractors	+8.5
COMPRESSOR4	1540 CFM stationary compressor.	EA	4/82	$57,800	Joy Mnftg. Co. (617)536-9207	+8
LOADERCAT950	130 HP, 2.5 cu. yd., cater-piller wheel loader. Model 950B	EA	4/82	$137,490	Caterpillar (617)435-6320 (Witt Eqmt. Co.)	+18
LOADERCAT963	130 HP, 2.5 cu. yd., track-type cat loader. Model 963	EA	4/82	$146,000	Caterpillar (617)435-6320 (Witt Eqmt. Co.)	+27

EQUIPMENT COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
LOADERCAT977	190 HP, 3.25 cu. yd., track-type cat loader. Model 977	EA	4/82	$185,100	Caterpillar (617)435-6320 (Witt Eqmt. Co.)	+11
TRACTORCAT6	140 HP, track-type cat tractor. Model D6	EA	4/82	$134,300	Caterpillar (617)435-6320 (Witt Eqmt. Co.)	+9
TRACTORCAT8	300 HP, track-type cat tractor. Model D8K	EA	4/82	$262,235	Caterpillar (617)435-6320 (Witt Eqmt. Co.)	+10
FORKLIFT25	25000 lbs. forklift. C500Y250	EA	4/82	$70,000	Clark (617)933-6200	+4
SHIELDEX18	18 ft. diam. shield, with excavator, including backup.	LS	4/82	$1,755,000	Contractors	+8.5
SHIELDEX20	20 ft. diam. shield, with excavator.	LS	4/82	$1,872,000	Contractors	+8.5
SHIELDEX22	22 ft. diam. shield, with excavator.	LS	4/82	$2,106,000	Contractors	+8.5
SHIELDEX24	24 ft. diam, shield, with excavator.	LS	4/82	$2,340,000	Contractors	+8.5
SHIELD18	18 ft. diam. shield, with hydraulics.	LS	4/82	$760,500	Contractors	+8.5
SHIELD20	20 ft. diam. shield, with hydraulics.	LS	4/82	$819,000	Contractors	+8.5

EQUIPMENT COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
SHIELD22	22 ft. diam. shield, with hydraulics.	LS	4/82	$848,250	Contractors	+8.5
SHIELD24	24 ft. diam. shield, with hydraulics.	LS	4/82	$877,500	Contractors	+8.5
BREASTING	Breasting system for shield.	LS	4/82	$87,750	Contractors	+8.5
STLRINS	Steel Liner installer.	LS	4/82	$117,000	Contractors	+8.5
PRECSTCONINS	Precast concrete liner installer.	LS	4/82	$175,500	Contractors	+8.5
RIBINST	Rib installer.	LS	4/82	$87,750	Contractors	+8.5
SHIELDSPARE	Shield spare parts cost as % of total.	PCNT	4/82	10% + $.76/ cu. yd. of excavation	Contractors	+8.5
POLINGHOOD	Poling hood.	LS	4/82	$175,500	Contractors	+8.5
CALIFORNIASW	California switch.	LS	4/82	$117,000	Contractors	+8.5
FAN24	24" ventilation fan system (per fan). 40 hp	EA	4/82	$6,000	Joy Manufacturing (216)339-1111	-
FAN36	36" ventilation fan system (per fan). 100 hp	EA	4/82	$10,000	Joy Manufacturing	-
FAN48	48" ventilation fan system (per fan). 100 hp	EA	4/82	$11,000	Joy Manufacturing	-
AIRLOCK	Air lock.	LS	4/82	$99,450	Contractors	+8.5

EQUIPMENT COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
AIRCONTAINER	Oxygen container for rescue purposes.	EA	4/82	$2,808	Contractors	+8.5
STAIRS	Stairs & ladders for exit.	LS	4/82	$11,700	Contractors	+8.5
RADIO	Radio communication equipment.	LS	4/82	$29,250	Contractors	+8.5
ELECTRIC1	Surface generator, 10 kW.	EA	4/82	$27,000	Means	+10
ELECTRIC2	Surface generator, 25 kW.	EA	4/82	$43,300	Means	+12
TRAILER	Trailer equipment & temporary offices (12' x 60').	EA	4/82	$11,000	Carpenter Northeastern (315)656-7205	-
REPAIRSHOP	Repair Shop	LS	4/82	$46,800	Contractors	+8.5
TOILET	Toilet facility.	EA	4/82	$3,800	Means	+13
MISCTOOLS	Miscellaneous surface tools (pneumatic, electric, hydraulic, ...)	PCNT	4/82	5.85% of labor	Contractors	+8.5
TRUCKSAUTOS	Trucks & autos for surface services.	LS	4/82	$58,500	Contractors	+8.5
FORMEQUIP	Forming equipment (Hydraulic traveler).	LS	4/82	$29,250	Contractors	+8.5
VIBRATOR	Concrete vibrators. Model 200E	EA	4/82	$1,000	P.J. Equipment (617)387-9545	-

EQUIPMENT COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
AGITATORCAR	Agitator car for concrete applications.	EA	4/82	$29,250	Contractors	+8.5
CLAMBUCKET	Clam shell bucket.	LS	4/82	$64,350	Contractors	+8.5
BACKHOE1	Back hoe, small. Model 715C	EA	4/82	$42,600	Allis Chalmers (913)354-8401	+11
BACKHOE2	Back hoe, large.	EA	4/82	$117,000	Contractors	+8.5
VIBPILEDRIVE	Vibratory pile driver. Model 5H-1	EA	4/82	$169,500	Delmay-Pileco (713)691-3638	+10
DBPILEHAMMER	Double-acting pile hammer.	EA	4/82	$140,400	Contractors	+8.5
TRANSFRM600	.6 KVA isolating transformer.	EA	4/82	$61	Means	+2.5
TRANSFRM5000	5 KVA isolating transformer.	EA	4/82	$280	Means	+10

APPENDIX G

LABOR COSTS DATA FILE

Labor rates are an essential part of cost methodology and accurate input is critical for precise cost estimating. Therefore, when developing the data base file accurate information pertaining to actual labor rates were solicited. Sources that were used were from completed tunnel projects and input from local union contracts which list hourly wage rate for tunnel laborers and operating engineers. The figures shown in Table G-2 are based on a national average and are dated Jan. 1, 1982. Conversion factors for 23 cities have also been entered into the data bank compensating for different construction locations. (See Table G-1.) These conversion factors were taken from R.S. Means "30 city average" in the 1982 Labor Rates for the Construction Industry Book. The job classifications listed in Table G-2 are the total wage rates for each job classification. The total wage rates were used instead of the base hourly rate and fringe because of the city to city variation of the fringe rate.

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APPENDIX G LABOR COSTS DATA FILE

TABLE G-1. LABOR RATE ADJUSTMENT FACTORS

SOURCE: 1982 Labor Rates (Means)

	City	Adjustment Factor
1.	Atlanta	.813
2.	Baltimore	.869
3.	Boston	1.002
4.	Chicago	1.049
5.	Cleveland	1.068
6.	Denver	.969
7.	Detroit	1.162
8.	Houston	.953
9.	Los Angeles	1.243
10.	Miami	.846
11.	Milwaukee	1.023
12.	Minneapolis	.931
13.	New Orleans	.85
14.	New York	1.147
15.	Oakland	1.397
16.	Philadelphia	.983
17.	Pittsburgh	1.003
18.	Portland	1.139
19.	San Francisco	1.397
20.	Seattle	1.153
21.	St. Louis	.979
22.	Washington D.C.	.929

TABLE G-2. JOB CLASSIFICATION

CODE NAME	DESCRIPTION CATEGORY	TOTAL WAGE RATES*
PROJMANAGER	Project Manager	45.00
PROJENGINEER	Project Engineer	28.00
FLDENGINEER	Field Engineer	19.00
OFFENGINEER	Office Engineer	16.00
JRENGINEER	Junior Engineer	15.00
PARTYCHIEF	Party Chief	19.00
GENSUPER	General Superintendent	32.00
SURVEYOR	Surveyor	16.00
OFFMANAGER	Office Manager	18.50
PURCHAGENT	Purchasing Agent	17.50
EEOOFFICER	EEO Officer	13.00
SAFENGINEER	Safety Engineer	20.00
SECRETARY	Secretary	7.50
FIRSTAIDER	First Aid Nurse	9.00
OILER	Oiler	14.50
FORKLIFTER	Fork Lift Operator	18.50
GENLABORER	General Misc. Laborer	15.00
SIGMAN	Signal Man	14.50
SHOPMECH	Shop Mechanic	18.00
SHIFTSUPER	Shift Superintendent	27.00
MASTMECH	Master Mechanic	19.50
ELECTRICIAN	Electrician	20.00
COMPRESSOPER	Compressor Operator	16.00
CHANGATTEND	Change House Attendent	14.50

* Hourly rate and fringe (National Average, January 1, 1982)

TABLE G-2. (CONT'D)

CODE NAME	DESCRIPTION CATEGORY	TOTAL WAGE RATE
DEWATLABOR	Dewatering Laborer	15.00
LOCOOPER	Locomotive Operator	18.00
BRAKEMAN	Brakeman	15.00
SHAFTLABOR	Bottom Shaft Laborers	15.50
CRANEOPER	Crane Operators	20.00
SPOTTER	Spotter	15.00
TRUCKDRIVOR	Truck Driver	17.00
MECHANIC	Mechanic	18.00
WELDER	Welder	16.00
FOREMAN	Foreman	20.00
SHIFTER	Shifter (Walking Boss)	18.00
MINER	Miner (Installing Support)	15.50
TUNOPER	Tunnel Operator	18.50
HEADENGINEER	Heading Engineer	17.00
GROUTOPER	Grout Pump Operator	17.50
GROUTLABOR	Grout Laborer	15.25
GROUTMIXER	Grout Mixer	15.00
BULLGANG	Bull Gang (1 foreman, 3 Lab)	61.00
WALKER	Walking Supervisor	21.00
CHUCKTENDER	Chucktender	15.50
NIPPER	Nipper	15.50
POWDMAN	Powderman	15.50
MUCKER	Muckers	15.50
CONPUMPOR	Pumpman (Concrete)	15.50
HYDRFORMOR	Hydraulic form operator	16.00
RODMAN	Rodman	15.75

TABLE G-2. (CONT'D)

CODE NAME	DESCRIPTION CATEGORY	TOTAL WAGE RATE
PUMPOR	Pump Operator	15.50
PILEDRIVER	Pile Driver	18.00
IRONWORKER	Ironworker	19.00
TOPLABOR	Top Laborer	15.00
CLAMOPER	Clamshell Operator	18.50
EXCAVOPER	Excavator Operator	18.50
TOPLANDER	Top Lander	15.50
BACKHOPER	Backhoe Loading Operator	18.00
BULLDOPER	Bulldozer Operator	18.50
JUMBOPER	Jumbo Operator	18.00

APPENDIX H

MATERIAL COSTS DATA FILE

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MATERIAL COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
DRILLBIT	2" drill bits, 1500 ft. life. #3136527-120.	EA	4/82	$60.00	Joy Mnftg. Co. (617)536-9207	+ 4
DRILLSTELL	$1\frac{1}{4}$" diam., 12 ft. long, drill steel. #1139731-1512	EA	4/82	$135.00	Joy Mnftg. Co. (617)536-9207	-
GROUT	Grout used for ground control. (Cement and sand, 1:1 mix, maximum).	CUFT	4/82	$5.00	Means	+ 5
CONCRETE	Ready mix concrete, 4000 psi.	CUFT	4/82	$1.88	Means	+12
SHOTCRETE	Shotcrete/gunite for tunnel support.	SQFT	4/82	$2.35	Means	-
CURING	Curing compound, 55 gal. lots.	GAL	4/82	$4.65	Means	+18
FORMLUMBER	Lumber used for concrete formwork.	BF	4/82	$.46	Means	-
RESTEEL	Reinforcing steel, fabricated.	LBS	4/82	$.45	Means	+ 6
FORMSTEEL	Steel formwork for concrete pouring in tunnel.	SQFT	4/82	$21.65	Means	+10
FORMVIBRATE	Vibrating forms for concrete applications in tunnel.	FT	4/82	$39.00	Contractors	+15
SAND	Sand.	TON	4/82	$5.70	Means	+ 7
PIPE4	4" porous wall concrete pipe.	FT	4/82	$1.20	Means	+10

MATERIAL COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
PIPE6	6" porous wall concrete pipe.	FT	4/82	$1.25	Means	+ 9
PIPE8	8" porous wall concrete pipe.	FT	4/82	$2.00	Means	+ 8
PIPE10	10" porous wall concrete pipe.	FT	4/82	$2.90	Means	+13
PIPE15	15" porous wall concrete pipe.	FT	4/82	$5.15	Means	+17
PIPE18	18" porous wall concrete pipe.	FT	4/82	$6.75	Means	+ 9
PIPEFITTING	Pipe fittings, threaded.	EA	4/82	$650.00	Means	+15
VENTLINE24	24" ventilation line, aluminum 18 gauge.	FT	4/82	$8.45	Means	+32
VENTLINE36	36" ventilation line, aluminum 18 gauge.	FT	4/82	$12.71	Means	+32
VENTLINE48	48" ventilation line, aluminum 18 gauge.	FT	4/82	$16.95	Means	+32
COMPAIRLINE2	2" compressed air line, 50 ft. long.	EA	4/82	$369.00	Joy Mnftg. Co. (617)536-9207	+11
COMPAIRLINE4	4" compressed air line, 50 ft. long.	EA	4/82	$487.00	Joy Mnftg. Co. (617)536-9207	+11
COMPAIRLINE8	8" compressed air line, 50 ft. long.	EA	4/82	$780.00	Contractors	+15
WATERLINE2	2" water line.	FT	4/82	$1.30	Contractors	+15
WATERLINE4	4" water line.	FT	4/82	$1.95	Contractors	+15
WATERLINE6	6" water line.	FT	4/82	$2.60	Contractors	+15

MATERIAL COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
ELECTRIC600	600 volt copper armored cable, #8, 3 wire.	FT	4/82	$1.25	Means	+29
ELECTRIC5000	5000 volt copper armored cable, #8, 3 wire.	FT	4/82	$13.00	Contractors	+15
LIGHTING	200 watt bulb/socket, wire (every 40 ft.).	FT	4/82	$2.75	Means	+19
COMMUNICATE	Antenna and telephone lines, underground.	FT	4/82	$26.00	Contractors	+15
ELECENERGY	Electric energy consumption.	KWH	4/82	$.13	Boston Edison (617)424-2271	+15
CAULKING	Contact grouting.	FT	4/82	$.33	Contractors	+15
STEELTIE	Steel ties for rail mucking system (2 ties every 4 ft.).	FT	4/82	$15.80	Bethlehem Steel (617)267-2111	-
WOODTIE	Wood ties for rail mucking system (2 ties every 4 ft.).	FT	4/82	$17.00	Means	+ 3
RAIL40	40 lbs. rail.	FT	4/82	$5.20	Contractors	+15
RAIL80	80 lbs. rail.	FT	4/82	$10.40	Contractors	+15
SWITCHFAST	Switches and fasteners.	EA	4/82	$325.00	Contractors	+15
CABLE	Cables for rail mucking system.	FT	4/82	$40.00	Bethlehem Steel (617)267-2111	+12

MATERIAL COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
RIB614	W6 x 14 steel beams for tunnel support.	LBS	4/82	$.55	Commerical Shearing (216)746-8011	+11
RIB620	W6 x 20 steel beams for tunnel support.	LBS	4/82	$.55	Commerical Shearing (216)746-8011	+11
RIB820	W8 x 20 steel beams for tunnel support.	LBS	4/82	$.55	Commercial Shearing (216)746-8011	+11
STEELRIB	W6 x 15, W6 x 20, W8 x 21 steel beams.	LBS	4/82	$.29	Bethlehem Steel (617)267-2111	+13
PILE10	H10 pile, 42 lbs./ft.	FT	4/82	$10.58	Bethlehem Steel (617)267-2111	+12
PILE12	H12 pile, 53 lbs./ft.	FT	4/82	$13.36	Bethlehem Steel (617)267-2111	+12
PILE14	H14 pile, 74 lbs./ft.	FT	4/82	$18.65	Bethlehem Steel (617)267-2111	+12
WOODLAGGING	Wood lagging.	SF	4/82	$1.40	Means	+11
SHEETMETAL	Sheet metal plates (assuming reuse).	LBS	4/82	$.25	ENR	-
SHEETPILE	Steel sheet piles (assuming salvage).	SQFT	4/82	$3.05	Means	+19
ROCKBOLT1	1 1/4" diam. rock bolt (10-15 ft.).	FT	4/82	$1.88	Bethlehem Steel (617)267-2111	+12
ROCKBOLT2	1 3/8" diam. rock bolt (10-15 ft.).	FT	4/82	$2.25	Bethlehem Steel (617)267-2111	+12

MATERIAL COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
ROCKBOLT3	1 5/8" diam. rock bolt (10-15 ft.).	FT	4/82	$3.25	Bethlehem Steel (617)267-2111	+12
CAPSWIRE	Caps & wire for blasting, per hole.	LS	4/82	$3.27	Hercules, Inc. (302)575-5000	+ 9
DYNAMITE	Dynamite.	LBS	4/82	$.77	Hercules, Inc. (302)575-5000	+ 9
STEELPLATE18	18 ft. diam. tunnel steel linear plate, 2000 lb./ft., 1/3" skin thick, 4" flanges, 5-6 segments/ring (includes bolts, gasketing, internal and external coating, shipment)	LBS	4/82	$.46	Commercial Shearing (216)746-8011	-
STEELPLATE19	19 Ft. diam. tunnel steel liner plate, 2110 lb./ft.	LBS	4/82	$.46	Commercial Shearing (216)746-8011	-
STEELPLATE20	20 ft. diam. tunnel steel liner plate, 2220 lb./ft.	LBS	4/82	$.46	Commercial Shearing (216)746-8011	-
STEELPLATE21	21 ft. diam. tunnel steel liner plate, 2330 lb./ft.	LBS	4/82	$.46	Commercial Shearing (216)746-8011	-
STEELPLATE22	22 ft. diam. tunnel steel liner plate, 2440 lb./ft.	LBS	4/82	$.46	Commercial Shearing (216)746-8011	-
STEELPLATE23	23 ft. diam. tunnel steel liner plate, 2550 lb./ft.	LBS	4/82	$.46	Commercial Shearing (216)746-8011	-
STEELPLATE24	24 ft. diam. tunnel steel liner plate, 2660 lb./ft.	LBS	4/82	$.46	Commercial Shearing (216)746-8011	-

MATERIAL COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
CASTLINER1	Precast concrete liner for tunnel length less than 2000 ft.	SQFT	4/82	$28.60	Contractors	+15
CASTLINER2	Precast concrete liner for tunnel length from 2000-5000 ft.	SQFT	4/82	$19.50	Contractors	+15
CASTLINER3	Precast concrete liner for tunnel length greater than 5000 ft.	SQFT	4/82	$14.30	Contractors	+15

APPENDIX I

LUMP SUM COSTS DATA FILE

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LUMP SUM COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
MINGENSITE	Minimal general sitework preparation (snow removal, insect & odor control, street cleaning,...).	LS	4/82	$13,200	Contractors	+16
MODGENSITE	Moderate general sitework preparation.	LS	4/82	$33,000	Contractors	+16
EXTGENSITE	Extensive general sitework preparation.	LS	4/82	$79,200	Contractors	+16
CHAINLINK	Installation of 6 ft. high chain link fence, 6 gauge.	FT	4/82	$10.64	Means	+ 7
WIREMESH	Installation of wire mesh fence on 4 in. by 4 in. posts, 8 ft. high.	FT	4/82	$8.20	Means	+ 5
PLYWOOD	Installation of painted plywood fence (sound barrier type), 4 in. by 4 in. frame, 8 ft. high.	FT	4/82	$8.54	Means	+ 4
LGTSURVEIL	Light surveillance for construction site (one guard).	MN	4/82	$2550	Means	+ 8
MEDSURVEIL	Medium surveillance (three-guard crew).	MN	4/82	$7650	Means	+ 8
HVYSURVEIL	Heavy surveillance (two crews, closed-circuit system with 3 cameras, monitor).	MN	4/82	$15,300/MN + $3700	Means	+ 7
TRAFFIC1	No traffic maintenance required.	MN	4/82	$0	Contractors	0

LUMP SUM COSTS DATA FILE

Field Name (12-Char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
TRAFFIC2	Closing off traffic completely.	MN	4/82	$660	Contractors	+16
TRAFFIC3	Limited two-way traffic.	MN	4/82	$1,650	Contractors	+16
TRAFFIC4	One lane of traffic with an officer controlling its direction.	MN	4/82	$2,640	Contractors	+16
OFFICEUTIL	Utilities setup for field offices (electric, phone, water, sewage).	LS	4/82	$3,960	Contractors	+16
POWERINS	Electrical installation for tunnel equipment.	LS	4/82	$330,000	Contractors	+16
LGTDEMO	Light demobilization and site cleanup.	LS	4/82	$99,000	Contractors	+16
MODDEMO	Moderate demobilization and site cleanup.	LS	4/82	$151,800	Contractors	+16
HVYDEMO	Heavy demobilization and site cleanup.	LS	4/82	$198,000	Contractors	+16
NOUTILRELOC	No utilities relocation.	LS	4/82	$0	Contractors	-
LITUTILRELOC	Little utilities relocation.	LS	4/82	$6,600	Contractors	+16
MODUTILRELOC	Moderate utilities relocation.	LS	4/82	$66,000	Contractors	+16
EXTUTILRELOC	Extensive utilities relocation.	LS	4/82	$198,000	Contractors	+16
MINMONITOR	Minimal building protection monitoring requirements.	LS	4/82	$13,200	Contractors	+16

LUMP SUM COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
MODMONITOR	Moderate building protection monitoring requirements.	LS	4/82	$66,000	Contractors	+16
EXTMONITOR	Extensive building protection monitoring requirements.	LS	4/82	$132,000	Contractors	+16
SMLBUILDINS	A small amount of building protection insurance.	MN	4/82	$990	Contractors	+16
MEDBUILDINS	A medium amount of building protection insurance.	MN	4/82	$1,980	Contractors	+16
LGEBUILDINS	A large amount of building protection insurance.	MN	4/82	$3,960	Contractors	+16
LGTTREE	Light congestion of trees in area to be cleared (cutting & stump removal).	SQFT	4/82	$.02	Means	+50
MEDTREE	Medium congestion of trees in area to be cleared.	SQFT	4/82	$.02	Means	-
HVYTREE	Heavy congestion of trees in area to be cleared.	SQFT	4/82	$.03	Means	+50
PAVEREM	Pavement (asphalt, or bituminous or plain concrete), curbing, and sidewalk removal using power equipment.	SQFT	4/82	$1.10	Means	+ 8
SMLDEMO	Small building demolition (one or two-story woodframed buildings).	CUFT	4/82	$.12	Means	+10

LUMP SUM COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
MEDDEMO	Medium building demolition (small masonry structures, light commercial, ...).	CUFT	4/82	$.15	Means	+12
LGEDEMO	Large building demolition (large masonry structures, multi-story, bridges, ...).	CUFT	4/82	$.17	Means	+10
MUCKTRANS	Transporting by muck truck.	CY/MILE	4/82	$.18	Contractors	+16
MUCKDUMP	Dumping and reworking muck at the dump site.	CUYD	4/82	$1.32	Contractors	+16
SLURRYWALL	Excavation of a slurry trench, slurry pumping, resteel installation, and 3000 psi concrete backfilling.	SQFT	4/82	$25	Means	+19
PITPIER	Pit piers underpinning.	CUY	4/82	$396	Contractors	+16
JACKEDPILE	Jacked piles underpinning.	FT	4/82	$363	Contractors	+16
PICKUPS	Additional foundation supports for ground settlement	EA	4/82	$13,200	Contractors	+16
TIEBACKS	Steel cables used for bracing soldier piles	EA	4/82	$136	Contractors	+16
SMLDUMPFEE	Minimal fee charged for dumping.	CUY	4/82	$4.62	Contractors	+16
MEDDUMPFEE	Moderate fee charged for dumping.	CUY	4/82	$5.28	Contractors	+16
LGEDUMPFEE	Large fee charged for dumping.	CUY	4/82	$7.92	Contractors	+16

LUMP SUM COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
CONCPLACE	Placing concrete & finishing (bottom & sidewalk).	FT	4/82	$56.00	Means	+12
RESTEELPLACE	Placing reinforcing steel.	LBS	4/82	$.36	Means	+10
MACHINEMOVE	Mining machine removal from tunnel.	LS	4/82	$33,000	Contractors	+16
SHIELDASSMBL	Assembly & setup of shield.	LS	4/82	$158,400	Contractors	+16
WOODFINISH	Wood float finish for tunnel concrete.	SQFT	4/82	$.49	Means	+11
BROOMFINISH	Broom finish for tunnel concrete.	SQFT	4/82	$.23	Means	+ 7
FORMFINISH	Form finish for tunnel and shaft concrete.	SQFT	4/82	$0.99	Contractors	+16
TUNNELCLEAN	Tunnel cleanup activities.	FT	4/82	$59.40	Contractors	+16
FINALCLEAN	Final cleanup of tunnel	FT	4/82	$26.40	Contractors	+16
LEAKSTOP	Leak stoppage during tunnel excavation.	FT	4/82	$13.20	Contractors	+16
TOUCHUP	Touch-ups and repairs.	FT	4/82	$6.60	Contractors	+16
FUEL	Fuel costs as a percentage of labor costs.	PCNT	4/82	8%	Contractors	+16
SITECLEANUP	Cleanup of construction site.	LS	4/82	$39,600	Contractors	+16
CHEMGROUTING	Chemical grouting per cubic yard of soil mass.	CUY	4/82	$255	Means	+23

LUMP SUM COSTS DATA FILE

Field Name (12-char.)	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
CEMGROUTING	Cement grouting per cubic yard of soil mass.	CUY	4/82	$400	Means	+50
SOILFREEZING	Freezing soil for ground control.	CUY	4/82	$759	Contractors	+16
WELLEXCAV	Well excavation.	FT	4/82	$30	Means	+50
SHAFTFIT	Shaft fittings.	FT	4/82	$396	Contractors	+16

APPENDIX J

ADVANCE RATES

When estimating costs, the contractor has to make a crucial decision concerning the advance rate to assume. As mentioned earlier, the advance rate is a key factor in the determination of costs, and special care must be taken in its calculation.

The advance rate depends on such parameters as the construction method, the temporary support system, the geological and water conditions, the number and length of work shifts, and the shape, curvature, and slope of the tunnel. Values for advance rates that take all of these variables into account have been compiled in the following tables.

To obtain an advance rate from the table for a geological subsegment, the user first specifies the geological classification of the segment (rock or soft ground) and the construction method that will be used. Next, the user specifies the subsegment characteristics: soil classification of soft ground or strength of rock, tunnel curvature and slope, water inflow, compressed air requirements, and number and length of work shifts. The user proceeds to the relevant table and chooses the appropriate advance rate. The tables reflect an implicit assumption that, when operations are not conducted 24 hours a day, system availability increases from 55 to 60 percent.

For mixed face conditions, determination of the advance rate becomes more difficult. Advance rates drop markedly, regardless of subsegment characteristics, such as tunnel curvature or grade. In a mixed face condition, several excavation

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methods can be utilized. The first method entails mining the soft ground portion of the face with the aid of a shield. Full breasting equipment must be provided to support the soft ground. After excavation of the soft ground is complete, the rock is drilled, loaded with dynamite, covered with a metal cover (so as not to damage the shield during the blasting operation), and blasted. It becomes obvious that the advance rate here is very low. The second method consists of using forepoling to support the soft ground portion of the face while drilling and blasting the rock portion. The third method comprises using a shield with digger for the entire face if the rock part of the face is soft. The soft ground is excavated, supported by the breasting arrangement of the shield, and then the soft rock is excavated with the digger attached to the shield. These three methods are all very slow, and they are further complicated if water inflow problems along with associated compressed air requirements exist.

Since the advance rate for mixed face excavation is affected by many variables not readily identifiable or quantifiable, this advance rate was given a single constant value that is independent of any specific subsegment characteristics. This value is 8 ft/day when three shifts are employed. For one 8-hour shift, one-third of this value is assumed. System availability considerations are disregarded here because the advance rate is so slow and there is so much slack time that system availability is assumed to be 100 percent.

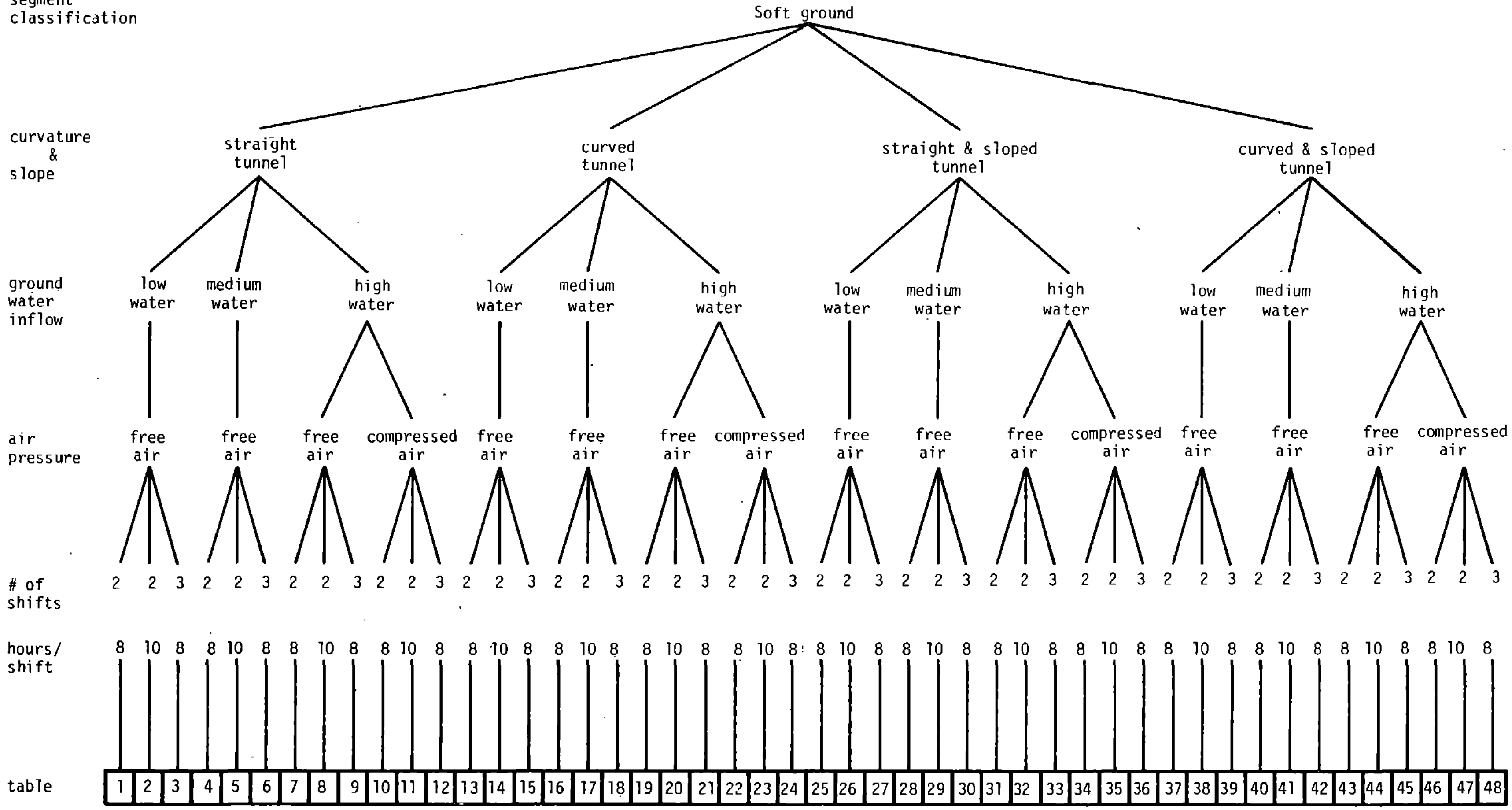
Note: The following advance rate tables are included in this appendix:

Soft ground - tables 1,2,3,13,14,15,25,26,27,37,38, and 39
Rock (TBM) - table 40

The data for the other tables are derived from these tables using the following factors:

curved tunnel - decrease straight tunnel advance rate by 35%
sloped tunnel - decrease straight tunnel advance rate by 15%
medium water inflow - decrease low water inflow advance rate by 15% (not needed for compressed air)
high water inflow - decrease low water inflow advance rate by 25% (not needed for compressed air)
compressed air - decrease free air with low water inflow advance rate by 50%
2 10-hour shifts - decrease 3 8-hour shifts advance rate by 9%
2 8-hour shifts - decrease 3 8-hour shifts advance rate by 27%

ADVANCE RATES
(FEET/DAY)



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high water inflow - decrease low water inflow advance rate by 25% (not needed for compressed air)
compressed air - decrease free air with low water inflow advance rate by 50%
2 10-hour shifts - decrease 3 8-hour shifts advance rate by 9%
2 8-hour shifts - decrease 3 8-hour shifts advance rate by 27%

Table 1 (Soft Ground)

Soft Ground, Straight tunnel, low water inflow, free air, 2 8-hour shifts	Segmented Steel Lining		Precast Concrete		Ribs & Lagging	
	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional
	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely
1. Uniformly soft & compact ground	44	24	35	20	65	36
2. Soft Clay	22	12	17	10	33	19
3. Firm Clay	33	19	26	14	49	27
4. Stiff, Cohesive Clay	44	24	35	20	65	36
5. Running sand, silt & gravel	33	19	26	14	49	27
6. Cohesive sand, silt & gravel	44	24	35	20	65	36
7. Cemented sand, silt & gravel	44	24	35	20	65	36
8. Uncemented sand, silt & gravel below water	22	12	17	10	33	19
9. Bouldery till	33	19	26	14	49	27

Advance rate = feet/day

Table 2 (Soft Ground)

Soft Ground, Straight tunnel, low water inflow, free air, 2 10-hour shifts	Segmented Steel Lining		Precast Concrete		Ribs & Lagging	
	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional
	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely
1. Uniformly soft & compact ground	55	31	44	25	82	46
2. Soft Clay	27	15	22	12	41	23
3. Firm Clay	41	23	33	19	62	35
4. Stiff, Cohesive Clay	55	31	44	25	82	46
5. Running sand, silt & gravel	41	23	33	19	62	35
6. Cohesive sand, silt & gravel	55	31	44	25	82	46
7. Cemented sand, silt & gravel	55	31	44	25	82	46
8. Uncemented sand, silt & gravel below water	27	15	22	12	41	23
9. Bouldery till	41	23	33	19	62	35

Advance rate = feet/day

Table 3 (Soft Ground)

Soft Ground, Straight tunnel, low water inflow, free air, 3 8-hour shifts	Segmented Steel Lining: Shield-digger Most Likely	Segmented Steel Lining: Shield-conventional Most Likely	Precast Concrete: Shield-digger Most Likely	Precast Concrete: Shield-conventional Most Likely	Ribs & Lagging: Shield-digger Most Likely	Ribs & Lagging: Shield-conventional Most Likely
1. Uniformly soft & compact ground	60	33	48	27	90	50
2. Soft Clay	30	17	24	13	45	25
3. Firm Clay	45	25	36	20	68	38
4. Stiff, Cohesive Clay	60	33	48	27	90	50
5. Running sand, silt & gravel	45	25	36	20	68	38
6. Cohesive sand, silt & gravel	60	33	48	27	90	50
7. Cemented sand, silt & gravel	60	33	40	27	90	50
8. Uncemented sand, silt & gravel below water	30	17	24	13	45	25
9. Bouldery till	45	25	36	20	68	38

Advance rate = feet/day

Table 13 (Soft Ground)

Soft Ground, Curved tunnel, low water inflow, free air, 2 8-hour shifts	Segmented Steel Lining		Precast Concrete		Ribs & Lagging	
	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional
	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely
1. Uniformly soft & compact ground	29	16	23	12	44	24
2. Soft Clay	14	8	12	7	22	12
3. Firm Clay	22	12	16	10	33	19
4. Stiff, Cohesive Clay	29	16	23	12	44	24
5. Running sand, silt & gravel	22	12	16	10	33	19
6. Cohesive sand, silt & gravel	29	16	23	12	44	24
7. Cemented sand, silt & gravel	29	16	23	12	44	24
8. Uncemented sand, silt & gravel below water	14	8	12	7	22	12
9. Bouldery till	22	12	16	10	33	19

Advance rate = feet/day

Table 14 (Soft Ground)

Soft Ground, Curved tunnel, low water inflow, free air, 2 10-hour shifts	Segmented Steel Lining		Precast Concrete		Ribs & Lagging	
	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional
	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely
1. Uniformly soft & compact ground	36	20	28	15	55	31
2. Soft Clay	19	10	14	9	27	15
3. Firm Clay	27	15	21	12	41	23
4. Stiff, Cohesive Clay	36	20	28	15	55	31
5. Running sand, silt & gravel	27	15	21	12	41	23
6. Cohesive sand, silt & gravel	36	20	28	15	55	31
7. Cemented sand, silt & gravel	36	20	28	15	55	31
8. Uncemented sand, silt & gravel below water	19	10	14	9	27	15
9. Bouldery till	27	15	21	12	41	23

Advance rate = feet/day

Table 15 (Soft Ground)

Soft Ground, Curved tunnel, low water inflow, free air, 3 8-hour shifts	Segmented Steel Lining		Precast Concrete		Ribs & Lagging	
	Shield-digger Most Likely	Shield-conventional Most Likely	Shield-digger Most Likely	Shield-conventional Most Likely	Shield-digger Most Likely	Shield-conventional Most Likely
1. Uniformly soft & compact ground	40	22	31	17	60	33
2. Soft Clay	20	11	16	9	30	17
3. Firm Clay	30	17	23	13	45	25
4. Stiff, Cohesive Clay	40	22	31	17	60	33
5. Running sand, silt & gravel	30	17	23	13	45	25
6. Cohesive sand, silt & gravel	40	22	31	17	60	33
7. Cemented sand, silt & gravel	40	22	31	17	60	33
8. Uncemented sand, silt & gravel below water	20	11	16	9	30	17
9. Bouldery till	30	17	23	13	45	25

Advance rate = feet/day

Table 25 (Soft Ground)

Soft Ground, Straight & sloped tunnel, low water inflow, free air, 2 8-hour shifts	Segmented Steel Lining		Precast Concrete		Ribs & Lagging	
	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional
	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely
1. Uniformly soft & compact ground	36	21	29	16	56	32
2. Soft Clay	19	10	14	8	27	15
3. Firm Clay	29	16	23	12	43	23
4. Stiff, Cohesive Clay	36	21	29	16	56	32
5. Running sand, silt & gravel	29	16	23	12	43	23
6. Cohesive sand, silt & gravel	36	21	29	16	56	32
7. Cemented sand, silt & gravel	36	21	29	16	56	32
8. Uncemented sand, silt & gravel below water	19	10	14	8	27	15
9. Bouldery till	29	16	23	12	43	23

Advance rate = feet/day

Table 26 (Soft Ground)

Soft Ground, Straight & sloped tunnel, low water inflow, free air, 2 10-hour shifts	Segmented Steel Lining		Precast Concrete		Ribs & Lagging	
	Shield-digger Most Likely	Shield-conventional Most Likely	Shield-digger Most Likely	Shield-conventional Most Likely	Shield-digger Most Likely	Shield-conventional Most Likely
1. Uniformly soft & compact ground	46	25	37	21	70	39
2. Soft Clay	23	13	19	10	35	20
3. Firm Clay	36	20	28	15	52	29
4. Stiff, Cohesive Clay	46	25	37	21	70	39
5. Running sand, silt & gravel	36	20	28	15	52	29
6. Cohesive sand, silt & gravel	46	25	37	21	70	39
7. Cemented sand, silt & gravel	46	25	37	21	70	39
8. Uncemented sand, silt & gravel below water	23	13	19	10	35	20
9. Bouldery till	36	20	28	15	52	29

Advance rate = feet/day

Table 27 (Soft Ground)

Soft Ground, Straight & sloped tunnel, low water inflow, free air, 3 8-hour shifts	Segmented Steel Lining		Precast Concrete		Ribs & Lagging	
	Shield-digger Most Likely	Shield-conventional Most Likely	Shield-digger Most Likely	Shield-conventional Most Likely	Shield-digger Most Likely	Shield-conventional Most Likely
1. Uniformly soft & compact ground	50	28	41	23	77	43
2. Soft Clay	25	14	20	11	38	21
3. Firm Clay	40	22	31	17	58	32
4. Stiff, Cohesive Clay	50	28	41	23	77	43
5. Running sand, silt & gravel	40	22	31	17	58	32
6. Cohesive sand, silt & gravel	50	28	41	23	77	43
7. Cemented sand, silt & gravel	50	28	41	23	77	43
8. Uncemented sand, silt & gravel below water	25	14	20	11	38	21
9. Bouldery till	40	22	31	17	58	32

Advance rate = feet/day

Table 37 (Soft Ground)

Soft Ground, Curved & sloped tunnel, low water inflow, free air, 2 8-hour shifts	Segmented Steel Lining		Precast Concrete		Ribs & Lagging	
	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional
	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely
1. Uniformly soft & compact ground	25	14	20	11	36	21
2. Soft Clay	11	6	10	6	19	10
3. Firm Clay	19	10	14	8	27	15
4. Stiff, Cohesive Clay	25	14	20	11	36	21
5. Running sand, silt & gravel	19	10	14	8	27	15
6. Cohesive sand, silt & gravel	25	14	20	11	36	21
7. Cemented sand, silt & gravel	25	14	20	11	36	21
8. Uncemented sand, silt & gravel below water	11	6	10	6	19	10
9. Bouldery till	19	10	14	8	27	15

Advance rate = feet/day

Table 38 (Soft Ground)

Soft Ground, Curved & sloped tunnel, low water inflow, free air, 2 10-hour shifts	Segmented Steel Lining		Precast Concrete		Ribs & Lagging	
	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional
	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely
1. Uniformly soft & compact ground	32	17	25	14	46	25
2. Soft Clay	14	8	12	7	23	13
3. Firm Clay	23	13	19	10	35	20
4. Stiff, Cohesive Clay	32	17	25	14	46	25
5. Running sand, silt & gravel	23	13	19	10	35	20
6. Cohesive sand, silt & gravel	32	17	25	14	46	25
7. Cemented sand, silt & gravel	32	17	25	14	46	25
8. Uncemented sand, silt & gravel below water	14	8	12	7	23	13
9. Bouldery till	23	13	19	10	35	20

Advance rate = feet/day

Table 39 (Soft Ground)

Soft Ground, Curved & sloped tunnel, low water inflow, free air, 3 8-hour shifts	Segmented Steel Lining		Precast Concrete		Ribs & Lagging	
	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional	Shield-digger	Shield-conventional
	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely	Most Likely
1. Uniformly soft & compact ground	35	19	27	15	50	28
2. Soft Clay	15	8	13	7	25	14
3. Firm Clay	25	14	20	11	38	21
4. Stiff, Cohesive Clay	35	19	27	15	50	28
5. Running sand, silt & gravel	25	14	20	11	38	21
6. Cohesive sand, silt & gravel	35	19	27	15	50	28
7. Cemented sand, silt & gravel	35	19	27	15	50	28
8. Uncemented sand, silt & gravel below water	15	8	13	7	25	14
9. Bouldery till	25	14	20	11	38	21

Advance rate = feet/day

TABLE 40. ROCK EXCAVATION WITH TBM ADVANCE RATES

Input	Use
ribs & lagging	ribs spaced 4' apart and lagging
steel sets	4'x4' rock bolt pattern for 10% of tunnel length
precast concrete	4'x4' rock bolt pattern for 10% of tunnel length
rock bolts	4'x4' rock bolt pattern
rock bolts & shotcrete	4'x4' rock bolt pattern
rock bolts & steel sets	4'x4' rock bolt pattern
ribs & shotcrete	ribs and shotcrete
shotcrete	4'x4' rock bolt pattern for 10% of tunnel length
none	4'x4' rock bolt pattern for 10% of tunnel length

Rock, Excavation Using TBM	4'x4' Rock Bolt Pattern for 10% of Tunnel Length	4'x4' Rock Bolt Pattern	Ribs and Shotcrete	Ribs Spaced 4' Apart and Lagging
Straight tunnel, low water inflow, free air, 3 8-hour shifts	Most Likely	Most Likely	Most Likely	Most Likely
1. Decomposed Rock	70	60	46	36
2. Soft Rock	65	55	44	34
3. Medium Rock	55	47	39	32
4. Hard Rock	45	39	33	30

Advance rate = feet/day

APPENDIX K

MISCELLANEOUS COSTS DATA FILE

MISCELLANEOUS COST DATA FILE

Field Name	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
TAXES	TAXES	LS	4/82	$121,000	Contractors	+10
BONDING	BONDING	PCNT	4/82	.5%	Contractors	+10
INSURC	INSURANCE	PCNT	4/82	2.5%	Contractors	+10
PRPTAX	PROPERTY TAXES	LS	4/82	$121,000	Contractors	+10
LICENS	LICENSE FEES	LS	4/82	$24,200	Contractors	+10
DUES	DUES	LS	4/82	$18,150	Contractors	+10
CONTRB	CONTRIBUTIONS	LS	4/82	$12,100	Contractors	+10
LEGAL	LEGAL FEES	LS	4/82	$48,400	Contractors	+10
ACCNT	ACCOUNTING	LS	4/82	$48,400	Contractors	+10
ENTERT	ENTERTAINMENT	LS	4/82	$12,100	Contractors	+10
PHOTOG	PHOTOGRAPHY	LS	4/82	$12,100	Contractors	+10
EMPEXP	EMPLOYEE EXPENSES	LS	4/82	$72,600	Contractors	+10
TRAVEL	TRAVEL EXPENSES	LS	4/82	$24,200	Contractors	+10
EMPREL	EMPLOYEE RELOCATION	LS	4/82	$60,500	Contractors	+10
SMTOOL	SMALL TOOLS	PCNT	4/82	11%	Contractors	+10
MAINT	MAINTENANCE	PCNT	4/82	4%	Contractors	+10
FUELS	FUEL EXPENSES	PCNT	4/82	6%	Contractors	+10

MISCELLANEOUS COST DATA FILE

Field Name	Description	UM	Date of Cost	Cost/UM	Cost Source	Inflation Index (%/yr)
SAFETY	SAFETY	PCNT	4/82	1%	Contractors	+10
TESTING	TESTING	LS	4/82	$181,500	Contractors	+10

APPENDIX L

REPORT OF NEW TECHNOLOGY

This project was a study of the cost estimating process in subway tunnel construction, and no patents or inventions resulted from this work. However, this report presents an original prescriptive framework for estimating costs that should help planners and designers in making key managerial decisions as to the feasibility of a subway project.

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