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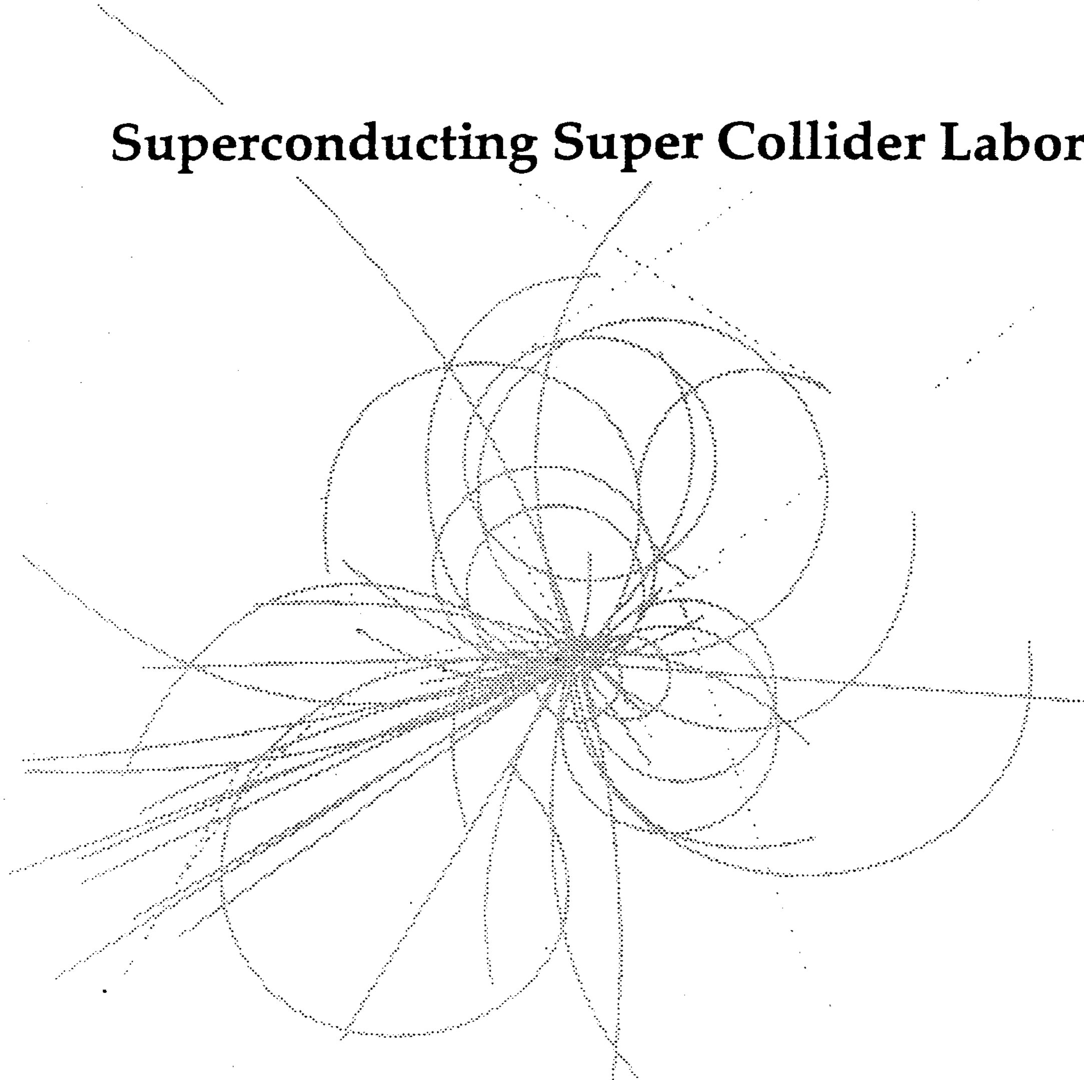

Contractor-Style Tunnel Cost Estimating

Don Scapuzzi, RTK Joint Venture

June 1990

SSCL-316

CONTRACTOR-STYLE TUNNEL COST ESTIMATING*

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Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave.
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SUPERCONDUCTING SUPER COLLIDER

CONTRACTOR-STYLE TUNNEL COST ESTIMATING

by

Don Scapuzzi

RTK, Oakland, CA

ABSTRACT

Keeping pace with recent advances in construction technology is a challenge for the cost estimating engineer. Using an estimating style that simulates the actual construction process and is similar in style to the contractor's estimate will give a realistic view of underground construction costs.

For a contractor-style estimate, a mining method is chosen; labor crews, plant and equipment are selected, and advance rates are calculated for the various phases of work which are used to determine the length of time necessary to complete each phase of work. The durations are multiplied by the cost for labor and equipment per unit of time and, along with the costs for materials and supplies, combine to complete the estimate. Variations in advance rates, ground support, labor crew size, or other areas are more easily analyzed for their overall effect on the cost and schedule of a project.

TUNNEL CONSTRUCTION COST ESTIMATING

Modern tunneling methods are changing and improving rapidly. The innovations made in excavation machinery, i.e., tunnel boring machines (TBMs), and support systems, i.e., the New Austrian Tunnel Method (NATM) have revolutionized the industry in the last 20 years at a rate which is more rapid today than at any time in history. Creating a tunnel cost estimate that is current with the latest tunneling technology is a challenge that has to be met in the most realistic way available to the cost estimating engineer. The estimating style needs to be as current as the tunneling method to be employed. This article describes a method similar to the procedure used by the tunnel contractor during the bidding phase of a project.

ESTIMATE TYPES

Estimating the cost of tunnel construction has traditionally been accomplished by one of two methods. The estimator may take the unit costs of pay items from previous contracts. He may expand or contract them in relation to the size of the current tunnel diameter and other geometric conditions. He should escalate the costs from the time of the previous construction to the time the planned construction. He may also have to make allowances for geotechnical conditions which are different from those which were encountered in the previous project.

This style of construction cost estimating is often employed by engineers. The accuracy of the estimate depends on the size and age of the available data base. This style does little to recognize the constant advances in modern tunneling or how changing conditions underground affect the cost of tunneling.

Another method the estimator may use is to break down the various elements of work into labor, equipment, materials, overhead, and profit. Each phase of the work effort is estimated in detail by determining the labor, equipment, materials, and time required to complete that phase. In this way, effects of changes in ground conditions, materials, quantities, and work methods are more realistically evaluated.

This style of construction cost estimating is most often employed by contractors. The accuracy of the estimate depends on the knowledge of the estimator and his construction experience. This style allows new methods and equipment to be incorporated into the process. The major divisions in a typical format are described below.

Basic Data

At the beginning of the estimate, the basic data used in all subsequent calculations is listed. This includes dimensions, assumed support methods, calculations of production rates and wage rates for the labor crafts.

Plant and Equipment

In this division, the costs for all facilities without a salvage value (site grading, roads, water treatment ponds) necessary to construct the project as well as materials and equipment which do have a salvage value (TBM, mucking system, miscellaneous shops and tools) are listed.

Direct Cost

The cost of direct labor, supplies, permanent materials, and subcontract items are calculated for the shafts, starter tunnel, main tunnel, and all concrete work.

Indirect Cost

This is a summary of project supervision, home office overhead, insurance, taxes, and all other costs not directly connected to any of the contract pay items.

Figure 1 is a flow chart for the methodology of a "contractor-style" estimate.

CREATING THE ESTIMATE

Each of the following tasks is interrelated with the other tasks, and the estimator continues to review decisions made in previous tasks as the estimate proceeds. The job layout has to be studied for all conditions which will have an effect on the work. This includes access to the job site, restrictions on working hours if the job site is in a city, weather patterns, and the availability of labor forces. Any special requirements set by the client must also be noted, such as completion time, portions of the job set for early beneficial occupancy, or owner-furnished equipment which is to be installed by the contractor.

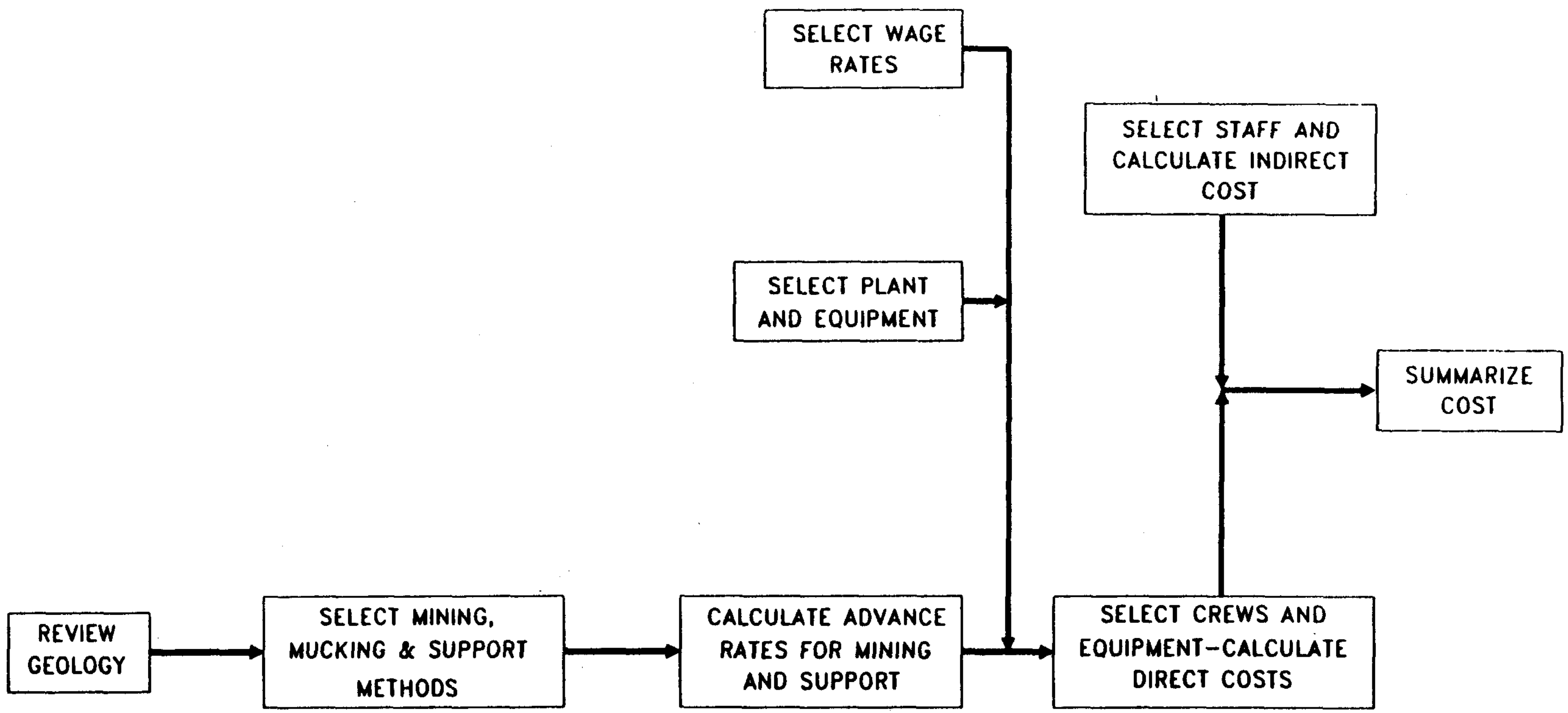

FIGURE 1. ESTIMATING METHOD

The wage rates for the labor force and the working rules which will be in effect for the life of the project must also be determined. This information includes overtime rates, fringe benefits, workers' compensation, public liability and property damage insurance; federal, state and local taxes; and subsistence and travel pay. Local labor union offices are a good source for this information.

A geological review must be made which will be the controlling factor for estimating the daily progress once the mining is underway. All underground conditions which can be determined from subsurface exploration must be noted. The nature of the material to be removed has an effect on all construction operations, including excavation, muck handling, temporary or permanent support, and handling of water. The pace at which each of these operations takes place determines the overall progress and cost of the job.

A contractor-style estimate for a tunnel in Taylor Marl was selected as the example for this article. The mining method uses a Tunnel Boring Machine (TBM) equipped with tooth cutters. Segmental precast concrete liners with a flat invert section are used for initial support and need not be augmented for final lining.

The project includes a shaft at the starting point of the tunnel, and a 91-m-long "starter tunnel" in which the TBM and its trailing gear are assembled prior to the start of tunnel excavation. It is assumed that a second shaft has been constructed by others at the end of the project. When the TBM reaches this shaft, it is disassembled and removed through this shaft. The tunnel is then ready for construction of the final concrete floor.

SELECTING PLANT AND EQUIPMENT

Once the plans have been studied and the mining method is chosen, the plant and equipment can be selected. In this example, all new plant and equipment are assumed; however, in reality, a mix of new equipment and used equipment from the contractors' yard will probably be selected. Included in plant and equipment are the general allowances for setting up the shops and offices, site grading, water treatment, etc.

ESTIMATING ADVANCE RATES

Estimating advance rates is one of the most important steps in contractor-style estimating. Here the estimator identifies the items of work appropriate to the planned construction method and estimates the time to complete each of them. During this process the estimator must also recognize and estimate any feature of the construction process which will delay the work.

Shaft and Starter Tunnel Excavation

The details of estimating the advance rates for the shaft and starter tunnel are shown in Figures 2 and 3. A detailed description of these estimates has been omitted from this paper for the sake of brevity, however, they are similar to the various steps described for the TBM tunnel.

TBM Tunnel Excavation

For tunnel excavation, everything which affects the progress of the excavation process must be identified (see Figure 4).

When a TBM is used, the instantaneous penetration rate must be estimated for each type of ground to be excavated (see Figure 5). These rates, in meters per hour, divided into the respective lengths of ground, determine the length of excavation time for the TBM.

The TBM operates on a 1.2-m-long stroke. At the end of each stroke, the cutter wheel is stopped and the hydraulic shove jacks which propel the TBM forward are retracted to begin the next "shove." This is called the regrip time and it is calculated for the length of the project.

If temporary support for the rock is required, installation time must also be totaled. This estimate uses a precast concrete segmental lining which serves as both the initial temporary support and the final lining.

RTK — 12'ID TBM TUNNEL — 09-Feb-90
SSC PROJECT — 04:29 PM
ROCK UNIT COST MODEL WITH PRECAST LINER — MARL (TEXAS) — 1988 DALLAS DOLLARS — D. SCAPUZZI

1.60 ACCESS SHAFT DATA

1. DIAMETER (Finished Inside)	30 FT
a. SOFT GROUND	
- "A" Line	34 FT
- "B" Line	34 FT
b. ROCK	
- "A" Line	31 FT
- "B" Line	33.67 FT
2. DEPTH	
a. SOFT GROUND	30 LF
b. ROCK(SUPPORTED)	100 LF
c. ROCK(UNSUPPORTED)	20 LF
	----
d. TOTAL DEPTH	150 LF
3. MUCK VOLUMES	
a. SOFT GROUND (BANK: to B Line)	33.6 CY/LF DEPTH
b. SOFT GROUND (EXCAVATED: 40% SWELL)	47.0 CY/LF DEPTH
c. ROCK (BANK: to B Line)	33.0 CY/LF DEPTH
d. ROCK (EXCAVATED: 60% SWELL)	52.8 CY/LF DEPTH
4. CONCRETE LINING VOLUMES	
a. SOFT GROUND (12 Inches thick)	3.8 CY/LF DEPTH
b. ROCK (6" Shotcrete - Includes allowance to replace last 2' damaged by blasting & 20% for rebound)	3.2 CY/LF DEPTH
5. EXCAVATION CYCLE LENGTH	4 LF
6. EXCAVATION DURATION (See calculation adjacent)	
a. MOBILIZATION	2 DAYS
b. SOFT GROUND (DEPTH / PROGRESS/DAY)	7 DAYS
c. ROCK-SUPPORTED (DEPTH / PROGRESS/DAY)	33 DAYS
d. ROCK-UNSUPPORTED (DEPTH / PROGRESS/DAY)	6 DAYS
e. CONCRETE MOBILIZATION	2 DAYS
f. CONCRETE LINING	5 DAYS
	----
d. TOTAL	55 DAYS

1.65 CALCULATION OF SHAFT EXCAVATION DURATION

		HOURS		
	QUANTITY	ROCK SUPPORTED	ROCK UNSUPPORTED	SOFT GRND
1. DRILL HOLES (Perimeter holes at 2.0 foot centers) + (1 burn hole and 4 starter holes) + (1 hole per 6.25 s.f. of surface area)	188			
2. # OF HYDRAULIC TRAC DRILLS : (# DRILLS)	2			
3. HOLES PER DRILL : (#HOLES)	94			
4. DEPTH OF HOLE DRILLED (DEPTH PER CYCLE + 1 FT) : (FT)	5			
5. TOTAL DEPTH OF HOLES DRILLED BY EACH DRILL (# HOLES X DEPTH) : (LF)	470			
6. DRILLING TIME @ 5LF/MIN + 1 MIN/HOLE SETUP TIME :	188	3.1	3.1	
7. HOIST EQUIP IN & OUT OF SHAFT :		1.0	1.0	
8. LOAD & SHOOT (# HOLES/30 HOLES PER HOUR PER MINER-USE 3 MINERS) :		2.1	2.1 (*)	
9. MUCK OUT:				
a. SOFT GROUND - (EXCAVATED CY/FT DEPTH) X (DEPTH PER CYCLE) / (20 CY/HR) :				9.4
b. ROCK - (EXCAVATED CY/FT DEPTH) X (DEPTH PER CYCLE) / (20 CY/HR) :		10.6	10.6	
10. SET STEEL AND LAGGING :				4.0
11. INSTALL ROCKBOLTS & SHOTCRETE		4.0	0.0	
		----	----	----
TOTAL CYCLE TIME :		20.8	16.8	13.4

12. PROGRESS PER DAY (16 HOURS)
   a. SOFT GROUND: (16 HRS) / (CYCLE TIME) X (DEPTH/CYCLE) : 4.8 LF/DAY
   b. ROCK(SUPPORTED): (16 HRS) / (CYCLE TIME) X (DEPTH/CYCLE) : 3.1 LF/DAY
   c. ROCK(UNSUPPORTED): (16 HRS) / (CYCLE TIME) X (DEPTH/CYCLE) : 3.8 LF/DAY

(*) 30 MINUTES OF VENTILATION IS PROVIDED DURING LUNCH BREAK

FIGURE 2. ACCESS SHAFT DATA

RTK	12'ID TBM TUNNEL		09-Feb-90
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ROCK UNIT COST MODEL WITH PRECAST LINER	MARL (TEXAS)	1988 DALLAS DOLLARS	D. SCAPUZZI

1.70 STARTER TUNNEL DATA

1. TUNNEL SIZE (HORSESHOE)	
a. Finished Inside and "A" Line	18 FT
b. "B" Line	20.67 FT
2. TUNNEL FACE AREA (Finished Inside)	289 SF
3. MUCK VOLUMES	
a. BANK (to B Line)	14.1 CY/LF
b. EXCAVATED (60 % SWELL)	22.6 CY/LF
4. LENGTH	
a. WITH STEEL RIBS AND LAGGING	20 LF
b. WITH ROCKBOLTS	50 LF
c. WITHOUT SUPPORT	230 LF
	-----
d. TOTAL	300 LF
5. EXCAVATION CYCLE LENGTH	8 LF
6. EXCAVATION DURATION (See calculation adjacent)	
a. MOBILIZATION	2 DAYS
b. RIBS AND LAGGING (LENGTH / PROGRESS)	2 DAYS
c. ROCKBOLTS (LENGTH / PROGRESS)	3 DAYS
d. WITHOUT SUPPORT (LENGTH / PROGRESS)	9 DAYS
	----
e. TOTAL	16 DAYS

1.75 CALCULATION OF STARTER TUNNEL EXCAVATION DURATION

	QUANTITY		
1. DRILL HOLES (Perimeter holes at 2.0 foot centers) (1 burn hole and 4 starter holes) (1 hole per 6.25 sq. ft. of surface area)	87		
2. NUMBER OF HYDRAULIC TRAC DRILLS = (# DRILLS)	2		
3. HOLES PER DRILL = (# HOLES)	44		
4. DEPTH OF HOLE DRILLED (DEPTH PER CYCLE + 1 FT) = (FT)	9		
5. TOTAL LENGTH OF HOLES DRILLED BY EACH DRILL (# HOLES) X (DEPTH) = (LF)	396		
6. MUCK VOLUME (CY/LF) X (CYCLE LENGTH) = (CY)	181		
7. MUCK TIME (3MIN/TRIP) X (CY) / (4CY/TRIP) = (MIN)	135.75		
8. CYCLE TIME (MINUTES)	RIBS & LAGGING	ROCK-BOLTS	W/O SUPPORT
- SET STEEL RIBS AND LAGGING	150	0	0
- MOVE DRILL IN	5	5	5
- INSTALL ROCKBOLTS AND CHAIN LINK FENCING	0	120	0
- INSTALL SHOTCRETE	120	100	0
- DRILL OUT (4 LF/MIN)	99	99	99
- LOAD HOLES (2 MIN/HOLE)/(2MEN LOADING)	87	87	87
- MOVE OUT	5	5	5
- SHOOT AND VENT	30	30	30
- MOVE LOADER IN	5	5	5
- BAR DOWN	15	15	15
- MUCK OUT	135.75	135.75	135.75
	-------	-------	-------
- TOTAL CYCLE TIME (MINUTES)	651.75	601.75	381.75
- TOTAL CYCLE TIME (HOURS)	10.9	10.0	6.4
- CYCLES/22.5 HR DAY	2.1	2.3	3.5
- LF/DAY	16.8	18.4	28

FIGURE 3. STARTER TUNNEL DATA

RTK — 12'ID TBM TUNNEL — 09-Feb-90
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ROCK UNIT COST MODEL WITH PRECAST LINER — MARL (TEXAS) — 1900 DALLAS DOLLARS — D. SCAPUZZI

1.50 CALCULATION OF T.B.M. UTILIZATION RATE

	QUANTITY	HOURS: OTHER	HOURS: PRODUCTION
1. TBM EXCAVATION (TUNNEL LENGTH/ INSTANTANEOUS PENETRATION RATE) :			1042
2. TBM STROKE LENGTH : (LF/STROKE)	4		
3. REGRIP : TUNNEL LENGTH / STROKE LENGTH X 2 MIN/STROKE / 60 MIN/HR		208	
4. ALLOWANCE FOR UNFAVORABLE GROUND CONDITIONS: 22.5 HOURS / 1,000 L.F. :		563	
5. INSTALL PRECAST LINER AND PEA GRAVEL: TUNNEL LENGTH / 4 LF/RING @ 11 MIN/RING :		1146	
6. ADD VENT LINE: TUNNEL LENGTH / 30 FT/MOVE X 10 MIN/MOVE / 60 MIN/HR :		139	
7. MAIN POWER:			
a. TUNNEL LENGTH / 1,000 FT/ CABLE/MOVE X 4 HRS/MOVE :		100	
b. OUTAGES: 1 EACH 26 WEEKS FOR 8 HRS :		16	
8. CUTTERS:			
a. *ADDITIONAL TIME REQUIRED TO CHANGE* CUTTERS (See calculation adjacent) :	(*)	0	
b. INSPECT 10 MIN/SHIFT X 10 SHIFTS/WEEK X DURATION (WEEKS) / 60 MIN/HR :	(*)	58	
c. MISC CUTTER CHANGES: 1 /WEEK X 1.0 HRS/CHANGE X DURATION (WEEKS) :	(*)	35	
9. MAINTENANCE AND REPAIRS:			
a. *ROUTINE MAINTENANCE:* (2.0 HRS ON TUE-FRI) + (7.5 HRS ON SAT)	(*)	543	
b. OTHER: (DERAIL, ETC.): 2 HR/WEEK		70	
10. START-UP: 2 WORKWEEKS		256	
11. HOISTING DELAY: 2 HR/WEEK		70	
12. WAITING FOR TRAINS (MUCKBOUND) (2% OF PRODUCTION TIME)		21	
13. LUNCH: (30 MIN/SHIFT) X (16 SHIFTS/WEEK) X (DURATION-WEEKS)		200	
		------	------
		3505	1042
TBM AVAILABILITY =(TOTAL HOURS - (*) HOURS) / TOTAL HOURS =			86%
TBM UTILIZATION RATE = PRODUCTION / TOTAL HOURS =			23%

FIGURE 4. CALCULATION OF TBM UTILIZATION RATE

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1.30 CALCULATION OF TUNNEL EXCAVATION DURATION

TRIAL EXCAVATION PERIOD :	177 DAYS	35 WEEKS	
CALCULATED EXCAVATION PERIOD :	177 DAYS		(72,000)
1. MATERIAL:	MARL (TEXAS)		(2,000)
2. UNCONFINED COMPRESSIVE STRENGTH:	400 PSI =	3 MPa	
3. INSTANTANEOUS PENETRATION RATE :	24.0 FT/HR		
4. MACHINE UTILIZATION RATE :	23 % (See page 5)		
5. HOURS PER WORKWEEK :	120 HOURS		
6. AVERAGE DAILY ADVANCE RATE	141 FT/DAY		
7. EXCAVATION DURATION: (LENGTH) / (PROGRESS/DAY) :	177 DAYS		

FIGURE 5. CALCULATION OF TUNNEL EXCAVATION DURATION

After the 1.2-m-long segmental ring has been erected and fastened to the previously installed lining, the shove jacks are brought to bear against the lining and the next round of excavation begins.

As the excavation progresses, the utilities (electricity, compressed air, water, pump discharge), ventilation duct work, fans, and rails must be extended. Some of this work can be done concurrently with the excavation. The time it takes to accomplish the remainder is totaled for the length of the tunnel.

All maintenance time on the TBM must be estimated. Current practice is to spend one-half of the day shift the last four days of the week and one full shift on Saturday for preventative maintenance, repairs, and cutter changes. Additional time during the remainder of the work week is also allowed for inspecting the cutters and unscheduled TBM maintenance and repairs.

The muck handling cycle must be closely analyzed. Whenever the TBM is excavating, muck must be loaded into a muck handling system which is capable of receiving the muck as fast as it is being excavated. Whenever the muck handling system is incapable of receiving the muck, the excavating system becomes "muckbound" and the TBM is prevented from excavating. In the case of a rail muck handling system, being muckbound can be caused by an insufficient number of trains to complete the load-haul-dump-return cycle in time to keep a continuous supply of empty muck cars behind the TBM, equipment breakdowns, and derailments. This total amount of time must be estimated for the entire length of the project.

Any special geotechnical problems which are not accounted for in the regular computation of mining time should also be totaled. In this case, an allowance of one lost day per 300 m of tunnel was provided because of the lack of more complete data from subsurface investigations.

When a tunnel project is started there is a certain amount of time which is spent learning the whole excavation-mucking-support system. The inefficiency of this start-up period must be accounted for. For this example, the crews will average only 50% efficiency in the first month. A start-up time of two weeks is used as time lost from production.

The time allowed for lunch on each shift is also calculated for the life of the project.

The excavation time for the TBM divided by the grand total of all excavation time plus non-production time gives the percentage of time that the TBM is working, or its "efficiency." The efficiency multiplied by the instantaneous penetration rate of the TBM multiplied by number of hours worked per week divided by the number of days per week which were spent excavating with the TBM equals the average daily progress for the TBM. The estimator should compare his calculated daily advance rate with similar-sized tunnels in similar types of ground for reasonable agreement and revise the assumptions if necessary.

The average daily advance rate divided into the length of tunnel to be mined gives the total length of time for direct excavation costs.

TUNNEL INTERIOR CONCRETE

The interior concrete is subdivided into six sections: (1) removal of the vent line, (2) initial cleanup, (3) pouring an invert in the tunnel, (4) pouring the floors of the hand-mined tunnels, (5) grouting the pea gravel installed between the segmental liner and the excavated ground, and (6) the final cleanup.

The progress rate for each of these items of work is based on past experience rather than on a detailed examination of the individual subdivisions since the work is relatively uniform from job to job.

Some phases of the concrete work overlap, resulting in a reduction of the total overall time used for maintenance and outside support costs. A schedule of the interior concrete work is shown in Figure 6.

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ROCK UNIT COST MODEL WITH PRECAST LINER | MARL (TEXAS) | 1988 DALLAS DOLLARS | D. SCAPUZZI

1.40 CALCULATION OF INTERIOR CONCRETE CONSTRUCTION DURATION

DESCRIPTION	QUANTITY	PROGRESS (LF/DAY)	MOBILIZE TIME (DAYS)	TOTAL DURATION (DAYS)
1. REMOVE VENT LINE	25,000 LF	7,500		4
2. INITIAL CLEANUP	25,000 LF	600		42
3. POUR INVERT	25,000 LF	450	3	59
4. POUR FLOORS OF HAND MINED TUNNELS	6,200 SF	3,000		2
5. PEA GRAVEL GROUT	25,000 LF	600		42
6. FINAL CLEANUP	25,000 LF	1,000		25
TOTAL DURATION (*)				174

(*) This work not accomplished in consecutive order. Some items overlap, resulting in a reduction of the time required for maintenance and outside support cost. For more information see the Construction Schedule. USE: 99 DAYS : 20 WEEKS

FIGURE 6. CALCULATION OF INTERIOR CONCRETE CONSTRUCTION DURATION

CALCULATING DIRECT COSTS

A crew is required for each underground task identified previously in determining advance rates. In addition, an outside support crew is also required to provide necessary support services such as mechanical and electrical maintenance, crane or hoist operation, and muck handling. The cost of wages and fringe benefits for the crews is totaled to establish the daily cost of direct labor (see Figures 7 and 8).

Next, the equipment to be used by both the underground and outside support crews is identified and this daily operational cost is totaled (see Figure 9).

Then, any routinely reoccurring miscellaneous costs are calculated, such as power, shop supplies, temporary support materials, and maintenance overtime. These can be calculated as a daily cost, a unit cost per lineal foot of work performed, or as a lump sum or subcontract price (see Figures 10 and 11).

The total direct costs for tunneling are summarized in Figure 12.

Direct Concrete Costs

The direct costs for the concrete operations are derived similarly to the direct tunneling costs. A discussion of these details has been omitted for the sake of brevity.

INDIRECT COSTS

The indirect crew consists of the project manager and his staff of supervisors and administrative personnel. Their salaries, taxes, and profit sharing are calculated as indirect labor costs.

General expenses are also part of the indirect costs and consist of monthly expenses such as office utilities and supplies as well as special consultant fees, the main office charges for support of the project, and other fees incurred by the project.

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ROCK UNIT COST MODEL WITH PRECAST LINER | MARL (TEXAS) | 1988 DALLAS DOLLARS | D. SCAPUZZI

ACCOUNT NUMBER	DESCRIPTION	QUANTITY	UNITS MH	UNITS EV	UNITS MAT	UNITS EQ	TOTAL MNHRS	LABOR RATE	LABOR & BURDEN	EQUIPMENT USAGE	MATERIAL	EQUIPMENT	CONTRACTOR'S OH & P	TOTAL
6.00	DIRECT DAILY COSTS - TBM TUNNEL													
6.10	UNDERGROUND CREW													
	HEADING CREW (3 SHIFTS PER DAY, 8 HOURS PER SHIFT)													
	SHIFTER (MH/DAY)	3 MEN	8				24	$16.63	$399	$0	$0	$0	$200	$599
	MINERS (MH/DAY)	3 MEN	8				24	$15.13	$363	$0	$0	$0	$182	$545
(1)	MOTORMEN (MH/DAY)	5.4 MEN	8				43.2	$17.38	$751	$0	$0	$0	$375	$1,126
(2)	CALIF SWITCH OPERATOR (MH/DAY)	2.4 MEN	8				19.2	$15.80	$303	$0	$0	$0	$152	$455
	TBM OPERATOR (MH/DAY)	3 MEN	8				24	$18.96	$455	$0	$0	$0	$228	$683
	CONVEYOR OPERATOR (MH/DAY)	3 MEN	8				24	$15.80	$379	$0	$0	$0	$190	$569
	MECHANIC (MH/DAY)	3 MEN	8				24	$18.96	$455	$0	$0	$0	$228	$683
	CHAINMAN (MH/DAY)	1 MAN	8				8	$17.38	$139	$0	$0	$0	$70	$209
	INSTRUMENT MAN (MH/DAY)	1 MAN	8				8	$17.38	$139	$0	$0	$0	$70	$209
	SUBTOTAL: HEADING CREW	24.8 MEN					198.4		$3,384	$0	$0	$0	$1,692	$5,076
	BULL GANG (1 SHIFT PER DAY, 8 HOURS PER SHIFT)													
	FOREMAN (MH/DAY)	1 MAN	8				8	$11.35	$91	$0	$0	$0	$45	$136
	LABORERS (MH/DAY)	3 MEN	8				24	$10.61	$255	$0	$0	$0	$127	$382
	SUBTOTAL: BULL GANG	4 MEN					32		$345	$0	$0	$0	$173	$518
	SUBTOTAL: UNDERGROUND CREW	28.8 MEN					230.4		$3,729	$0	$0	$0	$1,865	$5,594
	SUBSISTENCE	28.8 MEN						$0.00	$0	$0	$0	$0	$0	$0
	SMALL TOOLS, SAFETY, RUBBER, ETC.	28.8 MEN			$13.00		0		$0	$0	$374	$0	$0	$374
	TOTAL DAILY DIRECT LABOR FOR UNDERGROUND CREW						230.4		$3,729	$0	$374	$0	$1,865	$5,968
	AVG. COST / MANHOUR	$16.19												

(1) USE AN AVERAGE OF 1.8 MOTORMEN PER SHIFT OVER THE LENGTH OF THE JOB
(2) USE AN AVERAGE OF 0.8 OPERATORS PER SHIFT OVER THE LENGTH OF THE JOB

FIGURE 7. DIRECT DAILY COSTS - TBM TUNNEL (UNDERGROUND CREW)

RTK
SSC PROJECT
ROCK UNIT COST MODEL WITH PRECAST LINER

12'ID TBM TUNNEL
MARL (TEXAS)

1988 DALLAS DOLLARS

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ACCOUNT NUMBER	DESCRIPTION		QUANTITY	UNITS MH	UNITS EV	UNITS MAT	UNITS EQ	TOTAL HOURS	LABOR RATE	LABOR & BURDEN	EQUIPMENT USAGE	MATERIAL	EQUIPMENT	CONTRACTOR'S OH & P	TOTAL
6.20	OUTSIDE SUPPORT CREW (3 SHIFTS PER DAY, 8 HOURS PER SHIFT)														
	MECHANIC FOREMAN	(MH/DAY)	1 MAN	8				8	$17.21	$138	$0	$0	$0	$69	$207
	MECHANICS	(MH/DAY)	4 MEN	8				32	$16.51	$528	$0	$0	$0	$264	$792
	ELECTRICAL FOREMAN	(MH/DAY)	1 MAN	8				8	$40.85	$327	$0	$0	$0	$163	$490
	ELECTRICIAN	(MH/DAY)	3 MEN	8				24	$39.85	$956	$0	$0	$0	$478	$1,434
	LOADER OPERATOR	(MH/DAY)	1 MAN	8				8	$15.12	$121	$0	$0	$0	$60	$181
	TOP & BOTTOM MAN	(MH/DAY)	6 MEN	8				48	$9.52	$457	$0	$0	$0	$228	$685
	CRANE OPERATOR	(MH/DAY)	3 MEN	8				24	$15.12	$363	$0	$0	$0	$181	$544
	CRANE OILER	(MH/DAY)	3 MEN	8				24	$15.12	$363	$0	$0	$0	$181	$544
	LABORERS	(MH/DAY)	6 MEN	8				48	$9.52	$457	$0	$0	$0	$228	$685
	TOOL ROOM ATTENDANT	(MH/DAY)	1 MAN	8				8	$9.52	$76	$0	$0	$0	$38	$114
	SUBTOTAL: OUTSIDE SUPPORT CREW		29 MEN					232		$3,785	$0	$0	$0	$1,893	$5,678
	SUBSISTENCE		29 MEN						$0.00	$0	$0	$0	$0	$0	$0
	SMALL TOOLS, SAFETY, RUBBER, ETC.		29 MEN			$13.00		0		$0	$0	$377	$0	$0	$377
	TOTAL DAILY DIRECT LABOR FOR OUTSIDE SUPPORT CREW							232		$3,785	$0	$377	$0	$1,893	$6,055
	AVG. COST / MANHOUR		$16.32												

FIGURE 8. DIRECT DAILY COSTS - TBM TUNNEL (OUTSIDE SUPPORT CREW)

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ROCK UNIT COST MODEL WITH PRECAST LINER | MARL (TEXAS) | 1988 DALLAS DOLLARS | D. SCAPUZZI

ACCOUNT NUMBER	DESCRIPTION	QUANTITY	UNITS MH	EU	MAT	EO	TOTAL MHOURS	LABOR RATE	LABOR & BURDEN	EQUIPMENT USAGE	MATERIAL	EQUIPMENT	CONTRACTOR'S OH & P	TOTAL
6.30	EQUIPMENT DAILY OPERATING COST - TBM TUNNEL													
6.31	UNDERGROUND EQUIPMENT													
	LOCOMOTIVES: AVG 8 X SHIFTS X HR/SH	41 HR		$15.00			0		$0	$615	$0	$0	$0	$615
	MUCK CARS: AVG 8 X SHIFTS X HR/SH	504 HR		$1.10			0		$0	$554	$0	$0	$0	$554
	ALL OTHER CARS	1 LT		$54.00			0		$0	$54	$0	$0	$0	$54
	CALIFORNIA SWITCH: AVG 8 X 10 HR/DAY	8 HR		$13.00			0		$0	$104	$0	$0	$0	$104
	FANS: AVG 8 X SHIFTS X HR/SH	156 HR		$1.30			0		$0	$203	$0	$0	$0	$203
	PUMPS	1 LT		$32.00			0		$0	$32	$0	$0	$0	$32
	MISC. (ALLOWANCE)	1 LT		$107.00			0		$0	$107	$0	$0	$0	$107
	SUBTOTAL: UNDERGROUND EQUIPMENT						0		$0	$1,669	$0	$0	$0	$1,669
6.32	OUTSIDE EQUIPMENT													
	100 TON CRANE	18 HR		$43.00			0		$0	$774	$0	$0	$0	$774
	COMPRESSORS (2 EA)	10 HR		$8.60			0		$0	$86	$0	$0	$0	$86
	PUMPS	1 LT		$32.00			0		$0	$32	$0	$0	$0	$32
	LOADER	6 HR		$27.00			0		$0	$162	$0	$0	$0	$162
	HYDROCRANE	2 HR		$21.00			0		$0	$42	$0	$0	$0	$42
	FLATBED TRUCK	6 HR		$11.00			0		$0	$66	$0	$0	$0	$66
	SHOP & MISCELLANEOUS	1 LT		$215.00			0		$0	$215	$0	$0	$0	$215
	ELEVATOR	6 HR		$5.50			0		$0	$33	$0	$0	$0	$33
	SUBTOTAL: OUTSIDE EQUIPMENT						0		$0	$1,410	$0	$0	$0	$1,410
6.33	TUNNEL BORING MACHINE													
	a. OPERATION: BANK EXCAVATION X AVERAGE DAILY ADVANCE	652.00 CY		$2.20			0		$0	$1,436	$0	$0	$0	$1,436
	b. CUTTERS: (ALLOWANCE)			$100.00			0		$0	$100	$0	$0	$0	$100
	c. TRAILING GEAR: 22.5 HR/DAY X UTILIZATION RATE :	5.16 HR		$23.00			0		$0	$119	$0	$0	$0	$119
	SUBTOTAL: TBM						0		$0	$1,655	$0	$0	$0	$1,655

FIGURE 9. EQUIPMENT DAILY OPERATING COSTS - TBM TUNNEL

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ROCK UNIT COST MODEL WITH PRECAST LINER

12'ID TBM TUNNEL
MARL (TEXAS)

1988 DALLAS DOLLARS

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ACCOUNT NUMBER	DESCRIPTION	QUANTITY	UNITS MH	EU	MAT	EQ	TOTAL MHRS	LABOR RATE	LABOR & BURDEN	EQUIPMENT USAGE	MATERIAL	EQUIPMENT	CONTRACTOR'S OH & P	TOTAL
6.40	DIRECT MISCELLANEOUS COSTS - TBM TUNNEL													
6.41	ASSEMBLE & DISASSEMBLE TBM & TRAILING GEAR:													
	a. LABOR: 12 MEN/SHIFT (40 SHIFTS TO ASSEMBLE) (30 SHIFTS TO DISASSEMBLE)	70 SHIFTS	96				6,720	$16.19	$108,797	$0	$0	$0	$54,398	$163,195
	b. EQUIPMENT USEAGE & POWER:			$600.00			0		$0	$42,000	$0	$0	$0	$42,000
	c. SUPPLIES, TOOLS, ECT.				$600.00		0		$0	$0	$42,000	$0	$0	$42,000
	SUBTOTAL: ASSEMBLY AND DISASSEMBLY						6,720		$108,797	$42,000	$42,000	$0	$54,398	$247,195
6.42	MUCK DISPOSAL: (MUCK VOLUME W/SWELL) X (TUNNEL LENGTH)	204,000 CY		$5.00			0		$0	$1,020,000	$0	$0	$0	$1,020,000
6.43	MAINTENANCE OVERTIME (SATURDAYS ONLY):													
	a. LABOR: 12 MEN X DURATION (WEEKS)	35 SHIFTS	96				3,360	$24.29	$81,598	$0	$0	$0	$40,799	$122,396
	b. POWER: 10,000 KWH/DAY X $0.08/KWH	35 DAYS		$800.00			0		$0	$28,000	$0	$0	$0	$28,000
	c. SUPPLIES, TOOLS, ETC.	35 DAYS			$700.00		0		$0	$0	$24,500	$0	$0	$24,500
	SUBTOTAL: MAINTENANCE OVERTIME						3,360		$81,598	$28,000	$24,500	$0	$40,799	$174,896
6.44	PRECAST CONCRETE LINER	25,000 LF			$300.00		0		$0	$0	$7,500,000	$0	$0	$7,500,000

FIGURE 10. DIRECT MISCELLANEOUS COSTS - TBM TUNNEL

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ROCK UNIT COST MODEL WITH PRECAST LINER

12'ID TBM TUNNEL
MARL (TEXAS)

1988 DALLAS DOLLARS

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ACCOUNT NUMBER	DESCRIPTION	QUANTITY	UNITS MH	UNITS EU	UNITS MAT	UNITS EQ	TOTAL MHHRS	LABOR RATE	LABOR & BURDEN	EQUIPMENT USAGE	MATERIAL	EQUIPMENT	CONTRACTOR'S OH & P	TOTAL
6.50	DIRECT MISCELLANEOUS SUPPLIES - TBM TUNNEL								($/LF)	($/LF)	($/LF)	($/LF)	($/LF)	($/LF)
	SHOP & ELECTRICAL SUPPLIES ($600/DAY) / (PROGRESS/DAY)	1 LF			$4.26		0		$0.00	$0.00	$4.26	$0.00	$0.00	$4.26
	MISC. SUPPLIES, HOSE, ETC.	1 LF			$25.00		0		$0.00	$0.00	$25.00	$0.00	$0.00	$25.00
	PEA GRAVEL	0.128 CY/LF			$15.00		0		$0.00	$0.00	$1.92	$0.00	$0.00	$1.92
	POWER													
	TBM: HP X AVAILABILITY % :	0 HP												
	COMPRESSORS: 0 X HP X 20% :	80 HP												
	FANS: AVG 0 X HP :	650 HP												

	SUBTOTAL HORSEPOWER	730 HP												
	HP X .76 X 24 HR/DAY / 0.8 POWER FACTOR	16,640 KWH												
	LIGHTS: 200W @ 40X AVG LENGTH :	1,500 KWH												
	PUMPS, SHOP, ETC.:	3,000 KWH												

	DAILY TOTAL	21,140 KWH												
	(KWH/DAY X $0.08/KWH) / AVERAGE DAILY ADVANCE	1 LF			$13.21		0		$0.00	$0.00	$13.21	$0.00	$0.00	$13.21
							---------		--------	--------	--------	--------	--------	----------
	TOTAL MISC. SUPPLIES						0		$0.00	$0.00	$44.39	$0.00	$0.00	$44.39

FIGURE 11. DIRECT MISCELLANEOUS SUPPLIES - TBM TUNNEL

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ACCOUNT NUMBER	DESCRIPTION	QUANTITY	UNITS MH	UNITS EV	UNITS MAT	UNITS EQ	TOTAL MHOURS	LABOR RATE	LABOR & BURDEN	EQUIPMENT USAGE	MATERIAL	EQUIPMENT	CONTRACTOR'S OH & P	TOTAL
6.60	DIRECT COST SUMMARY - TBM TUNNEL													
6.41	ASSEMBLE & DISASSEMBLE TBM & TRAILING GEAR	70 SHIFTS	96	$600.00	$600.00		6,720	$16.19	$108,797	$42,000	$42,000	$0	$54,398	$247,195
6.10 & 6.31	EXCAVATION AT HEADING	177 DAYS	230.4	$1,669.00	$374.40		40,781	$16.19	$660,241	$295,413	$66,269	$0	$330,121	$1,352,044
6.20 & 6.32	OUTSIDE SUPPORT	219 DAYS	232	$1,410.00	$377.00		50,808	$16.32	$829,187	$308,790	$82,563	$0	$414,593	$1,635,133
6.33	TBM	177 DAYS		$1,655.00			0		$0	$292,935	$0	$0	$0	$292,935
6.50	MISCELLANEOUS SUPPLIES	25,000 LF			$44.39		0		$0	$0	$1,109,750	$0	$0	$1,109,750
6.42	MUCK DISPOSAL	204,000 CY		$5.00			0		$0	$1,020,000	$0	$0	$0	$1,020,000
6.43	MAINTENANCE OVERTIME													
	a. LABOR	35 DAYS	96				3,360	$24.29	$81,598	$0	$0	$0	$40,799	$122,396
	b. POWER	35 DAYS		$800.00			0		$0	$28,000	$0	$0	$0	$28,000
	c. SUPPLIES	35 DAYS			$700.00		0		$0	$0	$24,500	$0	$0	$24,500
6.44	PRECAST CONCRETE LINER	25,000 LF			$300.00		0		$0	$0	$7,500,000	$0	$0	$7,500,000
	TOTAL DIRECT COSTS FOR TBM TUNNEL						101,669		$1,679,822	$1,987,138	$8,825,082	$0	$839,911	$13,331,953

FIGURE 12. DIRECT COST SUMMARY - TBM TUNNEL

The costs for builders' risk insurance (0.2% of the contract value per year), bond (0.6% of contract value), and property taxes paid on plant and equipment are included in the indirect costs.

These indirect costs are typical for a large tunneling project. However, smaller project require a much different mix of indirect costs and the cost estimator must take this into account.

SUMMARY OF TUNNEL COSTS

The summaries of each of the various categories are brought forward in the summary sheet (see Figure 13).

SENSITIVITY STUDIES

Once the estimating format has been established, sensitivity studies can easily be performed on any phase of the project, especially if the estimate is computerized (the author used a Lotus Symphony spread sheet).

Labor rates, support methods, or crew sizes can be changed, and their effect on the total project cost and schedule can quickly be analyzed. Another exercise might be to substitute a used TBM with a lower net cost and shorter mobilization time but a slower advance rate and more maintenance costs.

One of the most valuable features for sensitivity studies is the effect of an unforeseen changed ground condition. With the example used for this article, incremental delays of from one day to 20 days were added for passing through an area of material that was harder than anticipated. No extra materials or supplies were used. The results of this change are shown in Figure 14.

Because of the ability to study changed conditions in a more realistic manner, the contractor-style estimate is also useful to the construction manager. Actual job conditions can be loaded into the format and the effect of change orders or changing ground conditions can be more easily understood by

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ACCOUNT NUMBER	DESCRIPTION	QUANTITY	UNITS MH	UNITS EU	UNITS MAT	UNITS EQ	TOTAL MHRS	LABOR RATE	LABOR & BURDEN	EQUIPMENT USAGE	MATERIAL	EQUIPMENT	CONTRACTOR'S OH & P	TOTAL	AMOUNT FOR CHANGED CONDITIONS
1.00	SUMMARY TUNNEL COSTS														
3.50	PLANT AND EQUIPMENT COSTS						0		$0	$10,231,270	$0	$3,049,075	$0	$7,182,195	$7,182,195
4.50	ACCESS SHAFT						9,600		$135,133	$154,715	$270,474	$0	$67,566	$627,000	$627,000
5.00	STARTER TUNNEL						5.632		$85.201	$83,010	$129,496	$0	$41,601	$337,300	$337,300
6.60	DIRECT TUNNEL COSTS						101,669		$1,679,822	$1,987,130	$8,825,002	$0	$839,911	$13,331,953	$13,331,953
7.00	OMITTED														
8.00	DIRECT CONCRETE COSTS						52,304		$822,112	$374,850	$1,455,127	$0	$411,056	$3,063,145	$3,063,145
9.40	INDIRECT TUNNEL COSTS						56,400		$1,200,554	$1,004,435	$0	$0	$640,277	$3,005,266	$3,005,266
	TOTALS						225,605		$4,000,823	$13,915,410	$10,600,178	$3,049,075	$2,000,411	$27,547,755	$27,547,755

FIGURE 13. SUMMARY TUNNEL COSTS

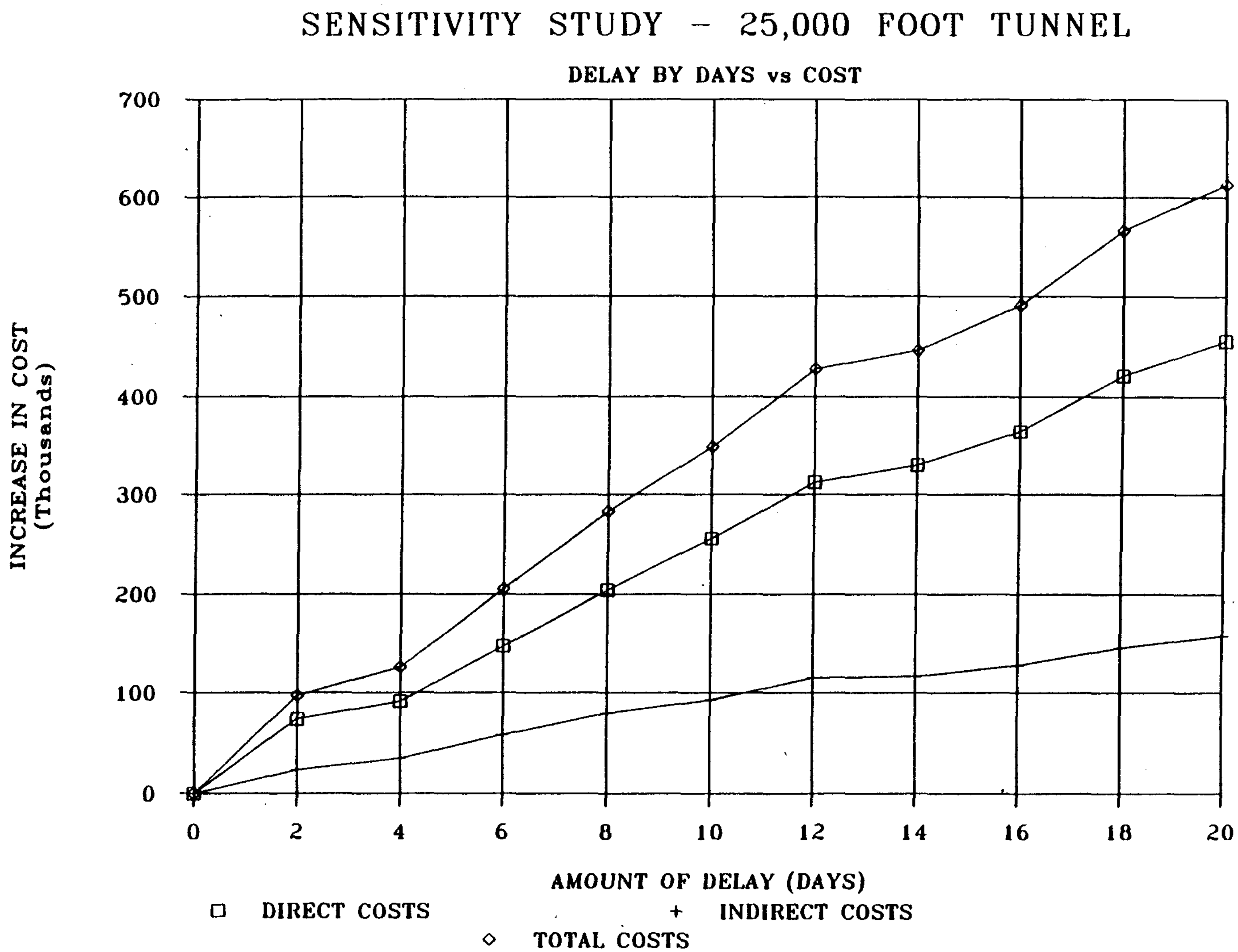

FIGURE 14. SENSITIVITY STUDY

the construction manager and owner. This is especially useful if underground conditions are encountered which were not anticipated and provided for in the bid documents and a claim for extra compensation is submitted by the contractor.

CONCLUSIONS

The assumptions made in this example are intended to develop a budget estimate for the client and not to be the "Low Bid." Far more elaborate detail is required for a true contractor's estimate.

Albert D. Parker, "Planning and Estimating Underground Construction" (1970).