Tunneling Technology

Newsletter

NUMBER 12
DECEMBER 1975

Richard J. Robbins
Committee Chairman

O. Allen Israelsen
Executive Secretary

PARAMETRIC ESTIMATES OF COSTS FOR TUNNELING IN ROCK

2036

Frank T. Wheby[1]
Consulting Civil and Geotechnical Engineer

At the conceptual and planning stages of major projects, engineers and planners frequently need estimated costs of tunnels for evaluating alternative routes, selecting construction methods, establishing budgets, and checking estimates. Sources of such cost data include: manual estimates for each tunnel conceived, which is considered a costly and time-consuming process; use of existing computer programs, which is inconvenient for many users who do not have both the computer and the software immediately at hand; or cost curves. The latter are very convenient and, despite the requirement for periodic updating as costs escalate and new technology emerges, can serve a useful purpose. This paper presents a complete set of cost curves from which up-to-date costs may be easily read for both drilled-and-blasted and machine-bored tunnels in rock. The costs were computer-generated from a program in which the logic and methodology were modeled after manual methods of cost estimating. The program has been calibrated against a number of constructed tunnels and found to be well within the range of accuracy expected for conceptual cost estimates.

INTRODUCTION

The computer program COSTUN, on which these costs are based, was developed under a Harza Engineering Company contract with the U.S. Department of Transportation. It is available through the National Technical Information Service.[2] COSTUN was described in a paper presented at the 1974 Rapid Excavation and Tunneling Conference (RETC) and was published in the *Proceedings* of that conference.[3]

The COSTUN program is easy to use, even for persons with little orientation to either automatic computation or tunneling technology. The program does, however, require the user to supply voluminous data relating to tunnel geometry, site conditions, and other parameters. It is the author's observation that very little use has been made of the program in the three years it has been available to the public. The limited use of the program is believed to stem not only from the difficulties of data-gathering and operation but also from a lack of confidence by many engineers in using a method that cannot be readily evaluated.

The above difficulties can be largely avoided through the use of cost curves. Although the curves are generated by computer, as were those presented herein, their validity can be subjectively judged; and moreover, their accuracy can be verified as cost data for each newly-constructed tunnel becomes available. Curves have the additional advantage of readily permitting evaluation of the sensitivity of various parameters to tunnel costs, though the absolute magnitudes of these costs may be questioned. The cost curves are by no means intended to supplant estimates of probable cost made by more conventional methods. Manual estimates should continue to be made for many tunnels in the final stages of planning and feasibility analyses, and always for final design as costs from the COSTUN program cannot possibly reflect all the individual details of actual projects.

HOW THE CURVES WERE GENERATED

The costs presented herein were developed through the use of the COSTUN program. Points from which the curves were drawn were generated by entering into the program a number of definite values

[3]Wheby, Frank T., and Edward M. Cikanek (1974). "A Computer Program for Estimating Costs of Tunneling," *Proceedings, 1974 Rapid Excavation and Tunneling Conference*, San Francisco, California. Published by American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, NY.

[4]Deere, Don U., Andrew H. Merritt, and Richard F. Coon (1969). *Engineering Classification of In-Situ Rock.* Report AFWL-TR-67-144, Air Force Weapons Laboratory, Kirtland AFB, New Mexico.

RECENT CONFERENCES ON PROBLEMS & SOLUTIONS – APPLICATIONS OF IMPROVED TECHNOLOGY

U.S. DEPARTMENT OF TRANSPORTATION PROGRAM OF SEMINARS & WORKSHOPS – IMPROVED TUNNELING TECHNOLOGY

A number of seminars and workshops are being sponsored by the Urban Mass Transportation Administration, U.S. Department of Transportation, for presentations and discussions on improved techniques in underground design and construction. The program covers such subjects as subsurface exploration, tunnel liners, slurry wall techniques, subway ventilation design, contracting practices, and materials handling. The first two seminars in this program were hosted by the Chicago Urban Transportation District on October 20-22, and by the Maryland Mass Transit Administration on November 17-18, 1975.

The seminar in Chicago focused on anticipated construction problems in the Chicago Central Avenue Transit Project and reviewed underground construction techniques used in the U.S., Europe, and Japan, with emphasis on applications of advanced techniques, especially construction in slurry trenches. The Baltimore seminar concentrated on the use of precast concrete lining systems and relative costs of these systems, as widely used in Europe and Japan, compared with conventional poured-in-place concrete lining or metallic lining systems used in the U.S.

Planned future workshops will include use of the Subway Environmental Simulation (SES) computer program for ventilation design and exploratory and monitoring instrumentation systems for underground construction. Participants in the seminars and workshops are interested contractors, designers, owners, and others on a limited attendance basis.

For further information contact Mr. Glenn Larson, U.S. Department of Transportation, Transportation Systems Center (TSC-600), Kendall Square, Cambridge, Massachusetts 02142, or telephone (617) 494-2300.

PLANNING FOR AN INTENSIVE SHORT COURSE FOR CIVIL AND ENGINEERING GEOLOGY FACULTY MEMBERS — PROSPECTIVE PARTICIPANTS URGED TO REPLY

Preliminary plans are being made for a one-week intensive short course on underground construction for civil and geological engineering faculty members desiring to develop broader capabilities in geotechnical engineering. The course, to be held in the summer of 1976, will be designed to familiarize faculty members with current and developing rock and soil tunneling practices. The need for this short course was indicated by responses of faculty members to a questionnaire distributed in January 1975 by the Subcommittee on Education and Training of the U.S. National Committee on Tunneling Technology.

Attendance will be limited. Faculty members interested in being considered for this short course are urged to write for further information to the course coordinator, Dr. Ronald E. Heuer, 2230 Civil Engineering Building, University of Illinois, Urbana, Illinois 61801. The course will be sponsored by the U.S. Department of Transportation and organized in cooperation with the Subcommittee on Education and Training of the U.S. National Committee on Tunneling Technology.

AMERICAN UNDERGROUND ASSOCIATION (AUA) — A NEW, UNITED STATES, OPEN MEMBERSHIP ORGANIZATION DEDICATED TO PROMOTING EARLY RECOGNITION OF THE GREAT POTENTIAL OF THE UNDERGROUND

This new Association was provisionally formed on November 1, 1975. An *ad hoc* committee, consisting of the current officers of the American Society of Civil Engineers' Underground Construction Research Council, was organized to draft a constitution and nominate officers to be presented to the Association membership in June 1976.

The additional costs of tunneling in a wet heading are given by Figures 6a through 6d. If the tunnel is to be lined, the additional cost of the lining is found from Figure 7. In the case of a lined tunnel, Figures 5a-d and 6a-d should be entered with the finished diameter, as the additional incremental cost of driving the larger excavated diameter required to accommodate the lining is included in the costs of Figure 7.

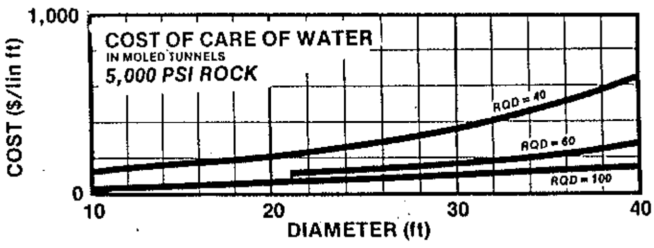

FIGURE 6a

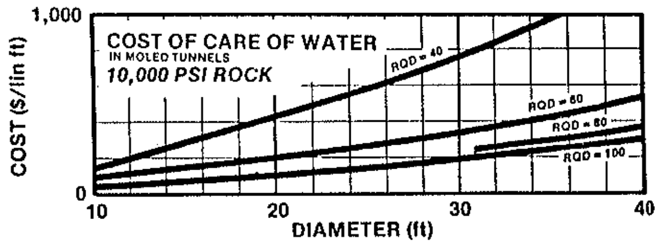

FIGURE 6b

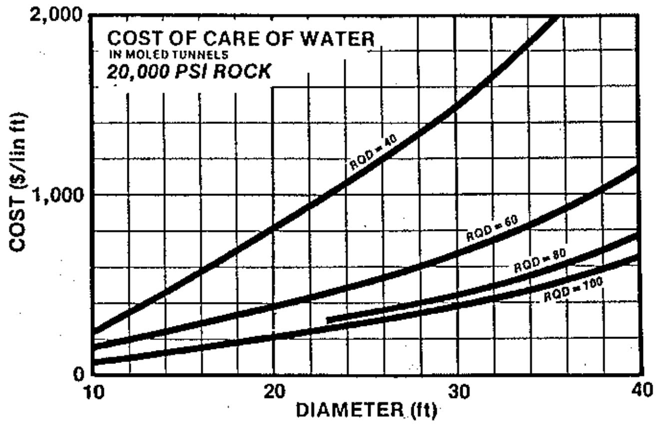

FIGURE 6c

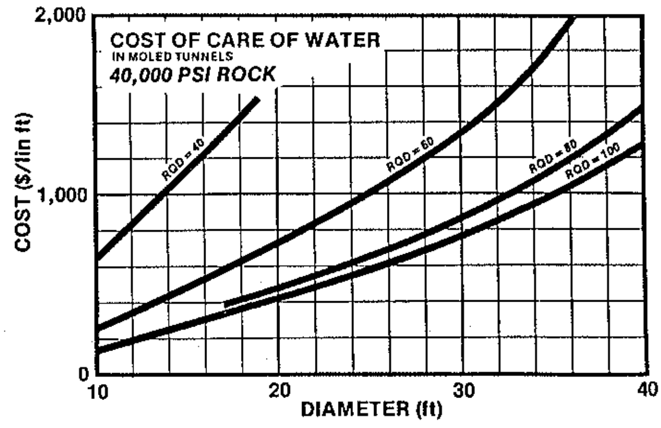

FIGURE 6d

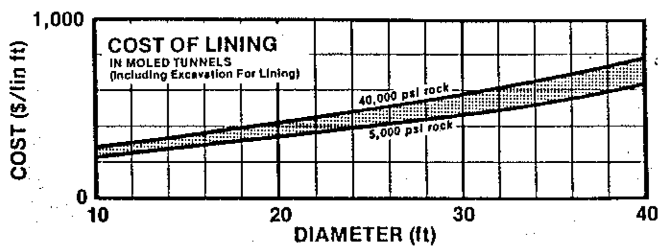

FIGURE 7

The costs from Figures 5a-d, 6a-d, and 7 are additive. For example, to find the cost of a 5,000-ft-long (1,520 m), 20-ft-diameter (6 m) tunnel in a wet heading, driven through rock with RQD 60 and strength of 20,000 psi (140,000 kN/m^2), entering the curves at the finished diameter of 20 ft (6 m) yields the following costs:

Excavation	$ 860/ft	($2,800/m)
Water	$ 380/ft	($1,200/m)
Lining	$ 380/ft	($1,200/m)
Total	$1,620/ft x 5,000 = $8,100,000	
	($5,320/m x 1,520 = $8,100,000	

[1]Frank T. Wheby, 1603 Orrington Avenue, Evanston, Illinois 60201, established his practice as a consulting civil and geotechnical engineer in February 1974. For the previous 10 years, he was employed at Harza Engineering Company in Chicago where he was head of the Geotechnical Division and was in charge of the development work on the COSTUN program.

[2]Wheby, Frank T., and Edward M. Cikanek (1973). *A Computer Program for Estimating Costs of Tunneling (COSTUN)*. Prepared for the U.S. Department of Transportation. Available under Accession No. PB 228 740 from the National Technical Information Service, Springfield, Virginia 22161.

compared with a lined drilled-and-blasted tunnel, or with a drilled-and-blasted tunnel of a larger size.

Another factor to be considered is that the total time required for mobilization and construction for a machine-bored tunnel may be considerably greater than for a drilled-and-blasted tunnel. To shorten the construction time would require the mobilization of additional crews and equipment, which is relatively much more costly for a machine-bored than for a drilled-and-blasted tunnel. Moreover, the average time required for fabrication and mobilization of a tunnel-boring machine is on the order of 9 to 12 months, but this is expected to decrease as a larger number of used machines becomes available for immediate remobilization.

A third point is that the technology of machine tunneling is advancing at a faster rate than that of drilling and blasting, and is therefore likely to experience a slower rate of cost escalation. Whereas it was once universally agreed that tunnel-boring machines were much more sensitive to changing geologic conditions than was drilling-and-blasting construction, there is now a contention by some tunnel-boring machine manufacturers that the reverse is true today. Whether this contention is entirely true does not alter the fact that a great deal of research, both public and private, is going into machine tunneling, and that ultimately the state of the art will advance.

GENERATION OF COSTS. The costs for machine-bored tunnels were generated, like those for drilled-and-blasted tunnels, by entering a large number (192) of input data sets. Each set of data represents a separate tunnel and provides one point on the plots of costs. Input data for machine-bored tunnels were generally the same as for drilled-and-blasted tunnels except that the shape was changed to circular, since this is the most common shape for machine-bored tunnels and is the only shape available in COSTUN for machine-bored tunnels.

HOW TO USE THE CURVES. As for drilled-and-blasted tunnels, the basic tunneling costs from Figures 5a through 5d include the costs of all the usual construction operations in a dry, unlined heading: excavation, mucking, supports, and ventilation.

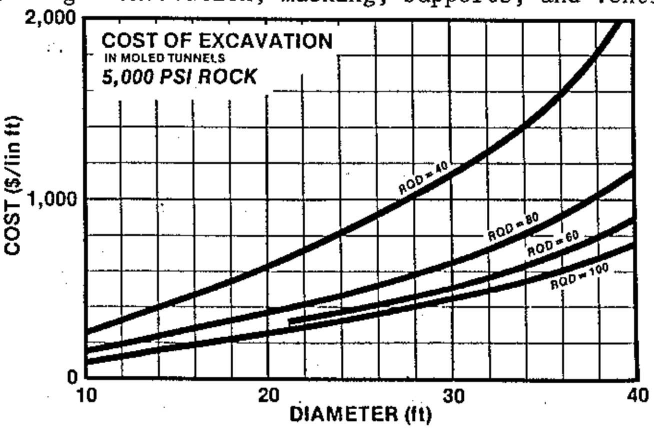

FIGURE 5a

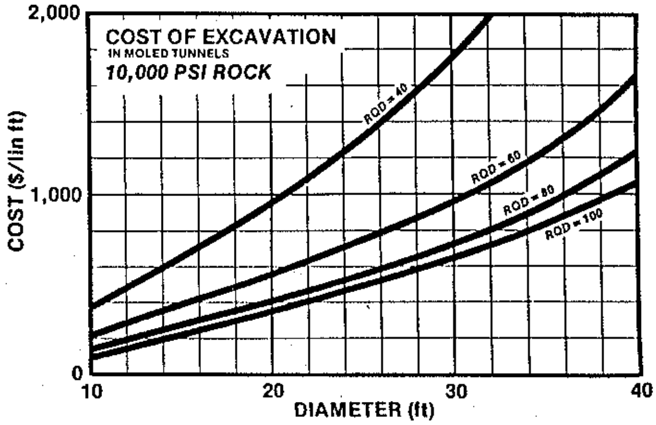

FIGURE 5b

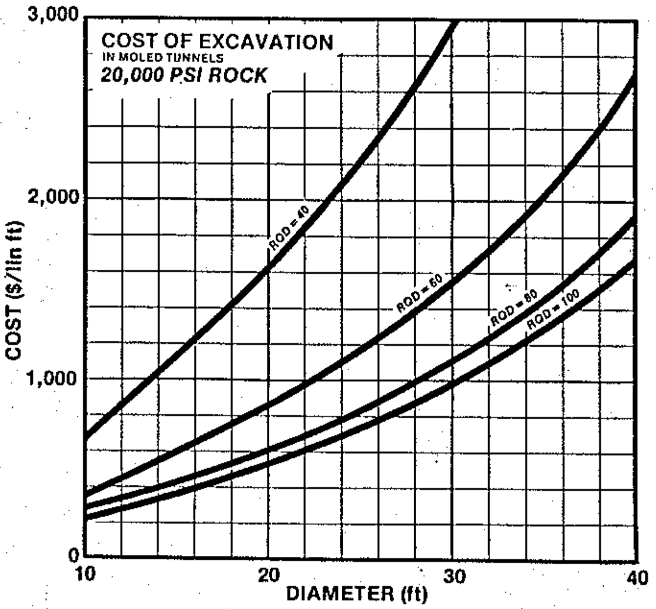

FIGURE 5c

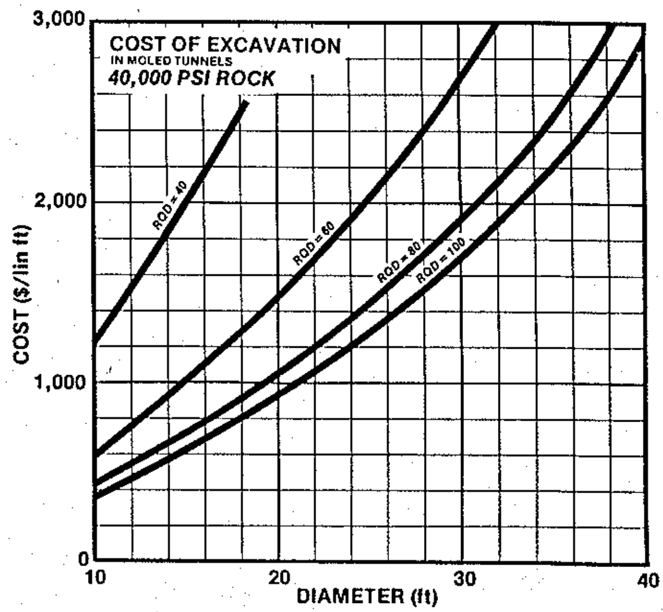

FIGURE 5d

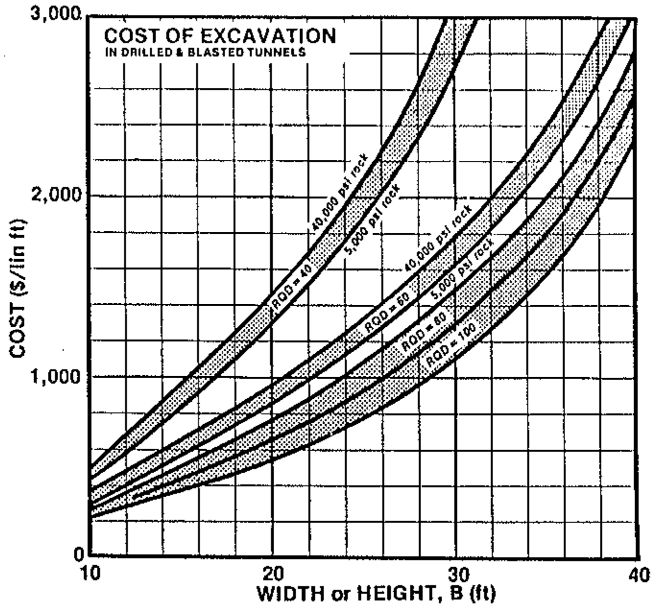

FIGURE 2

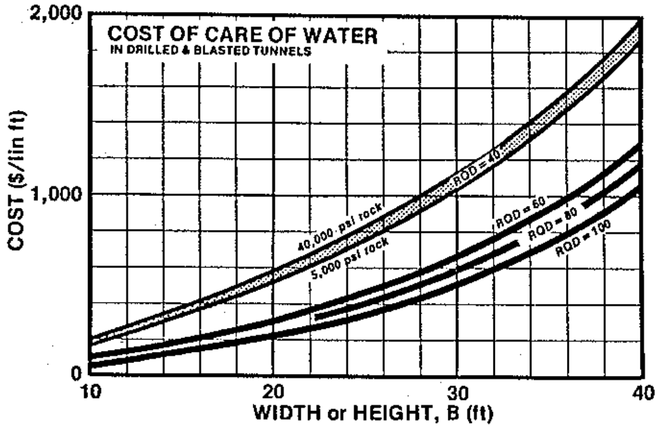

FIGURE 3

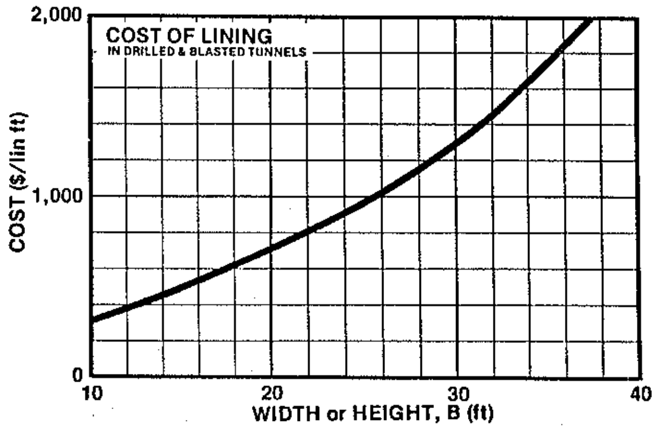

FIGURE 4

All of the costs from Figures 2, 3, and 4 are additive. For example, to find the cost of a 5,000-ft-long (1,520 m), 20-ft-wide (6 m) lined tunnel in a wet heading, driven through rock with RQD 60 and strength of 20,000 psi (140,000 kN/m^2), all of the curves should be entered at the nominal finished size of 20 ft (6 m). The resulting cost of the tunnel is:

Excavation	\$ 900/ft	(\$2,900/m)
Water	\$ 300/ft	(\$ 980/m)
Lining	\$ 720/ft	(\$2,300/m)
Total	\$1,920/ft x 5,000 = \$9,600,000	
	(\$6,300/m x 1,520 = \$9,600,000)	

COSTS FOR MACHINE-BORED TUNNELS

The above descriptions of the application of the program to drilled-and-blasted tunnels generally apply to machine-bored (or moled) tunnels. The presentation of the cost data is necessarily somewhat more elaborate for machine-bored tunnels because of the greater sensitivity to rock strength of tunneling by machine than by drilling and blasting.

TUNNELING BY MACHINE VERSUS DRILLING AND BLASTING. In the expectation that many users will wish to compare estimated costs of drilling and blasting versus machine tunneling, a few words may be in order to suggest areas where blind usage of the cost curves might lead to an erroneous conclusion. The character of the surface of a machine-bored tunnel is quite different from that of a drilled-and-blasted tunnel. The machine-bored surface usually will be smooth, with an appearance and roughness more like formed concrete than the surface of the drilled-and-blasted tunnel. Therefore, if hydraulic characteristics are an important criterion, the machine-bored tunnel should be

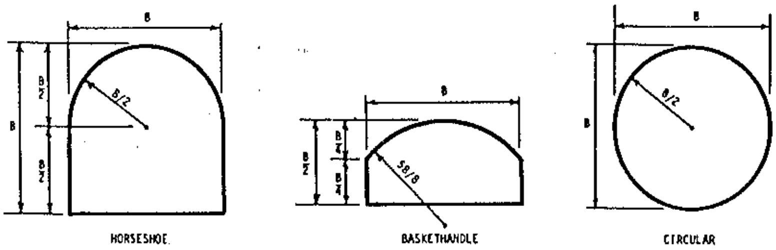

FIGURE 1 Alternative tunnel shapes for drill-and-blast excavation.

COSTS FOR DRILLED-AND-BLASTED TUNNELS

INPUTS FOR COST CURVES. The variable inputs for generating costs for the curves are as follows:

RQD: 40, 60, 80, and 100%

Rock Strength: 5, 10, 20, and 40 ksi
(3.5, 7, 14, and 28 x 10^4 kN/m^2)

Tunnel Width (B): 10, 20, 30, and 40 ft
(3, 6, 9, and 12 m)

Water Inflow at Face: 0 and 200 gal/min
(0 and 0.8 m^3/min)

Lining: not lined and lined

Muck Haulage: train for 10- and 20-ft (3 and 6 m) tunnels;
truck for 30- and 40-ft (9 and 12 m) tunnels

Parameters for which assumed fixed values were input include the following:

Groundwater Elevation: 50 ft (15 m) above tunnel invert

Labor, Equipment, and Material Cost Indexes: for Chicago at year end 1975

Tunnel Length: 10,000 ft (3,050 m)

Tunnel Shape: horseshoe

Lining Type: concrete

Lining Designed to be Watertight: yes

WHAT THE COSTS INCLUDE. The cost curves include all direct costs of tunneling, including contractors' overhead costs and profit. They do not include costs of portals and shafts, permanent lighting and ventilation, roadways, and architectural finishes. Also not included are all above-ground costs such as for utility and roadway relocations, acquisitions of rights-of-way, traffic detours, and environmental protection.

These cost curves should not be used for small projects (less than about $1,000,000 in tunneling), and should be adjusted for tunnels whose lengths differ materially from the input length of 10,000 ft (3,050 m). Usually, costs per foot of tunnel will decrease somewhat with increasing tunnel length.

HOW TO USE THE CURVES — COSTS FOR DRILLED-AND-BLASTED TUNNELS. To estimate the cost of an unlined tunnel being driven through a dry formation, enter Figure 2 with the nominal clear dimension (B) of the tunnel and read off the cost at the applicable RQD and rock strength. This cost includes costs of all of the usual operations in driving unlined tunnels in dry headings: excavation (including overbreak), mucking, supports, and ventilation.

If the tunnel is in a wet heading, the additional cost for tunneling in wet conditions is found from Figure 3. In addition to the direct costs of collection and disposal of water, the curves in Figure 3 include all the indirect additional costs of excavation, mucking, and supports caused by the presence of inflowing water.

If the tunnel is to be lined, the additional cost of lining is found by entering Figure 4 with the finished opening size of the tunnel. The costs from Figure 4 include the costs of the additional excavation, mucking, and supports required for the increased size of the opening to provide space where the lining is to be constructed. It is unnecessary to enter Figure 2 with the actual excavated size for a lined tunnel; enter both Figures 2 and 4 with the finished size (and Figure 3, if applicable).

This *Newsletter* is distributed by the U.S. National Committee on Tunneling Technology (USNC/TT) to further the exchange of information on improvements in tunneling technology and their applications. The *Newsletter*, published quarterly, contains timely short articles and notices of interest to those concerned with improving tunneling technology and news of the cooperating organizations represented on the Committee (Interagency Committee on Excavation Technology/ICET; Associated General Contractors of America/AGC; American Society of Civil Engineers/ASCE; American Institute of Mining, Metallurgical, and Petroleum Engineers/AIME; Geological Society of America/GSA; and Association of Engineering Geologists/AEG. For subscription information see the note on page 12.

Contributions of information to be included in the *Newsletter* are encouraged.

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of parameters (size, rock quality, etc.) that affect tunnel costs. Some parameters — those that are relatively unimportant to costs — were input as a single fixed value. Others that are relatively more important, and to which costs are more sensitive, were input as variables with several specific values.

For example, the cost of tunneling appears to be only mildly affected by its geographic location (provided one ignores the anomously high costs generally seen for the environs of New York City). Therefore, in generating the cost curves, geographic factors relating to a single specific location (Chicago) were used. On the other hand, tunnel costs are highly sensitive to some parameters, such as the size of the tunnel and the geology through which it is driven. For that reason, these parameters were given several values, and the costs are plotted as functions of size and geologic conditions.

A separate cost computation was made for each combination of every value of input parameters. The costs on which the curves presented in this paper are based required 384 separate runs of the program.

ABOUT THE PROGRAM

The COSTUN program is tunnel-oriented rather than computer-oriented. Its built-in costing relationships and logic are as closely as possible a direct simulation of the mental processes of tunnel designers and cost estimators. The program does not utilize mathematical of probabilistic concepts beyond those that would normally be utilized in a manual design or estimate. The program output has been verified and calibrated against a number of actual tunneling projects as a part of its development and acceptance by the U.S. Department of Transportation.

The program contains built-in designs for lining and support, but the user has some control over the way these designs are applied to his particular tunnel. For example, he can specify that the lining is to be either shotcrete or cast-in-place concrete. Other inputs are optional; that is, if the user wishes to specify a method or value, he may do so and the computer will use the input value. Examples of such optional inputs are advance rate and thickness of concrete lining, which, if the user inputs, will be utilized by the computer. If the user has no value in mind for one of these optional inputs, the computer will select a value based on built-in criteria. Other data, such as characteristics of the ground through which the tunnel is to be driven, are absolutely required as inputs from the user.

Most of the important parameters will be familiar to planners and engineers. A possible exception is RQD (Rock Quality Designation), the parameter used for classifying the rock according to its intensity of jointing.[4] Table 1 relates RQD, which can be considered to be a modified measure of core recovery, to descriptive rock terms.

TABLE 1 Rock Quality Designation (RQD)

RQD	Description
90-100	Excellent
75-90	Good
50-75	Fair
25-50	Poor

Tunnel shapes available for alternative selection by the user for drill-and-blast excavation are shown in Figure 1. The circle is the only permissible shape for machine-bored tunnels.