Pittsburgh's Mt. Lebanon Tunnels- Case History

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SYNOPSIS Discussions of basic design philosophy and comparison of alternative contract bid options are presented. Also discussed are descriptions of field monitoring activities with respect to the construction methods, ground response, installation of materials and their performance. Finally, conclusions are reached relative to the NATM philosophy as applied to this project and its place as a design process within the context of United States underground construction practice.

INTRODUCTION

Background

The Mt. Lebanon tunnels construction using New Austrian Tunneling Method (NATM) principles is the first significant application of this foreign technology in U.S. tunnel design. This historic first is the result of the efforts of the U.S. Department of Transportation's Urban Mass Transportation Administration (UMTA) to demonstrate the cost effectiveness of innovative domestic and foreign design and construction technologies.

NATM was selected by UMTA for demonstration because of the successful application in Europe and the Far East. U.S. owners and designers had been reluctant to try this innovative technology which had become the state-of-the-art in many parts of the world. The costly economics of underground construction in Europe and the Far East led to the acceptance of NATM design and construction with its light steel supports, rock anchors, and shotcrete in many major tunnel projects at considerable savings in the range of 30 to 50 percent.

Much of the reluctance of U.S. owners and designers was centered around the apparent lack of ability to adapt U.S. contracting practices to meet the flexibility, sharing of risk, and cooperative environment required by NATM. The primary difference between U.S. and foreign practice is the cooperative contractual relationship between the owner and the contractor which allows changes to be made in the contract without costly litigation. Arbitration is often incorporated into the process for its use if required. The Mt. Lebanon tunnel project provided the opportunity to develop design and contractual practices that fit into traditional U.S. contract documents and specifications to allow for the needed flexibility and risk sharing. Finding an owner willing to participate in this demonstration project with its increased risk was, fortunately, a relatively easy task.

The Port of Authority of Allegheny County and its General Engineering Consultant, Parsons Brinckerhoff-Gibbs & Hill (PBGH) were approached by a team of U.S. design consultants to determine their interest in such a demonstration using the Mt. Lebanon tunnels. The Port Authority agreed to the concept of preparing alternative designs to be bid competitively to allow the marketplace to determine the cost effectiveness of the NATM design. The Port Authority applied for and received a research, development and demonstration grant from UMTA to prepare an alternative design using NATM principles. The other alternative design was prepared to conform to traditional U.S. practices and was funded through an UMTA capital grant awarded to the Port Authority for the project's design and construction.

The Port Authority requested PBGH to oversee the design of both alternatives. The traditional design, Option A was prepared by Parsons Brinckerhoff Quade and Douglas. The NATM design, Option B, was prepared by Law Engineering Testing Company's Geotechnical Design Services Group and Geoconsult, a Salzburg, Austria based design firm. The two firms formed a separate affiliate now known as Law/Geoconsult International.

Site Description

The Mt. Lebanon tunnels are part of the Port Authority's South Hills Corridor Light Rail Rehabilitation Program to completely reconstruct 10.5 miles (17 km) and renew electrification and signalization of the remaining 12 miles (19 km) of the South Hills LRT system (Figure 1). The Mt. Lebanon Project includes 2,480 feet (755 m) of twin, single-track tunnels and 2,363 feet (720 m) of cut-and-cover, open-cut and at-grade line. Passenger stations will be built at each portal of the tunnels.

The Mt. Lebanon tunnels are parallel, twin tubes with a finished inside diameter of approximately 18 feet (5.4 m). The tunnels will pass through five vertical curves and three horizontal curves. The vertical alignment includes grades of approximately 8 percent.

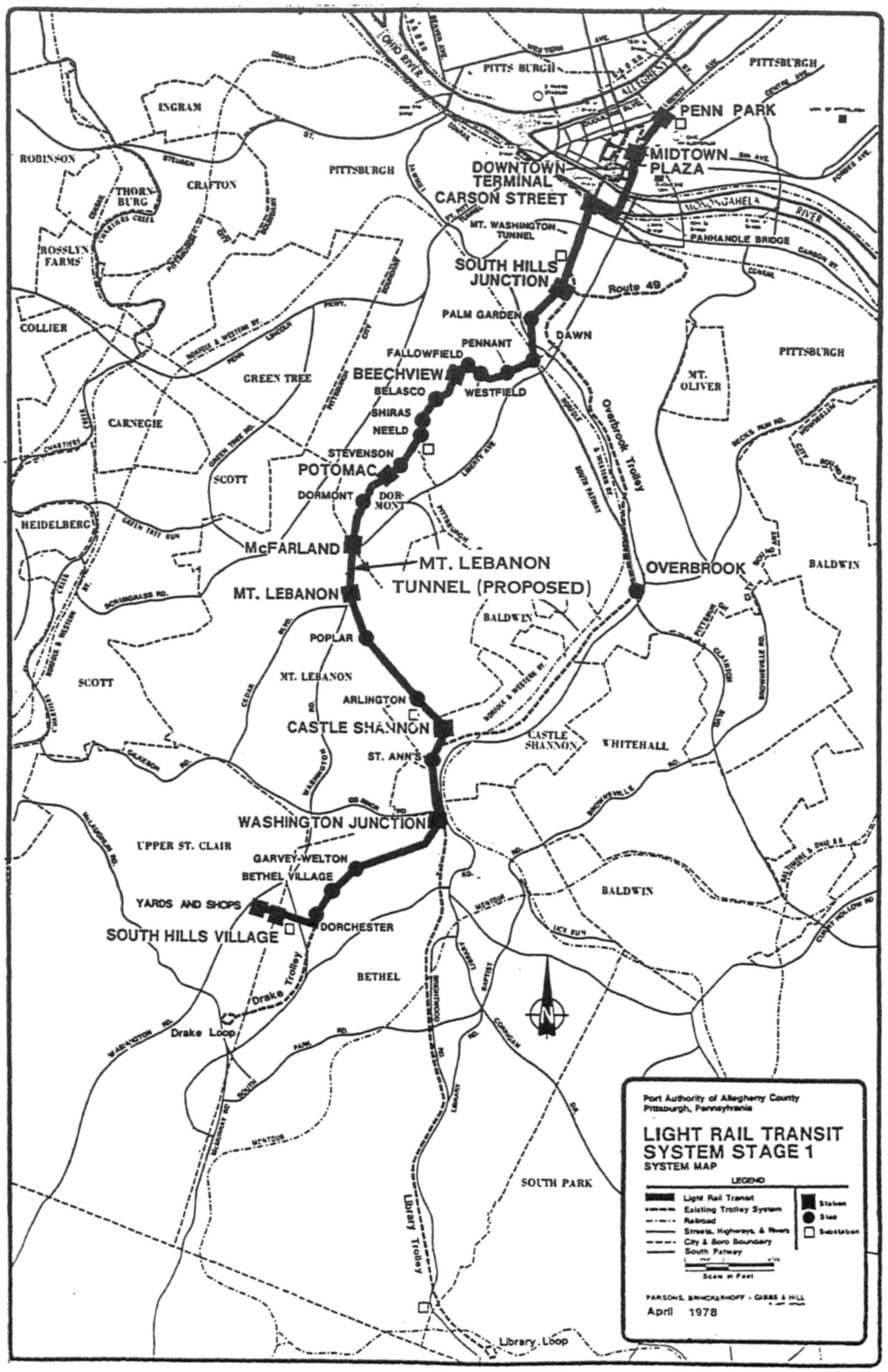


Figure 1

GEOLOGICAL SETTING

General

The tunnels are located in the Appalachian Plateau physiographic province of Pennsylvania, an area generally characterized by broad, open folds. The alignment lies about midway between, and roughly parallel to, the axes of the Nineveh syncline (to the west) and the Castle Shannon anticline (to the east).

Predominant rock types occurring along the tunnel alignments consist of alternating strata of Paleozoic Age limestones, siltstones, sandstones, shales, coal and dolomite belonging to the Upper Pittsburgh and Uniontown formations of the Monongahela Group and the Waynesburg formation of the Dunkard Group (Figure 2). A maximum of about 100 feet (30 m) of overburden exists above the deepest portion of the alignment.

Rock beds have a regional dip of 10 to 40 feet per mile to the south or southwest. Locally the attitude of beds may vary. Joints observed in the vicinity of the tunnels are typically vertical to near vertical and trend northeast-southwest and northwest-southeast. Joint spacings observed in angle borings near the portals were measured at about two and one-half feet (0.8 m). No faults are reported in the vicinity of the tunnels (E. D'Appolonia, 1981).

Geologic Hazards

Many coal seams of varying thickness and lateral continuity including the Pittsburgh Coal underly the tunnel alignment. This coal seam, which lies about 240 feet (73 m) beneath the tunnels, has a history of mining dating back to the early 1900's. There are reports of room and pillar partial extraction as well as areas of complete extraction of this seam.

Methane gas is anticipated in the coal bearing shale formations. Gas concentrations are controlled at safe levels by the ventilation system.
Chemical analyses of rock samples performed during exploration indicated that some of the coals and black shales along the alignment have pyrite contents of more than one percent. In the Pittsburgh area experience has shown that these materials can demonstrate swelling pressures under certain conditions in directions perpendicular to the bedding planes.

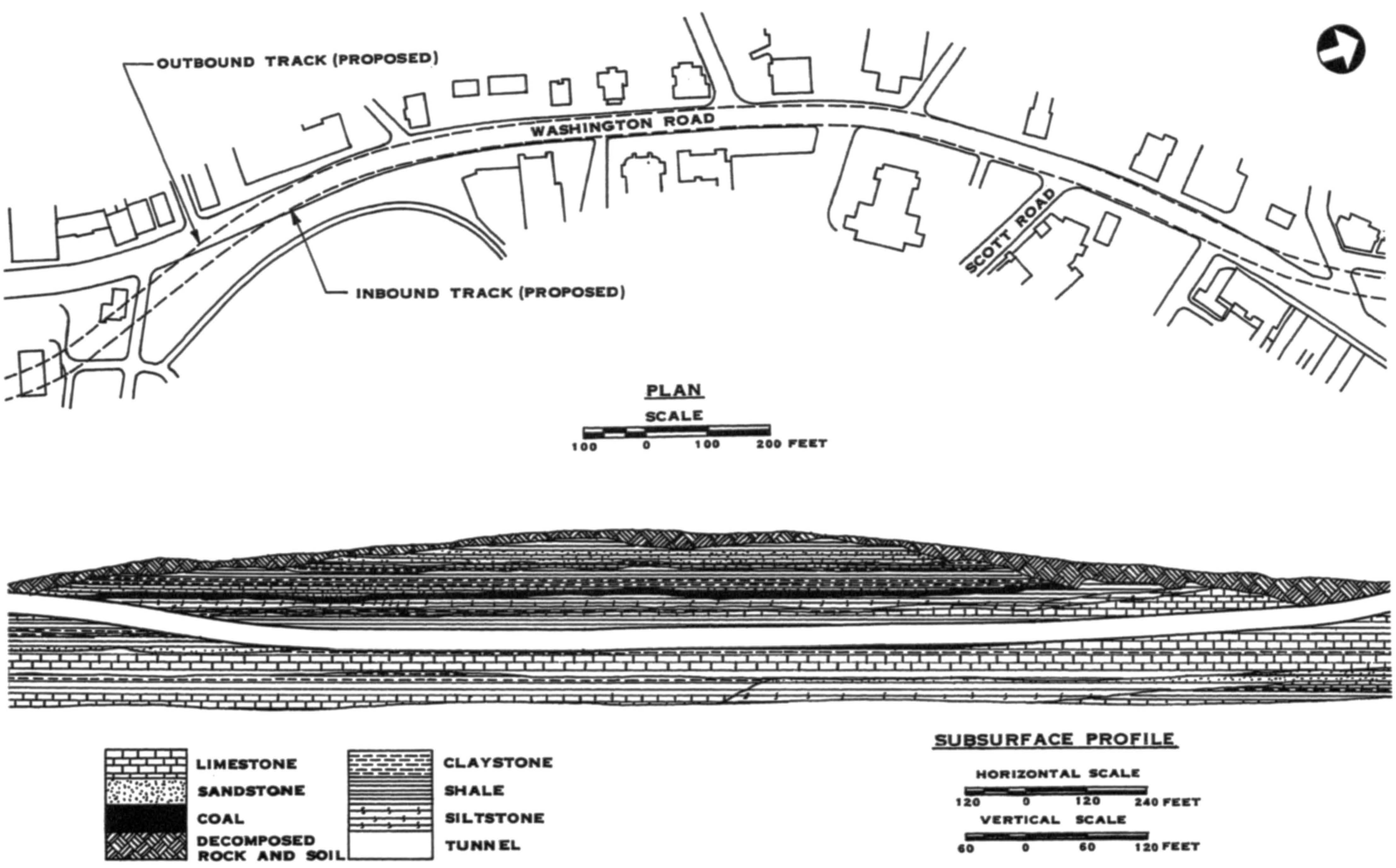


Figure 2

ealing of these materials to prevent exposure o air and water is the preferred approach to andling the swelling potential, however, some ver-excavation of these materials is nticipated.

he regional groundwater table appears to be at r below the Pittsburgh Coal Seam, well below he tunnels. Groundwater occurences at tunnel rade are anticipated to be perched water which an be controlled by suitable dewatering rrangements during construction. Provisions xist for adequate drainage through the final iner to avoid build up of water pressures fter construction.

Ground Classification

'or purposes of specification and payment of the work, ground conditions have been classified based on anticipated behavior. Elements taken into consideration in developing the Ground Types for the tunnel included:

- Quality and structure of the rock or soil mass;
- Influence of water and the effect of air contact on newly exposed surfaces;
- Type and average quantities of required support elements;
- Sequence of excavation and installation of support elements;
- Allowable methods of excavation including full face or top headings and benches, separation of headings and anticipated maximum length of rounds.

Three Ground Types have been determined for the tunnels. These are described as follows:

Ground Type I - Full face excavation is feasible in this ground type. Allowable lengths of tunneling rounds are generally unrestricted, however, are determined from test blasts. Initial rock support requirements include a two-inch (50 mm) thick outer shotcrete lining with occasional rock bolts where directed by the Engineer.

Ground Type II - Full face excavation is feasible, however, top heading and bench methods may be required if, in the opinion of the Contractor or Engineer, ground stability is more effectively achieved particularly in the vicinity of the portals. Maximum allowable lengths of tunneling rounds are limited to eight feet (2.4 m). Initial rock support shall include a four-inch (100 mm) thick lining of reinforced shotcrete in the crown and ribs and occasional tensioned rock bolts and rebar straps.

Ground Type III - Top heading and bench construction methods are required. Allowable lengths of tunneling rounds are not allowed to exceed five feet (1.5 m) in the top heading and nine feet (2.7 m) in the bench. Initial rock support includes a six-inch thick (150 mm) lining of reinforced shotcrete, tunnel face se ing, light weight steel ribs, dri dowels and occasional engineer ordered r bolts.

The Contractor has responsibility for initia determining the ground type subject approval by the Engineer. In the event disagreements, a unilateral determination ground type is made by the Engineer.

DESIGN PROCESS

General

The tunnel construction contract was divi into a base bid and the two tunnel optic The limit of the tunnel contract was construction portals. The base bid contai the systemwide elements with the exception the ventilation fan (the ventilation design the NATM option required a slightly larger capacity). Systemwide elements included were not limited to: catenary poles foundations, track underdrain, ventilat structures, and miscellaneous civil works.

Each tunnel option included tunnel excavati initial tunnel support, final tunnel lini track road bed, systemwide attachments instrumentation. The difference in the desi can perhaps be best illustrated by a summary the major bid items required for each des option (Table I).

The above summary shows a larger number of items for Option B than Option A which illustrative of the flexibility that is bu into the design to provide for a more c effective tunnel construction as reflected the bids. Generalized tunnel cross sections Options A and B are shown in Figure 3.

NATM Design Philosophy

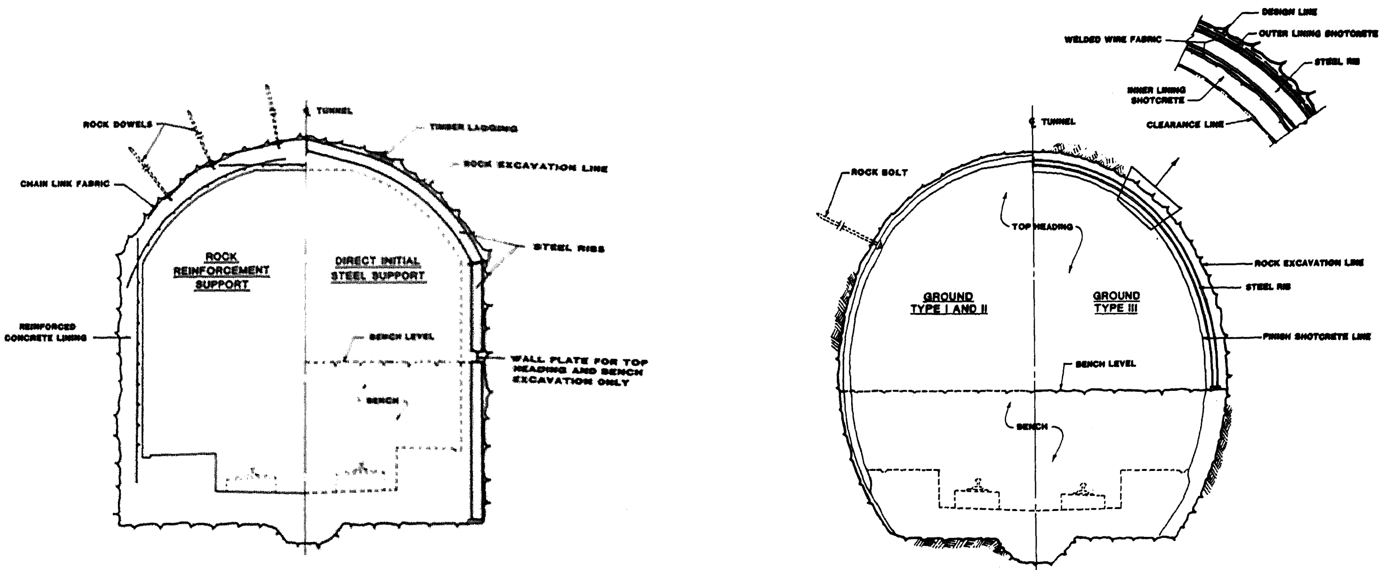
We believe that NATM is a common se geotechnical approach to the design underground support systems that can embody variety of support elements and excavat techniques. It also makes extensive use monitoring of ground behavior dur construction to corroborate design assumptio

Much of the success that NATM has had in t past two decades can be attributed to i capability of dealing with a variety of grou conditions, it's provision for maxin flexibility in choice of ground support a construction methods as applied to tunnels all sizes and shapes, and it's establishment a mechanism for alternate constructi approaches for varying geologic conditions sensitive areas. NATM does not require unusu tunneling equipment or skill on the part workmen. But like other tunneling methods, relies heavily on the skill of the tunn foreman, his tunneling crews, as well as understanding of basic geotechnical principl by the Engineer in charge.

It is a basic principle of NATM to provide initial support at the heading immediately upon excavation to prevent deformation from becoming excessive and causing irrevocable loosening of the medium, particularly relative to difficult ground conditions. In this way, NATM attempts to take advantage of the principle that minimum support is required and the maximum inherent self-carrying capacity of the medium itself is realized. Too often in U.S. practice, careful attention is not given by both designer and contractor to the need to prevent excessive deformation at the heading prior to the installation of initial support. The result is that deformations exceed the optimum efficiency of the ground reaction mechanism resulting in the need for a more substantial support system than otherwise would have been necessary.

TABLE I - Comparison of Major Bid Items for Option A and B

Option A		Option B	
Description	Unit	Description	Unit
Convergence Pins	Lump Sum	Convergence Pins	Each
Borehole Extensometers	Linear Foot	Borehole Extensometers	Linear Foot
Tape Extensometer	Each	Settlement Points	Each
Monitoring	Lump Sum	Standby Time	Hour
Tunneling	Lump Sum	Excavation and Initial Support Ground Type I	Linear Foot
		Excavation and Initial Support Ground Type II	Linear Foot
		Excavation and Initial Support Ground Type III	Linear Foot
		Excavation and Initial Support in Pump Station and Passageway	Lump Sum
		Excavation and Initial Support in Cross Passageway	Lump Sum
		Excavation and Initial Support in North and South Portals	Lump Sum
Expansive Rock Over-Excavation	Cubic Yard	Expansive Rock Over-Excavation	Cubic Yard
Class C Concrete	Cubic Yard	Class C Concrete	Cubic Yard
Sealing Shotcrete	Square Foot	Sealing Shotcrete	Square Foot
Tunnel Rock Reinforcement	Linear Foot	Engineer Ordered Tensioned Rock Bolts	Each
		Engineer Ordered Rebar Straps	Linear Foot
Cast-in-place Concrete Tunnel Lining	Lump Sum	Inner Lining Shotcrete	Square Foot
		Cast-in-place Concrete	Cubic Yard
Portland Cement Contact Grout	Cubic Foot	Systemwide Element Attachment	Lump Sum



GENERALIZED TUNNEL CROSS SECTION
OPTION A DESIGN

GENERALIZED TUNNEL CROSS SECTION
OPTION B DESIGN

Figure 3

NATM makes use of an integrated design concept, thereby maximizing the efficiency of the total support system. In this concept, the design engineer lays out the sequencing of each stage of support which becomes incorporated into the permanent support system. The initial support is generally developed by shotcrete, anchors, and other supplementary support elements which are usually installed immediately after excavation. In addition to providing initial stability during construction, these elements become incorporated into the permanent support system. Later in the tunneling process, more support elements may be added until complete installation of the total support unit has been accomplished. In this way, maximum efficiency is made of the materials used in the support process. In addition, as much of the inherent strength of the medium as possible is mobilized into a quasi self supporting arch.

It is inherent in the NATM design process to prepare a number of proposed support systems in anticipation of varying ground conditions through a particular job site. The exact number of different ground support systems for a particular site is obviously a function of the anticipated variation of ground conditions at that site. Traditionally, three to six different ground support systems are designed for a particular site. These vary between minimal support requirements involving randomly placed rock anchors to a complete integration of several layers of shotcrete, wire mesh, anchors, and light steel ribs. It could also involve subsequent placement of a cast-in-place concrete liner. The bid documents show an estimate of the total linear footage anticipated on the project for each of the support systems. The contractor is then asked to bid on estimated quantities of the anticipated elements of each of the support systems. A field decision is then made during construction between the contractor's representative and the owner's representative where possible change from one support system to another is anticipated. Minor adjustments are generally made in a unilateral decision at the heading by the tunnel foreman.

Mt. Lebanon Option B Design

The following basic principles of NATM were applied to the Mt. Lebanon tunnel design:

- Careful excavation procedures must be applied to minimize detrimental rock loosening effects.
- Support elements must be designed to deal with the changed stress conditions; thus helping the rock to keep its inherent strength. Creating or conserving triaxial stress conditions through the timely use of shotcrete and rock bolts add to the carrying capacity of the rock mass and avoid loosening.
- Selection of a proper shape with due regard to the primary stress situation, strength parameters, joint systems, etc., reduce stress concentrations and contribute significantly to the overall stability.
- Support systems must be designed to allow for changing rock conditions without radical alterations in the general system.

The following data and representative properties and characteristics of different type of rocks were required for finite element analysis and NATM tunnel design:

- Rock mass properties described in terms of unit weight, cohesion, angle of internal friction, modulus of deformation and Poisson's Ratio.
- Frequency, location and orientation of joints and faults at each analysis section, shear strength and properties of filler material.
- Location of groundwater and the effects of tunneling on the groundwater regime, both in the short and long term.
- Swelling potential of earth materials.

CONSTRUCTION BID PROCESS

Background

Due to the research and demonstration aspects of this project, several bidding strategies were considered by UMTA and the Port Authority. One strategy was to follow the bidding process used to demonstrate precast concrete tunnel linings in the Baltimore Metro. For that case, the precast concrete lining was bid as an alternative to metallic liners. Because that was the first time use and the relative short length of tunnel was anticipated to be an economic disadvantage to precast concrete, UMTA committed an undisclosed amount of funds to offset the potential difference to reduce the lowest precast concrete bid after the bids were opened. Also, bidders were required to bid both alternatives.

After carefully examining aspects of the particular Mt. Lebanon construction, it was decided that the bidding process should not follow the Baltimore Metro example and that bidders would not be required to bid both design options and that there would be no funding to offset or "reduce" the NATM bid. UMTA and Port Authority both agreed that the most satisfactory way to determine the cost effectiveness of the NATM option was to let it compete unaided in the marketplace.

Prequalification

Because of the expertise required to successfully construct the twin tunnels by either design option, the Port Authority decided to prequalify organizations for tunnel excavation and support prior to receiving bids. The prequalification applied only to the 2,480 feet (755 m) of twin-tunnel construction.

A brief summary of the prequalification criteria follows:

Option A

a. The organization shall have 10 years experience in rock tunnel construction including at least one rock tunnel comparable to the Mt. Lebanon tunnels.

b. The proposed Project Manager shall be a registered Professional Engineer and successfully served at that level for at least one comparable rock tunnel.

c. The organization shall have at least six supervisiory personnel of a classification of foreman or above who had rock tunnel construction experience for a duration of two years within the last 10 years.

Option B

a. The organization shall have completed in the past 10 years at least 200,000 square feet (18,000 m^2) of surface area of rock tunnel and/or rock caverns using rock bolts and shotcrete as the primary means of support.

b. Same as Option A.

c. Same as Option A.

The Port Authority conducted a briefing to explain the prequalification process and to respond to any questions. Based upon the application submittals, the Port Authority prequalified 21 organizations for Option A and 20 for Option B. Interestingly, 19 organizations that were prequalified for Option A were also prequalified for Option B.

Concurrently with the prequalification process, the Port Authority released the plans and advertised the job. After the list of prequalified bidders was announced by the Port Authority, a pre-bid conference was held in which the Port Authority and PBGH described the project in detail, answered questions submitted by the plan bidders in writing and conducted a field inspectin of the project site.

The prequalification process included a procedure to allow contractors who were not initially prequalified to appeal the decision and if accepted, to submit further written questions regarding the plans.

Bidding

The Mt. Lebanon Tunnel project bid was divided into three parts:

Base Bid: Included all work that was common to the project excluding the tunnel excavation and lining.

Option A Bid: Traditional U.S. tunnel design practice.

Option B Bid: New Austrian Tunneling Method tunnel design principles.

Bidders were required to submit a total unit price bid to include the Base Bid and either the Option A or Option B Bid. The Engineer's Estimate for the project was:

Base Bid	$14.2 M
Option A Bid	$16.8 M
Total Base & Option A	$31.0 M
Option B Bid	$14.7 M
Total Base & Option B	$28.9 M

Sixteen contractors submitted bids. Fifteen chose to bid Option B and one chose Option A. The low bidder was Paschen-Dick Joint Venture with a total bid of $17.2 M. This winning bid was $7.1 M for the Base Bid and $10.1 M for the Option B tunnel.

Table II summarizes the bid submittals.

The cost effectiveness of the NATM desig option is made very apparent by the response o the construction industry. The average bid fo Option B was $8.7 M, $6.0 M below th engineer's estimate. The Paschen-Dick Join Venture subcontracted the tunnel work to th fourth low bidder, Ilbau Aktiengesellschaft o Austria.

TABLE II - Construction Bid Summary

Bidder	Base Bid	Option A	Option B	Total
1	$ 7,131,693		$10,060,307	$17,192,00
2	10,483,524		6,815,411	17,318,93
3	10,696,960		6,747,161	17,444,12
4	12,170,345		5,651,968	17,822,31
5	10,427,675		8,100,971	18,528,64
6	11,755,751		6,783,151	18,538,90
7	10,794,475		8,927,803	19,722,27
8	12,064,248		7,813,040	19,877,28
9	11,537,938		8,827,472	20,365,41
10	12,148,221		8,299,410	20,447,63
11	10,908,415		9,561,585	20,470,00
12	11,580,660		9,156,730	20,737,39
13	10,982,230		10,085,811	21,068,04
14	8,540,080		12,592,920	21,133,00
15	10,511,525	$10,853,213		21,364,73
16	11,441,000		11,483,205	22,924,21

CONSTRUCTION RESEARCH

Objective

An important part of this demonstration project and implementation of the NATM principles is the observation and monitoring of the construction process. Documentation of state-of-the-art advancements in the design and application of initial rock support, subsequent shotcreting operations and the related contractual practices all of which are designed to provide the cost savings, was an important element in the Port Authority's decision to undertake this demonstration project. Therefore, a detailed report evaluating the design and construction process will be prepared following completion of the tunnels. This document will include a tunnel completion report containing as-built geologic conditions, instrumentation and observation data, changes and modifications to design, a case history of the sequence of events, descriptions of testing conducted in the field, and a detailed discussion and analysis of the technical performance of the design.

Organization

In order to successfully accomplish this, Law/Geoconsult entered into a contract with PBGH to provide on-site research personnel. The primary functions of these personnel are to provide proper evaluation and documentation of the NATM design during construction, assist the resident staff of PBGH in construction management matters and produce a final research document dealing with experience gained during design and construction.

Evaluation and Documentation

Of paramount importance to this project, is the assessment of ground conditions during tunneling and specifically the impact of excavation on ground behavior. Timely and accurate geologic mapping forms the foundation for this effort. Mapping is performed on each shift in each tunnel. Face and wall maps are developed with systematic description of key geologic features. Typical reports contain information relating to:

- Rock types encountered;
- Estimated rock quality designations including the range of RQD's for a particular location and average values for all rock types encountered at that location;
- Water conditions are described relative to the features along which they

occur and include the mode of occurrence (moist surfaces, dripping, water, etc.);

- Discontinuities are identified by type (bedding, joints, faults, etc.) and by specific characteristics:
  - Attitude (strike and dip)
  - Continuity
  - Spacing or frequency
  - Separation (degree of openness of the discontinuity and description of filler material if appropriate)
  - Geometry (normally measured over a minimum length of 1m)
  - Surface characteristics (slickensided, smooth, rough, etc.)

- The degree of weathering of the exposed rock surfaces is estimated based on physical appearance of the rock mass.

Liberal use of photographs to document geologic conditions is encouraged. Periodic evaluation of tunnel geometry by photographic silhouettes is also provided.

These rock mass characteristics coincidently permit evaluation through NGI (Barton, Lien and Lunde 1974) and RMR (Bieniawski 1979) classifications. These rock classifications are used for research purposes and do not replace evaluation of Ground Types according to the contract documents.

In addition to the geologic mapping, LGI personnel provide comprehensive documentation of tunneling procedures and performance on a daily basis. Elements of the project which are paid particular attention include:

- Contractor's tunneling cycles for various ground types;

- Interruption or delays to the contractor's cycles;

- Drilling accuracy. This is routinely evaluated by counting lengths of remnant blast holes at a particular heading;

- Appropriateness of blasting schemes to certain ground types (routinely evaluated);

- Inspection of shotcrete linings for performance and changes in water conditions;

- Installation of support. Specific elements are monitored for workmanship and performance.

Testing and Instrumentation Monitoring

Shotcrete liners are routinely sounded for continuity and systematically cored for strength testing. Similarly, rock bolts are sampled on a systematic basis and tested for pull-out strength.

Instrumentation consisting of tunnel convergence points, boreholes extensometers and settlement points are routinely monitored. These results are used to verify certain design assumptions and the results compared to observed behavior.

Conclusions

The value of alternative bidding has been firmly established on this project. In addition, the Mt. Lebanon Tunnel project has demonstrated the adaptability of standard U.S. tunnel design and construction practices to NATM principles. For this project certain of these principles were observed. These included:

- Sequencing of excavation and support in a way that avoids decrease in ground strength and allows development of a load bearing ring around the opening;

- Selection and sizing of initial support elements to assist the ground in maintaining its inherent strength;

- Selection of the overall support system based on its adaptability to changing rock conditions within the tunnel, thereby reducing the need for radical alterations as tunneling proceeds;

- Selection of tunnel shape considering prevailing stress conditions and ground mass strength. This reduces stress concentrations and contributes to overall stability;

- Specification of thin and flexible linings in full contact with the ground in order to minimize absorption of bending moments;

- Use of careful excavation methods (controlled blasting) in an effort to minimize disturbance of the ground outside the limits of the excavation.

It is noteworthy that these principles are not necessarily related to any particular excavation technique or specific support elements. For this project, however, unreinforced and reinforced shotcrete with rock bolts and light weight steel ribs have been shown to economically satisfy the technical requirements of the job.

Monitoring of geologic conditions and measurement of deformations are also an integral part of the NATM for controlling the safety of the tunnel and verifying design assumptions. Convergence pins are used to determine deformation of the tunnel lining and extensometers and settlement points to evaluate the behavior of the ground around the excavation.

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