Chapter 35

TUNNELING ON THE TREN URBANO PROJECT, SAN JUAN, PUERTO RICO

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ABSTRACT

The new Tren Urbano heavy rail transit project in San Juan, Puerto Rico has one very significant part, the Río Piedras Contract, being constructed underground. This paper will give an overview of the tunneling work that started construction in 1997. Design-Build procurement for tunneling is addressed.

The new and modern transit system in San Juan will be 17.2 km (10.7 mi) long and have 16 stations in its first segment of construction, which is due to open in 2001. The line connects the city center district of Santurce to the outlying suburban municipality of Bayamón. All construction is being done under design-build contracts as a demonstration project funded by the Commonwealth of Puerto Rico and the Federal Transit Administration (FTA).

The Río Piedras Contract is completely underground and involves practically all types of construction in soft ground. One station is built as cut-and-cover at the University of Puerto Rico. One portion has twin tunnels to be driven with an Earth Pressure Balance Machine (EPBM) and lined with one-pass precast concrete segments. Another has four short tunnel drives at a turnout that will be constructed with an initial support of shotcrete and lattice girders (i.e., the New Austrian Tunneling Method of construction). The most complex construction is the Río Piedras Station, which is being built as a stacked drift with a total of 15 individual tunnel drifts. After being sequentially excavated and concreted, they will form the arch of the 19 m (62 ft.) wide by 16 m (53 ft.) high cavern station. This structure is excavated in soil with less than 5 m (16 ft.) of cover to overlying historic buildings.

INTRODUCTION

Background of the Tren Urbano Project

The island of Puerto Rico, a self governing commonwealth of the United States, is located approximately 1,500 km (930 mi) from Miami, Florida (see **Figure 1**). Though only 160 km (100 mi) long by 56 km (35 mi) wide, Puerto Rico has a population of 3.8 million. About one-third of the Island's residents, 1.3 million, live in the San Juan Metropolitan Area (SJMA), a region on the northeast

Figure 1. Map of Northern Caribbean

coast encompassing 13 municipalities and 1,000 km^2 (390 mi^2). The population of the SJMA generates about 3.2 million vehicular trips per day. An estimated 4,200 vehicles per square mile in the central SJMA create one of the most congested urban roadway networks in the world. By 2010, vehicle trips per day are expected to rise by 45% over 1990 levels.

In the spring of 1994 the present administration of the Government of Puerto Rico approved plans for a heavy rail transit system. Tren Urbano (translated as Urban Train) was chosen as the name of the project, as well as the organization formed to build and maintain the project. The Tren Urbano Organization (TUO) is associated with the Puerto Rico Highway and Transportation Authority (PRHTA). The initial phase of the Tren Urbano Project will serve three central municipalities of the SJMA (Bayamón, Guaynabo, and San Juan), and will cost an estimated $1.25 billion. The Federal Transit Authority (FTA) provides 30% of the project's funding, with the balance provided by the PRHTA.

The Turnkey Demonstration Program, created by Congress in the Intermodal Surface Transportation Efficiency Act of 1991, is testing alternative turnkey, and design-build, construction techniques with the goal of expediting project time lines, reducing project costs, and rationally allocating project risks. Tren Urbano is one of four demonstration projects in the United States. The goal is to provide a cost effective project while achieving project economic, transportation, energy, environmental and safety objectives.

The Phase I alignment of the Tren Urbano Project connects the populous western municipality of Bayamón with Santurce, passing through the municipality of Guaynabo and the districts of southern and central San Juan known as Río Piedras and Hato Rey (see **Figure 2**). The line is 17.2 km (10.7 miles) from end to end; it has 16 stations and a centrally located storage and maintenance yard where the operations center will also be located. About 40% of the line will be at-grade and 60% elevated over principal avenues. The only exception is the tunnel

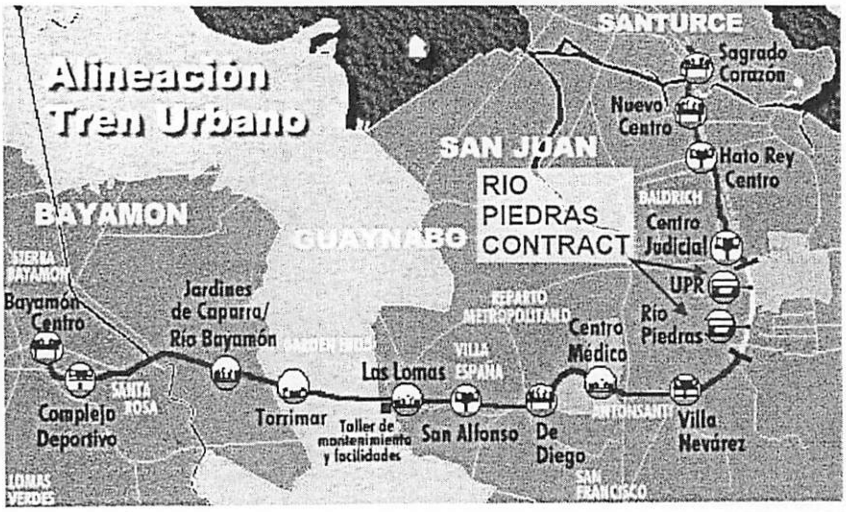


Figure 2. Phase I Tren Urbano Alignment

section through most of the heavily congested and historically rich district of Río Piedras. This paper describes the tunneled guideway sections and station that comprise the Río Piedras Contract.

Río Piedras Contract

In 1994, the PRHTA engaged a General Management, Architectural and Engineering Consultant (GMAEC) to produce a 30% design that would be bid on as design-build contracts. The GMAEC team members include Daniel, Mann, Johnson, and Mendenhall; Frederic R. Harris, Inc.; Eduardo Molinari y Asociados; and Barret & Hale. The Río Piedras Contract was advertised by the PRHTA in June of 1996. Three joint ventures of contracting and engineering design firms submitted proposals. Award and notice to proceed were given simultaneously on April 18, 1997 to the KKZ/CMA joint venture, which comprises three contractors: Kiewit Construction, Kenny Construction, and H.B. Zachry Company. The managing designer is the Puerto Rico firm, CMA Architects & Engineers. Subcontractor engineering firms include Jacobs Associates (tunnel structural design), Sverdrup Civil (station structural/architectural design and mechanical/electrical design), and Woodward-Clyde (geotechnical exploration and instrumentation). The bid by KKZ/CMA of $225,600,000 was determined to be the best value of the three bidders.

The Río Piedras Contract consists of a 1,500 m (4900 ft.) long underground rapid transit guideway with two underground subway stations (see **Figure 3**). The project is situated in a dense urban area, and geotechnical conditions consist of weathered alluvium (soft ground). Most of the project structures are located below the groundwater table, and many of the tunnels pass beneath occupied historical buildings with less than 5 m (16 ft.) of cover.

Sections of the guideway and the University Puerto Rico Station are being constructed by cut-and-cover methods. The other guideway sections and the Río

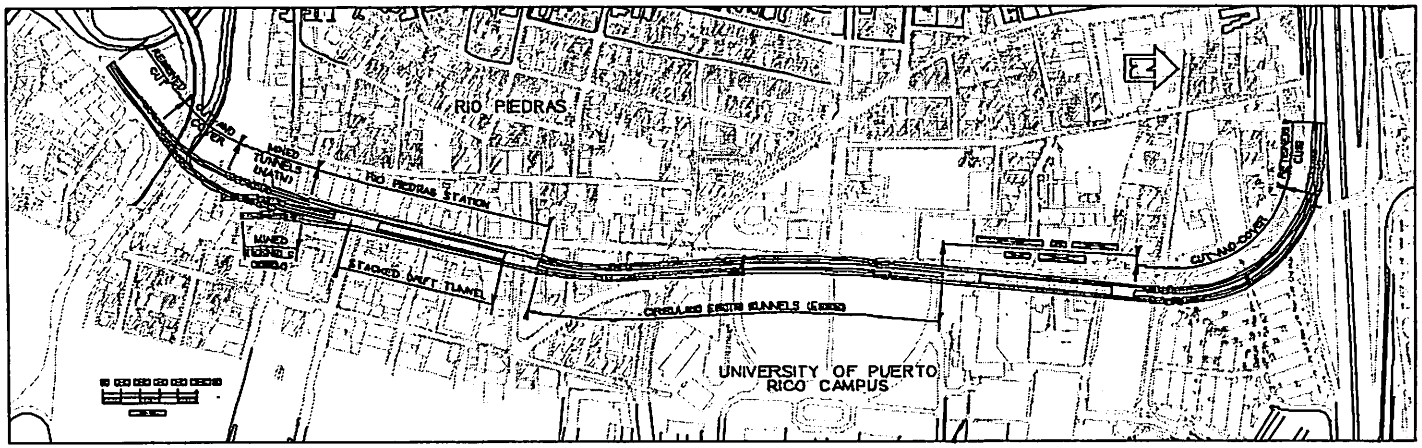


Figure 3. Plan of Río Piedras Contract

Piedras Station, which are being constructed by various tunneling methods, are the focus of this paper. The tunneled portions of the work have three different construction methods:

- Mined Tunnels (NATM).
- Río Piedras Station - Stacked Drift Tunnel.
- Circular Earth Tunnels (EPBM).

GEOTECHNICAL CONDITIONS

Site stratigraphy principally includes thick sequences of marine deposits overlain by alluvium. Locally, artificially placed fills are present, reflecting urban development along the project alignment. Soil and rock units (in descending order) that influence design and construction include:

- Artificial Fills.
- Hato Rey Formation (old alluvium).
- Aquada Limestone.

A simplified geologic profile along the project alignment is shown on Figure 4.

Underlying the man-placed fills in the project area, the Hato Rey Formation (old alluvium) consists of silty clays, silts, and clayey to silty sands with occasional interbeds of comparatively clean sands. The thickness of the Hato Rey Formation identified in the project borings ranges from about 15 to 20 meters. The density of the sands is variable but usually dense to very dense (SPT blow counts of 50 and higher), and the consistency of the fine grained soils ranges from medium to stiff. The most characteristic feature of the old alluvium is the extensive conversion of non-quartz constituents to clay, although the original sand and gravel texture of the deposits is usually visible despite the advanced state of alteration and weathering. In addition, the old alluvium is preconsolidated by desiccation.

Excluding the small cap of fill (generally less than 1 meter thick), the tunnels are generally within the Hato Rey Formation. For the design, the Hato Rey Formation within the tunnel profiles has been divided into three soil layers for simplicity. These layers are referred to (from top to bottom):

- *Layer 1 - Upper Clays:* Characterized as overconsolidated, stiff silty clays. This layer was assumed to be a cohesive soil (f=0).
- *Layer 2 - Middle Stratified Zone:* Characterized as alternating layers of clean sand, silty sand, clayey sand, and clay. These soils contain relict structure of the original sand and gravel texture of the alluvium. The clay layers are stiff to very stiff, and silty/sandy layers are typically medium

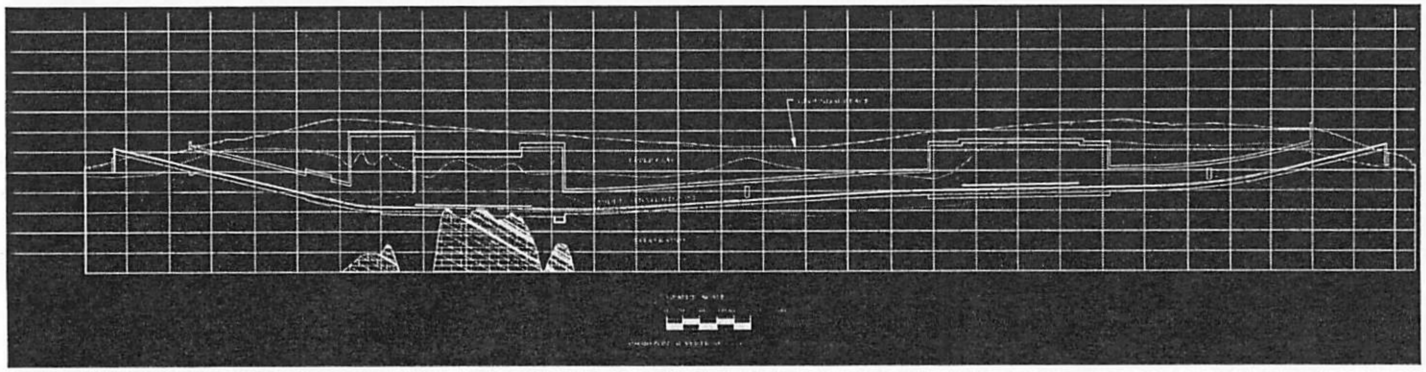


Figure 4. Geologic Profile of Río Piedras Contract Alignment

dense with density increasing with depth. Silty and clayey layers contain appreciable fines (30 to 50 percent). The transition between Layer 1 (silty clays) and Layer 2 (silty/clayey sands) is the result of weathering and is therefore gradational in nature. Layer 1 is distinguished from Layer 2 by the greater fines content in the Layer 1. This is due to weathering, in that a greater percentage of the sands have weathered to clay near the ground surface. Both layers are highly lenticular. However, to simplify the analyses, this weathering profile has been broken into these two layers. Layers 1 and 2 have fairly low hydraulic conductivities in the vertical and horizontal directions. Layer 2 was also assumed to be a cohesive soil (f=0).

- *Layer 3 - Lower Sand:* Characterized as interbedded sands, silty and clayey sands, and clays. Layer 3 contains clean lenses of coarse-grained deposits up to 2 meters in thickness. Cemented horizons within Layer 3 occur in horizontal layers 1 to 2 meters in thickness. Layer 3 is a distinctly different layer that has different material properties from Layers 1 and 2. It is a more coarse grained layer (more sand) and has higher hydraulic conductivities that are more conducive to dewatering than Layers 1 and 2.This layer was assumed be a soil with both c and f.

Below the Lower Sand lies the Aquada Limestone. In portions of the alignment, the Aquada Limestone forms pinnacles or buried karst features that intrude into the Río Piedras Station invert. At these locations the limestone is slightly to moderately weathered, and does not make much water.

A typical geotechnical profile for the Mined Tunnels is shown on Figure 5. The numbers on **Figure 5** (1, 2, 3 and 4) indicate the sequence of excavation.

Seismicity. Puerto Rico has a record of earthquake activity since Spanish colonization and is situated between three major fault zones. No active faults have been identified on the island, but epicenters of deep and moderate depth earthquakes have been identified beneath the island. Hundreds of small magnitude shocks occur in the vicinity of Puerto Rico each year, but most go unnoticed except by highly sensitive seismographs. Historically, large magnitude events have been felt in Puerto Rico. The entire island is rated as Seismic Zone 3 by the 1997 Uniform Building Code.

In the case of the Río Piedras underground structures, the design team concluded that the Río Piedras alignment does not cross any active faults that could impart displacement due to fault rupture.

DESIGN OF UNDERGROUND STRUCTURES

Design Approach on a Design-Build Project

The design approach on a design-build project is somewhat different than is typically experienced on design-bid-build projects. On the Tren Urbano project, there were three primary factors that drove the design approach:

1. *Compressed Schedule.* The short contract duration, only 43 months, meant that construction had to start at the same time as the design. This led the designers to issue "definitive designs" with concrete outlines so that installation of temporary excavation support could proceed.

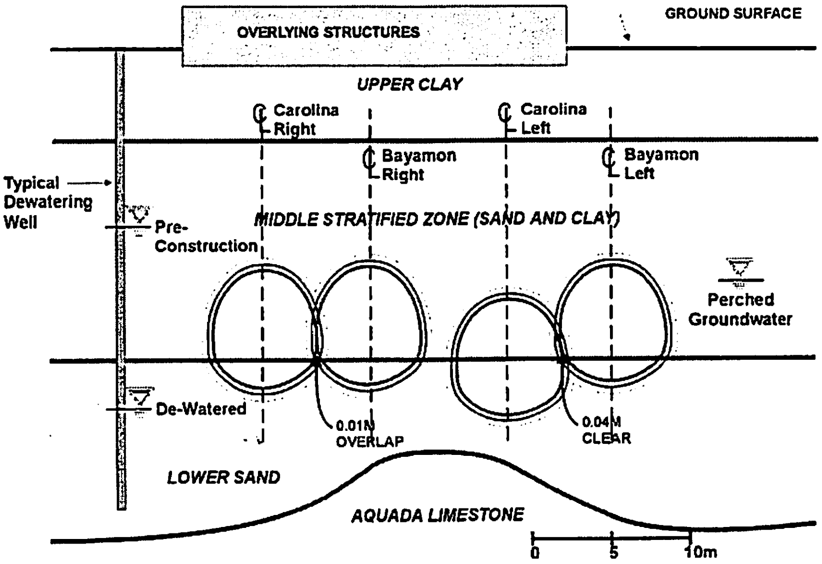


Figure 5. Typical Geotechnical Profile for Mined Tunnels

2. *Owner-Provided Preliminary Design.* The 30% design provided by the owner was essential to define overall facility requirements. However, it was necessary to customize the preliminary design to the specific underground construction methods being used by the contractor. This sometimes lead to significant redesign efforts.

3. *Focus on Procurement to Meet Schedule.* In order to meet material procurement requirements, particularly on an island where many materials had to be shipped overseas, designers had to advance designs so that the procurement schedule was not impacted. This required a concerted effort to keep design ahead of procurement and construction. It also meant that the designers had to anticipate requirements for the final structure, even though the final design had not yet been completed.

In addition to these factors, the designer/contractor relationship is different than the typical design/owner relationship. The designer best serves the contractor-client by meeting schedule. However, the designer is still "engineer of record" for the work, with all the responsibilities that are inherent in the profession, such as public safety, adherence to governing laws and codes, ethical conduct, etc.

Building Protection and Dewatering

For the Río Piedras contract documents, the owner specified threshold limits and specific actions for various levels of settlement. Compensation grouting has been selected as an appropriate building protection method since it is considered the most appropriate procedure to mitigate settlements caused by excavation of the various tunnels. Compensation grouting design and construction is being provided by Soletanche-Bachy of Paris, France.

The phases of the compensation grouting program above the tunnels are as follows:

1. Identify the areas to be protected.
2. Drilling and installation of sleeve port pipes (also termed tube-a-manchete) in an array beneath areas that are expected to be influenced by excavation settlements. (The sleeve port pipes make it possible to inject compensation grout precisely beneath a particular zone utilizing an inflatable double packer.)
3. Pre-grouting or pre-conditioning is performed to recover relaxation due to drilling, and to pre-compact the ground so that subsequent injections are more immediately effective in compensating for settlement.
4. The compensation grouting phase is undertaken as required during the excavation work to compensate for ground loss and limit settlement to an acceptable value. The pressure, volume, and location for injection of grout is based on information obtained through instrumentation of buildings and surface movement.

The concept of compensation grouting is shown in **Figure 6**. Details of the compensation grouting program are given in "Ground Control Program for the Río Piedras Project, Tren Urbano Program, San Juan, Puerto Rico" by Morrison et al., which is also in these proceedings.

Dewatering for the tunnels is being performed from deep pumped wells and by pumping in the open cuts. In addition, probe holes are being drilled ahead of tunnel excavations if warranted by geologic conditions. Horizontal drains and/or vacuum lances have been used to pre-drain tunnel headings to control unfavorable ground conditions. In general, the soils encountered during tunnel excavation are silty to sandy clays and clayey to silty sands with low hydraulic conductivities.

Tunnel Design and Analysis Approach

Design of the NATM and EPBM tunnels generally followed industry practice for design of flexible linings in soft ground. However, due to the shallow depth and the relatively stiff nature of the stacked drift tunnel, numerical models were used to determine stresses and deformation of structures. In addition, due to the close proximity of the NATM tunnels to one another, numerical models were also used to analyze the interaction between parallel tunnels.

Three structural models were used to analyze the behavior of the NATM tunnels and the Stacked Drift Tunnel:

- *Finite Difference Continuum Model:* Used for the NATM tunnels and Stacked Drift Tunnel to analyze the behavior of the tunnel linings. This analytical approach involved modeling the excavation sequence and the installation

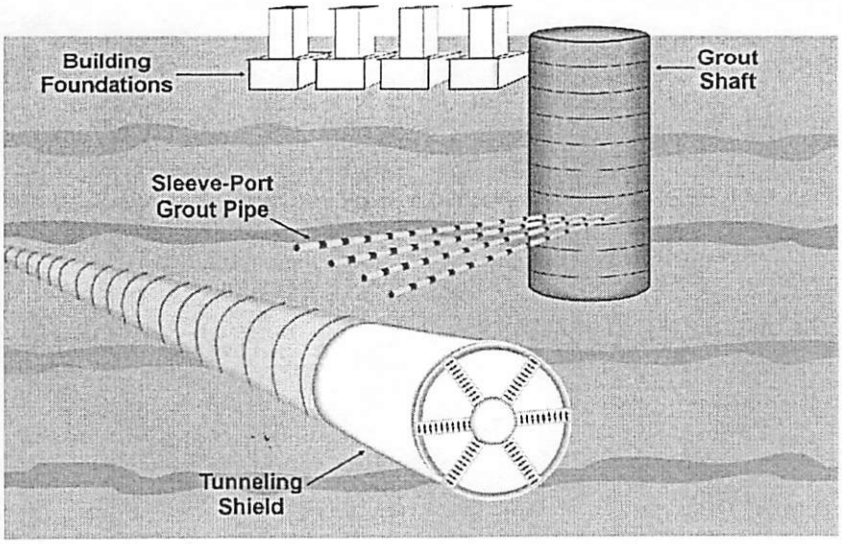


Figure 6. Compensation Grouting Schematic

of initial linings at the appropriate stage of construction. The FLAC software, produced by Itasca Corp., was used for these models. The 2-dimensional numerical models simulate the soil as an elasto-plastic continua and models the initial linings either as structural beam elements or as elastic continua.

- *Beam-Spring Model:* Structural frame analyses where used for the final linings of the NATM tunnels and the Stacked Drift Tunnel. With this method the linings are modeled as a network of beams. The interaction of the lining with the surrounding ground is modeled by a series of springs. Elastic material properties were used and structural loads were directly entered into this model.
- *Three-Hinged Arch Model:* This simplified representation of an arch structure as a statically determinant structure, with a hinge assumed at the centerline of the arch at the crown, was used for analysis of the Stacked Drift Tunnel. The three-hinge arch model was used to compute the reactions at the foundation and invert slab levels.

The design of each individual tunnel structure is summarized below.

Mined Tunnels (NATM)

The Mined Tunnels will be constructed to preserve two historic structures located near the southeast corner of the intersection of Georgetti Street and Ponce de León Avenue. Because of the short length of tunnels, mechanized shield tunneling was not considered an economically viable option for tunnel excavation. In addition, to limit settlement and prevent damage to the existing buildings above the tunnel, consideration was given to various tunnel excavation and support methods. It was concluded that *construction aspects* of the NATM offer the most flexibility in construction, and is an effective method for controlling surface ground settlement (Rippentrop and Kolitsch 1997).

A total of four mined guideway tunnels, each approximately 100 m (330 ft.) long, will be constructed under two historic structures. Two of the four tunnels will be constructed as part of a turnout to a future line. Cover over the Mined Tunnels ranges from 20 m (66 ft.) to 5 m (16 ft.). Some of the tunnels are located less than 1 meter from each other in the turnout section. Critical sections of the Mined Tunnels are shown on **Figures 7** and **8**.

A two-pass system consisting of a lattice girder and mesh reinforced shotcrete initial lining and a cast-in-place concrete final lining was considered appropriate for these tunnels. The initial lining as constructed is shown in **Figure 9**. The final lining for the NATM tunnels serves to support long-term hydrostatic and seismic loads, and provide a foundation and dynamic envelope for trains and walkways. A waterproof membrane will be installed between the initial lining and the final lining.

Due to the complex geometries and excavation sequences of the various tunnels in relation to each other, the finite difference method was used for analysis of the initial support. The analysis took into consideration the deformation of the ground prior to placement of the final lining. Furthermore, stress redistributions were fully taken into account as one tunnel is excavated and supported next to an adjacent, previously constructed tunnel.

Río Piedras Station Stacked Drift Tunnel

The tunnel for the Río Piedras Station platform, 150 meters (490 ft.) long by 19 m (62 ft.) wide by 16 m (53 ft.) in height, will be one of the largest diameter soil tunnels ever constructed (see **Figure 10**). This structure will be built using a stacked drift design, in which the tunnel lining, consisting of 15 concrete filled drifts, is constructed to form a horseshoe-shaped arch. Construction of the arch is followed by removal of the soil core under the arch. Many factors, which include variable soil conditions, overlying historic structures, relatively shallow tunnel depth (less than 5 m), and small permissible ground settlements, have influenced this design and construction approach.

The approach has precedents in the United States in very poor ground conditions for a part of the Eisenhower Tunnel on Interstate 70 in Colorado (Hopper et al. 1972) and for the Mount Baker Ridge Tunnel on Interstate 90 in Seattle, Washington (Robinson et al. 1983; Johnson et al. 1983).

The Stacked Drift Tunnel could be considered to behave like an unreinforced arch where loads are accommodated as compressive forces (thrust) across individual arch segments. As an arch it could be stable without steel reinforcement. This was the case for the Mount Baker Ridge Tunnel. The difference between these two projects, however, are significant: Mount Baker Ridge has a full circular ring, is situated in clayey soils without appreciable groundwater, and has less

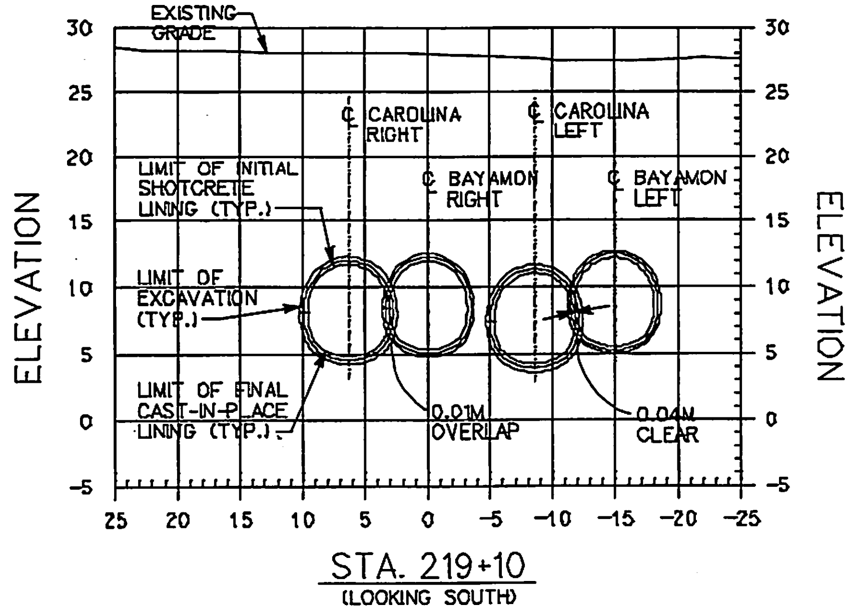


Figure 7. Mined Tunnels Cross-Section at Station 219+10

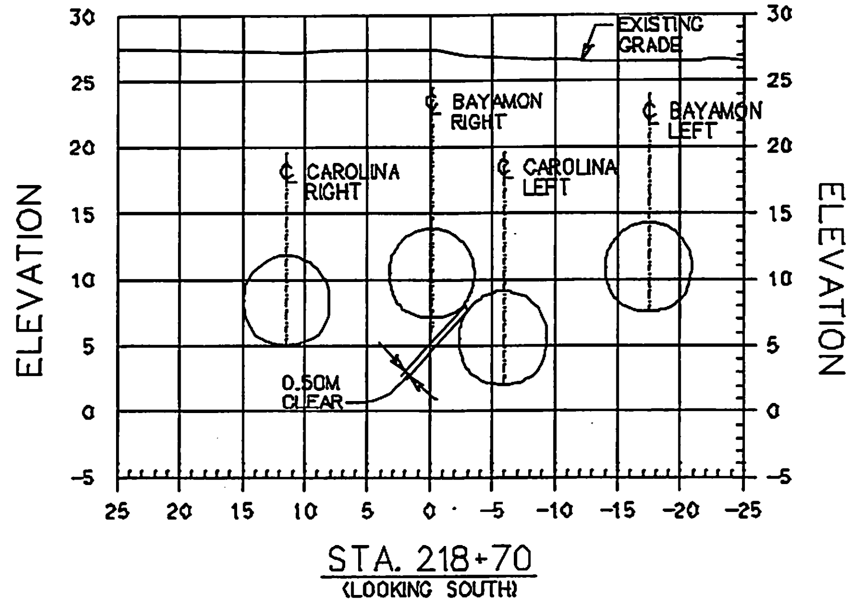


Figure 8. Mined Tunnels Cross-Section at Station 218+70

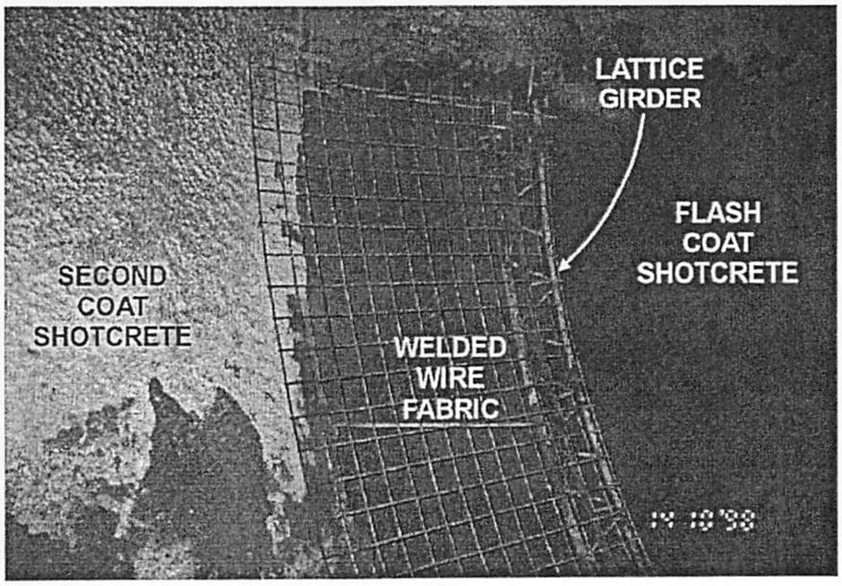


Figure 9. Lattice Girder and Mesh Reinforced Shotcrete Lining

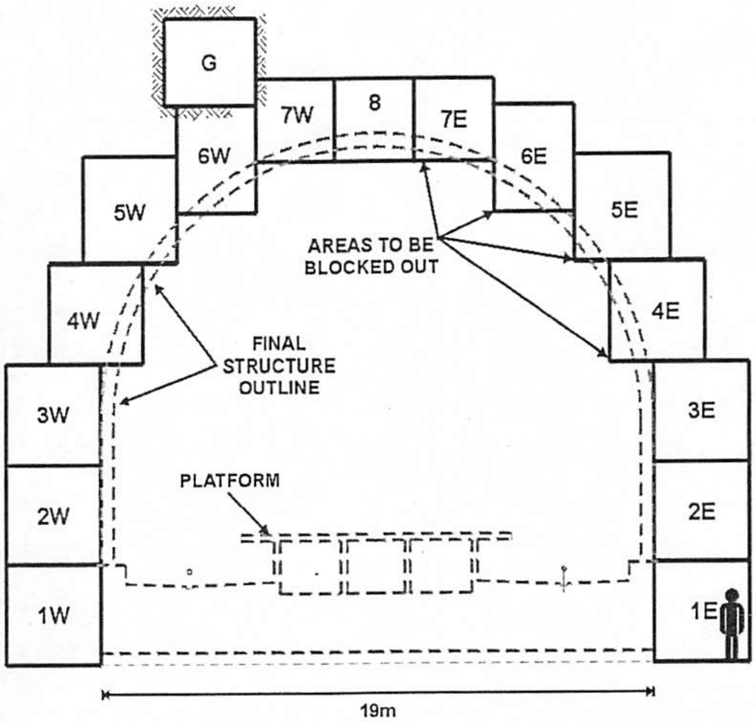


Figure 10. Stacked Drift Tunnel

concern for overlying structures. The Río Piedras Station arch is not circular but horseshoe in shape, has significant groundwater concerns, and has occupied commercial and residential structures directly overhead. Thus, regardless of how much the Stacked Drift Tunnel might actually function as an arch, a reinforced concrete arch was deemed to be appropriate for this situation.

Since the arch will be structurally effective before the soil core is removed, it was designed to accommodate loads associated with both short term and long term conditions. In conventional tunneling, most of the elastic and some of the inelastic deformations of the ground occur before tunnel supports are installed and become structurally effective. This results in arching of soil, thus reducing load on the tunnel supports. Because of the construction method planned for the Rio Piedras Station, substantial soil arching cannot develop.

Tunnel Geometry. Drifts were sized to achieve a constructable opening yet be small enough to minimize construction impact on overlying structures. Structural requirements for the arch did not control size. For constructability reasons the drifts are oversized with respect to minimum structural requirements. For the lower drifts forming the sidewall, a nominal size of 3 m (9.8 ft.) by 3 m was selected. Drifts were designed to be rectangular in shape. In the upper drifts, blockouts are necessary where the drift encroaches on the clearance required inside the tunnel (see Figure 10).

Steel Reinforcement. For the most part, structural steel is being used to create a reinforced concrete structure. Where possible, parts of the steel sets required for individual drift construction are used for reinforcement of the overall stacked drift structure. Sidewall reinforcement is provided by the sidewall drift posts, while portions of the crown reinforcement of the arch are provided by drift cap beams. Short-term and long-term loading conditions require reinforcement on different faces of the structure, as shown in **Figure 11**.

Special attention is given to reinforce the arch for cases when a positive moment (tension on the inside face of the arch) develops. In this situation, the initial steel installed in the drifts cannot be utilized for reinforcement due to their location. A separate installation is made of structural steel to provide tension reinforcement on the inside face of the crown of the arch. This arch steel is necessarily spaced between the initial support steel. A special reinforcing bar connection is made in drifts 3, 4 and 5 to avoid problems of connecting structural sections that have been pieced together from drift to drift.

Arch steel will be placed on regular spacing of 1.2 m (4 ft.) between the drift steel. It will be installed in sections as the upper drifts are excavated. Blockouts must be placed in the sides and inverts of the upper drifts prior to concreting of the drifts to form a curved surface on the inside face of the arch (see Figure 11).

Certain connections between the various structural steel members acting as arch reinforcement must develop full strength of the member in tension. Other connections need only be partial-strength connections. The locations of the full-strength and partial-strength connections are noted in Figure 11.

Circular Earth Tunnels (EPBM)

Twin bore guideway tunnels will be constructed between the University of Puerto Rico Station and the Río Piedras Station, a distance of approximately 430

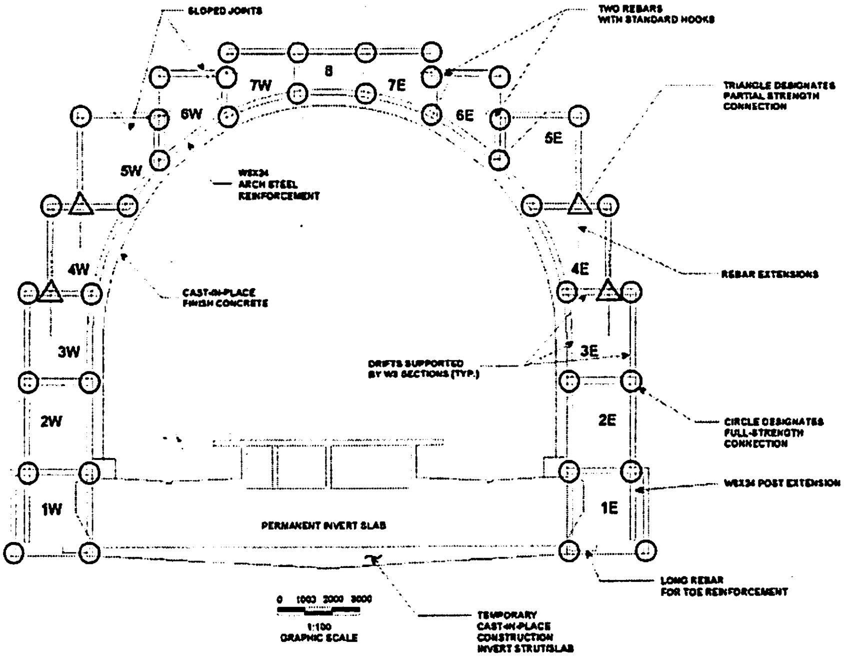


Figure 11. Structural Requirements for Stacked Drift Tunnel Reinforcement

m (1,400 ft.). The twin 6.3 m (20.7 ft.) outside diameter Circular Earth Tunnels will be excavated using a Lovat Model 254 earth pressure balance tunnel boring machine (EPBM) that was used on the Washington, D.C. subway system, Contracts F6a and F6c.

The EPBM will be used with a "one-pass" precast concrete segmental lining system where individual segments with gasketed joints are bolted to form a watertight lining (see **Figure** 12). The tunnels pass under an historic fence owned by the University of Puerto Rico, as well as under several occupied buildings. A single cross passage structure will be built between the two tunnels.

The one-pass lining is assembled in the tail-shield of the EPBM and bolted together. Grouting of the gap behind the segmental lining that is left by overexcavation of the tunnel will be done immediately behind the shield. The lining is a seven piece, 250 mm (10 in.) thick, 1.2 meter (4 ft.) wide ring. Primary circumferential reinforcing is eight #6 reinforcement bars on each face. Each segment will be joined using two 25 mm (1 in.) bolts in the circumferential direction (14 total for 7 segments), and twelve 25 mm bolts in the longitudinal direction.

The one-pass segmental lining is relatively flexible in relation to the ground. As a result, the precast segmental lining will interact with the surrounding soil. This concept is fundamental to tunnel designs of this type. As a result, the design for static loading conditions was based on traditional flexible liner design concepts (Hansmire 1989; Keusel, et al. 1996; Peck 1969; Peck et al. 1972; and Ranken 1978).

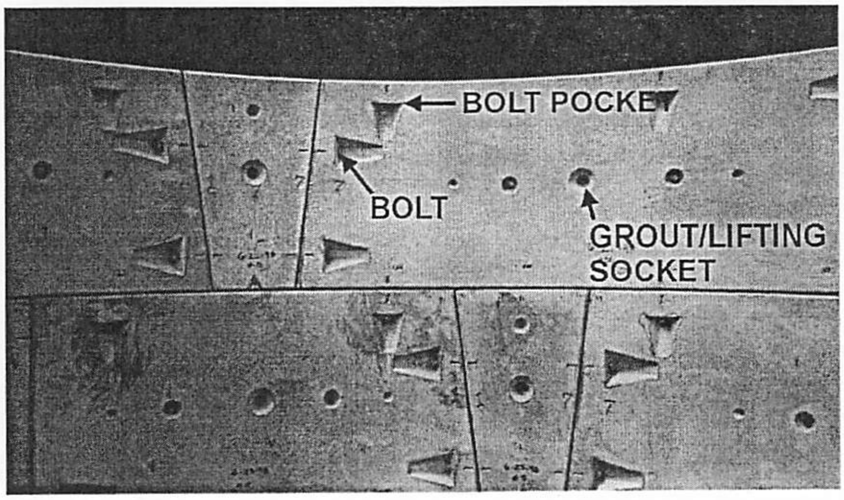


Figure 12. Precast Segment Bolting Arrangement

Various loading conditions were considered, including static soil loads, hydrostatic pressures, building surcharges, construction loads, grouting loads, jacking loads, and seismic conditions. Additional considerations included reinforcement of the cast-in-place invert slab, gaskets between segments, and potential for corrosion and sulfate attack. Effects of excavating two tunnels adjacent to one another were also considered. Structural adequacy of the concrete segments was characterized by moment-thrust interaction diagrams for reinforced concrete.

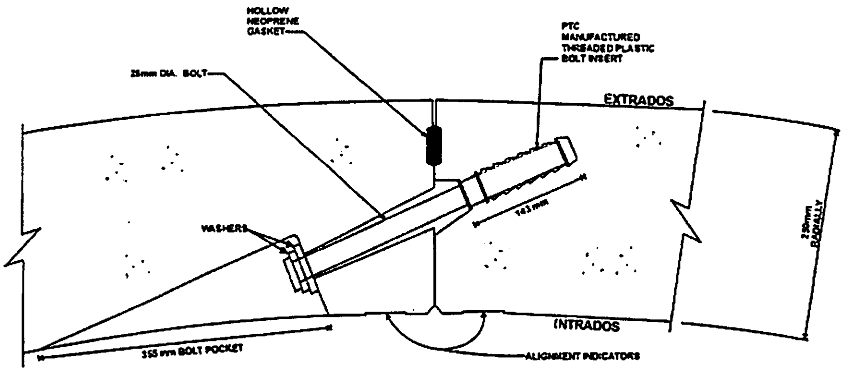
The following details were developed to adapt the "two-pass" segment design that was recently completed on the WMATA F6a contract in Washington, D.C. (See **Figure 13**):

- Bolt pocket detail was revised to minimize breakage of the segment that occurred in some instances as the bolts were tightened. Additional reinforcement was used around the pockets.

- The segment thickness was revised from the thinner (230 mm, 9 in.) section used in Washington, D.C. to a 250 mm (10 in.) thick segment to provide greater concrete cover over reinforcement. In addition, a seven piece ring was used in Puerto Rico instead of a five piece ring. These revisions are expected to alleviate cracks experienced in some segments that were located in the crown of the tunnel.

- The gasket groove was revised to maximize the distance between the groove and the edge of the segment. This is intended to minimize chipping of the gasket groove edge during handling.

- Threaded plastic inserts, similar to what are being used on the Toronto Transit Sheppard tunnels, were used in lieu of steel coil inserts.



REINFORCEMENT NOT SHOWN FOR CLARITY

Figure 13. Typical Detail of Segment Connection

Seismic Design of Tunnels

Earthquakes have several effects on soft-ground tunnels:

- Ground strains induced by seismic wave propagation; and
- Localized displacements induced by fault rupture.

It has been concluded that the Río Piedras alignment does not cross any active faults that could impart displacement due to fault rupture. Therefore it was only necessary to examine the additional seismic loads imposed on the tunnel structures, which are a manifestation of the ground strains induced by seismic wave propagation.

If the wavelength is long compared to the size of the opening (as is anticipated for the Río Piedras Contract), the dynamic loads can be approximated by using pseudo-static methods. For the case of a discontinuous medium, ground acceleration can be used to calculate the seismic loads, and in the case of a continuum, the dynamic stress can be calculated from wave propagation theory, provided the structure is sufficiently flexible.

Earthquakes cause transient deformation of the ground as these various types of waves travel through the ground. Many underground structures are flexible in relation to the ground; if this is the case, structures will be subject to the same strains as the ground in which they are embedded. Tren Urbano supplied design criteria that gave formulas for axial, curvature, and hoop deformation for tunnel structures with cross-sections that are nearly circular. These formulae are variations on the plain-strain equations used for determining seismic strains for flexible tunnel linings due to seismic wave propagation (Wang 1993). Since the Mined Tunnels and Circular Earth Tunnel linings met the criteria for "flexible" tunnels in relation to the ground, the owner furnished criteria was used for the seismic analysis of these structures. For the Stacked Drift Tunnel, which is a relatively stiff structure, a "racking" analysis was performed using a beam-spring numerical model.

CONSTRUCTION PROGRESS

Mobilization to an Island

Stockpiles of construction materials are generally kept very small on the island of Puerto Rico. With the exception of cement, almost all materials of any substantial quantity must be ordered from off island and delivered.

Material is transported to Puerto Rico via barge or vessel to the main docks in San Juan. Several restrictions on shipping drastically affected procurement of materials: (1) All barges and vessels must be American flagships per Cooper Act requirements; (2) The average length of materials (such as steel sections) is usually limited to 15 m (50 ft.) due to vessel or container size; (3) A minimum tonnage is required by the shipping companies; (4) Available space on ocean going vessels is limited and material placed on the top deck must endure exposure to the elements.

Integration of Procurement Schedule with Design

At the start of this design-build project the drawings and specifications were at a 30% design level. It was then necessary for the contractor to identify critical procurement items so that the designer could advance the designs for those specific materials. Items that have a long lead time are of particular importance, such as forms for precast tunnel segments and fabricated steel sets and lattice girders for tunnel support. The contractor must also resist the urge to label all procurement items as "critical," otherwise the designer will be unable to meet procurement milestones.

Progress as of January 1999

Building Protection and Dewatering. Sleeve port pipes have been installed in various locations below buildings within the zone of influence above the tunnels. Installations have been made from the surface, within grout shafts, and within the grout gallery (drift G) above the Stacked Drift Tunnel. Dewatering has been underway for over a year, and has drawn down the water table below tunnel invert level in most locations.

Temporary Support of Cut-and-Cover Excavations. Major cut-and-cover excavations for the stations were substantially completed in 1998. Typical construction is soldier pile and lagging walls with internal bracing of structural steel or pipe. In limited areas secant pile walls were constructed next to building structures. Shafts were expedited to permit start of tunneling and other excavations proceeded in parallel for the University of Puerto Rico Station and the cut-and-cover guideway section at the north end of the project.

NATM Tunnels. Mining of the first of the four tunnels was completed at the end of 1998 (see **Figures 14 and 15**) and the second tunnel had turned under. In an over/under configuration for a future rail line turnout, the final lining is specifically being delayed in order to avoid unnecessary stress in the final lining by construction of the second, overlying tunnel. After mining all tunnels, a final cast-in-place concrete lining will be placed.

Stacked Drift Tunnel. Shafts on either end of the Stacked Drift Tunnel had been sunk to invert level (see **Figure 16**). Mining of the level 2 drifts was in progress. Mining and concreting of the lowest drifts (level 1), which form the tunnel foundation, were completed in October of 1998 (see **Figure 17**). Mining the foundation drifts involved substantial time as new work crews were trained for the somewhat unique mining techniques required. In addition, limestone was encountered in the lower half of the foundation drifts for substantial reaches. For about the southern one-third of these drifts, soft soils were present at foundation level, and two meter deep pits had to be dug by hand to a firmer stratum, which was then concreted to form short piers. Perched water within permeable soil lenses, and water from utility discharge above have contributed to excavation and ground support difficulties in drifts 1 and 2.

EPBM Tunnels. Segment forms were built in Texas by Hamilton and delivered to Puerto Rico in the late spring of 1998. Marmolejo Contractors began segment production in June of 1998 (see **Figure 18**). The Lovat EPBM, which recently completed WMATA subway tunnels in Washington, D.C., was shipped to Puerto Rico in the early fall of 1998 after being refurbished. Mining had just started in earnest in January 1999 driving south from the University of Puerto Rico Station excavation (see **Figure 19**). The plan is to turn the machine around in what is termed the North Shaft of the Río Piedras Station and drive the second tunnel to the north.

THE DESIGN-BUILD EXPERIENCE — PERSPECTIVES FROM UNDERGROUND

Although many personnel on the KKZ/CMA team had previous underground design-build experience in Europe and Australia, many new lessons were learned on the philosophy, organization, roles and responsibilities inherent in this "American" design-build project. A summary of these lessons and experiences is given below:

- Schedule is a key factor on the project. Money spent to keep the project on schedule will save money in the long run.

- A learning curve exists for personnel and organizations not experienced with design-build. For example, construction personnel and owner staff must realize that construction submittals are reviewed and approved by the designer, not the owner. The contractor must make a greater effort to stay on top of field quality control. The designer must learn to balance contractor's bid with owner's requirements. In addition, the designer must be aware of schedule. The owner is responsible for rapid review and approval of design for conformance with operational quality requirements. The owner should also provide some review of construction quality control.

- A firm organizational structure with defined duties for each position is required. The Design Manager is a key position for liaison with construction

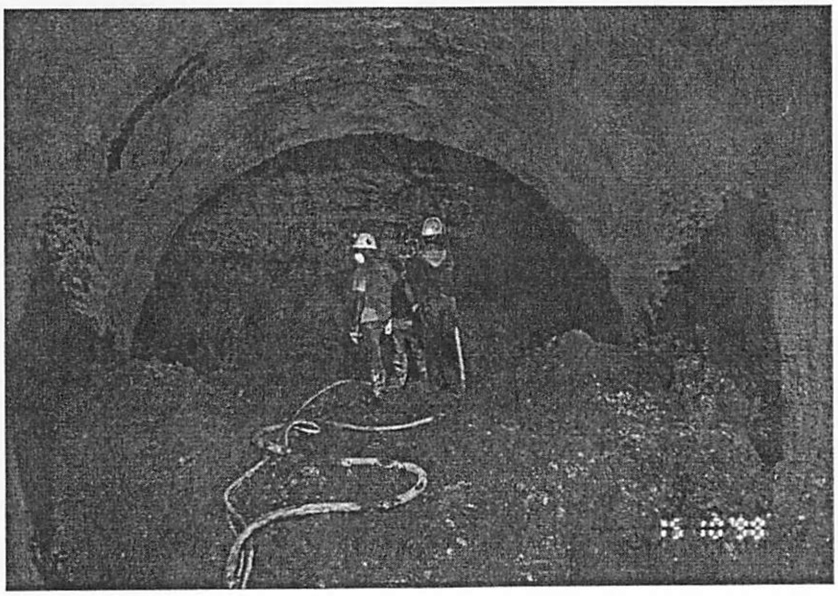


Figure 14. Heading of Carolina Left NATM Tunnel

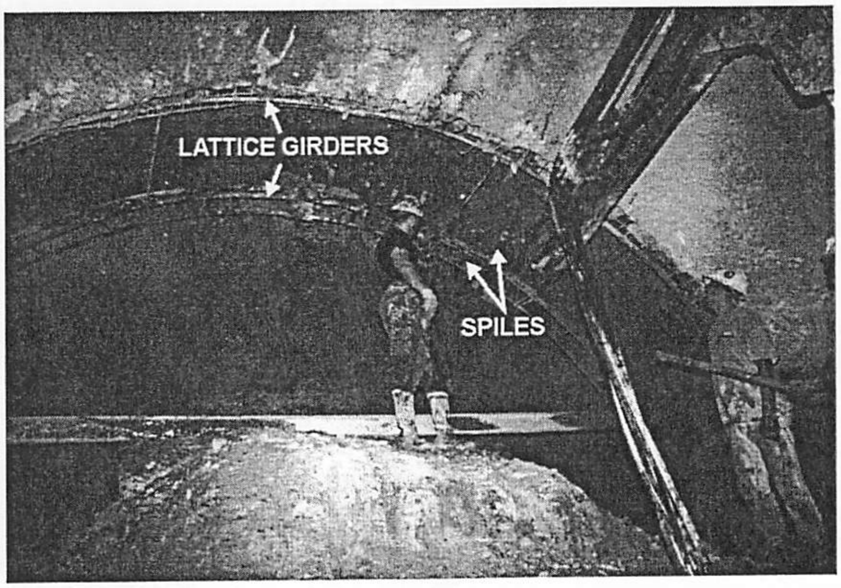


Figure 15. Spiles Being Driven in Carolina Left NATM Tunnel

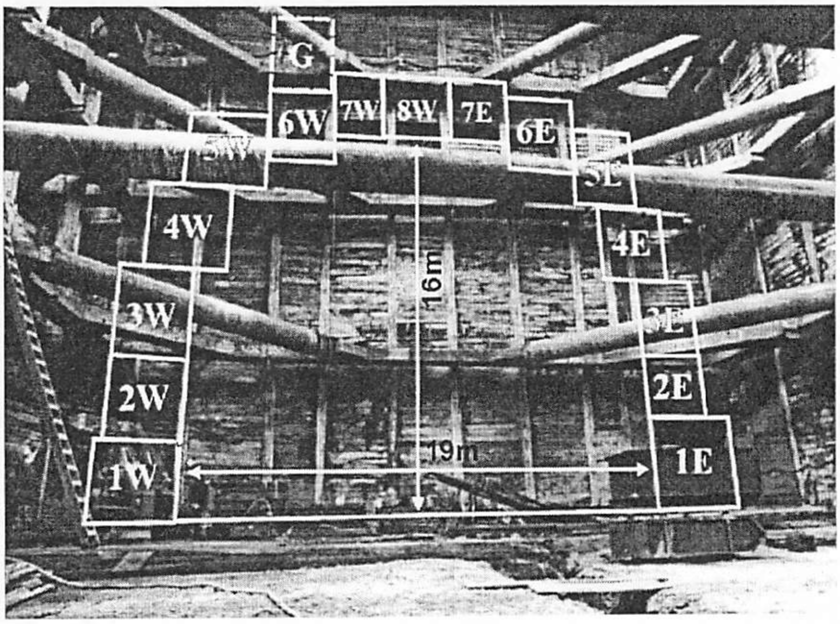


Figure 16. Stacked Drift Tunnel Viewed from South Shaft of the Río Piedras Station

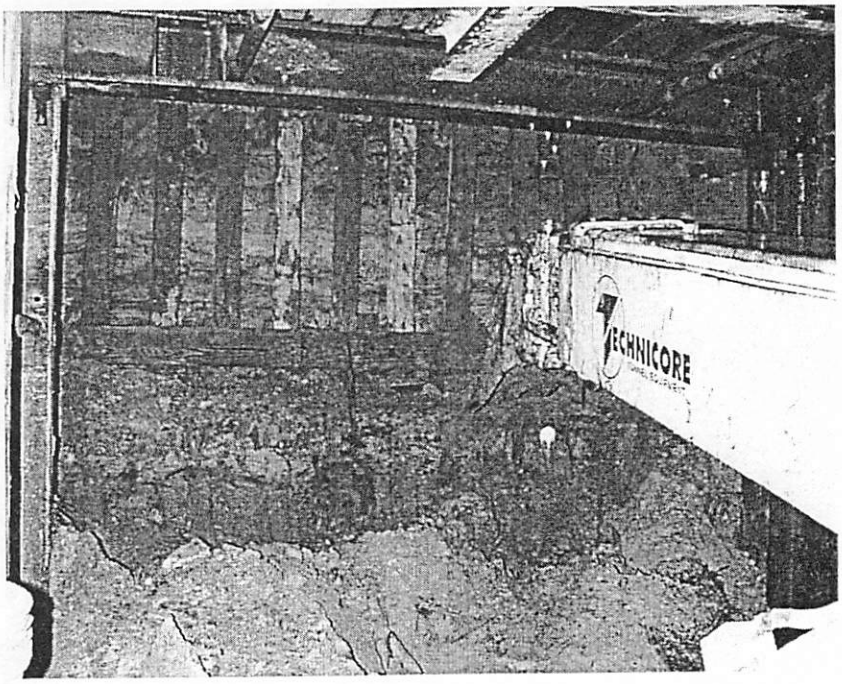


Figure 17. Tunnel Digging Machine Excavating Bench in Foundation Drift 1W

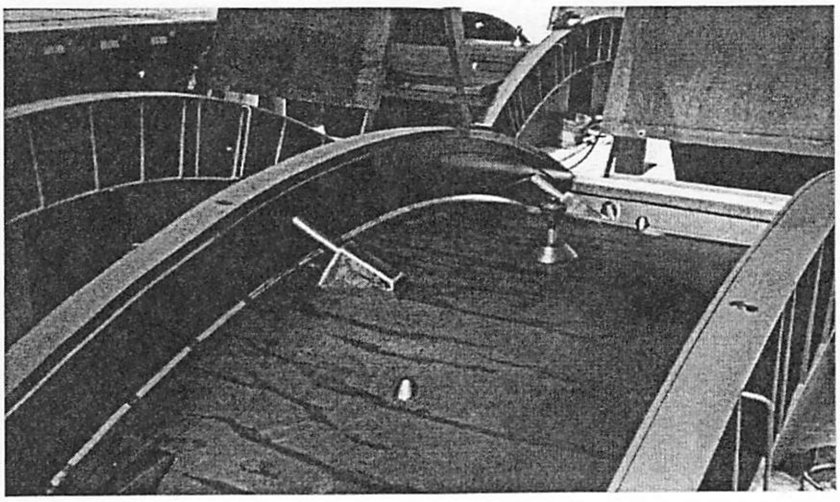


Figure 18. Precast Segment Forms

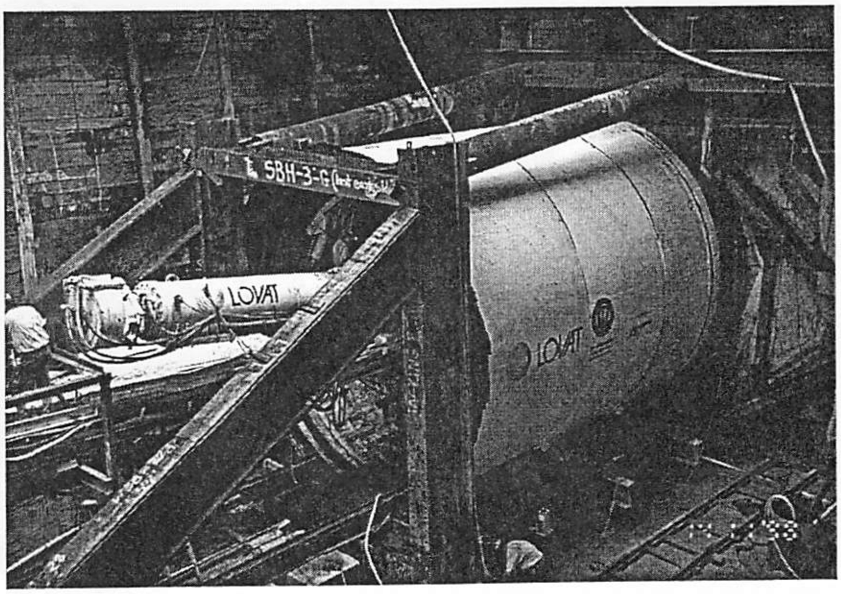


Figure 19. EPBM Ready for Launch

personnel. Key requirements for such a position: experience with delivering a transit system design package and interfacing with contractor's staff.

- The owner's system for approving design must be different from the traditional method. For example, the owner will not have a complete system to review at the various design stages (30%-60%-90% design levels). The owner will have to approve different disciplines at different times.
- On design-build teams that are contractor led, more management is required than the contractor is normally used to.
- Contractors must establish a viable Community Relations program. This was very well done on the Tren Urbano project, by both the owner and the contractor.
- In addition to operational requirements, the owner must clearly define the level of quality that is desired. This is a difficult task.
- Construction personnel can fall into a false sense of security (thinking the designer will take care of all the engineering details) and tend to relax on planning, construction submittals and construction engineering.
- Fast, efficient, and comprehensive document control is critical to the owner and the design-build team.
- Design is on the critical path. Delays in design, including owner or contractor changes, can delay the delivery date.
- Paying on the basis of a cost-loaded schedule can be a problem. It changes the entire focus of the schedule from planning to payment.
- Coordination of the overall transit system is very important. It is probably not necessary or prudent to have the civil contractors install systems elements, but they need systems information. It is recommended that systems design and procurement be scheduled long in advance of civil design.
- Specification writing requires different skills from the traditional specification writers. Specifications have to be different: fewer construction options (we know what we want to build) but more field QC requirements, since the owner will not be providing construction management, as is typical on design-bid-build projects. Since the contractor is responsible for QC, the designer must specify what the contractor's QC personnel are to "check."
- Contractors don't buy design any cheaper than owners do. Money saved on not doing lots of alternate designs (typical for design-bid-build) is spent re-doing designs because of different construction methods.

- The contractor can influence the way the design is developed and therefore can better control the project during construction. The designer knows what construction methods will be used and can tailor design specifically for those methods (unusual in traditional underground design-bid-build). Synergy between the contractor and designer results in a more constructable project that can reduce material costs.

- Disputes between contractor and designer over scope of work can arise when unanticipated work is necessary. Requires a good contractor-designer contract. Not a lot of precedent for this as there is for owner-contractor contract language.

REFERENCES

Deere, D.U. 1955. *Engineering Properties of the Pleistocene and Recent Sediments of the San Juan Bay Area, Puerto Rico*; Ph.D. Thesis, University of Illinois, Urbana.

Hansmire, W.H., B. Schmidt, and J.E. Monsees 1989. Perspectives on Soft Ground Tunnel Lining Design. *The Art and Science of Geotechnical Engineering*; Prentice Hall.

Hopper, R.C., T.A. Lang and A.A. Mathews 1972. Construction of Straight Creek Tunnel, Colorado. *1972 Rapid Excavation and Tunneling Conference Proceedings.*

Johnson, E.B., L.J. Holloway and G. Kjerbol 1983. Design of Mt. Baker Ridge Tunnel in Seattle *1983 Rapid Excavation and Tunneling Conference Proceedings.*

Keusel, T.R., E.H. King and J.O Bickel editors 1996. *Tunnel Engineering Handbook, 2nd Edition*; Chapman and Hall.

Peck, R. B. 1969. Deep Excavations and Tunneling in Soft Ground. *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering.*

Peck, R.B., A.J. Hendron, and B. Mohraz 1972. State of the Art of Soft-Ground Tunneling. *1972 Rapid Excavation and Tunneling Conference Proceedings.*

Ranken, R. E. 1978. *Analysis of Ground-Liner Interaction for Tunnels*;. Report No. UMTA-IL-06-0043-78-3.

Rippentrop, G., and P. Kolitsch 1997. Successful Soft Ground NATM Approach in Metro Section E4B in Washington, D.C. *1997 Rapid Excavation and Tunneling Conference Proceedings.*

Robinson, R.A., H.W. Parker and S.R. Thompson 1983. Geotechnical Aspects of the Mt. Baker Ridge Tunnel Design. *1983 Rapid Excavation and Tunneling Conference Proceedings.*

Wang, Jaw-Nan 1993. Seismic Design of Tunnels, *A Simple State-of-the-Art Design Approach*; Parsons Brinckerhoff Inc, NY.