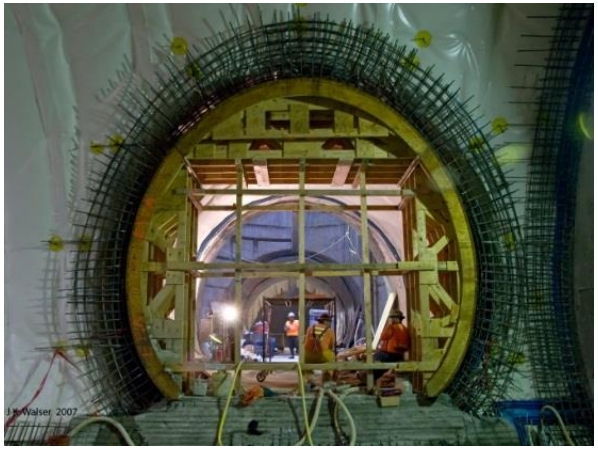
Central Link Section 710: Beacon Hill Station and Tunnels



LOCATION:

Seattle, Washington, USA

SUBMITTING FIRM:

Hatch Mott MacDonal

FIDIC MEMBER:

American Council of Engineering Companies (ACEC)

International Federation of Consulting Engineers
The Global Voice of Consulting Engineers

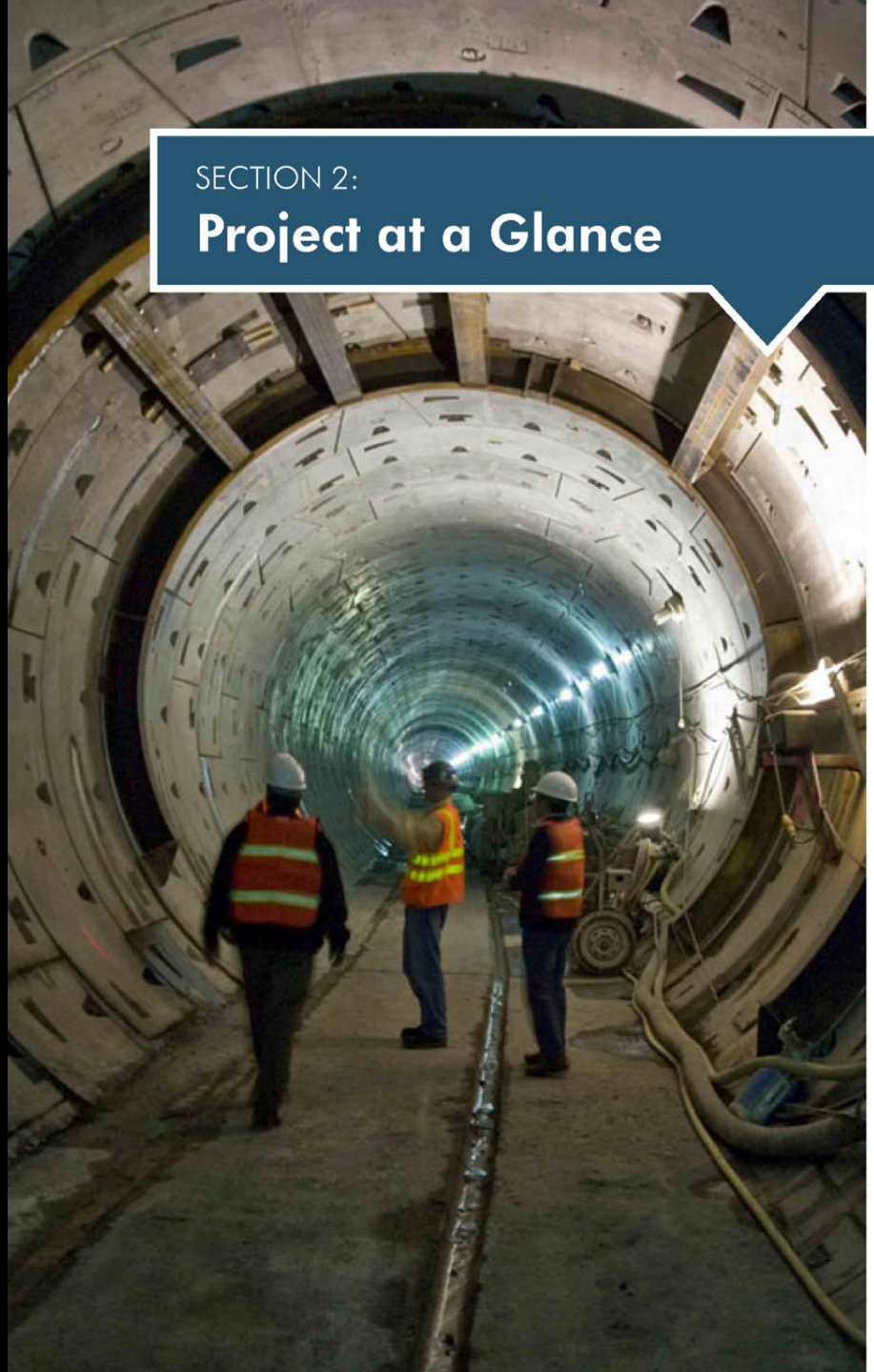
2014 Award Submittal

Central Link Section 710: Beacon Hill Station and Tunnels

Location: **Seattle, Washington, USA**

Owner: **Sound Transit**

Submitted By: Hatch Mott MacDonald and JACOBS

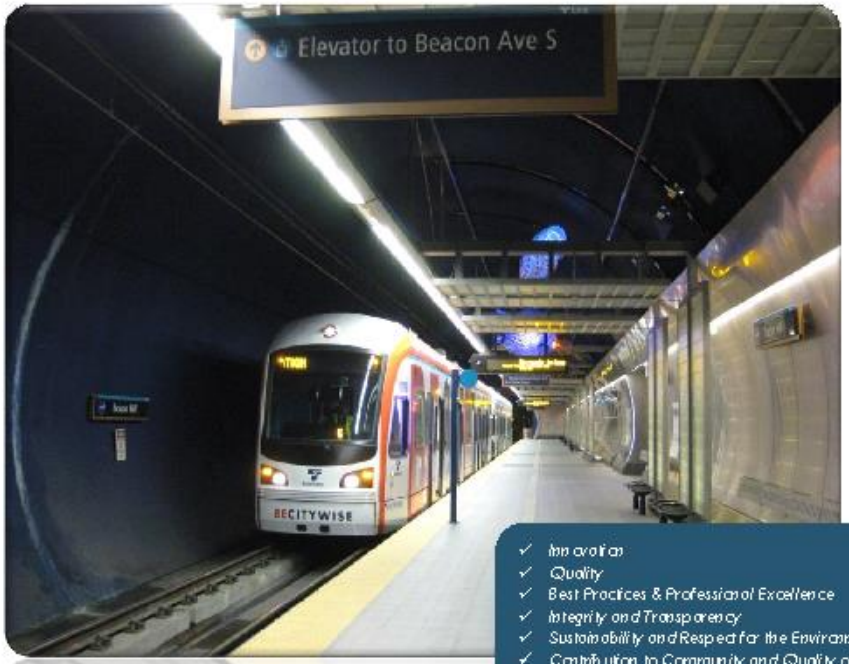


SECTION 2:

Project at a Glance

Section 2: Project at a Glance

Central Link Section 710: Beacon Hill Station and Tunnels

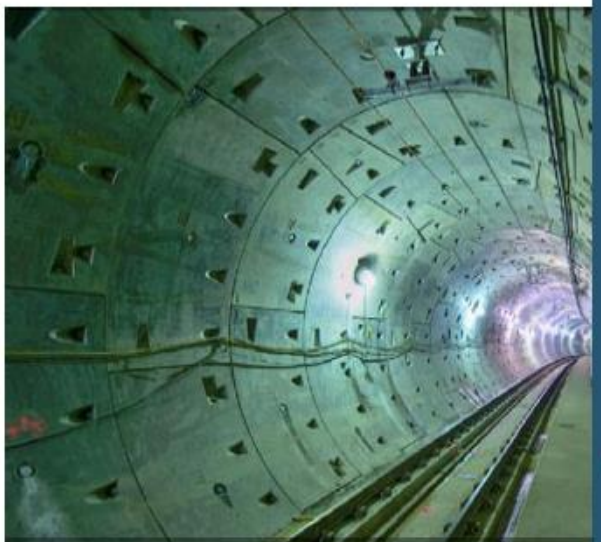


- ✓ Innovation
- ✓ Quality
- ✓ Best Practices & Professional Excellence
- ✓ Integrity and Transparency
- ✓ Sustainability and Respect for the Environment
- ✓ Contribution to Community and Quality of Life

Location: Seattle, Washington, USA
Design Completed: 2004
Construction Completed: 2009
First Year in Operation: 2009
Construction Cost: $313 Million
Nominating Organization: American Council of Engineering Companies (ACEC)
Owner: Sound Transit
Engineer of Record: Hatch Mott MacDonald and Jacobs Civil Joint Venture (HMMJ)
Architect of Record: OTAK Architecture
Station Concourse/Platform Design: Dr. G. Sauer Corporation
General Contractor: Obayashi Corporation

The joint venture team of Hatch Mott MacDonald and Jacobs Civil (HMMJ) was awarded a contract for the final design of the Central Link Section 710, Beacon Hill Station and Tunnels project. The HMMJ team provided final design for the tunnels and support structures; design support during construction; and SEM oversight. Design was completed in 2004, and construction was completed in 2009. See the Appendix section for a complete list of firms, subconsultants, and contact details.

As the lead JV partner, Hatch Mott MacDonald was responsible for overall project management and controls, as well as detailed design of all tunnels and portals, shafts, and mined station tunnels, including final linings and waterproofing. The scope of work included scheduling, cost estimating, and contract drawings and specifications. HMM also provided design support during construction, including the engineering oversight of the critical SEM excavation and support activities.

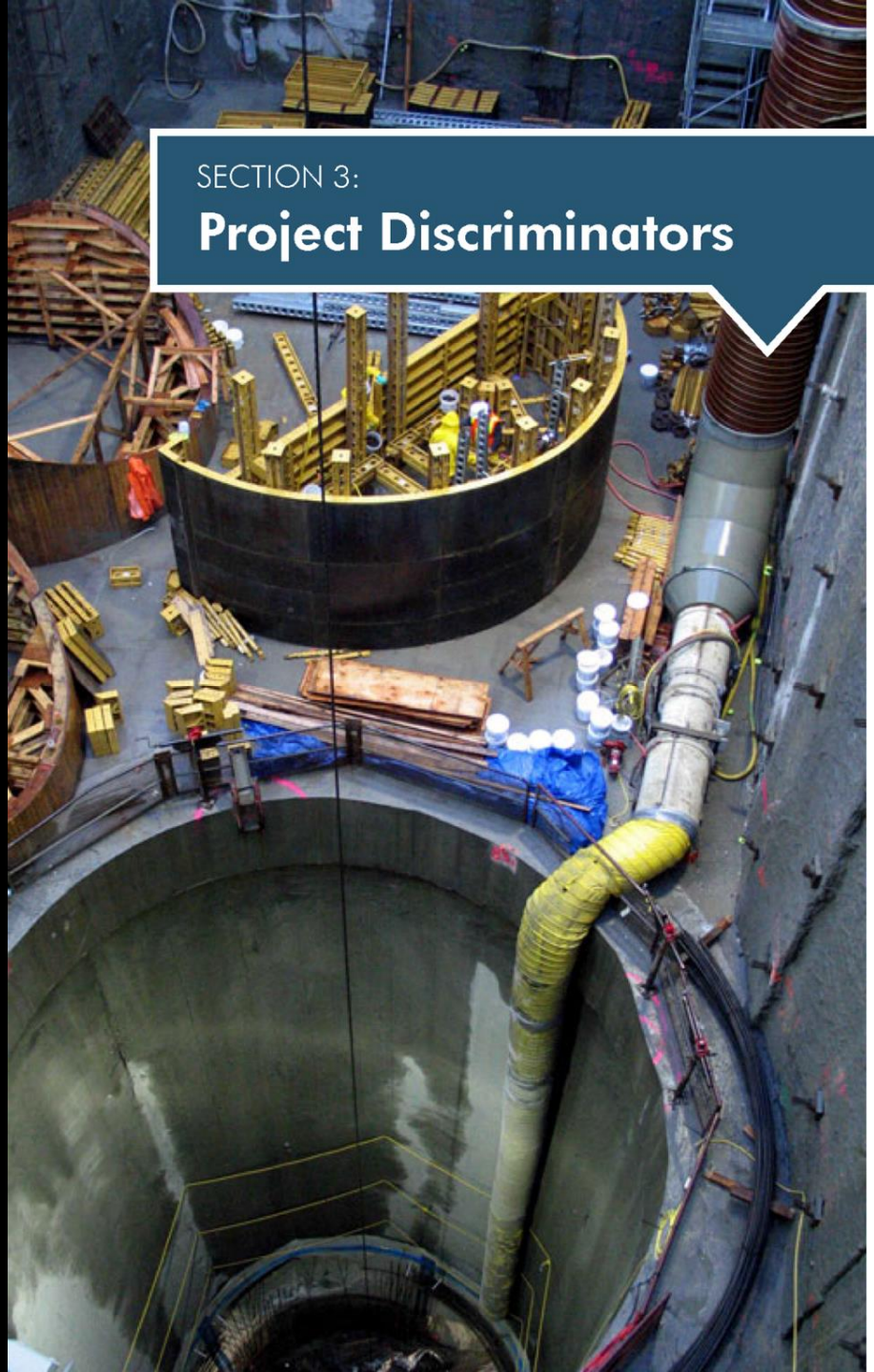


Running tunnel prior to train testing. Temporary lighting and cables on left awaiting removal after final lighting installation.

- ✓ Longest and deepest soft ground excavation carried out using SEM in glacial soil in North America
- ✓ Completed with virtually no ground settlement or disruption to businesses and transportation
- ✓ Twin 4200-ft.-long tunnels
- ✓ 185-ft.-deep shafts
- ✓ 380-ft.-long platform tunnels plus connector tunnels
- ✓ 45-ft.-diameter concourse adits
- ✓ EPB TBM sequential excavation
- ✓ One-pass precast segmental tunnel lining
- ✓ Soil improvement jet grouting and dewatering
- ✓ Stage-grouted barrel vault pipes and grouted pipe spiles formed presupport
- ✓ Innovative "Tool box" support items
- ✓ Extensive noise control measures implemented on 24-hour construction schedule
- ✓ Project won ACEC 2010 top honor, the Grand Award, for the year's most outstanding engineering achievement
- ✓ Design completed on time and within budget

"The project is an engineering and construction marvel that will be known throughout the world."

Larry Phillips, Councilman, City of Seattle



SECTION 3:

Project Discriminators

Section 3 – Project Discriminators

A. First in North America

The Central Link Section 710: Beacon Hill Station and Tunnels Project holds the record in North America for the deepest soft ground excavation carried out using the Sequential Excavation Method (SEM) in glacial soil. While SEM techniques have been used extensively in Europe and Asia, they have been used to a lesser extent in North America.

> ***First in North America***
> *Largest and deepest soft ground excavation carried out using the Sequential Excavation Method (SEM) in glacial soil in North America.*

The project included construction of one mile of twin running tunnels and a deep mined station consisting of twin shafts and a complex configuration of vehicle, pedestrian and ventilation tunnels ranging in size from 16 to 46 feet. The station location necessitated the development of an innovative approach to deep complex tunneling in very poor soils. The depth and dimension of these tunnels far exceeded anything done previously in soft ground in North America.

B. Project Awards

The Hatch Mott MacDonald/Jacobs Joint Venture received top honors from the American Council of Engineering Companies (ACEC) by being awarded the **2010 Grand Award for the most outstanding engineering achievement in 2010** for their deep tunneling design of the Beacon Hill Station and Tunnels. The project won three additional awards: the **2010 National Outstanding Civil Engineering Achievement Award Finalist, American Society of Civil Engineers** (ASCE); the **2010 Platinum Award, American Council of Engineering Companies** (Washington); and the **2009 Engineering Excellence Award, Association of Consulting Engineering Companies British Columbia**.

> ***Most Outstanding Engineering Achievement in 2010***
> *Beacon Hill Station and Tunnels has won three project awards including ACEC's top honor: the Grand Award for Most Outstanding Engineering Achievement in 2010.*

C. Innovation and Quality

A monstrous set of challenges faced the HMMJ design team on the Central Link Section 710: Beacon Hill Station and Tunnels project. The project included an underground station and very deep running tunnels one-mile long and 160 feet beneath a 352-ft.-high hill in highly variable soils. The biggest technical challenge for the deep tunnels came from the highly variable glacial soil deposits ranging from soft, water bearing sands to stiff, slickensided clays which are inherent in the Puget Sound region. Stabilizing the walls of two 160-ft.-deep shafts (a 50-ft.-wide main shaft and a 30-ft.-wide ancillary shaft) further complicated the design and construction challenges.

To meet these challenges a Risk-Adverse Design Approach was adopted, a test shaft was built, a rigorous geotechnical investigation was conducted, and advanced numerical analyses were performed to develop ground conditioning, pre-support, excavation support, design of the structures, and incorporation of an innovative procurement strategy and a comprehensive risk identification and mitigation program into the design and contract bid documents.

The design was undertaken recognizing the elevated level of risks associated with the complexity of the station arrangement, the depth and the anticipated geological variability. Sound Transit's direction was to acknowledge the risk up front by providing a more conservative and prescriptive design in the bid package than might have been provided under less risky conditions.

The decision by Sound Transit to have the HMM on site during excavation of the tunnels helped to ensure tunnel integrity and safety. Our presence facilitated the efficient resolution of design issues that arose from construction constraints, variations in ground conditions, review and response to submittals, and adjustments to construction sequences.

Primary Challenge

The primary challenge was how to design and safely build a structurally sound deep station and running tunnels in highly variable glacial soil deposits ranging from soft, water bearing sands to stiff, slickensided clays. A complicating compaonent t was how to stabilize the walls of two 160-foot-deep shafts.

Innovative Solutions to Ensure Quality

1. Risk-Adverse Deep Mining Design Approach – first in North America.
2. Construction of a test shaft to preempt potential issues due to extremely poor and variable soil conditions.
3. Rigorous, exhaustive geotechnical investigation.
4. Advanced numerical analyses to develop ground conditioning, pre-support, excavation support, and structural design.
5. Three-stage approach to SEM excavations.
6. Innovative Combination of Mining/Tunneling Design Specifications
7. Stabilizing deep shafts by:
   - Adoption of slurry wall design
   - Improving underground stability by jet grouting from the surface.
   - Continual 24-hour shifts of excavating and reinforcing horizontal passages.
8. Innovative procurement strategy
9. Comprehensive and judiciously developed risk identification and mitigation program.

1. Innovative Approach

In most civil engineering construction, the contractor designs temporary falsework and support systems that are put in place during excavation prior to the installation of permanent structures. For the Beacon Hill Station and Platform Tunnels, an innovative risk-adverse design approach was taken, in which the design consultant, HMMJ-JV, in conjunction with the Dr. Sauer Company, designed the complete excavation, including the initial and final support systems for the large diameter shafts and deep tunnels to be constructed using the Sequential Excavation Method (SEM). The location and depth below the community of Beacon Hill was determined based on the need to link the station with the rest of the system while maintaining a maximum grade of 5%, the design tolerance for the Sound Transit trains.

In SEM a tunnel is sequentially excavated and supported, and the excavation sequences can be varied. Initial ground support is provided by shotcrete in combination with fiber or welded-wire fabric reinforcement, steel arches, lattice girders, and sometimes ground reinforcement. The permanent support is usually a cast-in-place concrete lining.

To accommodate Sound Transit's requirement for normal and emergency egress, a station arrangement with two shafts, a transverse two-level concourse tunnel and two platform tunnels was developed as the base configuration. Emergency ventilation from each of the shafts to the Running Tunnels was accomplished by two sets of transverse and longitudinal ventilation adits, the junction of which was sized to accommodate motorized dampers.

Because of the perceived difficulty and high level of risk associated with constructing the platform tunnels by breaking out and over-cutting the segmental lining, the decision was made early in the design to construct the platform and connector tunnels first, then skid the TBM through and re-launch at the east end of the station. Tunnel drive lengths, including station tunnel skidding lengths are approximately 4860 feet for the southbound and 1500 4923 feet for the northbound tunnels.

2. Test Shaft: Unique Approach to Minimizing Risk

To minimize the risks and preempt the unknown inherent in tunneling through the extremely challenging and variable glacial soil, Sound Transit took an innovative approach by beginning the project with the construction of an 18-ft. diameter, 155-ft. deep test shaft in the area of the Beacon Hill main station shaft to confirm the initial geotechnical assumptions.

This test shaft, excavated by Coluccio Construction Company at an approximate cost of $2.5 million, provided engineers and contractors a glimpse of the actual ground conditions and helped them identify the optimum depth and construction methodology for the station and running tunnels. Findings during the test shaft program enabled project engineers to make final decisions on shaft and tunnel design, and construction methods. The test shaft facilitated a three-dimensional finite element analysis of tunnel excavation and of the initial support required for it, which represented a significant advance in the design of SEM tunnels. Test shaft construction also led to the successful use of Slurry Wall construction for the time critical vertical access shaft, as well as to the decisions on how to proceed with SEM tunnels, to use steel fiber reinforced concrete for large diameter tunnels, and the use of fiberglass reinforcing in slurry walls.

Flowing sands were encountered in the test shaft at the location of the main shaft, which presented a significant challenge in the design process. The groundwater regime was found to be significantly more complex than originally thought, with discontinuous aquifers containing sufficient fines to thwart stabilization measures using gravity and vacuum dewatering.

Based on extensive drilling and testing, it was determined that the station shafts and tunnels would be constructed through an extremely complex sequence of glacially overridden deposits consisting of very dense and hard clay, silt and sand, gravel and cobbles. Multiple ground water levels were detected in granular deposits, typically due to perched groundwater overlying clay and till units. The complex layering of these deposits, particularly thick zones of sands and silts, was very challenging for the design of shafts and tunnels for the station. Tunneling through the water bearing sands had the potential to create flowing conditions and voids at the tunnel site.

The test shaft site was within the area planned for four high-speed elevators and stairways to serve the Beacon Hill station. The goal was to take the information from the ground into the design.

3. Rigorous Geotechnical Investigation

A rigorous and comprehensive geotechnical investigation was conducted and a Geotechnical Baseline Report (GBR) developed that presented findings of the complex geology of the site and set baselines for anticipated ground behavior during tunnel excavation and construction.

Geotechnical conditions exposed by the exploration program had a major impact on the selection of excavation and support methods, dewatering requirements, size of openings, vertical alignment, and estimated cost of construction. Additional explorations were conducted during construction to further refine the geotechnical interpretations and provide an opportunity to use pro-active ground improvement techniques to optimize the station excavation and support requirements. A Tool Box of alternative additional support systems was developed to accommodate the varying ground conditions during construction of the station excavation.

To simplify the large number of unit descriptions and reduce the complexity of the geologic profile, geologic units were grouped into five major ground types summarized in the shaded box below. All of these ground types were expected to contain variable amounts of cobbles and boulders. Actual ground behavior would be a function of many factors such as excavation and initial support methods, ground improvements, and ground water conditions.

Table 1 summarizes the range of engineering properties for the five ground types. The interpreted ranges presented in this table are based on the results of field and laboratory tests, both in the immediate vicinity of the site and along the Beacon Hill Tunnel project alignment.

Table 1. Geotechnical design parameters

Material Description	Modulus, E, ksi (MPa)	Phi, ϕ	Undrained Shear Strength, S_u Tons/ft^2 (kPa)	K_0	Poisson's Ratio, ν
Clay B/C	43 (300)	20°	4 (384)	1.0	0.5
Clay C	29 (200)	16°	2 (192)	1.0	
Till	58 (400)	40°	6 (576)	0.8	0.5
Silt	58 (400)	35°	ignore	1.0	0.35
Sand/Gravel	58 (400)	40°	ignore	0.7	0.35

Subsurface Conditions and Characterization

Soft to Very Stiff Clay and Silt. These deposits generally consist of soft to very stiff, silty clay and clayey silt with variable amounts of sand and gravel with some medium dense to dense clayey sand. Since the unit only occurs in the upper five feet of the shaft its behavior is not discussed.

Till and Till-Like Deposits. These deposits consist of a dense to very dense or hard mixture of silt, sand and gravel and varying amounts of clay. These units range in consistency from extremely dense to very hard to a consistency of very soft rock or lean concrete. Till and Till-Like Deposits are expected to stand vertically in a tunnel heading or shaft walls with very little support for prolonged periods of time. The units are relatively impermeable, but perched water is often present in more pervious soils above or within them. Cobbles and boulders are common in these units and water-bearing silt and sand lenses may be present, but typically are not hydraulically connected to the regional groundwater regime. Groundwater will likely be perched and ponded above the irregular contact of the Till and Till-Like Deposits.

Very Dense Sand and Gravel. These deposits consist of non-glacial (interglacial) fluvial deposits of very dense sand, gravelly sand, and sandy gravel and lenses of gravelly cobbles. Locally, these soils may be silty to slightly clayey. Without dewatering or ground improvement, these granular soils will flow into the shaft or tunnel excavations or shaft bottoms will boil or blowout as the excavation proceeds below the groundwater level. Dewatered granular soils will still ravel and run unless fully supported. Pre-support may be required to stabilize these soils and to limit ground losses.

Very Dense Silt and Fine Sand. These deposits consist of non-glacial (interglacial) lacustrine deposits of very dense to hard silt, fine sandy silt, silty fine sand, and clayey silt. The cohesive portions of this unit appear to occur in random lenses. The soils that have some cohesion (slightly clayey to clayey) will behave similarly to, but somewhat poorer than the Very Stiff to Hard Clay described below. Without dewatering or ground improvement, the cohesionless portions of these soils will become unstable and will flow into the excavation, or the shaft bottoms will boil or blowout as the excavation proceeds below the groundwater level. The Very Dense Silt and Fine Sand is fine-grained and will be difficult to dewater or grout.

Very Stiff to Hard Clay. These deposits consist of glaciolacustrine deposits of very stiff to hard clayey silt and silty clay. The Very Stiff to Hard Clay has been a good tunneling and shaft excavation material above or below the groundwater table, in previous tunnel and shaft excavations throughout the Seattle area. The hard consistency and cohesive nature of the clays make them relatively easy to excavate with conventional soil excavation equipment. When unfractured, their intact strength properties promote good standup time in tunnel faces and in open cuts. Except for seams or lenses of sand and silt, the clay will not yield appreciable quantities of water and are stable for short periods in the presence of water. Slickensided fractures and shear zones are expected to be encountered in the Very Stiff to Hard Clay, especially in the high plasticity clays. As in rock, the presence of these discontinuities can significantly alter the properties and behavior of the soil mass from that of intact material alone. Sheared and fractured soils typically have lower strengths that may lead to raveling or slabbing condition and wedge block failures in unsupported shaft walls or tunnel excavations. In a mixed faced condition with granular soils the low permeability of the Very Stiff to Hard Clay will tend to perch water above the contact.

4. Advanced Numerical Analyses

Advanced numerical analyses were performed to develop ground conditioning, pre-support, excavation support and structural design. Analysis and design of the station tunnels, including geometry, excavation sequences, initial lining and final lining thickness and lining compositions was carried out concurrently by HMMJ and Dr. G. Sauer Corp., working from a unified design approach. Junctions were analyzed with 3-D non-linear numerical analysis (FLAC3D and ABACUS). The most significant structural issue—the breakout for the Main Shaft and construction of the two Concourse Cross Adits—was analyzed using ABACUS and the results checked using FLAC3D, with satisfactory agreement.

5. Three-Stage Approach to SEM Excavations

The Sequential Excavation Method (SEM), also known as New Austrian Tunneling method (NATM), is the safest and most conservative approach to large tunneling projects in more challenging ground. To mitigate the risks inherent in the substantial thicknesses and extents of sand and silt zones discovered in the later phases of the geologic exploration, the design team specified a three-stage approach to SEM excavations:

1. Prescriptive base design: excavation and support sequences and dimensions for single sidewall drifts for platform tunnels and dual sidewall drifts for concourse tunnels; shotcrete liner, and breakouts from shafts and tunnels.
2. Prescriptive ground conditioning and pre-support: jet grouting of sand zones; grouted barrel vaults in the crown on concourse tunnels and in platform tunnels at breakouts from concourse tunnels.
3. An SEM 'tool-box' of additional support measures, to be used as necessary and paid for on a unit price basis. These included:
   - Pre support measures (rebar, spiling, grouted pipe spiling, etc.)
   - Face stabilization measures (face stabilization wedge, pocket excavation, etc.)
   - Ground improvement measures (dewatering, grouting, etc.)
   - Annular support (additional shotcrete, soil nails, temporary invert)

6. Combining Tunneling Design Methods

The design team's specifications for the time-critical 60-ft.-diameter access shaft was for adaptation of Slurry Wall construction. The team also specified an innovative Dual Side Wall Drift technique for the 45-ft.-diameter concourse tunnels, and a Single Side Wall Drift method for the 35-ft.-diameter platform tunnels—both using the SEM.

Concourse tunnels were built as three separate tunnels, each approximately 1/3 of the width. Each drift was excavated in three steps, heading, bench, and invert, each about 1/3 height. Each excavation advance was three feet and exposed ground was supported by the immediate application of shotcrete (sprayed concrete), wire mesh, steel ribs, and more shotcrete for a total shotcrete thickness of 15 inches. The crowns of the

tunnels were pre-supported by a canopy of two rows of steel pipes installed in horizontal drilled holes and grouted in place. This incremental approach provided a high degree of ground support, enabling safe construction of the largest and deepest sequential excavation tunnels ever attempted in soft soil conditions in North America. The technique also represented a quantum leap in tunneling technology as it had never been tried before in North America.

Platform tunnels were similarly built with a single side-wall drift in which two separate half-width tunnels were constructed. The larger of the ventilation tunnels was constructed similarly to platform tunnels, and the smaller was excavated with a single heading. Despite the poor soils the tunnels were completed with virtually no ground settlement and were clearly the right combination of equipment and engineering procedures.

Running tunnels were excavated by an earth pressure balance tunnel boring machine (EPB-TBM). A single pass, pre-cast concrete liner, fitted with gaskets to ensure water tightness, was installed as the TBM advanced. The liner segments were fully gasketed and bolted, with six segments plus a key forming a completed ring. A high performance concrete mix was utilized to provide the high durability and protection against corrosion of reinforcement necessary to achieve the tunnel's design life.

7. Stabilizing 160-ft.-Deep Shafts

Digging and stabilizing the walls of two 160-foot-deep shafts—a 50-ft.-wide main shaft and a 30-ft.-wide ancillary shaft: to meet this challenge, the team adopted a slurry wall design. Working in small sections or panels, special equipment including a hydrofraise was used to dig approximately 3-foot-wide holes to full depth around the shaft perimeters that would be filled with concrete to form vertical walls. To keep these narrow and very deep panels from collapsing inward during the excavation phase, they were filled with thick bentonite slurry — thus the name slurry wall. Once a panel was excavated, reinforcing steel was installed and then concrete was pumped in, displacing the slurry. The finished product was a 3-foot-thick concrete wall built before any of the ground inside was removed.

Additionally, jet grouting techniques were used from the surface to improve the stability of underground soil that would be mined later. This involved using a tall-mast jet grout drill boom to pump cement grout into the ground at high pressure. This work was undertaken to reduce mining risks targeted to key underground areas where geotechnical tests showed particularly crumbly soils.

Once the main vertical shaft was excavated, Obayashi, the Contractor, began horizontal sequential excavation mining with specialized articulating-boom excavators and tunnel-mining drill rigs. The SEM work used a predetermined, highly-disciplined sequence for excavating horizontal passages in sections and temporarily supporting the ground using steel girders and shotcrete. The continual cycle of excavating and reinforcing required 24-hour work shifts.

8. Innovative procurement strategy

As explained in the narratives above, the team incorporated an innovative procurement strategy. This strategy included a risk-adverse design approach that enabled bidders to use a complete design with "tool box" items to be employed when and where needed; a test shaft that allowed bidders to see and feel the in-situ ground prior to submittal of their bids; a rigorous geotechnical investigation that provided bidders with comprehensive data; and a comprehensive risk identification and mitigation program explained below.

9. Comprehensive Risk Management Program

A comprehensive Risk Management/Risk Mitigation Plan was implemented into the design and contract bid documents to proactively reduce risks associated with construction. A detailed Risk Register was created to identify risks, rank risks, and facilitate the effective risk analyses. Systematic identification, avoidance, reduction and mitigation processes used throughout the design phase included:

- Performing exhaustive geotechnical investigations with Geotechnical Baseline Report that defined conditions and behavior separately for station shafts and individual station tunnels
- Construction of 18-ft.-diameter, 150-ft.-deep exploratory shaft at the location of the Station main shaft
- Modifying and optimizing the tunnel alignment to avoid contaminated ground water and to take advantage of more favorable soil conditions
- Providing a conservative and prescriptive design
- Specifying ground improvement measures and SEM "toolbox" items
- Conducting peer reviews
- Prequalifying the contractor
- Organizing owner and design consultant review panels
- Selection of 'binocular' station configuration to reduce the potential impacts of tunnel excavation on adjacent tunnels
- Continuing exploration during construction
- Providing engineering services during construction

D. Best Practices & Professional Excellence

Realizing that assessing, controlling and mitigating risk is the crucial element to the successful delivery of any project, the design team developed and implemented a stringent the risk management process that included a Risk Register; risk analyses, identification, ranking; and a **Risk Management/Risk Mitigation Plan**.

Recognizing that all parties to the construction contract would need to work together closely to deal with the variable ground conditions during tunnel construction, Sound Transit, the HMMJ design team, and Obayashi Corporation (the Contractor) embraced the **partnering** process from the beginning. Lines of communication remained open throughout the project allowing adjustments to the specified construction methodology to be discussed and accommodated in a timely fashion. Partnering was key to the successful completion of this challenging construction project.

The designer and contractor provided experienced staff at all levels of project bringing in **world-class SEM expertise**. The team provided excellent transfer of know-how to the labor force, which proved to be effective and critical to the successful delivery of this very high risk project.

E. Transparency and Integrity

As discussed in Section F above, all parties subscribed to the tenets of project partnering, which included a commitment to open communication, ethical conduct, the highest levels of integrity, and establishing and maintaining clear lines of communication. We are confident that this commitment helped ensure successful delivery of this highly complex project.

F. Sustainability and Respect for the Environment

Even though underground construction is generally considered to be a sustainable approach to the development of urban infrastructure insofar as the majority of the work does not impact the surrounding environment, on the Beacon Hill Station and Tunnels project additional efforts were made to minimize surface disruptions and other impacts at the station and tunnel portal surface works locations.

The mitigation of both short-term and long-term impacts to the neighborhood and to the environment was paramount during the project's development. With the environment itself presenting significant design challenges in terms of soil composition, the decision to have engineers design all aspects of the project served to mitigate risk of damage to the environment. Shaft and tunnel construction caused no negative impacts to the environment. There were few ground movement problems, thus few impacts to overlying or adjacent buildings or utilities, and there was no impact on biophysical environments.
Design optimization reduced the amounts of construction materials. For example, the use of the three dimensional finite element analysis resulted in the decision to use a reduced thickness for the initial and final liners in the tunnels. During construction, the public was minimally disrupted; economic activity in the neighborhood was maintained throughout the construction; and no businesses experienced interruptions to their operations.

G. Contribution to Community and Quality of Life

1. **CONNECTING COMMUNITIES**: Prior to construction of the Beacon Hill Station, the neighborhood surrounding the station was a relatively unconnected urban pocket. The station has provided residents with light rail transit connectivity and efficient access to all other communities on the light rail link system, including downtown Seattle and the Sea-Tac International Airport.

2. **REDUCTION IN GREENHOUSE GASES:** With access to the Sound Transit light rail transit system via the Beacon Hill station, the use of personal vehicles has been reduced, thereby reducing greenhouse gases.

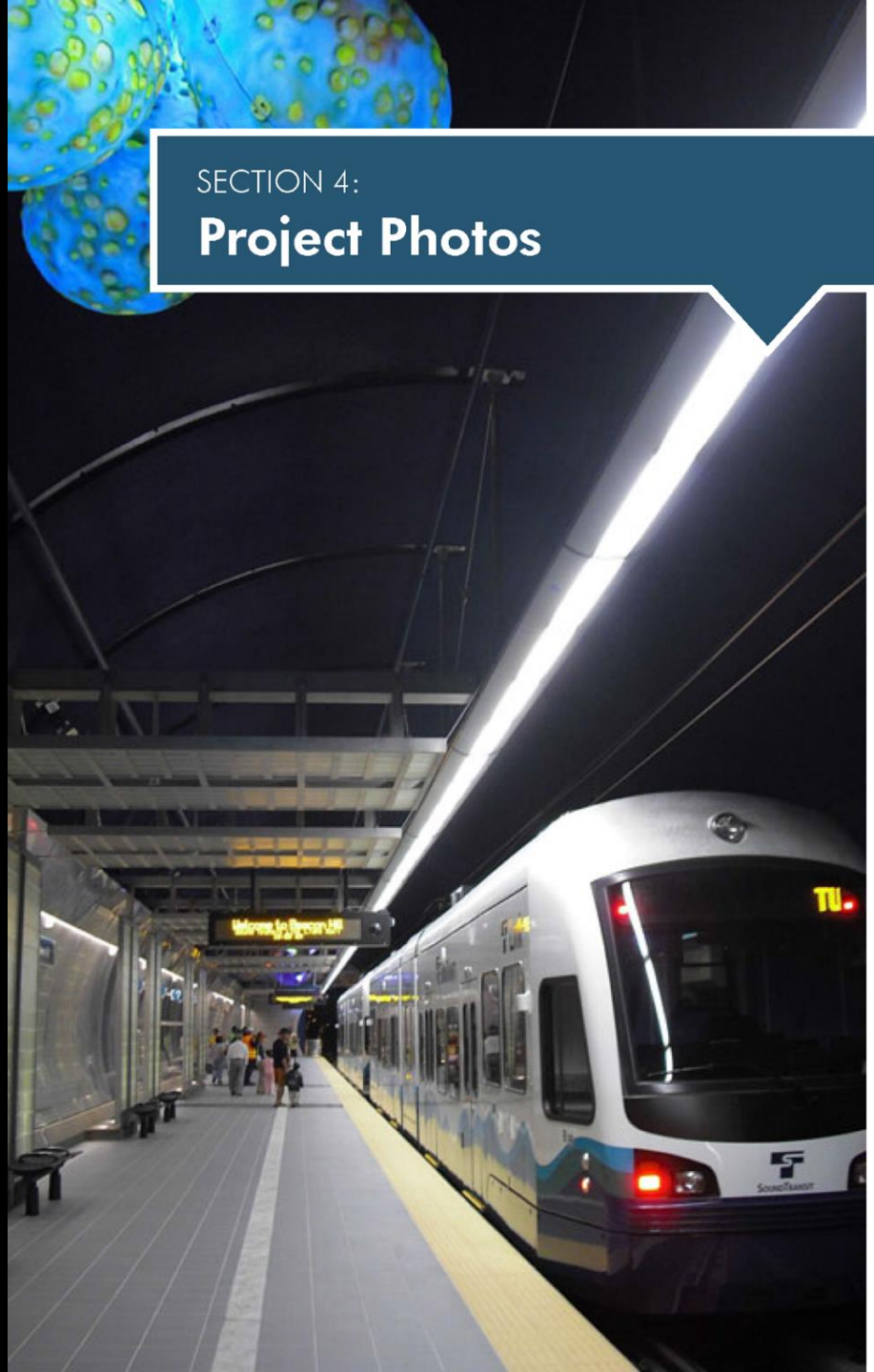
3. **ECONOMIC DEVELOPMENT**: This connectivity has resulted in positive economic redevelopment of the area surrounding the station. The attractive above-ground and below-ground structures provide enhancements to an area where deteriorating commercial structures and abandoned lots previously stood. Downtown Seattle businesses and entertainment have benefited from the Beacon Hill Station and transit link that connects the local community to the rest of the LRT system broadening the neighborhood's access to other communities and providing access to SeaTac Airport.

4. **NOISE MITIGATION DURING CONSTRUCTION:** One of the primary concerns of people living and working in the community was noise, particularly nighttime noise with the 24-hour construction schedule. The project team implemented noise control processes at the Beacon Hill Station site and the two tunnel portals. These processes included construction of a noise barrier wall; limitations on truck hauling during weekends and holidays; periodic reviews by the City of Seattle; and monthly meetings with the community regarding noise issues related to the project. The tunnels were completed with practically zero disruption to businesses and transportation above.

5. **COMMUNITY CHARRETTE**: As part of a planned citywide update of neighborhood plans, the City of Seattle organized a design charrette to explore future development around its light rail transit system and station areas. Hatch Mott MacDonald provided technical input and attended the charrette to answer any technical questions related to the tunnel that arose. Otak prepared materials for the charrette, which included 3-D models showing existing building massing allowed by zoning code, as well as potential future building massing of transit-oriented development at increasing levels.

SECTION 4:

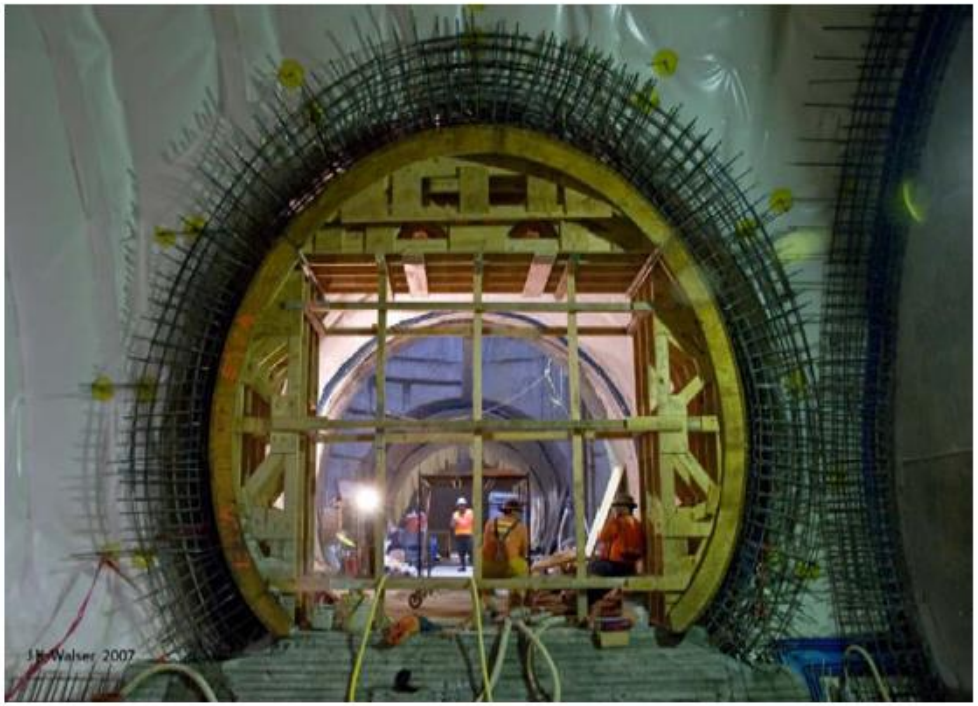
Project Photos



Section 4: Five Feature Project Photos

Feature Photo #1 – First in North America: *The Central Link Section 710: Beacon Hill Station and Tunnel Project is the deepest soft ground excavation using the Sequential Excavation Method (SEM) in glacial soil in North America.*

Feature Photo #2 – Station Concourse: *Photo taken from the northbound platform tunnel prior to platform pour looking toward the main concourse cross passage that contains the main shaft for elevators, stairs, air passage and utilities. The formwork is being constructed for the concrete liner covering the waterproofing membrane and initial shotcrete assembly. This cross passage will later have a second floor poured for auxiliary spaces and existing circulation.*



Feature Photo #3 - East Cross Passage: *Photo was taken from the end of the southbound platform tunnel (headwall and start of SB tunnel bore is at right side of photo) looking at the east ventilation cross adit. The east (auxiliary vent shaft) is above the area beyond the workers. Walls have waterproof membrane installed and are waiting for final concrete lining.*

Feature Photo #4 – Northbound Tunnel: *Photo was taken from the end of the west end of the northbound platform looking down the tunnel bore. The platform had not yet been poured. Jig for rail anchors/plinths is set for concrete pour. West vent adit can be seen on left of photo.*

Feature Photo #5 – Station Entrance: *Entrance to station with elevators accessed directly from the street. Vent shaft is the dark brick mass at far side of the building. Lighter brick mass houses four high speed elevators and the elevator machine room. Public art at the surface includes the steel banner poles. The engraved granite paved with textures from cultures throughout the world representing Beacon Hill residents past and present, and the Aztec patterned louver screen on the north wall of the building.*

SECTION 5:

Appendices

APPENDIX 1:

Project Desciption

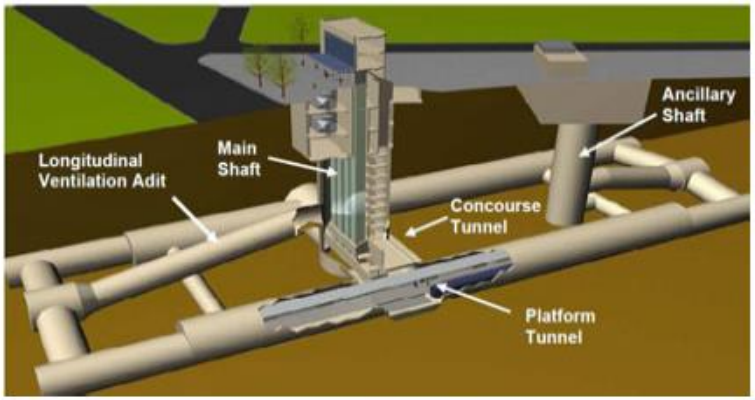
Appendix #1 - Project Description

The one-mile Beacon Hill Tunnels and Station is located just south of downtown Seattle and is a key section of Sound Transit's LINK light rail system. Twin bored running tunnels just under one mile in length were constructed from the west portal at the I-5 viaduct to the east portal at 25th Avenue South.

The design includes 4,300 feet of segmentally-lined bored twin tunnels and a deep mined station. With platforms located 156 feet below grade, the station is only the second large-scale mined station in the US. Its complex geometry combined with variable soil conditions (sands, silts and clays with slickensides) challenged the designer to come up with a SEM-based design to addresses the owner's risk, cost and schedule concerns.

The **main shaft** of the tunnel station holds the station's four high-speed elevators, and the secondary shaft which provides **ventilation** and emergency staircases) were excavated to 165 feet deep. Obayashi conducted mining activities including digging two one-mile tunnels, all station cross-passages and ventilation adits, and the **underground station concourse** using the sequential excavation technique.

Construction of a time critical 60-ft.-diameter access shaft was achieved by using an adaptation of Slurry Wall construction, while the below ground tunnels were successfully completed using an innovative Dual Side Wall Drift technique for 45 foot diameter concourse tunnels and a Single Side Wall Drift method for the 35 foot diameter platform tunnels. The result was the largest and deepest soft ground Sequential Excavation Method tunnels ever designed and constructed in North America.



Original Conceptual Rendering of the Beacon Hill Station and Tunnels, showing the complex arrangement of deep shafts running to a mined station 200 feet down from the surface, concourse tunnels, platform tunnels and dual running tunnels.

The underground station was constructed at approximately the mid-point of the running tunnels, and consists of twin shafts and a complex configuration of vehicle, pedestrian and ventilation tunnels ranging in size from 16 to 46 feet in diameter. Riders will access the Beacon Hill station via high-speed elevators that transport

them 160 feet down to the underground platforms. The station was being built on a one-square-block site located at the intersection of Beacon Avenue South and McClellan Street South.

The running tunnels were excavated using an earth pressure balance tunnel boring machine (EPB-TBM), in an application that has further advanced the use of this technology in soft soils. The TBM and trailing gear stretched longer than a football field and weighed approximately 642 tons with all its trailing gear. It had a 21-foot-diameter cutter head that revolved up to 2.5 times per minute. The cutter head was equipped with disks and other cutting tools, as well as openings for excavated soil and rocks to pass into the front of the TBM. The excavated earth was mixed with biodegradable conditioning agents sprayed through nozzles in the cutter head. Depending upon soil types, the conditioning agents include water, bentonite or polymers. The resulting paste was transported by a corkscrew-like conveyor located behind the cutter head, which deposited it on a conveyor belt that carried the spoils to a staging area outside the portal.

As the tunnel was constructed, it housed a temporary rail system used for moving in sections of the precast concrete segments that formed the permanent lining of the tunnel. Each section, or ring, was made up of seven segments that formed five linear feet of completed tunnel. A hydraulic arm inside the TBM positioned each piece and then the completed ring is secured into place with steel bolts and cement grout. This permanent tunnel lining enabled the TBM to move forward by providing a fixed surface to push against. The front section of the TBM is equipped with 16 hydraulic jacks spaced around its perimeter. Pushing against the liner, these jacks are used to propel and steer the machine. They are guided by sophisticated technology that controls the machine's position to an accuracy of within an inch.

For additional project detail see the papers titled "Overview of the Design of the Beacon Hill Station and Tunnels" and "Construction of the Beacon Hill Tunnel" that follow.

APPENDIX 2:

Technical Paper - Overview of the Design

OVERVIEW OF THE DESIGN OF THE BEACON HILL STATION AND TUNNELS

Don Phelps
Hatch Mott MacDonald

Christopher Tattersall
Hatch Mott MacDonald

David McAllister
Parsons Brinckerhof Quade & Douglas

ABSTRACT

Located south of downtown Seattle, the Beacon Hill Station & Tunnels is the key section of the southern segment of Sound Transit's proposed new LINK light rail system. This paper presents an overview of the design, which includes 4,300 ft of segmentally-lined bore twin tunnels and a deep mined station. With platforms located 156 feet below grade, the station itself is only the second large-scale mined station in soil the US. Its complex geometry combined with variable soil conditions—sands, silts and clays with slickensides—challenged the designer's to come up with a SEM-based design that addresses the owner's risk, cost and schedule concerns.

INTRODUCTION

The Central Puget Sound Regional Transit Authority, Sound Transit, is proceeding with construction of a new light rail transit line extending 15 miles southwards to SeaTac Airport, from Convention Place at the north end of the existing Downtown Seattle Transit Tunnel in the center of the City of Seattle. The existing one-and-a-half-mile long transit tunnel will be refurbished to accommodate light rail trains with the existing bus traffic. The balance of this initial line is now either in final design or construction. The one-mile Beacon Hill Tunnel and Station located just south of the downtown area will be the only tunneled portion in this initial segment as shown on Figure 1. The Sound Transit Board is scheduled to select a preferred alignment and initiate preliminary engineering later this year on the 7 or 8 mile extension northwards from Convention Place to Northgate. This northern extension is expected to include approximately 5 miles of twin bored tunnels.

In 2000, a joint venture team of Hatch Mott MacDonald and Jacobs Civil Inc., (HMMS) were awarded a contract for the final design of the Beacon Hill Tunnels D710 segment of the Central Link Light Rail Project. Dr. G. Sauer Corporation was awarded a sub-contract by HMMS for the design of the large platform and concourse excavations. A total of nine sub-contracts were awarded to local engineering consultants for alignment, civil, utilities, instrumentation and other support services.

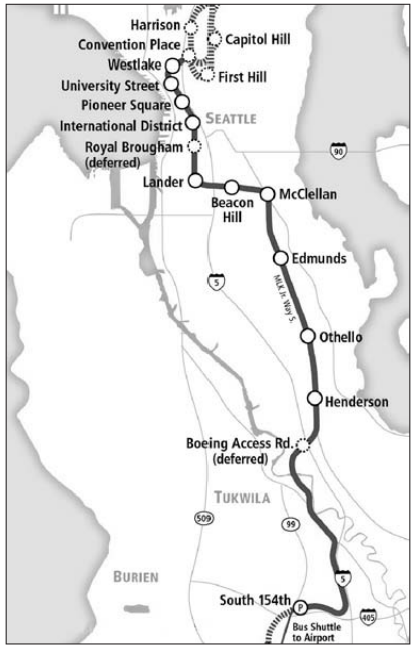


Figure 1. Initial segment of LINK light rail system

The D710 segment starts near Airport Way South and extends eastward about one mile under Beacon Hill, exiting near Rainier Avenue South, as shown on Figure 2. The West Portal area will consist of about 60 m (200 ft) of mechanically stabilized embankment (MSE); twin 8 m by 6 m (25 ft × 20 ft), 55 m (180 ft) long cut-and-cover box structures under the Interstate 5 (I-5) viaduct; and a permanent soldier pile bulkhead wall immediately east of I-5. Twin 6.4 m (21 ft) diameter tunnels will extend eastward about 550 m (1,800 ft) to the Beacon Hill Station, then an additional 760 m (2,500 ft) to the East Portal. A twin cut-and-cover box structure converging to a single box structure totaling 80 m (260 ft) will comprise the East Portal. While the West Portal will be engineer-designed, the East Portal will be contractor-designed to performance criteria.

The underground station, shown on Figure 3, will consist of twin shafts and a complex configuration of vehicle, pedestrian and ventilation tunnels. The invert of the platform tunnels will be 47.5 m (156 ft) below ground surface. Platform and connector tunnels will be 168 m (550 ft) long each and spaced 43 m (140 ft) apart, center to center. Access from surface to platform level will be provided by four high speed elevators from a station head-house. Shaft and tunnel design is described in subsequent sections.

Figure 2. D710 contract—horizontal alignment

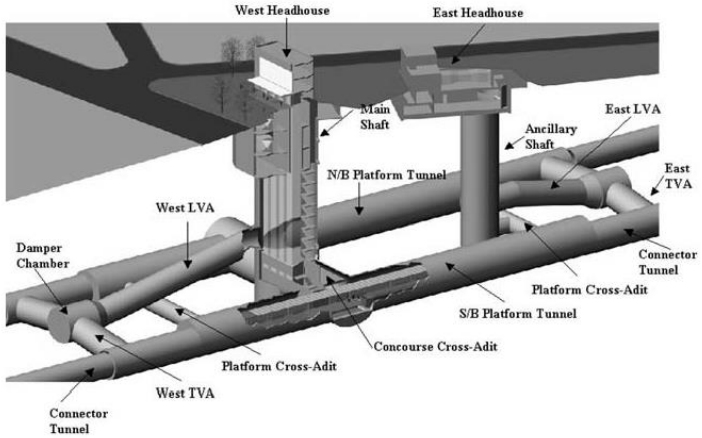


Figure 3. Station general arrangements

GEOLOGIC SETTING

Shannon & Wilson Inc. of Seattle, the geotechnical consultants for the D710 Beacon Hill Tunnels defined the geologic setting in their Geotechnical Report, Beacon Hill Tunnel Project, Exploratory Test Shaft and Tunnels, December 2002 as follows:

Seattle is located in the central portion of the Puget Lowland, an elongated topographic and structural depression bordered by the Cascaded Mountains on the east and Olympic Mountains on the west. This lowland is characterized by a series of north-south trending ridges separated by deeply cut ravines and broad valleys. These ridges and valleys are the result of glacial scouring and subglacial erosion. In general, the ground surface elevation is within 500 feet of sea level.

Geologists now believe that the Puget Sound area has been subjected to six or more major glaciations during the Pleistocene Epoch (2 million years ago to about

10,000 years ago), which filled the Puget Lowland to significant depths with a complex sequence of glacial and non-glacial sediments. These glaciers originated in the coastal mountains of British Columbia. The maximum southward advance of the ice was about halfway between Olympia and Centralia (about 50 miles south of Seattle). During the most recent ice coverage of the central Puget Lowland (Vashon Stage of Fraser Glaciation), the thickness of ice is estimated to have been about 3,000 feet in the alignment area. The last ice covering the alignment area receded about 13,500 years ago.

The distribution of the sediments in the Puget Lowland is complex, because each glacial advance partially eroded older deposits and deposited new sediments. During the intervening interglacial episodes, the complete or partial erosion or the reworking of some deposits, as well as the local deposition of other sediments, further complicates the geologic setting.

Since the last glaciation, extensive land sliding has occurred along the steep flanks of the hills, eroded valleys, and upland plateaus of Puget Sound. The accumulation of debris from the numerous small and medium size landslides has resulted in a mantle of landslide deposits covering intact soils along most steep slopes not exposed to marine erosion. Scattered very large rotational landslides and complexes of translational landslides are also evident along the steep slopes in Puget Sound. Some of these very large landslides may have been caused by oversteepening of the hillsides by glacial scouring and subsequently the removal of ice support from the flanks of the ridges during retreat of the Vashon ice sheet. More recent evidence suggests that strong ground motion from past earthquakes may have triggered some of these very large landslides.

Bedrock outcrops are present in only a few locations in the Seattle area and occur south of an east-west line extending from the City of Bremerton to the west, to the south end of Lake Sammamish toward the east. In the last 15 years, this line has been identified as the Seattle Fault, now considered to have ruptured within the Holocene Epoch (the past 10,000 years). Bedrock is exposed approximately 2,000 feet south of the project alignment near Boeing Field along I-5 and in the Rainier Valley. North of the Seattle Fault, the bedrock is deeply buried by Pleistocene and Holocene sediments. Based on deep drill holes and seismic profiling, the depth to bedrock in the vicinity of downtown Seattle is believed to be in the range of 2,700 to 3,600 feet. Bedrock depths at the project site are likely to be similarly deep.

SUBSURFACE CONDITIONS AND CHARACTERIZATION

Based on extensive drilling and testing, Shannon & Wilson concluded that the running tunnels, and station shafts and tunnels will be constructed through a complex sequence of glacially overridden deposits consisting of very dense and hard clay, silt sand, gravel and cobbles. Multiple ground water levels were detected in granular deposits, typically due to perched groundwater overlying clay and till units.

A large number of geologic units were identified over the depth and length of the project. In order to simplify the large number of unit descriptions and reduce complexity of the geologic profile, Shannon & Wilson grouped geologic units into five major ground types summarized as follows. Descriptions of these ground types and anticipated ground behavior is summarized as above.

- **Soft to Very Stiff Clay and Silt**. These deposits generally consist of soft to very stiff, silty clay and clayey silt with variable amounts of sand and gravel with some medium dense to dense clayey sand. Since the unit only occurs in the upper five feet of the shaft its behavior is not discussed.

- **Till and Till-Like Deposits.** These deposits consist of a dense to very dense or hard mixture of silt, sand and gravel and varying amounts of clay. These units range in consistency from extremely dense to very hard to a consistency of very soft rock or lean concrete. Till and Till-Like Deposits are expected to stand vertically in a tunnel heading or shaft walls with very little support for prolonged periods of time. The units are relatively impermeable, but perched water is often present in more pervious soils above or within them. Cobbles and boulders are common in these units and water-bearing silt and sand lenses may be present, but typically are not hydraulically connected to the regional groundwater regime. Groundwater will likely be perched and ponded above the irregular contact of the Till and Till-Like Deposits.
- **Very Dense Sand and Gravel.** These deposits consist of non-glacial (interglacial) fluvial deposits of very dense sand, gravelly sand, and sandy gravel and lenses of gravelly cobbles. Locally, these soils may be silty to slightly clayey. Without dewatering or ground improvement, these granular soils will flow into the shaft or tunnel excavations or shaft bottoms will boil or blowout as the excavation proceeds below the groundwater level. Dewatered granular soils will still ravel and run unless fully supported. Pre-support may be required to stabilize these soils and to limit ground losses
- **Very Dense Silt and Fine Sand.** These deposits consist of non-glacial (interglacial) lacustrine deposits of very dense to hard silt, fine sandy silt, silty fine sand, and clayey silt. The cohesive portions of this unit appear to occur in random lenses. The soils that have some cohesion (slightly clayey to clayey) will behave similarly to, but somewhat poorer than the Very Stiff to Hard Clay described below. Without dewatering or ground improvement, the cohesionless portions of these soils will become unstable and will flow into the excavation, or the shaft bottoms will boil or blowout as the excavation proceeds below the groundwater level. The Very Dense Silt an Fine Sand is fine-grained and will be difficult to dewater or grout.
- **Very Stiff to Hard Clay.** These deposits consist of glaciolacustrine deposits of very stiff to hard clayey silt and silty clay. The Very Stiff to Hard Clay has been a good tunneling and shaft excavation material above or below the groundwater table, in previous tunnel and shaft excavations throughout the Seattle area. The hard consistency and cohesive nature of the clays make them relatively easy to excavated with conventional soil excavation equipment. When unfractured, their intact strength properties promote good standup time in tunnel faces and in open cuts. Except for seams or lenses of sand and silt, the clay will not yield appreciable quantities of water and are stable for short periods in the presence of water.

Slickensided fractures and shear zones are expected to be encountered in the Very Stiff to Hard Clay, especially in the high plasticity clays. As in rock, the presence of these discontinuities can significantly alter the properties and behavior of the soil mass from that of intact material alone. Sheared and fractured soils typically have lower strengths that may lead to raveling or slabbing condition and wedge block failures in unsupported shaft walls or tunnel excavations.

In a mixed faced condition with granular soils the low permeability of the Very Stiff to Hard Clay will tend to perch water above the contact.

All of these ground types are likely to contain variable amounts of cobbles and boulders. Actual ground behavior will be a function of many factors such as excavation and initial support methods, ground improvements, and ground water conditions.

Table 1 summarizes our interpretation of the range of engineering properties for the five ground types. The interpreted ranges presented in this table are based on the

Table 1. Geotechnical design parameters

Material Description	Modulus, E, ksi (MPa)	Phi, ϕ	Undrained Shear Strength, S_u Tons/ft^2 (kPa)	K_0	Poisson's Ratio, ν
Clay B/C	43 (300)	20°	4 (384)	1.0	0.5
Clay C	29 (200)	16°	2 (192)	1.0	
Till	58 (400)	40°	6 (576)	0.8	0.5
Silt	58 (400)	35°	ignore	1.0	0.35
Sand/Gravel	58 (400)	40°	ignore	0.7	0.35

results of field and laboratory tests, both in the immediate vicinity of the site and along the Beacon Hill Tunnel project alignment, correlation between index and engineering properties previous experience with these soils in the Puget Sound area discussions between HMMS and S&W and engineering judgment.

RUNNING TUNNELS

The Running Tunnels are sized to a system standard of 5740 mm inside diameter (18´-10´) to accommodate the LINK light rail vehicle, overhead catenary system (OCS), walkway, rail and trackbed. Figure 4 shows the Running Tunnel cross section.

The Running Tunnels are being designed with single-pass, tapered precast concrete segmental linings. The segments are fully gasketed and bolted, with six segments plus a key forming a completed ring. The ring width is nominally 1500 mm (5´-0), with a 19 mm (0.75 in) taper to accommodate curves. This is a proven design that has been used very successfully on several recent soft ground tunnels including St. Clair River, Toronto's Sheppard Line and Minneapolis-St. Paul's Hiawatha Line. A high performance concrete mix is being considered to provide the high durability and protection against corrosion of reinforcement necessary to achieve the tunnel's design life.

An in-depth review of the geology along the alignment indicates that an Earth Pressure Balance (EPB) TBM is appropriate for the tunnel drives. In particular, boreholes have identified significant zones of outwash sands and other non-cohesive materials that would be potentially problematic with an open-faced TBM. The authors believe that current soil conditioning technology available for EPB TBMs enables these machines to achieve the same production as open-face TBMs.

Both tunnel drives are to be started from the West Portal site due to existing environmental agreements. This will require delivery and assemble of the TBM on the west side of the I-5 viaduct and skidding under the overpass prior to the start of tunneling. Initial alignment is on a vertical curve, which will require special care on the part of the contractor during the "learning curve" part of the drive.

Because of the perceived difficulty and high level of risk associated with constructing the platform tunnels by breaking out and over-cutting the segmental lining, the decision was made early in the design to construction the platform and connector tunnels first, then skid the TBM through and re-launch at the east end of the station. Tunnel drive lengths, including station tunnel skidding lengths are approximately 1480 m (4860 ft) for the Southbound and 1500 m (4923 ft) for the Northbound tunnels.

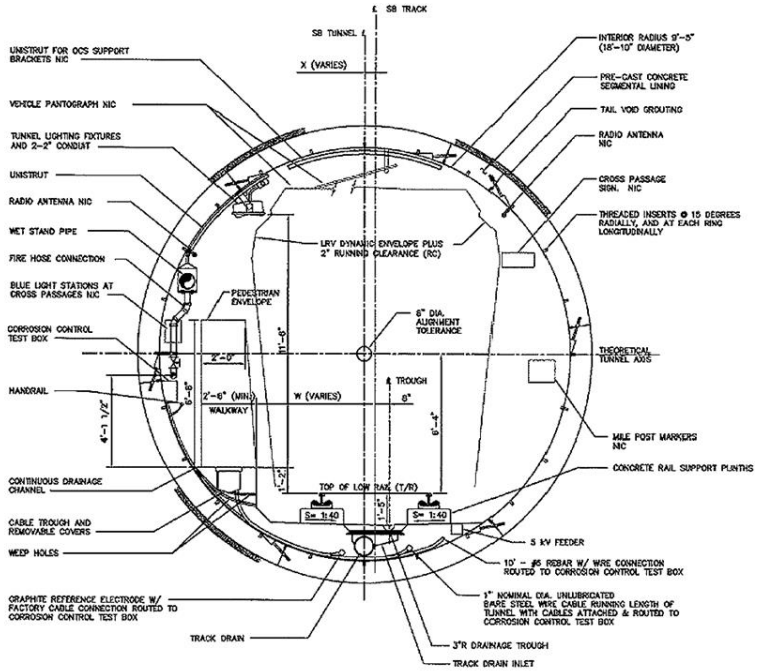


Figure 4. Running tunnel section

STATION SHAFTS AND TUNNELS

To accommodate the owner's requirement for normal and emergency egress, a station arrangement with two shafts, a transverse two-level concourse tunnel and two platform tunnels was developed as the base configuration. Emergency ventilation from each of the shafts to the Running Tunnels is accomplished by two sets of transverse and longitudinal ventilation adits, the junction of which is sized to accommodate motorized dampers. During the preliminary design, the tunnel sizes and arrangement were optimized with an eye on both simplifying the construction and staying within the favorable geology as much as possible. The resulting station arrangement is shown in Figure 3.

Design of the station underground works is based upon the Sequential Excavation Method (SEM), also know as the New Austrian Tunneling Method (NATM), whereby ground relaxation occurs ahead of the advancing face and the shotcrete primary lining is installed in an engineered sequence to minimize ground deformation. Pre-support measures such as rebar spiles, face bolts and grouted forepoling, as well as advance length and shotcrete thickness can potentially be tailored to the measured behavior of the ground.

The shotcrete initial support is to be lined with a membrane waterproofing system to provide a completely "tanked" station. Cast-in-place concrete final linings, bar or

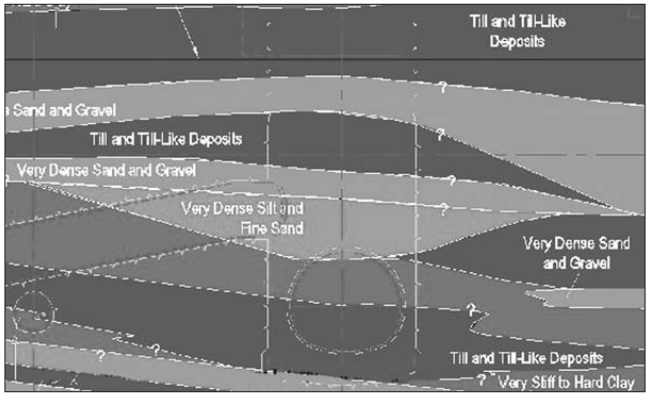


Figure 5. Main shaft arrangement interpreted geology

steel fiber reinforced and placed with conventional formwork will comprise the permanent structural station shell.

The main shaft is sized at 14 m (46 ft) inside diameter with a depth of 50 m (165 ft) and accommodates elevators, stairwell and 23 m^2 (250 ft^2) of ventilation duct space. Several shaft construction methods are under consideration, with preference being give to the SEM for several reasons. The most significant being that it appears this method results in the least disturbance to the ground in the vicinity of the shaft breakouts, which are in potentially problematic ground: non-cohesive silt and saturated sand. Figure 5 shows the main shaft configuration superimposed on the interpreted stratigraphy.

The 8 m (26 ft) inside diameter ancillary shaft, sized to accommodate a stair well plus 23 m^2 (250 ft^2) of ventilation duct, is of a similar depth to the main shaft and passes through similar geology.

Access to the platforms is provided by a large transverse concourse, accommodating both normal and emergency egress as well as electrical and systems equipment rooms. Although the size was kept as small as possible, the concourse cross adit requires a 14.0 m wide by 12.8 m high (46 ft × 42 ft) excavation. Construction of this from a 15 m (50 ft) diameter shaft in potentially problematic soil (see Figure 5) represents one of the key challenges faced by the design team. Current thinking is to pre-support the ground by installing grouted "canopy tubes" in the form of a barrel vault during shaft construction. Breakout from the shaft lining would proceed from dual sidewall drift top headings prior to completion of the shaft excavation. Completion of the concourse excavation sequence would follow the shaft excavation and structural closure of its base.

Platform tunnels are configured as shown in Figure 6A, with the shape governed by the platform height and width requirements. The tunnel excavations are 11.3 m wide by 9.8 m high (37 ft × 32 ft), requiring a single sidewall drift-type excavation sequence, as shown in Figure 6B. Indications from the geotechnical modeling undertaken are that the platform tunnels are in ground that is generally very good. Presupport in the form of rebar spiles should be adequate for the round lengths being considered.

The design of the ventilation system is beyond the scope of this paper, however the depth of the alignment and the location of the shafts at the highest point of that alignment

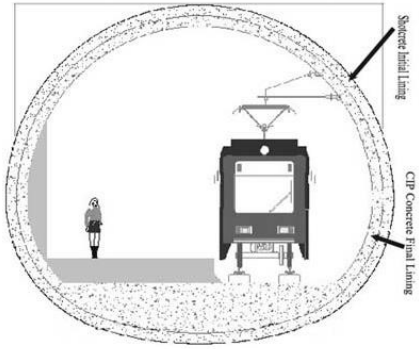


Figure 6a. Platform tunnel cross section

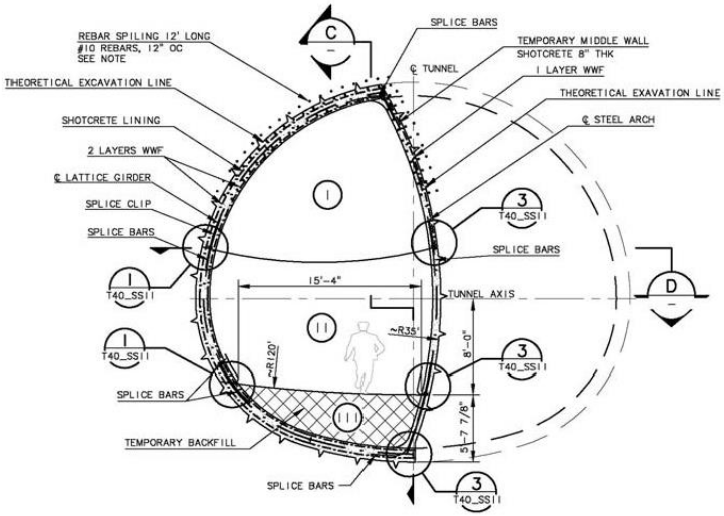


Figure 6b. Platform tunnel excavation and initial support

means that large air flows are required under emergency conditions. The nominal size of all ventilation tunnels from SES analysis is 23 m^2 (250 ft^2), with the damper chamber cross section increasing to 28 m^2 (300 ft^2) to accommodate the restriction of motorized dampers.

The shape of the individual tunnels is determined primarily by optimizing the shape of the junctions. In the case of the longitudinal ventilation adits, a near-circular shape has been used, whereas for the transverse ventilation adits a flatter shape has

Table 2. Ventilation tunnels

Tunnel	Excavated Width	Anticipated Pre-support Measures	Anticipated Excavation Sequence
Longitudinal Ventilation Adit	22.8 ft	Grouted forepole arch in sand, rebar spiles in clay	Full width: Top heading/Bench/Invert
Transverse Vent Adit	26.0 ft	Rebar spiles	Single sidewall drift: Top heading/Invert
Damper Chamber	32.8 ft	Rebar spiles	Single sidewall drift: Top heading/Invert
Connector Tunnel	27.0 ft	Rebar spiles	Single sidewall drift: Top heading/Bench/Invert

been selected. The connector tunnels are constructed to enable the junction between running tunnels and ventilation tunnels to be constructed in the SEM rather than breaking into the segmental linings, which, given that the diameters are very similar, would be very difficult to accomplish. The damper chamber is sized both to accommodate a 28 m^2 (300 ft^2) motorized damper and to enable breakout for construction of the subsequent ventilation tunnel. Table 2 summarizes the size and anticipated construction sequence of the ventilation tunnels.

SCHEDULE

Completion of construction is planned for March 2008. The following are major milestones:

- Completion of design: October 2003
- Bid Period: November 2003 to February 2004
- Construction: April 2004 to March 2008

APPENDIX 3:

Technical Paper - Construction of Beacon Hill Station

SEM Tunneling Underway in Seattle – Construction of the Beacon Hill Station

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Jürgen Laubbichler, PE
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ABSTRACT: Construction of the Beacon Hill Station in Seattle, WA, is presently underway. This project involves some of the deepest and largest scale SEM tunneling work ever undertaken in soft ground. This paper provides an update of the construction activities at the Beacon Hill Station site and summarizes some lessons learned so far.

The final design of the Beacon Hill Station and Tunnels was completed in December 2003. The project was awarded to Obayashi Corporation at a contract price of $280M. Notice to Proceed was given in June 2004.

To date, the contractor has completed preparatory work at the portals as well as the diaphragm walls for the station shafts and headhouses. SEM tunneling is underway and scheduled to be completed in late 2006. The design of the large diameter station tunnels is based upon a complex sequence of multiple drifts with an array of pre-support and ground improvement measures. To assist Obayashi in successfully employing these measures to deal with the highly variable ground, and ensure that construction is carried out in accordance with the design intent, the designers provided a technical support team consisting of experienced senior SEM engineers, engineering geologists, shift engineers and inspectors.

1 INRODUCTION

1.1 *Project Overview*

The Central Puget Sound Regional Transit Authority (Sound Transit) is proceeding with construction of the Central Link Light Rail Project, a new light rail transit line extending 14 miles southwards from Seattle towards SeaTac Airport. The one-mile Beacon Hill Tunnels and Station, located just south of the downtown area will be the only tunneled portion in this initial segment.

The underground station, shown in Figure 1, will consist of twin shafts and a complex configuration of vehicle, pedestrian and ventilation tunnels ranging in size from 16 to 46 feet in diameter. The invert of the platform tunnels will be 156 ft below ground surface. Tunnels will be excavated by the Sequential Excavation Method (SEM) with shotcrete liner and excavation in multiple drift sequences with ground conditioning and pre-support where needed. The final liner will be cast-in-place steel fiber-reinforced concrete, with conventional bar reinforcement at junctions.

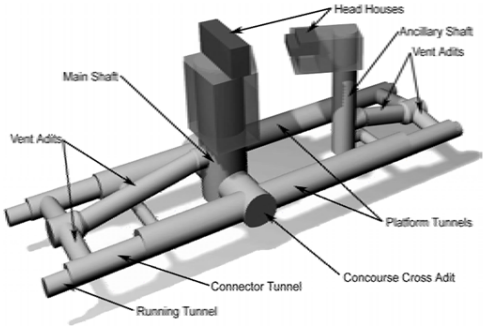

Figure 1 – 3D Diagram of Station

A joint venture team of Hatch Mott MacDonald and Jacobs Civil, Inc. (HMMJ) completed the final design of the Beacon Hill (D710) segment of the project between 2002 and 2004. Dr. G. Sauer Corporation (DSC) was awarded a sub-contract by HMMJ for the design of the station platform and concourse tunnels, monitoring and waterproofing. In addition to design support during construction, both HMMJ and DSC are providing SEM resident engineering services throughout this portion of the construction.

Puget Sound Transit Consultants, a joint venture of Parsons Brinckerhoff Quade & Douglas Inc., Earth Tech Inc. and URS Corporation, performed the preliminary engineering and provided program management services as an integrated team with Sound Transit.

The construction contract was awarded to Obayashi Corporation at a contract price of $280M; Notice to Proceed was given in June 2004. To help meet the contractual experience requirements for key SEM staff, Obayashi Corporation awarded a subcontract to Beton- und Monierbau (BEMO) of Austria to provide key field staff and knowledge transfer.

Previous papers – Phelps et al (2003); Gildner & Urschitz (2004); Laubbichler et al (2004); Tattersall et al (2004) – have provided an overview of the design of the Beacon Hill Station and Tunnels and the test shaft program. This paper focuses on the construction of the station tunnels and shafts, in particular the progress to date and what has been learned.

1.2 *Geology*

Based on extensive drilling and testing, it was determined that the running tunnels, and station shafts and tunnels, would be constructed through a complex sequence of glacially overridden deposits consisting of very dense and hard clay, silt and sand, gravel and cobbles. Multiple ground water levels were detected in granular deposits, typically due to perched groundwater overlying clay and till units. In order to simplify the descriptions of the large number of geologic units identified, and to reduce complexity of the geologic profile, geologic units were grouped into five major ground types. Detail is provided by Robinson et al (2005).

Soft to Very Stiff Clay and Silt. Soft to very stiff, silty clay and clayey silt.

Till and Till-Like Deposits. Dense to very dense or hard mixture of silt, sand and gravel and varying amounts of clay. Water-bearing silt and sand lenses are expected to be present.

Very Dense Sand and Gravel. Non-glacial (interglacial) fluvial deposits of very dense sand, gravelly sand, and sandy gravel and lenses of gravelly cobbles.

Very Dense Silt and Fine Sand. Non-glacial (interglacial) lacustrine deposits of very dense to hard silt, fine sandy silt, silty fine sand, and clayey silt.

Very Stiff to Hard Clay. Glaciolacustrine deposits of very stiff to hard clayey silt and silty clay. Slickensided fractures and shear zones are expected to be encountered in the Very Stiff to Hard Clay, especially in the high plasticity clays.

The complex layering of these units, particularly thick zones of sands and silts, were particularly challenging for the design of shafts and tunnels for the station.

1.3 *Risk Management and Design Approach*

The main focus of the risk management process was identifying and mitigating project risks related to geology and hydrology, construction methods, qualifications of the contractor and third-party impacts. The results of the risk management were implemented by:

- Performing extensive geotechnical investigations,
- Optimizing the tunnel alignment,
- Providing a conservative and prescriptive design,
- Specifying ground improvement measures and SEM "toolbox" items,
- Carrying out peer reviews,
- Pre-qualifying the contractor, and
- Providing engineering services during construction.

Detail of the risk management approach is provided by Phelps et al (2005).

2 BEACON HILL STATION CONSTRUCTION

2.1 *Mobilization and Site Installation*

The contractor started setting up the station construction operation at the Beacon Hill Station site, located between Beacon Ave and South 17th Ave, in the summer of 2004. The site installations were shifted several times to accommodate slurry wall installation, jet grouting, shaft excavation and SEM tunneling. Figure 2, below, shows the site in summer of 2005, when SEM tunneling began.

To support the shaft excavation and SEM tunneling, the contractor delivered a 200 ton Kobelco crawler crane to the site. A volumetric batch plant adjacent to the shaft collar is used for producing wet-mix shotcrete. Dry-mix shotcrete equipment is provided for the flashcrete and as a back-up to the wet mix plant. For the tunnel excavation, the contractor uses Liebherr 900 series tunnel excavators; Caterpillar excavators and track loaders are used for mucking.

Figure 2 – Beacon Hill Construction Site

2.2 *Exploratory Drilling*

The installation of the surface instrumentation, including inclinometers, extensometers and piezometers, also serves to provide additional information about the geological conditions.

The contractor carried out more than 30 borings using mud rotary and sonic core drilling methods. The information gained from this program was used to adjust the extent of the jet grouting and the dewatering.

During SEM tunneling, systematic probing ahead of the face is part of the regular excavation and support process. In addition, the contractor is extracting a continuous core along the centerline of each tunnel. The information gathered by probing and coring is reviewed by the SEM engineers on site and used to make field decisions regarding additional support measures and ground improvement.

2.3 *Headhouse Slurry Walls and Tiebacks*

Support of excavation for the east and west headhouses, one above each shaft, was left to the contractor to design to suit his means and methods. Probably because the shafts were to be slurry wall construction, the contractor elected to use the slurry wall approach to support headhouse excavations. These were designed by a local engineering firm and incorporated pretensioned tiebacks at up to six horizons up to 70 ft deep. The slurry wall panels were constructed at the same time as the shaft wall panels by specialty subcontractor Condon Johnson - Soletanche using a clam shell-type excavator. Tiebacks were installed and tensioned as the excavation progressed.

2.4 *Main Shaft Slurry Wall Shaft*

As part of the risk reduction strategy in response to results from the test shaft program, the shaft construction by the slurry wall method was specified for both Main and Ancillary Shafts. At a maximum depth of 181 ft, the required tolerances could only be achieved using hydrofraise equipment, as shown in Figure 3.

The slurry wall work was carried out by Condon Johnson – Soletanche. The configuration adopted for both shafts consisted of large curved primary panels comprised of three separate cages installed and placed as a single lift. These were joined together with single closure panels. Panels were reinforced with #8 and #10 bars spanning vertically. No additional provisions were made to accommodate breakouts in the slurry walls for the station tunnels.

Figure 3 – Hydrofraise for Main Shaft Slurry Wall

2.5 *Jet Grouting*

The base design required the contractor to jet grout the extrados of the shaft slurry walls at the tunnel "eye" locations in order to facilitate the initiation of the SEM tunneling and help prevent the vertical migration of ground water between aquifers due to the effects of local dewatering during mining. In addition, the easterly 50 ft of the West LVA was to be jet grouted because a zone of saturated sand and silt was predicted in that location.

When the results of the constructions phase borehole program were added to the general geological model, it emerged that at tunnel depth the stratigraphy was more complex than originally thought. The contract jet grouting was expanded to include parts of the Northbound and Southbound Platform Tunnels. At the west LVA, the zone of saturated granular material was found to be highly localized and to not warrant jet grouting.

Figure 4 – Jet grout rig (foreground) and pre-drill rig (background)

Jet grouting work was carried out by Condon Johnson – Soletanche. Initial tests of the jet grouting indicated that a nominal column diameter in the granular strata of 6 ft was achievable, and a pattern based on equilateral triangles with a diagonal spacing of 6.25 ft was used for the production grouting. The hole pattern was predrilled to the upper cut-off elevation using a mud rotary drill, and the jet grouting was performed by a Caterpillar 320 mounted CJ-3012 jet grout rig at depths down to 170 ft.

Specified quality assurance measures include wet grab sampling and drilling from the surface. To date, these results have been satisfactory and the exposed jet grout zones confirm that the targeted granular materials are grouted sufficiently.

Figure 5 – Exposed Jet Grout Columns at W-LVA Breakout

2.6 *Dewatering*

To establish stable ground conditions during SEM tunneling, water bearing sand and silt layers have to be de-pressurized prior to excavation. The design foresees the following measures:

- An array of vacuum assisted deep wells from the surface.
- Gravity and, if required, vacuum dewatering from within the tunnel.

Deep Wells

The deep wells are designed to reach a depth of approximately 140 ft below the ground surface. A vacuum system to enhance the groundwater flow in the granular materials is specified. The average well spacing is 20 ft around the Main Shaft and to either side of the Concourse and Platform Tunnels.

The contractor employed subcontractor Moretrench American to install the 10-inch deep level wells, which were advanced by air rotary drilling methods with a temporary casing. After installation, the wells were developed by pumping and surging and connected to the discharge and vacuum piping.

Figure 6 –Vacuum Pump Setup

Drilling and installation of the deep wells was carried out from fall 2004 to spring 2005. There was a delay in connecting all the wells to the system and bringing them on-line. During this time, the groundwater recharge rate canceled out the effects of the dewatering and the groundwater levels remained more or less constant. When the remaining part of the system came on-line mid-October 2005, the piezometers showed a significant drop in groundwater levels, and the horizontal drains, installed during barrel vault installation, that had previously produced water dried out.

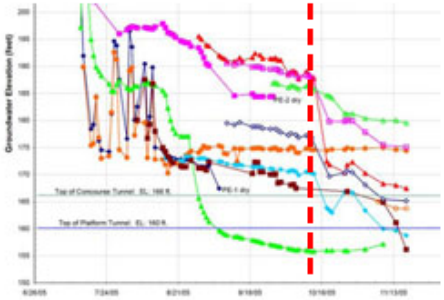

Figure 7 – Time vs. Groundwater Drawdown

In-Tunnel Dewatering

In order to dewater isolated, water-bearing sand layers not reached by the deep wells, the design includes gravity dewatering and vacuum dewatering from within the tunnel. The contractor is using perforated pipe spiles, pre-packed gravel packs and vacuum lances for this; the water is collected with PVC hoses and discharged by pump sumps. The granular soils encountered to date have been relatively free draining and responded well to gravity dewatering. Once dewatered, the standup time is sufficient to continue SEM tunneling.

2.7 *Barrel Vault*

For the North and South Concourse Cross Adit, the design provides for two rows of 4-inch diameter grouted barrel vault pipes. The grouted pipes are installed from the Main Shaft and serve as pre-support over the full length of the tunnel (approximately 75 ft). The geological conditions along the Concourse Cross Adit were recorded during the drilling operation.

To minimize ground loss during barrel vault installation, the barrel vault pipe is specified as a "lost casing system" with the pipe and drill bit remaining in the ground. Grouting is carried out through perforations in the barrel vault pipes spaced at 1 ft centers; to prevent inflow of water and granular material, these are equipped with valves.

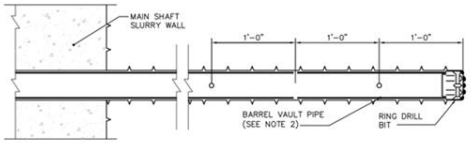

Figure 8 – Barrel Vault Pipe

Specialty subcontractor Northwest Cascade, Inc., installed the grouted barrel vaults beginning in July 2005 with core drilling through the slurry wall. Subsequently, the barrel vault pipes with individual lengths of 8 ft were installed using a Klem KR 806-3 hydraulic drill rig. To verify the directional accuracy of the installed pipes, the borehole survey system "Maxibore" was used. It was determined that 97 percent of the pipes were within the specified deviation of one percent.

Figure 9 – Barrel Vault Installation

Grouting was carried out in 3 stages:

- Stage 1 (bentonite seal): Weak bentonite grout was injected along the pipe and at the slurry wall to seal the annulus around the pipes.
- Stage 2 (microfine cement grout): A double packer setup with 5 feet of length between packers was inserted to the full depth of the pipe. Each 5 foot section was grouted to a target grout volume of 3 cubic feet per foot of barrel vault pipe or until the grouting pressure reached 200 psi and was maintained for 10 minutes.
- Stage 3 (neat cement grout): All Barrel Vault pipes were finally filled with neat cement grout.

2.8 *SEM Construction*

General

In accordance with the conservative design approach, prescriptive excavation and support sequences were developed and the following was specified in the contract documents: excavation sequence; length of each excavation round; distance to ring closure; size of the individual openings; demolition of temporary support sidewalls; and breakout sequences at junctions of shafts and tunnels.

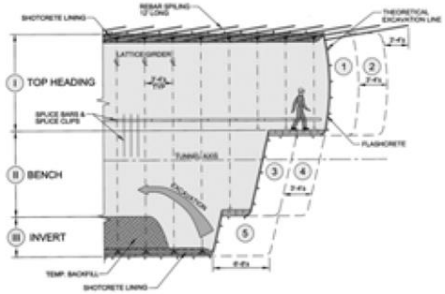

Figure 10 – Prescriptive Excavation Sequence

To address the variable ground conditions, the design includes SEM "Toolbox" items that are installed as required by ground conditions and paid for on a unit price basis. These include:

- Pre-support measures (rebar spiling, grouted pipe spiling, metal sheets, grouted barrel vault/pipe arch),
- Face stabilization measures (face stabilization wedge, pocket excavation, reduction of round length, face bolts),
- Ground improvement measures (gravity and vacuum dewatering, permeation grouting, fracture grouting, jet grouting), and
- Radial support measures (additional shotcrete, soil nails, temporary invert).

During construction, daily SEM meetings are held with Sound Transit's and the contractor's SEM engineer and the construction manager. In these meetings, the previous day's SEM activities, the geology encountered and the soil behavior are discussed and evaluated. Based on these, decisions about the required pre-support and ground improvement measures for the following excavation rounds are made and recorded in 'Required Excavation & Support Sheets' (RESS's).

West Longitudinal Ventilation Adit

Once the Main Shaft was excavated to approximately 130 ft below the surface, the contractor commenced SEM tunneling at the West Longitudinal Ventilation Adit (W-LVA). This tunnel is approximately 22 ft in diameter and excavated using a top heading / bench / invert excavation sequence.

Prior to breaking out, three 24 ft long exploration holes were drilled to determine the ground conditions ahead of the face. Line drilling through the slurry wall with approximately 50 holes 2-inch in diameter was carried out, and the slurry wall was subsequently demolished by hoe ram. A road header attachment was used to cut through the jet grout columns immediately outside the slurry wall.

Based on the results of the probe drilling, rebar spiling was installed and excavation and support commenced according to the prescribed sequence. In order to continue Main Shaft excavation, excavation was stopped after three rounds and a temporary headwall with 10" of shotcrete was constructed.

Figure 11 – Completed W-LVA Stub Tunnel

Concourse Cross Adit

The Concourse Cross Adit is approximately 45 ft wide by 41 ft high. Due to its size and the challenging geology, the tunnel is designed with a dual side wall drift excavation sequence. This sequence minimizes the area of the exposed faces and reduces the risk of instability at the face.

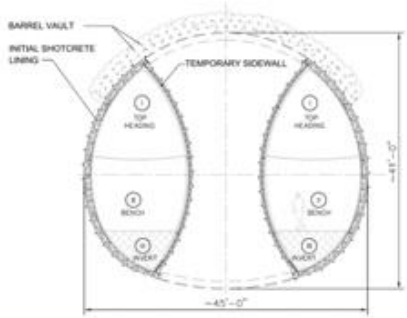

Figure 12 – Concourse Cross Adit Excavation Sequence

The contractor commenced excavation after the installation of the Barrel Vault and the required probe drilling was completed. The breakout from the Main Shaft was performed in several steps and the exposed surfaces were sealed with flashcrete.

Figure 13 – Breakout from Slurry Wall Shaft

After the first lattice girder was installed, the temporary sidewall was shotcreted and the top headings of the sidewall drifts were advanced concurrently. To establish ring closure within one tunnel diameter, a temporary shotcrete invert was installed close behind the excavation face.

Figure 14 – Concourse Cross Adit Top Heading Excavation

Geology and Soil Behavior

In the West Longitudinal Ventilation Adit, the geology encountered was mostly dark gray, stiff clay, which stood up well. Only minor water inflows (isolated dripping) were reported.

In the Concourse Cross Adit, the geology encountered was predominantly gray, slickensided clays with some silt and isolated layers of sand and gravel. To maintain face stability, face wedges and occasionally 30 ft long face bolts were used. It was observed that the slickensided clays deteriorated quickly when exposed to water. To prevent this, water from probe holes and sand lenses was collected with drainage sheets and piped off. The sand layers that were encountered stood up well once they were sufficiently dewatered.

In one instance, flowing sand was encountered when excavation hit a sand dyke that had not been dewatered or grouted previously. After installing grouted pipe spiles and dewatering the sand lens, the soil was carefully exposed and immediately shotcreted (pocket excavation).

Figure 15 – SEM Excavation in slickensided clay

Rate of Progress

Sound Transit's SEM site personnel maintain detailed records of all activities in the tunnels. From these records, the duration of excavation, installing wire mesh and applying shotcrete can be derived and the effects of the learning curve and the changing geology can be evaluated.

While SEM tunneling is not an overly complex means of construction, a great deal of hands-on experience is required to mine efficiently and safely through difficult ground. Therefore, the learning curve can be quite gradual.

The chart below clearly shows a decrease in cycle times, and therefore an increase in productivity, since the start of the SEM excavation. As the contractor's personnel become familiar with SEM procedures and the prevalent geology, it is expected that this productivity will continue to improve.

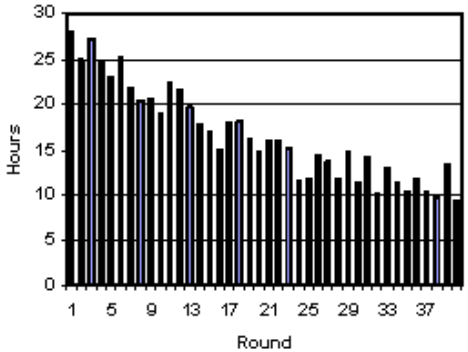

Figure 16 – Cycle Times, Concourse Cross Adit Top Headings

2.9 *Monitoring Program*

In the SEM tunnels, monitoring bolt arrays are used to monitor absolute and relative deformations; pressure cells and strain gauges records stresses and strains in the shotcrete lining. A surface monitoring program utilizes settlement points, inclinometers and extensometers to provide detailed information about ground movements during tunneling.

At the time of writing, recorded deformation, stresses and strains are well below threshold values.

3 CONCLUSION

The slurry wall shafts have proven to be very successful. The finished product is excellent and has provided a good structure for staging the station tunnel headings.

Indications are that the vertical jet grouting program has produced the desired results. QC testing and the first exposed columns are satisfactory. The jet grouting operation, however, did have a significant impact on the site, and unforeseen spoil disposal issues have contributed to making this operation relatively expensive.

After a slower than anticipated beginning, the dewatering system is beginning to show very promising results. As anticipated, it was important that the extensive pattern of wells be commissioned and operated for several months before these results could be seen.

SEM tunneling started off more slowly than anticipated. The combination of learning how the ground behaves and getting the mining crew up to speed with the complex sequence of operations in the SEM cycle has resulted in very slow rates of advance. These have been improving significantly, but the learning curve on a project of this complexity should not be underestimated.

Providing experienced staff at all levels for a project like this is important and the contractor should be commended for recognizing this and entering into strategic relationships in order to bring in world-class SEM expertise very early in the construction. The transfer of know-how to the labor force is proving to be very effective.

Recognizing that all parties to the construction contract would need to work together closely to deal with the variable ground conditions, both the owner and contractor embraced the partnering process from the beginning. Lines of communication have been open, allowing adjustments to the specified construction methodology to be discussed and accommodated in a timely fashion. The authors believe that this has been and will continue to be the key to the successful completion of this challenging construction project.

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APPENDIX 4:

Article - Tunnels & Tunnelling Magazine

MAY 2008

tunnels & tunneling NORTH AMERICA

Sound Transit's large-scale SEM station

Beacon Hill Station, in Seattle, comprises the largest SEM soft ground excavations in the US to date. **Jürgen Laubbichler**, of Dr G Sauer Corporation, describes their design and construction in highly variable soils with multiple groundwater horizons

Above: **SEM excavation of a Beacon Hill Station platform tunnel**

The $280 million C710 Beacon Hill Tunnels and Station contract forms part of the 14-mile (22km) long initial segment of Sound Transit's Central Link Light Rail Line, which extends between downtown Seattle and SeaTac Airport. The 4,300ft (1.3km) long twin running tunnels under Beacon Hill were recently completed using a 21ft (6.4m) diameter Mitsubishi EPBM, while the deep mined station has been built using slurry walls for the shafts and the Sequential Excavation Method (SEM) for the tunnels. With an excavated depth of 160ft (49m), the station is the deepest constructed in soft ground in North America.

Beacon Hill Station (Figure 1) consists of twin shafts and a complex configuration of vehicle, pedestrian and ventilation tunnels. From the Station Headhouse, a 181ft deep (55m), 46ft (14m) i.d. Main Shaft was constructed that will house four high-speed elevators, emergency staircases, ventilation shafts and M&E equipment. A 161ft (49m) deep, 26ft (8m) i.d. Ancillary Shaft will accommodate another set of emergency staircases and ventilation shafts.

From the Main Shaft, the 41ft (12m) wide Concourse Cross Adit (CCA) will provide passenger and emergency access to the Northbound and Southbound Platform Tunnels (NBPT and SBPT respectively). These are 380ft (116m) long by 32ft (9.8m) wide and were designed to accommodate the light rail tracks, platforms, artwork and architectural finishes. Two pedestrian Cross Adits connect the Platform Tunnels, and Ventilation Tunnels will provide airflow in normal operation and for emergencies, these range in size from 16ft (4.9m) to 26ft (8m) in diameter.

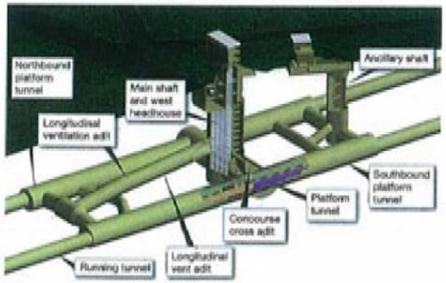
A JV of Hatch Mott MacDonald and Jacobs Civil (HMMJ) completed the final design of the Beacon Hill segment of the project between 2002 and 2004. Dr G Sauer Corporation (DSC) was awarded a subcontract by HMMJ for the design of the station platform and concourse tunnels, monitoring and waterproofing. In addition to design support during construction, both HMMJ and DSC have provided SEM resident engineering services throughout. Puget Sound Transit Consultants (PSTC), a JV of Parsons Brinckerhoff Quade & Douglas, Earth Tech and URS Corporation, performed the preliminary engineering and provided program management services as an integrated team with the client, Sound Transit. Parsons Brinckerhoff Construction Services is providing construction management as Resident Engineer for the contract.

Final design of the C710 contract was completed in February 2004 and bids were solicited following a pre-qualification process in which prospective contractors had the opportunity to examine a 16ft (4.9m) diameter Test Shaft[1], constructed within the footprint of the future Main Shaft.

Three teams of bidders pre-qualified: Obayashi, a JV led by Kiewit, and another JV led by Impregilo. However, Impregilo's team ultimately withdrew its bid. On May 15, 2005, the bids were opened, with Obayashi at $280 million and the Kiewit JV at $305 million. The Engineers estimate was $240 million. On June 28, Sound Transit issued Notice-To-Proceed to Obayashi.

Obayashi subsequently entered into an agreement with Beton und Monierbau to provide key SEM staff.

Below: **Fig 1. Ultimate configuration of Beacon Hill Station**



Geology

The Beacon Hill geology consists of glacial and interglacial soil units with a high degree of variation. This is evident locally to the extent that some units cannot be reliably correlated between adjacent borings. At the outset of the project, an extensive subsurface exploration program, with over 70 bore holes drilled, showed that most of the Beacon Hill Station would be excavated within glacial, over consolidated, partly fractured or slickensided clays and tills. Intermittent sand and silt layers were also found present, with multiple perched groundwater horizons. In order to simplify the descriptions of the large number of geological units identified, and to reduce the complexity of the geological profile, the soils were grouped into six classes:

1) Loose to dense granular deposits
2) Soft to very stiff clay and silt
3) Till and till like deposits
4) Very dense sand and gravel
5) Very dense silt and fine sand
6) Very stiff to hard clay

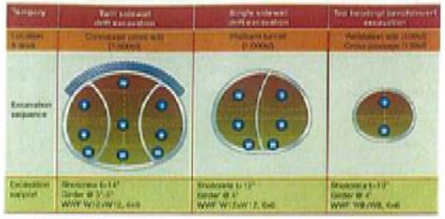
The complex layering of these units, particularly thick zones of sands and silts, was extremely challenging for the design of shafts and tunnels[2].

Ground treatment

For the reasons described above, the designers specified a post contract award subsurface exploration program to refine the geotechnical interpretations. Boreholes, drilled down to platform tunnel level using mud rotary and sonic core recovery methods, were combined with instrumentation including inclinometers, extensometers and piezometers.

The variable ground conditions, with the potential for saturated and unstable sand lenses, led to the consideration of large-scale ground improvement measures prior to sequential excavation. A series of deep dewatering wells and vertical jet grouting program was therefore specified[3].

Depending on the soil properties encountered during exploration and instrument drilling, the need for additional



Below: Fig 2. Baseline excavation and support scenarios

jet grouting or dewatering measures would be determined.

Between August 2004 and November 2005, 50 bore holes were drilled, with core extraction and sampling conducted under the engineering oversight of Shannon & Wilson[4].

It became evident during these investigations that sand layers, subject to water pressures of approx. 50ft (15m), within the Station tunnels were far more extensive than previously anticipated. This would have meant a 300% increase in the quantity of jet grouting specified in the contract[5]. Not only would the additional jet grouting cause significant delay to the construction progress and have major cost implications, there would also be a significant impact on the local community, as a large portion of the work would have to occur outside of the worksite, within street right-of-way and on private property.

Ultimately, Sound Transit and Obayashi developed the concept of a major "shift" in the configuration of the station components, including reversal of the Platform Tunnels lengths on either side of the Main Shaft and repositioning the East Damper Chamber. The final volume of jet grouting required as a result of this "Ultimate Shift" was only 10% greater than the original bid quantity.

The jet grouting was carried out by a JV of Condon-Johnson/Soletanche and provided a very competent soil stabilisation mass, with virtually no water influx encountered.

Primary lining & SEM pre-support

As discussed, the tunnel sizes required for the station set a new record for SEM tunneling in the US. The stability assessment for the excavation sequences and support measures was performed with 3-D Finite Element (FE) models using the programs ABAQUS and FLAC.

The lining forces derived from the numerical analysis were subsequently used to design the primary and final lining[6] using capacity limit curves based on ACI 318. Due to the mixed face conditions present over large portions of the tunnel alignment, no 'prescriptive' support was designed, but a baseline scenario (Figure 2) was chosen that included excavation sequence and standard support measures, such as shotcrete, welded wire fabric (WWF) and lattice girders.

The contractor later paid for a redesign and pre-construction performance flexural beam tests in order to substitute steel fibre reinforced wet-mix shotcrete for the double mats of wire mesh. This was primarily improve productivity and reduce worker risk at the tunnel face, as well as improve the overall quality of shotcrete application.

Additional SEM "Toolbox" items[7] were also included in the contract (supplemental unit price bid items) to be used in conjunction with conventional excavation support. These included: Pre-support measures such as rebar spiling, grouted pipe spiling, metal sheets and grouted barrel vaults (pipe arch); Face stabilisation measures including the use of a face stabilisation wedge, pocket excavation, reduction of round length, face bolts and additional shotcrete; Ground improvement measures such as gravity and vacuum dewatering, permeation grouting, fracture grouting and jet grouting; and annular support measures, including additional shotcrete, soil nails and use of a temporary invert.

The contract required a certain amount of shotcrete nozzle time for nozzlemen, which proved difficult to find in a tight labor market. In order to assist in boosting human resources available for SEM crews, a variance was made to allow for on-the-job training of nozzlemen, albeit under the direction of the certified nozzlemen and foremen already on site.

Shaft construction

Slurry wall construction of the Main and Ancillary Shafts, and the East and West headhouses, began in October 2004 and was completed in February by Obayashi's subcontracted JV partners Condon-Johnson/Soletanche. Main shaft excavation, including West Headhouse tiebacks and demolition of the remnants of the original Test Shaft, began in March 2005 and by the end of May 2005 the shaft had been sunk to a depth of 120ft (36.5m), ready for the West Longitudinal Vent Adit (WLVA) breakout.

WLVA breakout through the Main Shaft slurry wall began in June 2005 and SEM work, albeit for a 12ft (3.7m) stub tunnel, began in earnest. Originally sequenced for excavation in nine stages for the three lattice girder rounds, the work was adjusted in the field to five rounds, by combining bench and invert rounds. Only a few dozen rebar spiles were used in the top heading second round to bridge the gap between the remnants of the jet grout columns and the roof over the headwall.

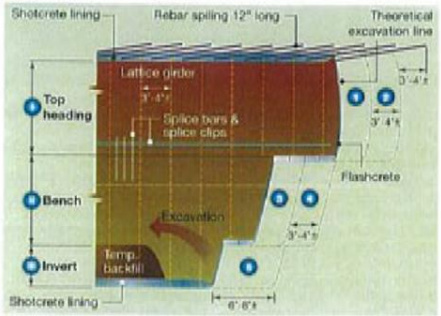
The on-site wet mix batch plant was still being assembled and fine-tuned while having trial batches run through and brought up to strength, so the initial lining for this breakout section was sprayed in with a 10" (250mm) thick dry-mix steel fiber flashcrete mix. A total of 33 shifts were needed to to complete the breakout, including securing the headwall for the better part of a year and the installation of deformation monitoring instrument pins.

Concourse construction

Excavation work in the Main Shaft continued after completion of the WLVA breakout in July 2005. The shaft was lowered down to just below the crown level of CCA for installation of the upper row of barrel vault pipes.

Northwest Cascade was subcontracted to drill 134 lost-casing pipes, evenly split with 67 each over the North and South Concourse brow of each heading. However, drilling over the North Concourse encountered more sandy soils and drew in groundwater along several of the first round of holes, which led to the lengthening of 12 holes along the inner row. Drilling over the South Concourse was relatively dry and clayey prompting deletion of the

Below: Fig 3. SEM excavation sequence for Platform Tunnels



Below: Waterproofing of the Platform Tunnels

outer row entirely. Barrel vault drilling, surveying and double-packer staged grouting with microfine cement was completed by mid-August 2005, setting the stage for further shaft sinking to the CCA springline.

A Cat 325 and a Cat 320 excavator, both with hoe rams, were used to break through the 4ft thick slurry walls for the NCCA and SCCA top headings. A series of line-drilled holes were drilled with a twin-boom drill jumbo to outline the breakout area and to help weaken the wall. Initially designed for localized breakout of each individual top heading, Obayashi broke through the wall in five stages, including a portion of the center drift top heading, leaving a concrete pedestal for interim face support.

Initial excavation of the first Concourse Cross Adit (CCA) top headings began in late August 2005 for both the North and South Concourses. The permanent lattice girders along the side drifts and the temporary TH-girder sections in the center drift were installed. A single lattice girder set from the center crown was also installed, connecting the East and West sides of each heading. This was used to help align the temporary interior sidewalls as the initial top heading excavation began. The South CCA East side drift was the first top heading excavated starting in September, followed by the South CCA West side drift. The North CCA East side, and then West side, followed.

After completion of all four top headings in December 2005 the Main Shaft was excavated down to the final invert elevation of 181ft (55m) below surface. A 30" (750mm) thick concrete invert slab was poured, then backfilled up to a working level.

The South CCA sidewall drift benches and inverts were then excavated before again filling the shaft temporarily to complete the centre drift top heading and upper bench of the South CCA.

The South CCA center bench and invert were excavated in February 2006, including demolition of the temporary sidewalls.

Platform tunnels

The Southbound Platform Tunnel (SBPT) was on the contract's critical path, with its completion necessary before the 21ft (6.4m) diameter Mitsubishi EPBM driving the running tunnels could break-in at the west end of the platform. The TBM would then be "walked" through the station and re-launched on the remainder of the Southbound running tunnel bore, before being removed and reassembled for the Northbound bore[8]. Work to complete the North Concourse and subsequent North Platform Tunnel (NBPT) excavation followed start-up on the SBPT concurrently.

A single sidewall drift method was specified for the Platform Tunnels, comprising a total of six segments per round (Figure 2). The first drift was excavated as a pilot tunnel, with the second drift following behind the first with a minimum specified offset. This offset rule allowed time to complete ring closure and gave the shotcrete time to develop strength in the first drift.

Obayashi investigated several ways to try and improve cycle times, in the interests of the schedule, and several minor changes were implemented. The single most effective of these was to increase the round length when possible, taking into account the results of probings, face maps and feedback from instrumentation in the shell.

In the design given to Obayashi, the lattice girder served only as a template and was not taken into account in the structural analysis. Therefore, the span length could be increased if the ground permitted. In the end, Obayashi adjusted the lengths in places, from 4' to 4' 6" or 5'.

Above: Centre bench excavation of a Concourse Cross Adit (CCA)

Given the space constraints and practical limits of equipment resources, the way excavation crews were organized was also analyzed and adjusted.

Since at times there were two headings working both side drifts, there were four available faces. In these cases, Obayashi established excavation crews, girder crews and shotcrete crews that rotated between headings, rather than establishing these capabilities in each individual heading team. This proved to be a more efficient use of resources and improved the overall progress globally.

SEM decision making

Experience levels were specified in the contract for key personnel responsible for the SEM activities. Under the oversight of the Obayashi Tunnel Manager, these key personnel include the SEM Manager, SEM Project Engineer and SEM Superintendents.

The SEM Superintendents worked shifts to facilitate immediate decision-making at the face during the six day, 24 hour week, schedule and were supported at the headings by Walkers and Shift Engineers. Generally two crews were working three 8 hour shifts. Sound Transit recognized the inherent risks involved and agreement was reached during the design stage to have the Designer represented on site during the implementation of the SEM design. To this end HMMJ and DSC provided experienced SEM engineers and inspectors to support the Construction Management team (Parsons Brinckerhoff) and oversee the SEM activities. Shannon & Wilson were also represented on site, providing oversight on geotechnical activities.

Daily SEM Meetings held at the site office followed joint inspections at the headings each morning. Sound Transit, Obayashi and HMMJ/DSC were represented at all of these meetings, to discuss the status of the works and the planned activities for the next 24 hours. Any necessary changes to the Construction Work Plans were agreed, and face maps were presented and discussed as well as the results of probing. A review of the latest instrumentation readings was also included to confirm stability of the headings.

On a weekly basis, shotcrete strength results were presented and discussed. RESS sheets (Required Excavation and Support Sheets) confirmed the required support and pre-support for each tunnel section and were used to assist communications.

Dewatering, monitoring & settlement

Geotechnical instruments specified for ground monitoring outside the excavated tunnels

Below: The Misubishi EPBM waits to be pulled through the South Platform Tunnel

included extensometers, inclinometers, open standpipe and vibrating wire piezometers, as well as optical survey points. Shannon & Wilson technicians read each instrument periodically, with the exception of the survey points that are checked by CH2M crews. Vertical and lateral displacements were tracked from the tunnel invert up through the crown to street level prior to excavation, then just above tunnel crown up to ground surface after SEM mining was completed, for any given tunnel section.

Data from the instrument readings are reviewed at the Daily SEM meetings and to date have shown a maximum of 1.6" (40mm) of vertical settlement over the station tunnels roughly 150ft (46m) below ground.

Street level surface settlement has only reached a maximum of 0.6" (150mm), most of which appears to be attributed to some water line replacement work in Beacon Avenue. In general surface settlement contours have followed the tunnel excavation sequence albeit with very small measurements, and not surprisingly there has been little to no measurable surface settlement over the jet grouted zones. All of this data compares quite favorably to the expected 4" (100mm) anticipated upon completion of tunneling.

Similarly, dewatering wells have proved quite effective with groundwater levels in the predominant sand layers above the tunnel crowns having dropped 20-40ft (6-12m). Groundwater levels are measured at 17 individual locations on site, typically with open standpipe bottom casings and vibrating wire piezometers at intermediate elevations in the upper sand layers. The vacuum-assisted dewatering well system has dropped from an initial 50gpm, through a steady state of 30gpm, down to 10-15gpm.

Waterproofing

The Beacon Hill Station is designed as a tanked structure and equipped with a membrane waterproofing system, which is placed between the initial shotcrete lining and the final lining. It consists of a non-woven geotextile to protect the waterproofing layer and flexible PVC membrane sheets welded together to form a continuous, impervious layer.

A remedial system consisting of a sectioning system and control and grout pipes is also installed. Obayashi contracted with specialty subcontractor Wisko America for the installation of the waterproofing.

Current status

As of May 2008, tunneling at Beacon Hill is complete: The TBM completed the second running tunnel drive by breaking through at the East Portal in early March. Subsequently, the excavation of the two remaining cross passages at the end of April marked the completion of the SEM works.

Currently, waterproofing installation and steel fiber reinforced cast-in-situ final lining construction[7] are ongoing in the North Bound Platform Tunnel, while finishing works are already progressing in the South Bound Platform Tunnel, the Concourse Cross Adits and the ventilation tunnels and egress trunnels. The waterproofing and concrete works in the Main Shaft, the Ancillary Shaft and the East and West Headhouse are also well underway.

Conclusion

The successful completion of the SEM tunnels was a major milestone for Sound Transit, but also for the contractor, designer, the construction manager, the geotechnical engineer and the inspection team.

The multitude of technical challenges that needed to be addressed throughout design and construction of this project could be resolved by a group of respectful and dedicated professionals working closely together. Open communication, good discipline and having qualified individuals in a partnering environment on site proved to be invaluable components for success. ■

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APPENDIX 5:

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