Tunneling Beneath Downtown Bellevue on Time and Under Budget

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ABSTRACT

Downtown Bellevue Tunnel (DBT) is part of Sound Transit's $3.7 billion, 14-mile light rail transit system from downtown Seattle, across Lake Washington, to the cities of Mercer Island, Bellevue, and Redmond. The tunnel was the first Sound Transit East Link project and posed significant construction risk. This paper discusses implementation of design changes to the soft ground tunneling method, implementation of several technologies such as the use macro-synthetic fiber initial shotcrete lining, use of spray-applied waterproofing, and use of shotcrete for the final tunnel lining. These efforts allowed for significant time and cost savings to the project.

OVERVIEW

The Downtown Bellevue Tunnel (DBT) is part of Sound Transit's East Link Extension Program, a 14-mile extension of the Sound Transit (ST) light rail transit system from downtown Seattle, across a floating bridge over Lake Washington, to the cities of Mercer Island, Bellevue, and Redmond. The DBT project consists of a 250-foot-long cut-and-cover portal structure at the southern end, a 1,983-foot-long SEM tunnel, and a mid-tunnel access shaft with a short adit connecting it to the tunnel. At the north end of the tunnel is a 200-foot-long cut-and-cover structure and the Downtown Bellevue Station, which is being constructed under a separate contract package.

The geology along the DBT consists of a thin layer of fill overlying a glacially overconsolidated stratigraphic sequence that includes Vashon till and Vashon advance outwash deposits. The design groundwater table generally follows the top of the advance outwash. See Figure 1 for a plan and profile view of the tunnel profile.

The DBT was the first contract released by Sound Transit for the East Link Program and was on the program's critical path. DBT alignment went through downtown Bellevue, passing within 3 feet of the Skyline building's underground parking garage, and ended directly in front of Microsoft's City Center building. The vicinity of the tunnel to the buildings and people working downtown posed a significant risk to the success of the project and the public's perception of the overall Sound Transit East Link Program. Sound Transit retained HDR for the Construction Management Consultant (CMC) with McMillen Jacobs Associates (MJ) was brought on as the subcontractor for HDR to lead the construction of the tunnel. Mott McDonald was the lead tunnel designer on the designer's joint venture team consisting of Hatch-Mott McDonald, Jacobs Engineering, and HNTB (H-J-H).

The DBT is an ovoid-shaped tunnel with a typical excavated cross section of 37.7 feet wide by 30.5 feet high. The tunnel cross section is enlarged to 42.3 feet wide by 37.7 feet high near the tunnel's midpoint to provide space for two emergency ventilation fans above the tracks. The original design for the DBT to excavate the tunnel

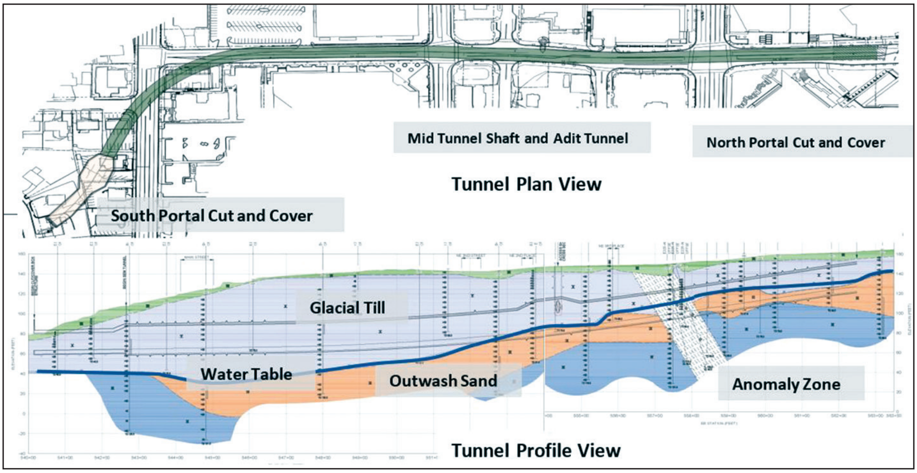

Figure 1. Plan and Profile View of Downtown Bellevue Tunnel

using the Sequential Excavation Method (SEM), based on the single side wall drift with a top heading, bench, and invert followed by the excavation on the other half with a minimum lag distance of 24 feet.

H-J-H provided a robust initial support design consisting of 12-inch-thick, steel-fiber-reinforced shotcrete lining. The initial support also included rebar spiles and grouted piles installed primarily along the crown of the excavated tunnel to provide pre-excavation support. A horizontal core hole would be installed to investigate the ground. Traditional probe holes were also installed during excavation to investigate the ground conditions. The horizontal core hole was later deleted and additional probe holes added during construction.

A minimum 1.5-inch-thick shotcrete smoothing layer was to be placed prior to installation of the waterproofing. The original design anticipated the use of sheet membrane waterproofing but allowed the use of spray-applied waterproofing as an alternative. Following installation of waterproofing, a 1-foot-thick cast-in-place concrete final lining was installed.

The DBT was a traditional design-bid-build contract. The procurement was handled by Sound Transit with assistance from the CMC and designers during the bid phase. Seven bids were received on October 27, 2015, with the winning bid provided by Guy F. Atkinson (Atkinson) at $121,446,551. The second lowest bidder was $142,751,000, with the engineer's estimate being $156,929,508. Notice to Proceed was issued on February 5, 2016.

After the DBT was complete, the tunnel was turned over to the follow-on E335 and E750 contracts to complete the fit-up of the tunnel. The E335 Contract is constructing the East Main Station just south of the south portal, and the Bellevue Downtown Station to the north of DBT. The E335 Contract also includes construction of ballasted and direct fixation tracks; and installs all the ventilation, lighting, fire and life safety elements, and all necessary wiring for those systems in the tunnel. The E750 Systems Contract will install the signaling, traction power stations, overhead catenary (OCS), supervisory control and data acquisition (SCADA), and communications systems for the East Link Project. The systems contractor will also be responsible for the integration, testing, and commissioning of all systems elements (hardware and software) of the East Link Segment.

DESIGN/CONSTRUCTION ALTERNATIVES

The project team held several roundtable exercises with the stakeholders, which included Sound Transit, Atkinson, CM, and the engineer of record (EOR), to develop opportunities to ensure the project would be completed on time and on budget. The project team evaluated various design and construction alternatives.

One of the alternatives was to employ an alternative SEM excavation sequence to increase the opportunity for overall time savings on the project. In April 2016 the CMC helped Sound Transit and Atkinson develop an agreement, the *E330 Downtown Bellevue Tunnel SEM Term Sheet*, in which the terms to develop the alternative excavation method were laid out. The term sheet also established the cost of the redesign efforts and a time savings bank, which was divided between Atkinson and Sound Transit.

The alternative excavation method involved redesign and modeling of the proposed excavation sequence, complete with benchmarks to measure performance of the tunnel excavation. The redesign efforts took several iterations and several months to complete. All the party members were intimately involved in the redesign component, including providing actual 24 hour strength performance of the shotcrete for various proposed mix designs, calculating the excavation reach of the tunneling equipment, and determining installation time for the various excavation support elements.

A result of the process was a three-heading SEM (Figure 2), which was incorporated into the contract for the first 50% of the tunnel length. This consisted of a full-width top heading, full-width bench, and full-width invert. For this first half of the tunnel, the excavation material was anticipated to be a full face of Vashon till. Excavation reverted to the design single side drift (i.e., six headings) when it reached the enlarged tunnel section at the fan area. This change also required additional instrumentation and monitoring requirements and criteria for reverting to the design sequence should excessive movement be encountered.

This approach was fortuitous since Atkinson started excavation during the wettest winter on record in the Pacific Northwest in late 2016 and early 2017. This resulted in

Figure 2. Three-Heading SEM Tunnel Excavation

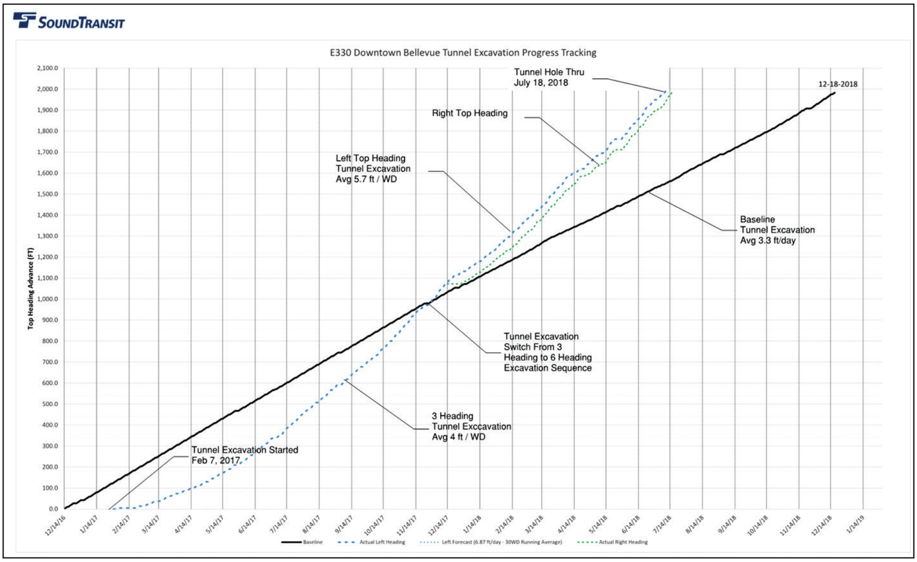

Figure 3. Tunnel Excavation Production Rates

delay in the completion of the soil nail walls, which formed the portal area, resulting in a 2-month delay to the start of tunneling.

Atkinson's crews were able to accelerate the learning curve in the first half of the tunnel with the larger excavation heading, allowing the crews to better train in controlling the excavation, installation of spiling and lattice girders, and the application of shotcrete.

Despite the initial delay to the start of tunneling, with the alternate construction sequence and other changes made during tunneling, the project team was able to accelerate construction, from a proposed production rate of 3.2 feet per day to over 4 feet per day. In some areas, Atkinson was able achieve production rates of up to 6 feet/day (see Figure 3).

This redesign effort was only possible because all parties were open to change and understood each other's needs. The partnering developed in these meetings allowed the team to have open discussions, avoid placing blame, and focus on the project. This provided a sound footing for the rest of the project.

MANAGEMENT OF THE TUNNEL EXCAVATION AND INSTALLATION OF THE SUPPORT ELEMENTS

During tunneling, the project team held daily Required Excavation and Support Sheets (RESS) meetings where the excavation progress from the past day and the plans for the current day were discussed. These critical meetings established the support elements that were going to be in place during tunnel excavation each day. The meetings were held by the CMC's Resident Engineer and attended by Atkinson's SEM Engineer and the Engineer of Record's representative.

As a result of good tunneling methods and favorable ground behavior, several modifications to the initial excavation and support sequence were allowed. These modifications included reducing the prescriptive spiling to an as-needed quantity based on the ground behavior, removing the face wedge requirement except where needed, increasing the advance length from 4 feet to 4-¼ feet, and eliminating some of the immediate flash shotcrete for the bench and invert advances. The team was also successful in eliminating other requirements such as an exploratory horizontal core by substituting logging of additional probe holes in the face. This was all accomplished while maintaining a high standard in tunnel construction. These modifications allowed tunnel production rates to increase and provided $2.7 million in cost savings to Sound Transit. Additionally, the judicious use of the additional toolbox items in SEM construction allowed for another $2.0 million in savings to Sound Transit.

The CMC team also worked with both the contractor and the EOR on improving the shotcrete mix design and delivery method. Atkinson's original plan was to have shotcrete delivered from off-site commercial batch plants. Atkinson had also planned for a small shotcrete robot to place the shotcrete. After various field evaluations and discussions, Atkinson revised its original plan to better suit the more aggressive schedule, mobilizing an on-site shotcrete batch plant and the use of a more versatile shotcrete robot to deliver the shotcrete. These changes allowed for Atkinson to not only recover the 2 months lost prior to the start of tunneling, but to complete tunnel excavation in late July 2018, several months ahead of schedule.

Managing Risk

During construction, Atkinson was required to take preconstruction videos of the existing storm lines along the tunnel alignment. In the area of 4th and 110th Streets, in one of the busiest arterial streets in the City of Bellevue, the video of the one of the existing storm lines revealed it to be in poor condition and much lower than shown in the drawings. The 12-inch storm line was perforated by design, and only several feet from the tunnel crown. Further investigation indicated it was typical to backfill the storm lines in this area with pea gravel. There was also an existing PSE electrical vault in the area over the top of the pipe that needed to be supported in place.

These discoveries posed a significant risk to tunnel construction. The CMC worked with the rest of the project team to develop and implement a solution to mitigate this risk and ensure tunnel construction was not delayed. Atkinson removed as much of the pea gravel as possible with an open cut and excavation via vacuum trucks while maintaining the pipe bedding in place as required by the City of Bellevue. PVC pipes were installed into the pea gravel bedding to allow it to be grouted with cement grout after the open excavation was backfilled with a low strength controlled density fill (CDF) mix (see Figure 4),

The project team analyzed the excavation plan for this area and required pocket excavation and spiling through this area and successfully excavated under the utilities with no significant issues. This was accomplished over two weekends with no significant delay to tunnel excavation.

Other Tunneling Improvements

Elimination of the Pipe Canopy Support at North Portal

Several key work items were associated with work at the North Portal. The first requirement was to improve the existing ground conditions because of the low cover in this area. This work element required Atkinson to excavate approximately 10 to 12 feet below the ground surface and replace the excavated material with low strength CDF. A second, post-bid investigation discovered the invert of one of the major electrical vaults in the area was encroaching in the initial tunnel lining. A major coordination

Figure 4. Mitigating the Storm Line at 4th and 110th Streets in the City of Bellevue

issue was to install a pipe canopy support from the North Portal part way through the excavation for the follow-on projects cut-and-cover structure, the pipe canopy being necessary to support the crown of the tunnel during final excavation and hole through.

During the initial brainstorming session, the project team determined the most efficient method to mitigate the issue with the electrical vault invert resting on the crown area of the tunnel (which could also eliminate a time consuming project interface with the follow-on contractor) was to build a concrete arch support. This was done by increasing the ground improvement section down to tunnel springline and removing and replacing the electrical vault a foot higher in elevation. The remaining ground improvement area was replaced down to tunnel springline with 2,000 psi concrete, eliminating the need for the pipe canopy. As the area was backfilled, steel plates were placed below a gas pipeline to prevent errant spiling from possibly damaging the pipeline. The tie-backs for the cut-and-cover SOE were installed during the excavation and backfill operation from the surface, which eliminated the risk of the follow-on contractor drilling through a hidden utility.

This value engineering decision eliminated a costly interface operation and between the E330 and E335 contractors, reducing exposure to Sound Transit from delays and improved the follow-on E335's construction schedule.

Macro-Synthetic Fiber in Shotcrete

There were interpretation issues regarding the testing requirements for the shotcrete initial lining mix in the contract specifications. This issue would have resulted in significant testing cost for either Atkinson or Sound Transit. The CMC team worked with Atkinson to implement beam testing, allowing both parties to mitigate the costs of testing and allowing Atkinson to use macro-synthetic fiber in the initial lining. Macro-synthetic fiber was not commonly used in initial lining shotcrete at the time and was not specified. The CMC team, Atkinson, and the EOR developed new specifications including a testing regimen to ensure the quality of the shotcrete was not compromised with the change from steel fiber. The result was a cost savings for Atkinson and mitigation of a significant testing cost issue for Sound Transit. The testing of the macro-synthetic shotcrete lining mix provided results within hours of shotcrete being applied and confirmed there was no issue using macro-synthetic fibers.

Spray-Applied Waterproofing

The contract documents allowed for the use of either elastomeric sheet membrane waterproofing or spray-applied membrane waterproofing. Atkinson chose to use spray-applied waterproofing, which was different than the product specified for the DBT, specifically Mapelastic TU System (Mapelastic). F.D. Thomas was chosen as the waterproofing subcontractor/installer. Quality control was also performed by the installer. In addition, a representative from MAPEI was present to supervise the installation of the product.

Various factors led to the contractor's choice of spray-applied waterproofing for the DBT. It was difficult to find a manufacturer and installer that would provide the contract-specified 10-year warranty. Cost and ease of installation was another factor driving the decision. The spray-applied waterproofing has the benefit of not requiring the installation of propriety anchors for reinforcing support penetrations and has a less stringent requirement for surface waviness. The amount of water anticipated and encountered in the tunnel was also factored into the decision.

The waterproofing system depicted in the contract consisted of a 1.5-inch-thick smoothing layer placed on the initial lining to cover the original specified steel fiber reinforced shotcrete. Geotextile would then be placed on the smoothing layer, with the sheet membrane then placed on top of the geotextile. WA anchors would be installed to support the reinforcement. After the sheet membrane was installed, at each construction joint (approximately 30 feet to 40 feet apart), a water barrier would be welded to the membrane and a regroutable hose would be installed at the joint. When the membrane was completed, reinforcing and 12-inch-thick cast-in-place concrete final lining would be placed.

The contract drawings required the waviness for the waterproofing to be less than W=L/60. With spray-applied waterproofing, the waviness requirement was reduced to W=L/12 after a large-scale demonstration that this would be adequate. The application of the spray-applied waterproofing appeared to be much faster than installation of sheet membrane. Additionally, spray-applied waterproofing bonds with both the shotcrete initial lining and the final lining, potentially allowing for a composite system, although this was not a considered as a factor in the design of DBT.

The use of spray-applied waterproofing also mitigated Atkinson's concern that the use of PVC sheet membrane might have prevented the concurrent final lining concrete activities because of the installation gantry requirements in the tunnel. Figure 5 below shows use of the tunnel rebar gantry to place the final lining reinforcement in the tunnel.

A new specification was developed for the use of the spray-applied waterproofing to accommodate the use of the Mapelastic product. Various adjustments were made during application to ensure successful installation of the waterproofing (Figure 6). This included the use of drainage panning at each girder location to direct the water to the invert under the smoothing shotcrete, the addition of waterproofing additives in the smoothing shotcrete to help mitigate some of the outstanding leaks, use of hydraulic cement patching and epoxy sealant to mitigate the remaining leaks prior to placing the waterproofing product, and placing the waterproofing in three applications instead of two thicker applications.

Once the product was placed and all parties bought off on it, including the waterproofing installer and manufacturer, the work on the final cast-in-place concrete lining began.

Figure 5. Tunnel Rebar Gantry in Place at the Face of the South Portal Tunnel Entrance

Figure 6. Crews Installing Panning Material to Control Leaks Through the Initial Lining (left) and Installed Waterproofing (right)

After the reinforcing, embedded conduit and concrete lining were placed, the few remaining leaks observed through the final lining were mitigated with the use of chemical and hydrophilic grout. These efforts resulted in a dry tunnel for Sound Transit with a 10-year warranty and provided a cost and schedule advantage to Atkinson. After a year since the final lining was completed, the tunnel has remained dry with some minor seepages observed in less than ½ dozen locations, primarily around the fuko boxes.

Shotcrete for the Final Lining

Shotcrete is not commonly used as a final lining on projects. When Atkinson proposed this as a means to accelerate the schedule, the project team organized site visits to the Northgate project site, where the shotcrete was employed to construct an underground garage, and provided various examples where shotcrete was used successfully as final lining on other projects around the United States.

New specifications were developed by the EOR with input from the CMC team and Atkinson for use of shotcrete for the final lining (Figure 7). The project team developed acceptance criteria for the shotcrete personnel and the testing procedures for the shotcrete. Various mockups were completed to ensure the shotcrete personnel could do the work. The use of shotcrete for the final lining allowed Atkinson to save costs in purchasing costly formwork for the short tunnel expanded zone where the tunnel transitions from a 37-foot-wide to a 43-foot-wide tunnel for two of the tunnel fans. Shotcrete was also used to construct the 1.5-foot-thick center wall dividing the tunnel into two separate trackways. The use of shotcrete for the final lining was a significant schedule advantage for Atkinson, since the use of traditional formwork would have blocked access to the northern half of the tunnel and resulted in delays in completing the remaining concrete work.

COST AND SCHEDULE PERFORMANCE

Overall, the project team was able to complete the project $1 million under the original contract bid. This allowed Sound Transit to use the 10% contingency amount allowed for DBT on other projects in the program. Additionally, the project was able to be completed on time. This included delays due to weather, delay in start of tunnel, and impacts from COVID-19. The project was able to achieve these goals with cooperation from all the stakeholders.

Cost Performance

- Engineer's Estimate $154,774,976
- Contract Bid Amount $121,446,551
- Final Construction Cost $120,334,876
- Value of Change Orders –$1,111,680

A total of $5.4 million in change orders was issued on DBT, with $5.9 million in cost saving credits to the overall contract. The $5.4 million in change orders issued by Sound Transit consisted of the following:

- Administrative Changes:
  - Setting up Work Directive Allowances
  - Payment for Dual Benefits
  - Payments for Washington Sick Leave Regulations
  - Payment for Fire Department Liaisons $1.86 million
- TCE and Design Changes at Skyline Garage $808,000
- Additional Paving of 110th Street $1.2 million
- Various Design Changes, Utility Conflicts $1.6 million

Most of the change orders issued on DBT consisted of administrative changes. The largest change order issued was for the additional paving of 110th Street and ADA curb ramp improvements at two intersections in downtown Bellevue. The second largest change order issued was for the additional work restrictions Atkinson had to adhere to during construction of garage improvements in the Skyline building and subsequent additional grouting work required because of the discovery of voids behind the existing garage wall. Another $1.6 million in change orders

Figure 7. Use of Shotcrete as the Final Lining in the Expanded Zone and in the Tunnel Center Wall

were issued for utility conflicts, differing site conditions encountered during construction, and various other design changes during construction.

The project team was able to provide additional cost savings to Sound Transit in the amount of $5.9 million. These changes were due to the changes in the SEM excavation method and the savings in the tunnel excavation support and toolbox items.

Combined, these efforts resulted in an overall cost savings of approximately $1,000,000 to the DBT Contract: $500,000 was due to the savings described above, and the remaining $500,000 cost savings was due to the unused allowance cost items on the project.

Schedule Performance

- Design Start Date: Summer 2012
- Design Completion Date: August 2015
- Construction Start Date: February 8, 2016
- Original Construction Duration: 1,445 days
- Construction Start Date: February 8, 2016
- Tunnel Construction Completion: January 21, 2020, 1,444 days (1 day earlier than Tunnel Substantial Completion)

DBT was the first Sound Transit East Link project to be executed and was on the critical path for the overall program. Anticipating potential delays to the program, Atkinson, the CMC team, the EOR, and Sound Transit worked as a team to implement significant design changes to the soft ground tunneling method, allowing Atkinson to perform tunnel excavation in three headings for the first half of the tunnel, rather than in six headings. This effort not only allowed Atkinson to make up for 2 months of delay at the start of the project, it allowed for tunnel excavation to complete months ahead of schedule.

Although tunneling completed early, it was soon discovered that completion of the follow-on work activities, such as waterproofing and final lining installation, would take longer than anticipated. As a result, the project team worked collaboratively to implement new construction methods, such as the use of spray-applied waterproofing, which allowed the concrete final lining and waterproofing activities to occur concurrently. The team also worked together to implement the use of shotcrete for a final lining. This allowed installation of the final lining to occur south of the expanded zone concurrently with the placement of shotcrete for the center tunnel wall, saving time to the overall schedule.

The project team and the follow-on contractor also worked closely together to allow the follow-on project early access to start the rail installation activities in the tunnel early. This enabled the follow-on project to have an early start on a critical path activity for the overall program. The project team also worked as a team to allow the follow-on project early access to the southern portion of the South Portal site, allowing it to start the East Main Station much earlier than anticipated.

CONCLUSION

The project was completed successfully because of the hard work and commitment by all parties, including Sound Transit, Atkinson, the CMC, and the designer. The project team was always open to trying out a new idea and thinking outside the box to tackle the various problems that came up during construction. All these efforts saved both cost and time to the E330 project and the follow-on contract, resulting in the Downtown Bellevue Tunnel E330 Contract being completed on time and under the original bid. Additionally, the coordination efforts with the follow-on contractors allowed critical path work to start earlier and mitigated potential delays to the overall East Link Extension Program.

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