

SUMMARY MEMORANDUM: TUNNEL CONSTRUCTABILITY STUDY

UPDATE TO THE 2010 DEIR FOR THE RED LINE/BLEU LINE CONNECTOR

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CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

Table of Contents

1. Introduction.....	1
2. Existing Conditions.....	3
2.1 Preferred Alternative.....	3
2.2 Geotechnical Information	4
2.3 Groundwater Mitigation.....	4
3. Construction Methods.....	6
3.1 Cut-and-Cover (C&C)	6
3.1.1 Application of Top-Down Methodology for the Connector	9
3.1.2 Mitigation of Disruption to Community Using Top-Down C&C Construction	10
3.1.2.1 Reduced Construction Duration.....	10
3.1.2.2 Restoration of Street Early in Construction	10
3.1.2.3 Project Cleanliness.....	11
3.1.2.4 Utility Disruption	11
3.2 Sequential Excavation Method (SEM)	12
3.2.1 Application of SEM Methodology for the Connector.....	15
3.3 Tunnel Boring Machine (TBM) Tunneling.....	17
3.3.1 Application of TBM Methodology for the Connector	20
4. Cost Estimate and Schedule.....	22
4.1 Top-Down C&C Cost/Schedule.....	25
4.2 TBM Cost/Schedule.....	26
4.3 SEM Cost/Schedule	27
5. Summary	28

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

Figures

Figure 1: Aerial View of the Connector Location	1
Figure 2: Preferred Option (Alternative 1) Profile.....	3
Figure 3: Alternative 1 Plan View	3
Figure 4: Cross Section of TBM Tunnels and Station (SEM)	4
Figure 5: Cut-and-Cover Construction Methods.....	8
Figure 6: Slurry Walls as Permanent Support, Bottom-Up Construction, Second Avenue Subway Phase One (96 th Street Station).....	9
Figure 7: Secant Piles as Permanent Support, Top-Down Construction, Copenhagen Metro.....	9
Figure 8: Top Heading, Bench, and Invert Sequence (left) and Chinatown Station: Central Subway, San Francisco, CA (right)	12
Figure 9: Different Pre-Excavation Ground Improvement Techniques - Inside the Tunnel.....	14
Figure 10: Ground Freezing from Surface, Extension of the NYCT No.7 Line Subway, New York, NY.	15
Figure 11: 2010 DEIR Proposed Sequence and Ground Improvement for the Storage Tail Tunnels	17
Figure 12: Typical TBM Tunnel.....	18
Figure 13: Unit Cost of Tunneling, TBM vs. SEM (Credit: Dr. Sauer & Partners)	19
Figure 14: Alternative 1 Schedule from 2010 Conceptual Design	22
Figure 15: Impact of Tunnel Length on Unit Cost of Tunneling.....	26
Figure 16: Downtown Bellevue Tunnel.....	27

Tables

Table 1: Alternative 1 Cost Estimate Breakdown from 2010 Conceptual Design.....	23
Table 2- Further Breakdown on 2010 DEIR Cost Estimate for "Tunnels and Stations"	24
Table 3: Recent Comparable TBM Projects	25
Table 4: Recent Comparable SEM Projects.....	25
Table 5: Comparison of Different Tunneling Methods.....	28

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

1. Introduction

This report summarizes the different construction methods under consideration for the proposed Red Line/Blue Line Connector project (the Connector) that would extend the Massachusetts Bay Transportation Authority (MBTA) Blue Line underground by 2,000 feet along Cambridge Street from the Bowdoin Station to the Charles/MGH Station. Figure 1 below illustrates an aerial view of the proposed subway tunnel alignment.

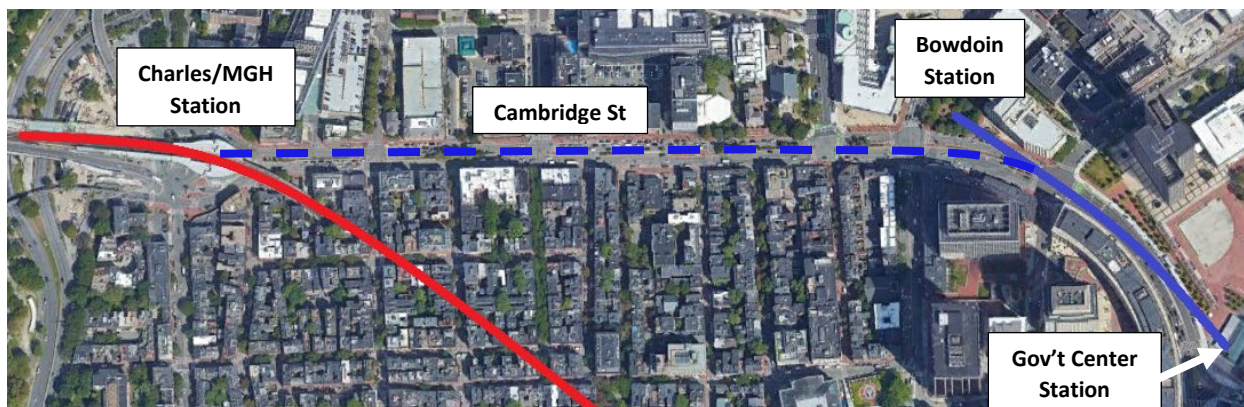


Figure 1: Aerial View of the Connector Location

The Connector project would link the only two MBTA subway lines that are not currently connected, thereby increasing transportation access for residents, primarily in communities along and in the vicinity of the Blue Line and improving passenger mobility.

In 2010, a Draft Environmental Impact Report (DEIR) for the Connector was completed. As part of the study, STV developed the 10% conceptual design and evaluated different construction methods and configurations to connect the two lines. Tunnel Boring Machine (TBM) tunneling was selected as the preferred method of excavation. Two configurations were studied:

- Alternative 1: Elimination of Bowdoin Station
- Alternative 2: Relocation of Bowdoin Station

Total project cost for Alternative 1 was estimated to be \$748M while Alternative 2 was estimated to be \$867M, using 2015 dollars. In the end, Alternative 1 was selected as the preferred option.

Due to budget constraints, the Connector was put on hold. In April 2018, the 2010 DEIR was revisited as part of a constructability study to determine if there were any changes in technology, tunneling methods, or contractor preferences that would affect either the assumptions or cost estimates provided in the 2010 DEIR.

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

This study focused on the constructability of the tunnel for the alignment from Alternative 1 of the 2010 DEIR. **This study does not consider or provide costs estimates for the constructability of the full project**, which would include consideration for traffic management and pedestrian disruption during construction, maintaining access to Massachusetts General Hospital, disruption to utilities, building redundant elevator service to ensure sufficient capacity for vertical movements in the station, other Charles/MGH station renovations, and updating designs to meet current construction and maintenance policies.

This study compares different possible tunneling methods and evaluates high-level assumptions and relative cost estimates for each method. Specifically, the cost estimate focuses only on the construction cost of heavy civil tasks, including excavating the “shell” of the tunnels, station, tail tunnels, and shafts, as well as utility relocations. It excludes station and tunnel fit-outs, finishes, system improvements, trainset costs, design costs, testing, and project closeout. It is expected that the additional cost due to these items would increase the total cost 30 to 40%. Moreover, it excludes the multipliers used in the 2010 study including contingency and escalation.

There are three main tunneling techniques that could be used to construct the Connector:

1. Cut-and-Cover (C&C) excavation
2. Sequential Excavation Method (SEM)
3. Tunnel Boring Machine (TBM) tunneling

The subsequent pages of this constructability study are organized as follows:

- Section 2 describes the project site’s existing conditions, including the geotechnical findings and information reported in the 2010 DEIR.
- Section 3 discusses different tunneling methods, referenced above, and their pros and cons.
- Section 4 reviews the project’s cost estimate and schedule, providing a relative comparison with the 2010 DEIR study (with the limited scope of this study, it is not possible to provide a detailed cost estimate or schedule for the project).
- Section 5 summarizes the findings of this study.

CONSTRUCTABILITY STUDY RED LINE/BLUE LINE CONNECTOR BOSTON, MASSACHUSETTS

2. Existing Conditions

2.1 Preferred Alternative

This section describes the would-be characteristics of Alternative 1 as determined in the 2010 DEIR. Figure 2, below shows the profile of Alternative 1. The majority of the alignment would be excavated using the TBM method. However, the alignment would also include portions of C&C, as well as SEM tunneling.

The length of the bored tunnels would be approximately 2,000 feet in length. The depth of tunnel is estimated to be approximately 50 to 60 feet below the existing grade. On the eastern end of the alignment, there would be an approximate 500 foot-long section of C&C tunnel. Access shafts, emergency egress, and ventilation structures are also C&C structures. The north and south storage tail tunnels would be 400 feet and 300 feet in length, respectively, and would be designed to be excavated using the SEM method. In addition, the Charles/MGH underground station would be designed to be excavated using the SEM method by breaking into the TBM tunnels and connecting them. Refer to Appendix A for details.

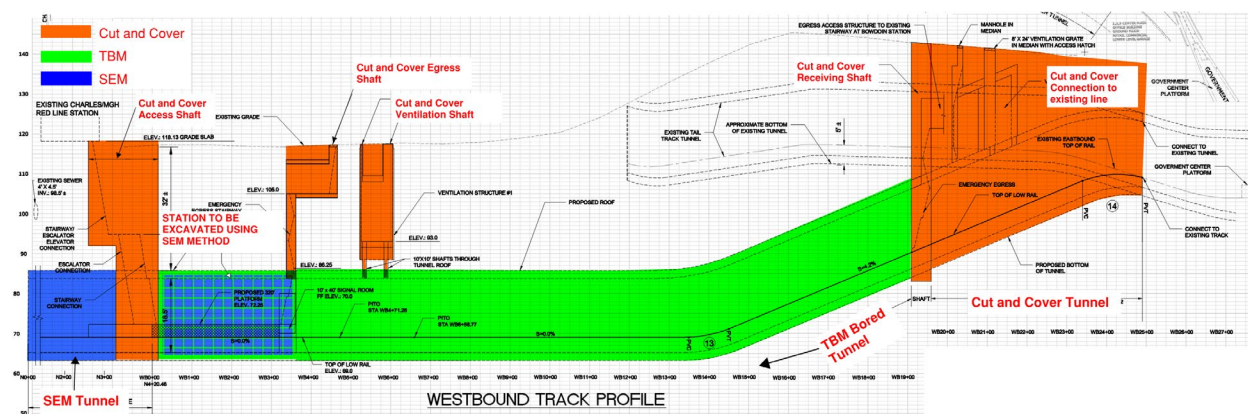


Figure 2: Preferred Option (Alternative 1) Profile

Figure 3, below shows a plan view of Alternative 1 and the likely extent of each excavation method. The proposed alignment would accommodate the following requirements:

- Space to park four trains at the proposed Charles/MGH Blue Line Station
- Inclusion of a crossover track near the Charles/MGH Blue Line Station
- Off-street locations of the primary access shaft and staging areas

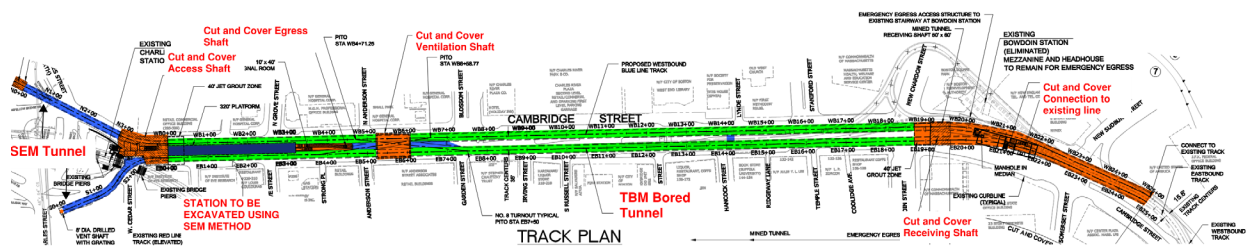


Figure 3: Alternative 1 Plan View

CONSTRUCTABILITY STUDY

RED LINE/BLEUE LINE CONNECTOR

BOSTON, MASSACHUSETTS

The twin TBM tunnels would be about 18-8” Inner Diameter (ID) with a 35-foot center to center separation and an approximate 13.5 foot soil pillar between the tunnels. At the Government Center station location, the tunnels would be connected using SEM method as shown in Figure 4.

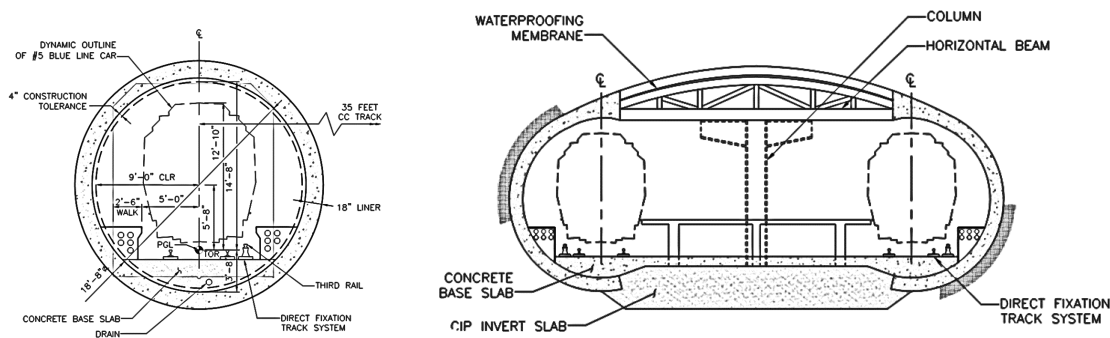


Figure 4: Cross Section of TBM Tunnels and Station (SEM)

2.2 Geotechnical Information

As part of the 2010 DEIR and 10% conceptual design, Haley & Aldrich Inc., as a sub-consultant to STV, developed a Geotechnical Data Report and Geotechnical Interpretive Report (GIR). No new borings were performed as part of the 2010 DEIR.

Soil layers that were identified in the project are listed below. Not all strata are present at any given location. Refer to Appendix B for the subsurface profiles, location, and thickness of strata.

- **Fill**
- **Organic Silt**
- **Marine Clay (Blue Clay):** This deposit typically exhibits an upper desiccated yellow silty clay layer containing a higher proportion of sand and gravel lenses grading into a blue-green silty clay below. The upper desiccated crust is not present at all locations.
- **Marine Sand:** This layer is discontinuous and found in two general areas.
- **Glacial Till**
- **Possible Glacial Moraine Deposits**
- **Bedrock:** Bedrock at the site is predominantly argillite and sandstone. The tunnel is expected to be above the top of bedrock. However, there are a few areas where the top of the bedrock elevation may be encountered toward the bottom of the proposed tunnels.

2.3 Groundwater Mitigation

Any tunneling work below Cambridge Street would be challenging due to a number of reasons, such as high water table, existing utilities, existing obstructions such as wood piles at Charles/MGH Station, and the close proximity to Massachusetts General Hospital and other buildings in the area.

The groundwater table is shallow in the vicinity of the project. As a result, the tunnels, station, and tail storage tunnels would all be constructed fully under the groundwater table. To mitigate settlement on

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

utilities and buildings within the project site, it will be important not to draw down the groundwater table during construction. Any proposed construction method should be watertight.

To reduce costs, improve the construction schedule, and minimize impact on buildings, utilities, and roadways it is recommended that the C&C tunnel structure be constructed using secant walls as both the temporary support of excavation (SOE) system and the permanent sidewalls of the C&C structural shell. The use of secant or slurry walls as permanent structures increases the number of vertical cold joints and thus the risk of some groundwater leakage into the structure. To eliminate that risk, our proposed C&C structure would be lined with inner waterproofed cast-in-place walls. These walls would be designed for hydrostatic pressures only. The external secant wall would support all ground, building, and traffic surcharge loadings. The TBM tunnels would be constructed with a double gasket system to minimize water infiltration. The SEM tunnels and the SEM portion of the TBM tunnels would be constructed using membrane waterproofing systems that would also minimize or eliminate seepage into the completed works. Finally, during construction all methods recommended: Cut-and Cover, SEM, and TBM, would be constructed such that the groundwater level external to the works would be maintained at its current levels throughout the construction period.

3. Construction Methods

3.1 Cut-and-Cover (C&C)

Cut-and-Cover (C&C) is a widely used tunnel construction methodology. In this method, the tunnel is usually shaped as a rectangular box structure. Curved structural elements required for mined tunnel are normally not used in C&C tunneling.

Bottom-Up Construction: C&C tunnels are commonly constructed “Bottom-Up”. First, the street and sidewalk are replaced by a temporary decking system. Utilities are either relocated or supported on the decking. The excavation down to the tunnel invert is supported by a multilevel cross-lot braced temporary earth support of excavation (SOE) system, such as secant piles, soldier piles and lagging, sheet piling, or slurry walls. The temporary decking acts as the top bracing level. Sequentially, additional bracing levels are installed below the decking as the excavation deepens. This process is called “downstage construction”.

“Upstage construction” is the reverse process. The tunnel structure is constructed within the SOE from the bottom up while removing bracing levels successively as the construction advances to the street level. Traditionally, the SOE is considered a temporary structure. The temporary decking system remains in place until the tunnel structure is completed and open area above the tunnel is backfilled and utility, roadway, and sidewalk systems are restored.

Top-Down construction: “Top-Down” construction is an alternative methodology for C&C tunnels. In this method, the final structure is being constructed as the excavation proceeds downward. Top-Down construction is possible because of the common use of rigid cast-in-place support of excavation structures, such as interlocking bored concrete pile wall (secant walls) and concrete diaphragm walls (slurry walls) as permanent subway tunnel sidewalls. Top-Down construction has two major advantages when compared to Bottom-Up construction:

1. There is no traditional temporary, throw-away SOE. Instead, the sidewalls, roof, mezzanine, and invert of the permanent structure act as the SOE system.
2. Because the tunnel roof is poured early in the Top-Down process, most of the decking can be removed and the street and sidewalk restored early in the construction project. Once the street is restored, the contractor’s work areas and access are limited to the shafts at one or both ends of the project.

At its best, Top-Down construction is closer to mined tunneling than it is to traditional Bottom-Up construction in terms of community impact. However, there is less risk compared to mined tunneling as it typically reduces both the cost and duration of construction.

One disadvantage is that both Bottom-Up and Top-Down construction require relocation of utilities along the perimeter of the SOE. During construction, utilities that fall within the excavation footprint must either be temporarily or permanently relocated. Sometimes utilities are supported from roadway/sidewalk decking system until the street surface is restored, usually before any excavation can take place.

As discussed previously, an SOE is required for C&C construction. The SOE serves four critical functions in urban C&C construction:

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

1. Supports the ground during excavation
2. Minimizes or eliminates dewatering external to excavation
3. Protects adjacent infrastructure and buildings
4. Supports roadway and sidewalk temporary decking systems

If the SOE is designed as a concrete diaphragm wall (slurry walls) or an interlocking bored concrete pile wall (secant wall), the system can form the sidewalls of the permanent subway structure. Top-Down construction also allows the permanent roof and lower level slabs such as mezzanine and invert slabs to support the SOE during Top-Down construction. Figure 5 below, illustrates a roof and mezzanine slab being used to support an SOE during Top-Down excavation. The ground is removed below the decking until the excavation reaches the level where the roof will be placed. At this point the roof can be poured directly on the ground and structurally attached to the SOE sidewalls. Openings or "glory holes" are maintained in the slab to allow excavation below the slab to continue. From this point, crews can excavate the remaining ground under the roof and the rest of the tunnel box can be constructed.

In summary, the advantages of Top-Down construction include:

- Earlier restoration of roadway and sidewalk surface
- Decreased costs from reduction of temporary works
- Shorter construction schedule

The disadvantages of Top-Down construction are:

- Inability to add external waterproofing results in increased risk of water leakage
- More complicated connections for roof and wall slabs
- Limited space for excavation/work under roof slab
- General contractors are less experienced with Top-Down than Bottom-Up construction

The disadvantages of Top-Down construction listed can be considered advantages in Bottom Up construction. However, these disadvantages of Top Down construction can be addressed and mitigated during design. On the other hand, Top-Down construction advantages including schedule, cost and reduced impact on the community cannot be duplicated in Bottom-Up construction.

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RED LINE/BUE LINE CONNECTOR
BOSTON, MASSACHUSETTS

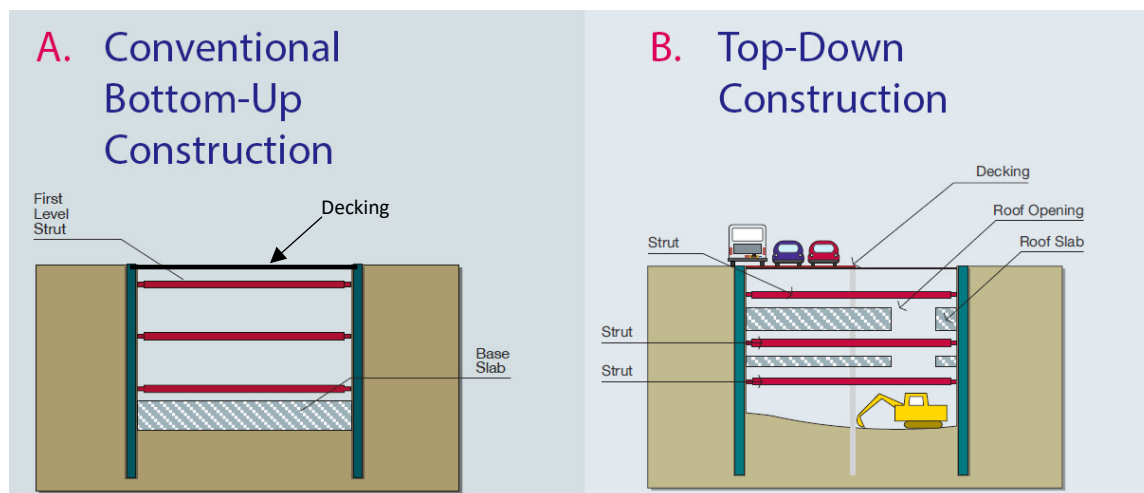


Figure 5: Cut-and-Cover Construction Methods

As stated previously, critical in the economics of Top-Down construction is the use of a slurry wall or secant pile wall to act as both the sidewalls of the permanent subway tunnel and the excavation SOE. An example of permanent slurry wall construction is the 96th Street Station in Manhattan (Figure 6, below) of the recently completed of the Second Avenue Subway (SAS) Phase 1. The 96th Street Station was Bottom Up construction and had a major impact on the community, particularly small business owners, surrounding the project. An example of permanent secant wall construction is the Copenhagen Metro Station in Denmark. The station was constructed Top-Down, as seen in Figure 7. In both New York City and Copenhagen both stations were located significantly below the water table.

In the Phase 2 of the SAS project, the current design assumes the SOE takes the soil, buildings, and surcharge loads while a smaller, inner wall is designed to handle the groundwater load – a method that may be applicable to the Connector project. The difference would be the use of Top-Down method instead of conventional Bottom-Up construction.

One significant advantage of Top-Down C&C construction as compared to SEM and TBM tunneling is the ability to significantly reduce the depth of the tunnel profile. Both SEM and TBM tunneling require a minimum depth of ground cover — usually one tunnel diameter — for ground stability during mining. The minimum cover is not required for C&C construction. This significantly reduces the volume of excavation; eliminates the need for mined cross-passages; and reduces the depth of entrances, shafts, and ventilation structures into the tunnel.

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RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS



Figure 6: Slurry Walls as Permanent Support, Bottom-Up Construction, Second Avenue Subway Phase One (96th Street Station)



Figure 7: Secant Piles as Permanent Support, Top-Down Construction, Copenhagen Metro

3.1.1 Application of Top-Down Methodology for the Connector

The connection between the Red Line and Blue Line along the Cambridge Street Corridor can best be accomplished by a Top-Down C&C tunnel. For this study, it is assumed that permanent sidewalls of the tunnel will be 39 inch (one-meter) diameter secant piles. To reduce the risk of water infiltration, shotcrete would be placed on the scalloped interior surface of the secant walls to sufficiently smooth the walls so a waterproofing membrane could be applied to their surface. Subsequently, an 18-inch interior wall is assumed to be cast against the waterproofing. Using the same geometry from the 2010 DEIR for minimum track separation (14 feet) and an 8.5-foot minimum distance from the tracks to the interior

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

walls, the overall width of the C&C tunnel would be 34 feet. After adding the SOE width (3.25 feet) the total footprint of the C&C box would be 40.5 feet. Considering the conceptual level of design, it is reasonable to use a more conservative assumption for the subway box. As a result, a total footprint of 46 feet is assumed in this study. It is assumed that the required width of the C&C box at the station would be 60 feet wide. Considering a minimum of 10 feet from the top of the roof slab to the existing ground surface, the tunnel invert would be 35± feet deep.

As previously mentioned, buildings along Cambridge Street on shallow foundations would settle if the existing groundwater level is lowered. To prevent this, the bottoms of the secant piles would need to be in an impervious stratum to provide a groundwater cut-off. Therefore, the secant walls would be bottomed out in either bedrock, the marine clay, or glacial till strata. The required penetration into each of these strata would vary. If a reasonable depth to cut-off is not economically feasible, other methods such as a horizontal jet grout plug would be considered.

The buildings along Cambridge Street would also be sensitive to ground deformations caused by C&C construction. However, ground deformations can be minimized to levels that cause little or no building distress by designing a rigid secant pile SOE and Top-Down C&C, which are the recommendations of this study.

3.1.2 Mitigation of Disruption to Community Using Top-Down C&C Construction

3.1.2.1 Reduced Construction Duration

Top-Down C&C construction will reduce the duration of construction by 12 to 15 months. Although utility relocation will take longer for Top-Down C&C construction than for mined tunneling, there is no delay for TBM procurement, shipping, re-assembly, initial launch, partial disassembly, re-assembly, and re-launch. There would also be no delays in TBM progress caused by mixed face tunneling through soft ground including boulders, glacial till and glacial moraine deposits.

3.1.2.2 Restoration of Street Early in Construction

C&C construction is normally considered to be more disruptive to a community than mined tunneling. However, this is less true for the Connector because of the relatively short length of the tunnel. Shafts and other tunnel support facilities that penetrate to the ground surface are independent of tunnel length. Therefore, in short tunnels they make up a higher percentage of space occupied for a project therefore occupy more of the street footprint.

The preferred alternative in the 2010 DEIR assumed two short TBM bored tunnels with a considerable amount of C & C construction. Along the main alignment, this construction included an access shaft on the west, an emergency egress shaft, a ventilation shaft, a more than 500-foot C&C excavation, receiving shaft, and finally the connection to the existing Blue Line east of Sudbury Street. Under these circumstances the community would be impacted by C&C construction whether the tunnels are mined or constructed using either Top- Down or Bottom-Up construction.

In addition to reducing overall construction duration, Top-Down C&C construction has the significant advantage of allowing for the restoration of the roadway and sidewalk much earlier than in traditional

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

Bottom-Up construction, a significant advantage in terms of minimizing community impact during construction. This is particularly important along Cambridge Street because of the presence of MGH, MEEI, doctor's out-patient offices, a fire station, and a significant number of commercial buildings, many requiring 24 hour access seven days a week.

In summary, while the street and sidewalks would be adversely impacted by all forms of construction, Top-Down C&C construction minimizes these impacts by allowing for street and sidewalk restoration while work is performed concurrently under the permanent tunnel roof slab. This is done by first designing the new subway structure as a shallow box supported by a roof and invert slab only. The roof slab is designed with a moment connection at the roof slab to the permanent secant wall while the invert slab connects to the secant wall with a pin support. The only surface penetration is a relatively small access shaft for muck removal and material supply.

3.1.2.3 Project Cleanliness

C&C construction can be a messy operation. This is especially true when ground conditions in an urban area, such as the route of the Connector, require an impervious, rigid SOE. An impervious, rigid SOE eliminates groundwater drawdown outside the SOE and minimizes inward movement of the SOE during downstage excavation. Both drawdown and SOE wall movements could adversely impact adjacent structures. Traditionally, these walls have been concrete diaphragm walls (slurry walls). This was the system used for most of the SOE work on the Central Artery Tunnel Project. Although slurry walls are effective structural elements, they can be very disruptive to install. The slurry panels are kept open by the use of a bentonite or polymer slurry. Mucking with clamshell buckets or even a hydromill through this slurry often overflows onto the sidewalks. Slurry splashing can coat the facades of adjacent buildings and pedestrians walking close to the work. Disposal of slurry-saturated soil requires specially sealed trucks that occasionally leak onto roadways. In addition, slurry excavations can have stability problems that result in over-excavation and possible ground subsidence. For these reasons, we recommend the use of interlocking bored concrete pile wall (secant wall) for the Connector.

3.1.2.4 Utility Disruption

Prior to the installation of the secant wall, some utility relocation would be required. As part of the current study, major utilities along the alignment were highlighted and the footprint of the C&C construction envelope were overlaid on top (see Appendix C). From west to east, the major utilities that would be affected are:

- ±400 feet of 36-inch x 51-inch combined sewer
- ±300 feet of 30-inch water main
- ±50 feet of 30-inch storm sewer and 30-inch water along New Chardon Street
- ±50 feet of 30-inch storm sewer along New Sudbury Street

Fortunately, the number of major utilities are limited. Cambridge Street is also over 80 feet wide, which when combined with a relatively narrow tunnel (46 feet wide) provides opportunities to reduce utility conflicts. The largest and most sensitive utility is the 36 inch by 51 inch combined sewer which, for most of its length, is located on the south side of Cambridge Street and runs parallel to the C&C construction. The other utilities primarily run north-south. The portion of the combined sewer at the west end of the project that conflicts with the secant wall installation would be relocated to the south and reconnected to

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

the interceptor system at Charles Street. The Top-Down construction footprint can be located north of the combined sewer to minimize relocation to a short section between Grove Street and Charles Street prior to the construction of the secant wall in that area. Secant wall construction is possible in most areas along the alignment with little or no utility disruption.

3.2 Sequential Excavation Method (SEM)

SEM is another tunneling method that can potentially be used to excavate the tunnels for the Connector. In this method, the main excavation is divided into multiple sections and excavated sequentially to minimize the unsupported ground, thereby enhancing the stability of the ground. Figure 8 shows a typical top heading (crown), bench, and invert construction sequence on the left. On the right, the excavation sequence that was used in Chinatown Station in San Francisco as part of the Central Subway project is shown. SEM is commonly used in soil or highly fractured rock where support of tunnel face and crown is problematic, and the tunnel cannot be excavated in full.

Surface disruption in this method will be the least when compared to the other methods. Except for access shafts during construction and limited areas needed for ground improvement, if required, there is no surface disruption.

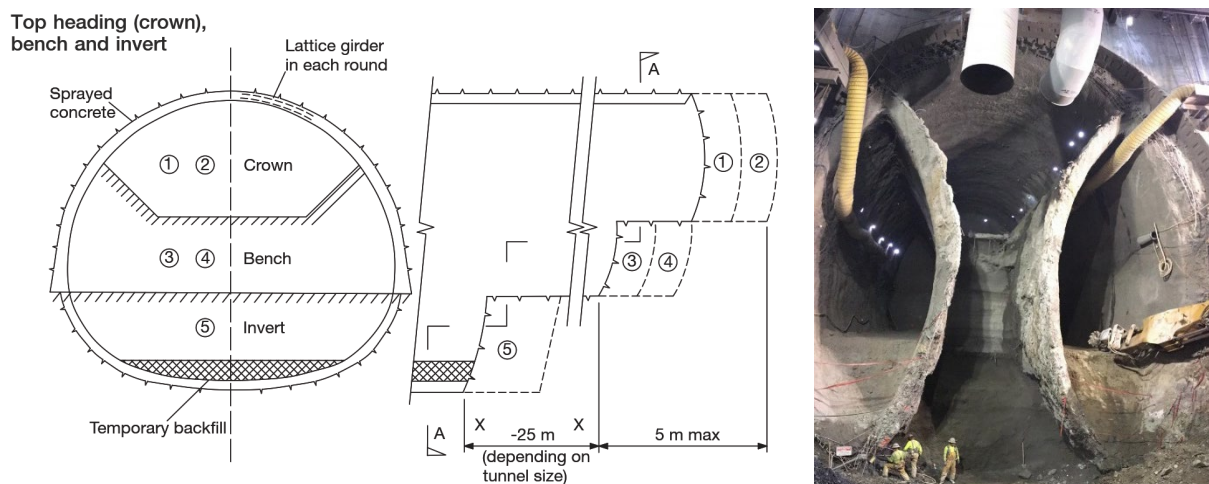


Figure 8: Top Heading, Bench, and Invert Sequence (left) and Chinatown Station: Central Subway, San Francisco, CA (right)

Another major advantage of SEM is its adaptability to obstructions, ground type, unforeseen ground, tight curves, and other challenging site conditions. However, if not designed and constructed properly, this method will lead to higher surface settlement and in cases, catastrophic surface failures.

Usually, the SEM method is accompanied by one or more ground improvement techniques prior to the excavation. Ground improvement is needed to enhance the ground properties and increase the standup time of the opening, in addition to controlling the groundwater inflow into the excavation. The required ground improvement methods vary in cost and can significantly increase the cost of a project. These methods include:

- **Fore-poling:** Driving steel bolts, sections of steel, slabs, etc. into the roof ahead of the tunnel face to stabilize the future excavation.

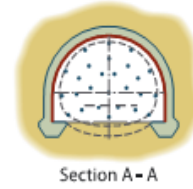
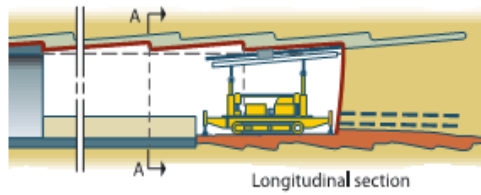
CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

- **Pipe canopy:** Same as fore-poling but using steel pipes in one or multiple rows (sometimes with grouting inside) to support the tunnel face ahead of the tunnel.
- **Jet-grouting:** Using high-velocity grout to mix with soil and construct cemented soil of varying geometries in the ground. This method is usually performed vertically from the ground surface but it can be done horizontally as well.
- **Face bolts:** Installing bolts (usually made of fiberglass) in the tunnel face ahead of the excavation.
- **Ground freezing:** Using liquid nitrogen or brine to cool down the ground and freeze the groundwater to stabilize the soil and eliminate the groundwater flow. This method can be done vertically from the ground surface or horizontally.
- **Others:** Grouting the tunnel face, drilling weep holes, soil-mixing, and any other method that enhances the ground and controls the groundwater prior to the excavation. These can vary from project to project.

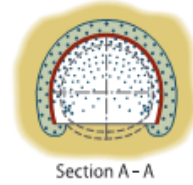
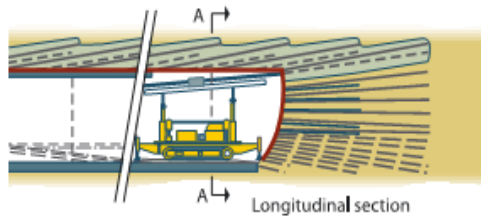
Some of these methods can be performed either from the ground surface or from within the tunnel. Figure 9 illustrates different options that can be used from within the tunnel to pre-support the tunnel roof and face. Figure 10 shows the footprint of the ground freezing effort for the extension of the New York City Transit No. 7 Subway Line in New York, NY.

CONSTRUCTABILITY STUDY RED LINE/BLUE LINE CONNECTOR BOSTON, MASSACHUSETTS

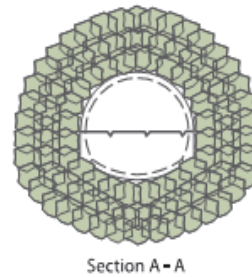
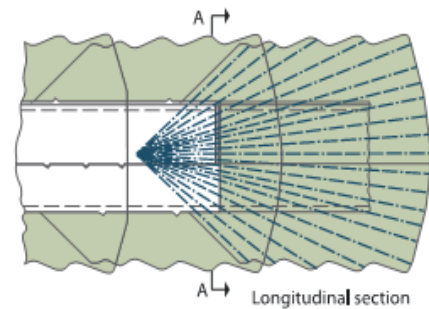
Sub-horizontal jet-grouting around the cavity and reinforcement of the core using fibre glass structural elements



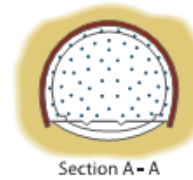
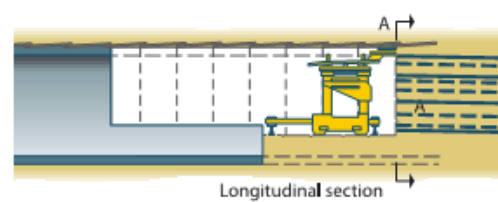
Ground reinforcement using fibre glass structural elements around the cavity and the core



Low pressure grouting



Full face mechanical precutting or pretunnel and reinforcement of the core using fibre glass structural elements



Sub-horizontal jet-grouting around the cavity and in the core

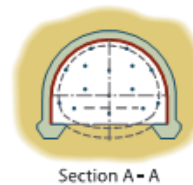
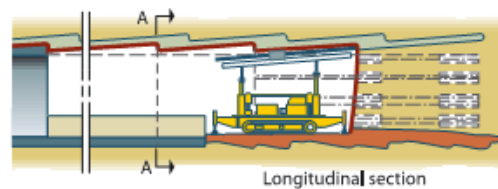


Figure 9: Different Pre-Excavation Ground Improvement Techniques - Inside the Tunnel

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS



Figure 10: Ground Freezing from Surface, Extension of the NYCT No.7 Line Subway, New York, NY

The advantage of performing the ground improvement from within the tunnel is that there is not any disruption to the community on the surface. However, this leads to disruption of the excavation efforts and would increase the duration of the tunneling.

SEM can be thought of as a “design as you monitor” method. The design is updated and enhanced as the tunnel advances and the ground reaction is monitored. Before any excavation takes place, a detailed geotechnical investigation must be performed to identify soil and water conditions. Depending on the size of the tunnel and the ground conditions, the excavation sequence and type will change. It is common to design multiple classes of support based on ground types, water ingress, and other construction issues that may be experienced on the project. Any SEM project requires an experienced contractor with proper understanding of the challenges and higher standard for checks and balances.

In general, the advantages and disadvantages of SEM can be summarized as follow.

Pros:

- Minimal amount of surface disruption (less than C&C and TBM)
- Can adapt to fit the ground conditions

Cons:

- Need for experienced workers
- Risk for ground surface settlement
- Need for ground improvement

3.2.1 Application of SEM Methodology for the Connector

While SEM has been used in the United States for a long time and on multiple projects, in general, there are fewer case studies and experience among the contractors as compared to C&C and TBM methods.

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

This is a major disadvantage of SEM and would increase risk for the project. Experience of SEM tunneling is particularly limited in the northeast United States and can add to the cost and risk of the Connector. However, the recent increase in number of projects that implemented SEM methodology, especially in California and Washington have led to more competition between the contractors and have enhanced the overall skills required for this method.

One major factor for the successful use of SEM for the Connector is the ability to properly control the groundwater ingress into the tunnel. It is important to provide a sealed excavation during construction. Groundwater drawdown around the excavation will lead to excessive settlement of the adjacent buildings. The GIR developed as part of the 2010 DEIR study confirms shallow groundwater along the entire project location. It also states that the “possible glacial moraine deposit” is more granular than glacial till and therefore more permeable. Moreover, lenses of marine sands and silts have been witnessed along the profile. Considering these findings, providing a completely sealed excavation in this project would be the major concern in using the SEM method and will significantly increase the cost and risk of the project.

The required ground improvement method would be the defining factor in using SEM and needs further evaluation. It is expected that large volumes of jet grouting or even ground freezing would be required. Both methods are among the most costly ground improvement techniques available and would make the SEM option a less desirable alternative.

It is possible to excavate two smaller tunnels for each track and use a larger section for the station. In this case, each track tunnel will be approximately similar to the 2010 DEIR proposed cross section for the storage tail tunnels (Figure 11). The advantage of using smaller size excavation is less settlement risk and better control of face and roof stability. However, this leads to work in tighter space; repetitive ground improvement for both tunnels; the need for two separate crews, equipment, and machinery; and a longer project duration.

Another option is to use a larger cross section for the entire project that houses two tracks. It is expected the tunnel would be no wider than 46 feet (same as C&C). Considering that Cambridge Street is a relatively wide street (± 80 feet from curb to curb), the tunnel would fit under the road along the entire alignment and far from the buildings. It is expected the settlement on the buildings due to excavation would be minimal. However, the settlement at the street right above the tunnel will depend significantly on the expertise of the crew and success of the ground improvement method. Large settlements and major failures have been reported worldwide using the SEM method.

At this stage, using a larger cross-section is our recommendation for the project due to its larger work area, speed of excavation, reduced ground improvement requirements, and the need for only one set of crew and machinery.

A major advantage of the SEM method is its ability to adapt to changes along the alignment. Based on 2010 DEIR, “there are numerous natural and man-made sources of potential obstructions along the tunnel alignment.” At this stage, it is not clear if major obstructions are to be found along the route, and it is possible that old piles, building foundations, wharf remnants, and other natural obstacles are buried along the tunnel alignment. This needs to be further investigated as obstructions could be considered a fatal flaw for the TBM method and a major advantage of using either SEM or C&C method.

CONSTRUCTABILITY STUDY
RED LINE/BLUE LINE CONNECTOR
BOSTON, MASSACHUSETTS

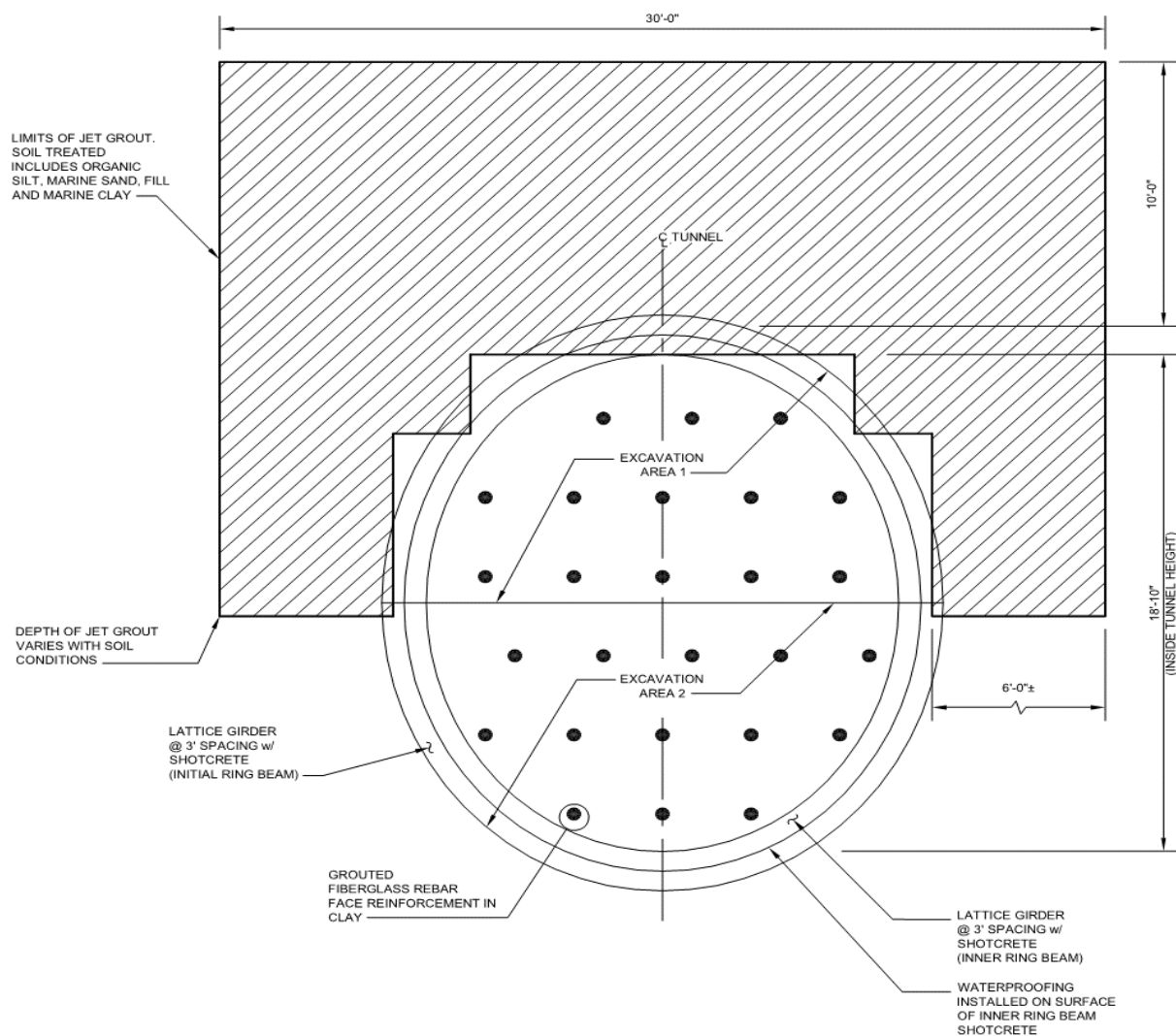


Figure 11: 2010 DEIR Proposed Sequence and Ground Improvement for the Storage Tail Tunnels

3.3 Tunnel Boring Machine (TBM) Tunneling

The last of the three possible excavation methods for the Connector is tunneling using a TBM. The use of TBM tunneling has been on the rise within the last few decades. Stronger and more equipped machines are being developed every year. Specifically, for rail and water tunnels TBM tunneling is the most common tunneling method in the United States.

The TBM is a large and expensive machine that carves the tunnel out of the ground. These machines get shipped to the site and must be assembled prior to use and disassembled after each run. The first step in the process is the construction of two vertical shafts that are used to launch and retrieve the TBM. After the shafts are excavated, the TBM can be assembled at the bottom of the shaft and set to launch. Once launched, the TBM will remove the soil and convey it out of the tunnel. In most cases, it will line the tunnel as it drives forward. Once the TBM reaches the end of the tunnel it can be disassembled, brought back to the launch shaft, and reassembled for the second tunnel. Typically, in a TBM tunnel there is some

CONSTRUCTABILITY STUDY
RED LINE/BUE LINE CONNECTOR
BOSTON, MASSACHUSETTS

SEM used to carve out the stations and any cross passageways. After the TBM is complete, it can be disassembled and brought to an offsite location.

There are different TBM types available depending on the ground type and groundwater elevation. Open TBM is used in rocks where groundwater is not an issue. Shield TBMs are used in soft ground, soils, and/or under groundwater. The shield is a large cylindrical structure used during the excavation as a temporary support against the ground that is soft, has poor quality, and is otherwise unstable. The tunnel's final lining — typically made of pre-cast concrete segments — is installed inside the shield and used as a support to push the TBM shield forward. In this report, the term TBM tunneling refers to Shield TBM tunneling.

Procuring a TBM for a project typically takes from 12 to 16 months depending on the complexity of the machine and other factors. It is possible to refurbish an old TBM and use it for a project. This may decrease the procurement period by a few months. TBM machines are manufactured by multiple companies. In recent years, the competition between the suppliers and advances in technology has led to less expensive machines. However, they are still an expensive investment, costing \pm \$15M for a machine with a \pm 23-foot diameter.

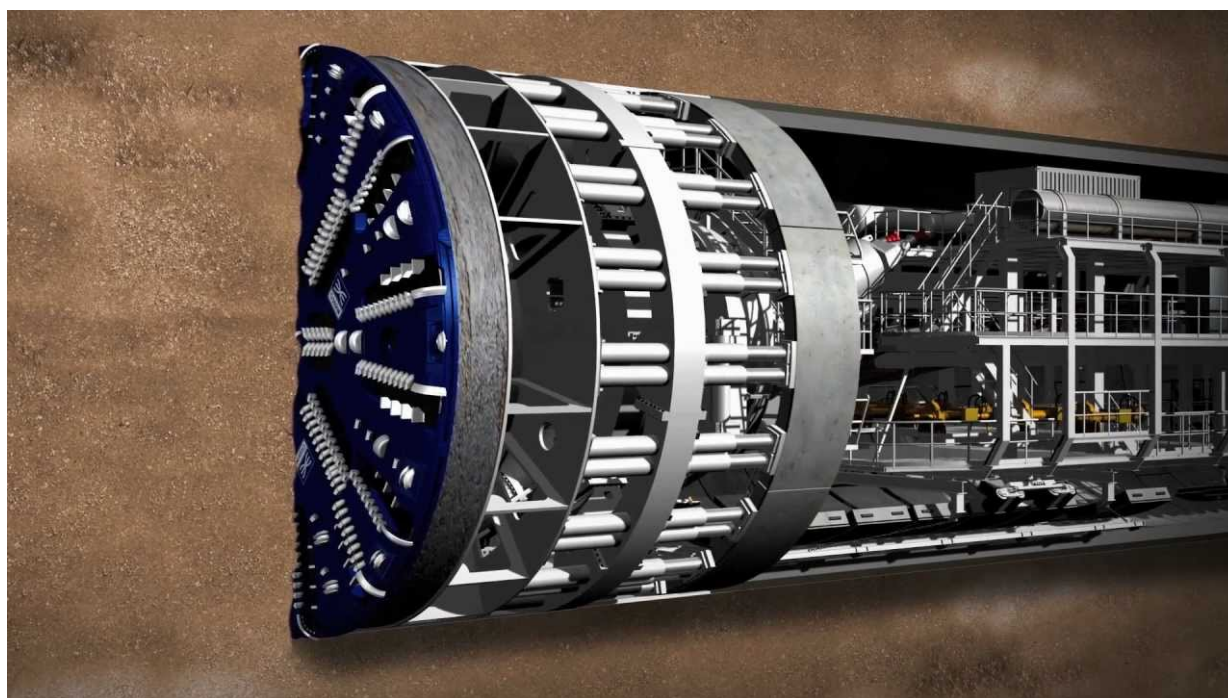


Figure 12: Typical TBM Tunnel

Compared to conventional drill and blast or SEM tunneling, the TBM advance rate is faster, less risky, and usually without the need for expensive ground improvement. In a typical week, TBM can advance a tunnel similar to the size required for the Connector by 250 feet.

Due to the long procurement and assembly time, as well as the high initial cost to procure a machine, TBM tunneling is not typically economical for short tunnel runs (less than a mile long). Figure 13 shows a comparison of tunnel cost per unit length between TBM and conventional tunneling. However, limitations such as community disruption, ground type, the need for groundwater control, and other

CONSTRUCTABILITY STUDY
RED LINE/BUE LINE CONNECTOR
BOSTON, MASSACHUSETTS

project specific requirements may lead to use of TBM as a more economical option even for short tunnels. As previously mentioned, the advances in technology and experience among contractors are constantly decreasing the minimum economical length of TBM tunnels and each year shorter tunnels are being built with this method. As a result, more contractors are using TBM for their projects; laborers are more experienced; and manufacturers are developing more sophisticated and less expensive machines. In summary, the increased use of TBM in recent years has increased competition among contractors for the construction of the project, thereby reducing cost. It would also decrease risk due to the availability of more experienced contractors.

Another major advantage of TBM tunneling when compared to SEM is the ability to control the stability of the tunnel roof and face without the need for elaborate and costly ground improvements. Using the TBM method, the Connector would be less risky as compared to the SEM method with generally less settlement on the ground and impact to existing structures.

One major limitation of the TBM tunneling is its inflexibility. The TBM machine cannot pass tight curves; the cross section of the tunnel cannot be changed along its entire length; and obstructions, such as piles, would pose a significant risk to the viability of this option. As a result, the majority of projects using TBM would require use of C&C, SEM, or another excavation technique to provide space for stations, shafts, etc.

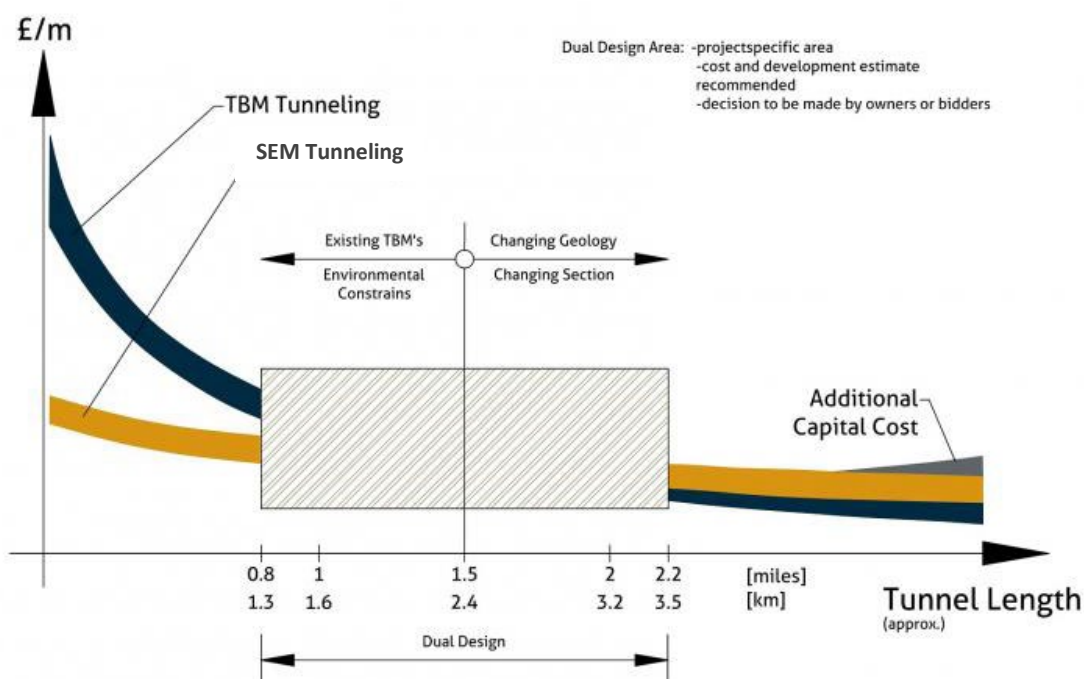


Figure 13: Unit Cost of Tunneling, TBM vs. SEM (Credit: Dr. Sauer & Partners)

Another shortcoming is the surface disruption compared to the SEM method. The TBM method needs to have launch and retrieval shafts and other surface excavations that would disrupt the community. This is more pronounced on smaller projects where the shafts would be located close to each other. Similar to the C&C method, the utilities would need to be relocated at the location of the shafts.

In general, the advantages and disadvantages of the TBM method can be summarized as follows:

CONSTRUCTABILITY STUDY
RED LINE/BLUE LINE CONNECTOR
BOSTON, MASSACHUSETTS

Pros:

- Once assembled, excavation goes very quickly
- Less surface disruption compared to C&C (this advantage is not as pronounced in this project)
- More experience and competition among contractors
- Less settlement and risk compared to SEM

Cons:

- Large vertical shafts are a major disruption, also require utility relocation at their location
- TBM must be delivered and assembled
- Can only excavate one tunnel at a time

3.3.1 Application of TBM Methodology for the Connector

TBM tunneling was considered as the preferred method of excavation for the main connector tunnels between the Red Line and Blue Line as part of the 2010 study. However, due to the lack of flexibility of this method, the storage tail tunnels were selected to be excavated using the SEM method. This was also true for the station and crossover cavern. Launch and retrieval shafts were considered as C&C excavations, as well as the connection to the Blue Line at the eastern end (see Appendix A for details). With multiple C&C structures, the disruption to the community would be less than the full C&C method, but still relatively high. This is especially true considering the short length of tunnel and close proximity of the C&C excavations.

As previously discussed, the procurement and assembly of the machine would be lengthy. During the wait time to procure and assemble the TBM, the site mobilization, excavation of the launch and retrieving shafts, the SEM tunneling of the tail storage tunnels, and C&C excavation on the east side can be performed. This would likely take the entire wait time for the TBM arrival and assembly (12 to 16 months).

Considering the short length of the tunnels and high advance rate of TBM tunneling, it is expected that the excavation of each of the tunnels would take only a couple of months. After finishing the first tunnel, the TBM would be disassembled, moved to the launch shaft, and the second tunnel excavation would proceed.

The need for SEM method for station excavation and storage tail tunnels would require the use of ground improvement techniques either from the surface or from the tunnel. This would add to the cost of this project. In general, in the TBM method all three tunneling methods (C&C, SEM, and TBM) would be used for some extent. Therefore, a range of equipment, specialty contractors, and laborers would be required.

If major obstructions such as steel piles and wharf remnants were found along the alignment, it would considerably affect the viability and cost of this method. In these cases, the obstructions have to be removed prior to TBM tunneling either by the SEM and/or C&C methods. If they were to be found during TBM tunneling, the excavation would have to stop and the obstructions removed with other methods. In both cases, major delays, increase in cost, and public disruption would be expected.

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

As an advantage, increased experience in TBM tunneling within the United States, especially in the northeast, would lead to less risk and more competition among contractors. Specifically, in the last 10 years, multiple TBM projects of similar tunnel diameter have been performed or are under construction in Washington, D.C., (Blue Plains Tunnel, Anacostia River Tunnels, First Street Tunnel, and Northeast Boundary Tunnel); New York, NY, (East Side Access, SAS Phase 1, Extension of No.7 Subway Line); Hartford, CT, (South Hartford Conveyance Tunnel); Narragansett, RI, (Narragansett CSO Phase 2); and other locations. This has increased the experienced labor pool and provided valuable experience among contractors on TBM projects.

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

4. Cost Estimate and Schedule

For the 2010 DEIR, a cost estimate and schedule for Alternative 1 was developed. The total schedule for Alternative 1, including design, was nine years. Utility relocation and the construction of the tunnels and station were estimated to last 5.5 years. Figure 14 shows the Alternative 1 schedule.

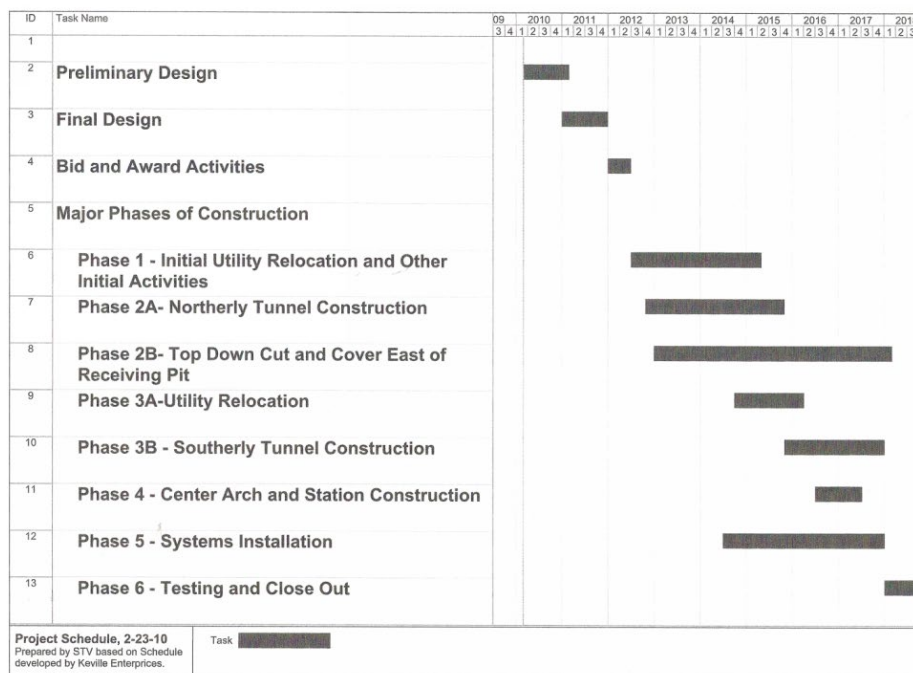


Figure 14: Alternative 1 Schedule from 2010 Conceptual Design

The total cost of the project was estimated at \$748M (2015). This included Tunnels and Stations fee of \$336M, design fee, contingency (40%), escalation (22%), and general contractor's overhead and profit (8%), in addition to the construction cost, trainset costs, and mitigation cost for use of the MEEI parking lot. Table 1 below shows the cost estimate breakdown used in the 2010 DEIR conceptual design.

The cost estimate was based on 10% design level for TBM tunneling. For the current constructability study, the SEM and C&C methods are not at the same level of design and therefore, it is not possible to provide the same level of cost estimate for these methods.

For the TBM method, change in technology, experience of contractors, and more competition in TBM tunneling business has led to a change in this estimate. In recent years, multiple tunnel projects with similar tunnel diameter (20 to 30 feet) have been performed in the United States. This includes numerous subways projects, Combined Sewer Overflow (CSO), and water tunnel projects around the country.

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

Table 1: Alternative 1 Cost Estimate Breakdown from 2010 Conceptual Design

		Alternative 1
Construction Costs		
Tunnels & Stations		\$ 336,000,000
System Improvements		
Traction Power		\$ 5,191,300
Communication		\$ 1,349,000
Signals		\$ 6,000,000
Subtotal		\$ 348,540,300
GC Overhead and Profit	8%	\$ 27,883,224
Subtotal		\$ 376,423,524
Contingency for 10% Design Level	40%	\$ 150,569,410
Total Present Construction Cost		\$ 526,992,934
Escalation (mid Point Construction)	22%	\$ 115,938,445
Total Escalated Construction Cost		\$ 642,931,379
Trainset Cost		
2005 Cost of Train Sets		\$ 13,085,000
Escalation to Revenue Time, Year 2018	33%	\$ 4,318,050
Total Escalated Train Set Cost		\$ 17,403,050
Design Costs		
Basic & Special: 10% of Present Construction Cost	10%	\$ 52,699,293
Escalation (mid point of design)	4.20%	\$ 2,213,370
Construction Phase: 4% of Present Construction Cost	4%	\$ 21,079,717
Escalation (mid point of construction)	22%	\$ 4,637,538
Total Escalated Design Cost		\$ 80,629,919
Mitigation Cost Of MEEI Parking Lot		\$ 7,000,000
Bussing Cost		
Present Bussing Cost		\$ 80,000
Escalation to Beginning of Construction	12%	\$ 9,600
Total Escalated Bussing Cost		\$ 89,600
Total Present Cost		\$ 620,936,944
Say Total Present Cost		\$ 621,000,000
Total Escalated Construction Cost		\$ 748,053,948
Say Total Escalated Construction Cost		\$ 748,000,000

Providing a new detailed cost estimate is not part of this constructability study. Considering the time and budget constraints, this study only focuses on high level comparative cost estimate between different tunneling methods and the 2010 DEIR cost estimate.

It is important to note that the “Tunnels and Stations” fee of \$336M in 2010 cost estimate included **total cost** of the construction and fit-out. In this report, the focus is limited to provide updated numbers for construction of the “**shell**” only. It includes heavy civil tasks including excavation of tunnels, station, and any other relevant openings. It also includes the utility relocation but excludes the tunnel fit-outs, track work, etc.

To accurately compare the DEIR and this study’s high-level cost estimate, it is necessary further breakdown the DEIR cost estimate to select. Table 2 illustrate which items in the DEIR cost estimate are comparable to those in this study. The cost of these items in the 2010 DEIR was \$302±M and duration of construction was estimated to be approximately 60 months. Escalated to 2018 dollars this translates to approximately \$413±M.

CONSTRUCTABILITY STUDY
RED LINE/BUE LINE CONNECTOR
BOSTON, MASSACHUSETTS

Table 2: Further Breakdown on 2010 DEIR Cost Estimate for "Tunnels and Stations"

Item	DEIR Cost	Can be compared with the current study	Shell Only Cost
Tail Tracks	20,565,385		20,565,385
NW tail shaft in parking lot	2,793,865	Yes	2,793,865
NW tail track	9,652,390	Yes	9,652,390
SW tail shaft	88,380	Yes	88,380
SW tail track	8,030,750	Yes	8,030,750
MGH Pier Modifications	2,181,942		2,181,942
Common for both	987,866	Yes	987,866
MGH Pier #6	1,038,963	Yes	1,038,963
MGH Pier #7	155,113	Yes	155,113
TBM Mined Twin Tunnels	83,837,870		83,837,870
W starter shaft	13,643,750	Yes	13,643,750
Tunnel construction	2,559,310	Yes	2,559,310
W shaft surface impacts	232,050	Yes	232,050
TBM machine	35,000,000	Yes	35,000,000
TBM IB	16,201,380	Yes	16,201,380
TBM OB	16,201,380	Yes	16,201,380
SEM Station Mining	36,339,495		36,339,495
MGH station cavern W	21,215,330	Yes	21,215,330
Crossover Cavern W	15,124,165	Yes	15,124,165
Accessory Tunnel Areas	16,180,292		11,200,882
Fan room @Anderson St	6,709,744	Partially	4,285,267
Fan room @ Bowdoin	3,213,723	Partially	658,790
E exit shaft	6,166,825	Yes	6,166,825
E shaft surface work	90,000	Yes	90,000
Surface Utilities	22,000,000		22,000,000
Surface utilities	22,000,000	Yes	22,000,000
MGH Station Buildout-Conceptual	23,008,090		0
MGH station fitout-conceptual	8,213,200		
MGH station connections to existing MGH	10,363,710		
MGH east emergency egress-from West Bowdoin Station	2,220,000		
Existing MGH Station Modifications	2,211,180		
Track Costs	3,416,000		0
Trackwork	2,903,500		
Tunnel finishes	512,500		
East of Bowdoin based on 22+61 cut	46,842,960		45,088,960
Cut and cover	39,013,260	Yes	39,013,260
Tunnel construction	4,871,200	Yes	4,871,200
Surface impacts	1,204,500	Yes	1,204,500
Trackwork	1,596,500		
Tunnel finishes	157,500		
Monthly Costs	81,446,294		81,446,294
Direct Work Support	38,158,400	Yes	38,158,400
General conditions-full duration	43,287,894	Yes	43,287,894
TOTAL	335,818,328		302,660,828

In this study, the SEM and TBM methods' cost estimate compares the project with similar recent projects in the United States. Table 3 lists some of the recent comparable TBM projects while Table 4 list the SEM tunnels. In general, the number of available SEM tunnels are less than TBM tunnels which is consistent with the industry trends.

**CONSTRUCTABILITY STUDY
RED LINE/BLUE LINE CONNECTOR
BOSTON, MASSACHUSETTS**

Table 3: Recent Comparable TBM Projects

Project	Location	Schedule	Length (ft)	Cost	Cost/ft	Soil	Notes
Northeast Boundary Tunnel	Washington DC	2017-2023	27,000	\$580M	21,500	Soft Ground	
Purple Line 3	Los Angeles, CA	2018-2022	Twin 12,300	\$410M	16,700	Dense Silty Sand	2 EPBM's
Anacostia River Tunnel	Washington DC	2013-2018	12,500	\$253M	20,200	Stiff Clay	
Ohio Interceptor Tunnel	Akron, OH	2015-2018	6,200	\$184M	29,700	Soft Ground	
Northgate Link Extension	Seattle WA	2013-2018	Twin 18,480	\$440M	11,900	Glacial Deposits	2 TBM's, Ground Freezing
1st St Tunnel	Washington DC	2013-2016	2,700	\$253M	58,100	Sand/Gravel	Ground Freezing
Blue Plains Tunnel	Washington DC	2013-2015	24,300	\$319M	13,100	Stiff Clay	
Black River Tunnel	Lorain, OH	2013-2015	5,280	\$52M	10,000	Soft Ground	
Central Subway	San Francisco, CA	2011-2015	Twin 7,920	\$234M	14,800	Soft Ground	2 TBM's
University Link	Seattle, WA	2010-2013	Twin 11,400	\$309M	13,600	Alluvium Soil	2 TBM's, Jet Grouting
Beacon Hill	Seattle, WA	2005-2009	Twin 5,280	\$309M	29,300	Glacial Deposits	Jet Grouting, Deepwells
2010 DEIR Red/Blue Connector	Boston, MA	2010	Twin 2,000	\$305M	76,250	Glacial Deposits	

Table 4: Recent Comparable SEM Projects

Project	Location	Schedule	Length (ft)	Cost	Cost/ft	Soil	Notes
Downtown Bellevue	Seattle, WA	2016-2020	2,000	\$133M	66,500	Glacial Till	10% Contingency Included
Caldecott 4th Bore	San Francisco, CA	2009-2013	3,400	\$417M	122,600	Rock	
Devil's Slide Tunnel	Pacifica, CA	2007-2011	Twin 4,100	\$268M	32,700	Rock	

Usually, cost per foot of TBM tunnels is less than SEM tunnels. However, when the short length of this tunnel is considered, the difference is not as significant. It should be noted that SEM tunnels are wider than TBM tunnels and would fit two tracks (and potentially the Charles/MGH station). Therefore, 2,000 feet of SEM tunneling would include two tracks, a cross passage, and potentially all excavations required for the crossover and station. For the TBM method, this would equal to construction of two 2000-foot long tunnels, plus excavation of crossover, station, and a cross passage with the SEM method.

4.1 Top-Down C&C Cost/Schedule

The cost estimate is based on unit prices for urban construction in the northeast United States. It is assumed the project will use union labor or prevailing rate.

The estimate assumes the Top-Down use of permanent secant piles. An interior cast-in-place wall, invert, and roof will be installed and water proofed. Traditional waterproofing, not overlapping secant piles, will be the primary means of preventing water from entering the subway structure. However, the secant wall will be designed to permanently support all ground pressures, building surcharge pressures, and all seismic loadings.

Based on experience from other projects and limited number of large utilities, this estimate includes a plug price of \$30M (2018) for utility relocation and temporary support on the decking system prior to early restoration as part of the Top-Down C&C methodology. Our study of Cambridge Street indicates that with the exception of ± 400 feet of 36-inch x 51-inch combined sewer, the utility relocation will not be a major concern. The combined sewer will require relocation prior to start of construction at the west end of the project.

This estimate is for the concrete shell of the running subway structure and station structure only. It does not include station and tunnel fit-outs, finishes, system improvements, trainset costs, design costs, testing, and project closeout. In addition, our estimate does not include MBTA contingency mark-ups. However, the unit prices we used to develop these estimates do include contractor margins (mark-up) and front

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

sheet (supervision). Based on the above, the estimate for Top-Down C&C construction will be in the \$200M to \$250M range (2018).

Based on experience with projects of this type, it is estimated the duration of construction will be in the 2.5- to 3-year range. This excludes the time required for design, station/tunnel fit out and finishes, system installation, testing, and project closeout.

4.2 TBM Cost/Schedule

The majority of TBM tunnels are more than one mile long and there are very few projects with similar length to the Connector. This is consistent with what was discussed in Section 3.3 as TBM tunneling is usually not economical for shorter tunnels unless there are project-specific needs that lead to the use of TBMs. Figure 15 shows the unit cost (cost/foot) and tunnel length of the same projects in Table 3. The only outlier (Black River Tunnel) is excluded. At this time, it is not clear why the construction cost for the Black River Tunnel is lower than other projects. In general, the trend in the graph is very similar to what was discussed previously and shown in Figure 13.

Although the details of each project need to be studied further and all projects have their own requirements that lead to change in cost, the overall trend is a good indication of the expected cost. Based on the graph, for construction of two 2,000-foot long tunnels, the unit cost can be estimated as $\pm \$45,000$ per foot. This leads to $\pm \$180M$ for the tunneling cost. This excludes the cost for crossover and station excavation (SEM) and the 500-foot C&C excavation at the east end of the project. It is expected that those items would cost \$120M to \$170M. In total, it is expected that the total construction cost for “Tunnels & Stations” would be in the range of \$300M to \$350M (2018).

Based on experience with other projects, it is estimated the duration of construction of these items would last three to four years. This excludes the time required for design, station/tunnel fit out and finishes, system installation, testing, and project closeout.

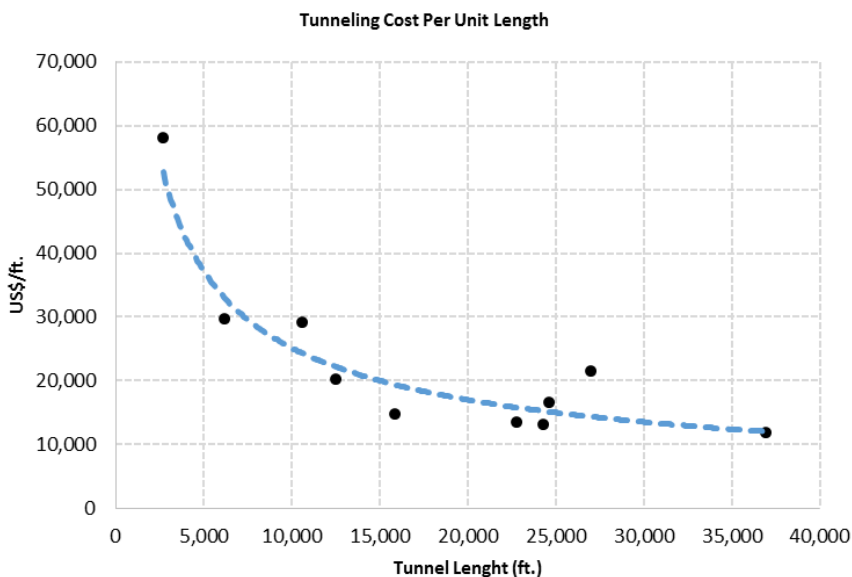


Figure 15: Impact of Tunnel Length on Unit Cost of Tunneling

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

4.3 SEM Cost/Schedule

The number of similar projects using SEM tunneling is very limited. Two of the projects were excavated in rock which dictates very different requirements to the project and are not comparable to the project under this study. The Downtown Bellevue project in Seattle is the closest project to the Connector tunnel in terms of size, length, and ground type. The major difference is the shallow groundwater table in the Connector project. This would dictate the use of expensive ground improvement techniques, as discussed in Section 3.2.1. Figure 16 shows the Downtown Bellevue project that is currently under construction. In comparison to the Connector, the cost of this project excludes the excavation of storage tail tunnels, access shaft, and break-in into existing tracks, in addition to the groundwater control. To include the tail tunnel cost, total length of the Connector can be considered as 2,500 feet. Using the cost/foot of \$66,500, the construction cost of tunnels is estimated as \pm \$170M. It is estimated that groundwater control, shaft excavation, and break-in cost would be in the range of \$80M to \$130M. In total, it is expected that the total construction cost for “Tunnels & Stations” would be in the range of \$250M to \$300M (2018).

Based on experience with other projects, it is estimated the duration of construction would last four to five years. This excludes the time required for design, station/tunnel fit out and finishes, system installation, testing, and project closeout.



Figure 16: Downtown Bellevue Tunnel

CONSTRUCTABILITY STUDY
RED LINE/BLEU LINE CONNECTOR
BOSTON, MASSACHUSETTS

5. Summary

Table 5 compares the major criteria across the possible excavation methods:

- Cost
- Surface disruption
- Schedule
- Risk

If the community can tolerate surface disruption, C&C would be the preferred excavation method. The TBM and SEM methods are preferable for minimizing surface disruption. While TBM would potentially be more expensive and cause more surface disruption than SEM, it is reliable, poses less risk, and requires less time for construction. In addition, contractors have more experience with TBM than SEM. SEM method would be less expensive, but with higher risk and less competition among contractors.

Table 5: Comparison of Different Tunneling Methods

Method	Cost of Tunnel Only (2018 US\$)	Surface Disruption	Construction of Tunnel Only (Years)	Risk
2010 DEIR (TBM)	\$413± M	Medium-High*	5	Low- Medium**
C&C	\$200 M to \$250 M	High	2.5 to 3	Low
SEM	\$250 M to \$300 M	Low-Medium*	4 to 5	Medium-High
TBM	\$300 M to \$350 M	Medium-High*	3 to 4	Low- Medium**

The cost estimates and schedules are for construction of the tunnel and stations shell only. They exclude station and tunnels fit-out, finishes, system improvements, contingency, escalation, trainset costs, design costs, mitigation cost of the MEEI parking lot, testing, and project closeout.

* Depending on the need for ground improvement and its type, surface disruption would defer.

** Given low risk of major obstructions.