Design-Build: Planning Alternative Concepts for Short, Urban Tunnels
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ABSTRACT
Tunneling is popular for installation of transit and utility infrastructure in urban areas. Bored tunnels require special equipment, but are usually preferred over deep, cut and cover excavation options as they provide reduced disruption and adverse third party impacts during construction. However, for short tunnels, cut-and-cover, sequential excavation, and jacked box are suitable alternative excavation methodologies. This paper compares alternative tunneling concepts for three design-build projects with short tunnels: (1) a 270-ft (82m) long jacked box tunnel versus a staged, deep-shored excavation; (2) a 1,350-ft (411m) long shallow, cut-and-cover tunnel versus twin, 21-ft (6m) diameter machine bored tunnels, and (3) a 1,020-ft (311m) long sequentially excavated hillside tunnel versus a deep cut and cover tunnel. This paper describes the pros and cons of each concept from design, construction risk, cost, and schedule perspectives, and concludes the recommended best practices for planning of urban short tunnels.

1 INTRODUCTION
There are a number of different construction methodologies available for short tunnels in urban areas, which include cut-and-cover, sequential excavation method (SEM), and jacked box tunnels. Among these options, only the cut-and-cover method requires installation of a shoring system along the entire tunnel alignment, and constructs tunnels using temporary top-down/bottom-up open excavation methods during construction. Other tunneling methods, at the most, only require temporary open excavations at the ends of the tunnel segment (i.e. launching and receiving shafts for tunnel boring machines (TBM), portals for SEM, or jacking pits for jacked box tunnel launching). Cut-and-cover tunnels may also require complex traffic management and weekend closures during shoring installation, while other tunneling methods may require extensive ground improvement in soft ground conditions.

Jacked box tunneling and SEM tunneling can be performed within tight spaces where site constraints forbid the use of TBM or cut and cover techniques. However, both methods require skilled constructors with specialized experience, and have their own limitations; for SEM tunnels, the ratio of tunnel depth to width of excavation could be critical; and, a curved alignment would likely preclude jacked box tunneling.

Typically, TBM bored tunnels are not an economical solution for short tunnels mainly because of the machine cost, the lead time for delivery, and the required length of trailing gear. However, if a TBM is already available and paid for from other sections of the same or a nearby project, a TBM bored tunnel option can provide an effective and efficient solution. Also, due to recent advances in TBM technology, the TBM option often offers the least potential for third party impacts among these options.

Four tunneling options for short, urban tunnels (i.e., jacked box, cut-and-cover, SEM and TBM bored tunnels) are compared in the following three case studies:

(1) a 270-ft (82m) long jacked box tunnel versus a staged, deep cut-and-cover construction;
(2) a 1,350-ft (411m) long shallow cut-and-cover tunnel versus twin bored tunnels with shallow ground cover; and
(3) a 1,020-ft (311m) long sequential excavation method (SEM) hillside tunnel versus a relatively deep cut and cover tunnel in residential areas.

Comparative analyses have been performed for each case using a simplified (high-level) qualitative risk assessment. The results of these analyses are then discussed, and best practices for planning of short, urban tunnels are recommended considering the pros and cons of each methodology from design, construction risk, cost, and schedule perspectives.

2 PROJECT CASE STUDIES
Three recent design-build projects that contain a relatively short tunnel segment are reviewed in this paper. For each case, the baseline tunnel methodology prescribed in the owner’s Request for Proposal is compared with the alternative methodology suggested by the authors. Please note that for ease of comparison, the structure geometries and ground conditions presented have been simplified and only one overall or critical section is shown.
2.1 Case 1: A 270-ft (82m) Long Jacked Box Tunnel versus a Staged, Deep Cut-and-cover Construction

**Project Information:** The majority of a new passenger rail alignment is planned inside a below grade, open trench in an urban area. A small section (less than 300 ft)(91m) of the trench will intersect an existing busy highway embankment, and a full traffic closure is not allowed in accordance with the government agency’s design criteria. A reinforced concrete jacked box tunnel is planned below the highway embankment and immediately adjacent to an existing bridge overpass (with pre-stressed concrete box girders). The alignment is relatively straight and very gently dipping in this section. Land acquisition and space is available on both sides of the embankment, and can be used for jacking and receiving pit construction. A general site plan for Case 1 is shown in Figure 1.

The adjacent, existing bridge is relatively new, and designed in accordance with recent codes. Although abutment replacement is not economical, underpinning of the bridge abutment is considered feasible.

Based on available geotechnical information, tunnel construction will encounter competent overburden soils (mostly silty and sandy deposits) that extend much deeper than the planned tunnel invert elevation. The groundwater level is at least 20 ft (6m) below the tunnel invert elevation, in normal conditions. The ground conditions are suitable for improvement, but this would be costly due to the deep depth (>75 feet)(23m) and large size (>53 feet)(16m) of the tunnel structure.

**Case 1 Baseline Methodology (Jacked box tunnel):**

At its nearest structure position, the top corner of the jacked box is situated approximately 7 ft (2m) behind and 16 ft (5m) below the adjacent bridge abutment footing as shown in Figure 2. Where the jacked box is to be cast and jacked into the existing embankment, the required right-of-way for the planned tunnel will be increased to accommodate the excavation shoring walls, and to allow sufficient working space for construction of the guide walls for the jacked box. There is sufficient space at the jacking and reception sides of the tunnel as shown in Figure 1, and the jacked box method was specified because it could be constructed in close proximity to the existing bridge footings with no traffic disruption.

The jacked box option requires that the structure be jacked under the roadway embankment while the remainder of the box is cast-in-place within open, shored, excavations. Ground conditions (competent and dry) are favorable for jacked box operations. The main benefit of the jacked box construction lies in the minimal disruption to existing highway traffic.

The jacked box can be a monolithic concrete section, though the contractor could also choose to divide the box into two or three segments with “intermediate” jacking stations between segments for ease of installation and alignment control. The length of the structure covers the entire highway right-of-way, and also allows for potential future roadway widening. The baseline construction procedure is shown in Figure 2.

**Case 1 Alternative Methodology (Cut-and-cover):**

An alternative cut-and-cover approach was also considered. This option requires the installation of a rigid vertical shoring system from existing grade, placement of temporary decking, top-down excavation, followed by cast-in-place tunnel construction, and backfilling to the surface. By switching the staging areas from one side of the lane to another, this alternative maintains the use of three lanes of traffic in both directions at all times during construction. In the event of any movement in the abutments, there is sufficient access available from the open cut excavation for corrective measures to be implemented.

The alternative tunnel construction sequence is shown in Figure 3. Traffic will initially be re-routed from the westbound lanes by shifting one westbound through lane across the median on to the existing eastbound roadbed. The westbound inside shoulder and the inside and outside eastbound shoulders will facilitate the movement by shifting the traffic south toward the eastbound lanes. Once construction below the westbound lanes is completed, similar traffic management will be performed to allow construction below the eastbound lanes.

The main benefit of the cut-and-cover construction is better ground deformation control. When bracing is closely spaced and preloaded, ground movement and...
deformation of adjacent structures should be minimal. However, some traffic disruption is inevitable.

It is also possible to use the rigid shoring system as the side walls of the permanent structure, in addition to providing temporary support of excavation. This approach was not considered acceptable due to concerns with water tightness and durability of the permanent structure.

2.2 Case 2: A 1,350-ft (411m) Long Shallow Cut-and-cover Tunnel versus Twin Bored Tunnels

Project Information: A new subway line, including twin TBM bored tunnels and underground stations, is planned beneath a major metropolitan (downtown) area. At the end of the bored tunnel section of this new alignment, a TBM reception pit (shown in Figure 4) will be constructed and will later form part of a new cut-and-cover tunnel that will run underneath a busy retail street between for approximately 1,350 ft (411m) to connect to an existing subway station. The interface of the planned bored and cut-and-cover tunnel sections are located at a major street intersection at a depth of approximately 50 ft (15m). Several utilities run above and parallel to the tunnel alignment. An existing abandoned tunnel also intersects the new tunnel within this final segment of the alignment.

A general site plan for Case 2 is shown in Figure 4.

The adjacent properties consist of hotels, offices and retail shops. Therefore, surface construction that may disrupt street traffic (or result in closure) will have to be performed on weekends.

Based on available geotechnical data, the tunnels will be excavated in mixed-face conditions, with overburden soils (mostly fill and alluvium) encountered in the upper tunnel envelope, soft rock in the lower envelope, and competent bedrock at the tunnel invert. Groundwater and perched water are expected (above tunnel crown) as well as gassy ground during tunnel construction.

Case 2 Baseline Methodology (Cut-and Cover Tunnel): The reinforced concrete cut-and-cover tunnel for this new subway line is an extension of the twin bored tunnels of the same alignment. Each of the twin bored tunnels require approximately 21-ft (6m) diameter to satisfy the code and operation requirements. Therefore, the size of the tunnel box is governed by the bored tunnel arrangement.

A 70-ft (21m) wide reception pit for an Earth Pressure Balance (EPB) tunnel boring machine is planned at the interface of the cut and cover and bored tunnels. The depth from the ground surface to the bottom of excavation (BOE) ranges from approximately 48 ft to 53 ft (15m to 16m). The cut-and-cover method was selected because of anticipated conflicts with existing tie-backs along this part of the alignment, existing utilities, the presence of an abandoned tunnel, and because the relatively shallow excavation depth provided shallow ground cover for a bored option.

However, many major financial businesses, retail stores, and hotels are located immediately adjacent to this final tunnel segment. Therefore, project specifications required that the shoring system and decking installation for the cut-and-cover tunnels, and material hauling and delivery during excavation, could only occur during non-business hours. Traffic detours would have to be implemented during the majority of the duration of cut-and-cover tunnel construction.

In general, the distance between the planned shoring walls and right-of-way/adjacent properties ranges between 20 ft and 35 ft (6m and 11m) along the planned alignment. However, at its nearest position, it would be less than 10 ft (3m). The widest section of the tunnel is located at the TBM reception pit (see cross-section A-A’ in Figure 4). The baseline construction sequence is shown in Figure 5.
evaluated. A very gentle change of tunnel profile is considered feasible to increase ground cover, if required, along the alignment.

Bored tunnels will be lined by 10-in (25cm) thick precast reinforced concrete segments (6,500 psi, 45MPa concrete), the same as other bored tunnel sections of this project. A typical section of twin bored tunnels is shown in Figure 6. The advantage of this option is that the TBM is already available for this project as well as segment casting facilities, and less traffic disruption is anticipated. In addition, some complex utility re-locations can be avoided. However, the disadvantage is the shallow ground cover, the short pillar distance between the twin tunnels, and the close proximity of the existing structures and potential obstruction. Ground improvement may be required where the center pillar becomes extremely narrow and where obstructions (i.e. tiebacks) are present. Tunnel centerlines can be pushed cut up to 5 ft (2m) at each side (since shoring is not required for the majority of the alignment) so that at least one tunnel diameter pillar width is available. It is anticipated that several temporary excavation pits extending to a depth of around 50 ft (15m) with shoring and underpinning systems will be required to support, demolish, and re-route the existing utilities and tunnel. (On the other hand, the cut-and-cover tunnel approach will expose these items during shoring and excavation, and can support any utilities in-place or demolish the existing tunnel as needed). In addition, where major and high-risk utilities are buried above the tunnel crown, mitigation measures such as jet grouting and/or compensation grouting are likely required prior to tunneling. Ground improvement at critical utility locations are feasible due to the presence of in-situ granular soils.

Sometimes, rather than twin bored tunnels, it is also possible to utilize a larger TBM/bored tunnel, and stack both tracks inside one tunnel. However, due to the shallow cover and mixed-faced condition, the single bored tunnel option is not considered as an alternative here.
Case 3 Alternative Methodology (Cut-and-cover with Arched-roof): Instead of the SEM approach, a cut-and-cover tunnel can be considered as an alternative for this section of the tunnel. An arched cut and cover tunnel geometry is shown in Figure 8.

The sequence of construction for this cut-and-cover alternative is very similar to that of Cases 1 and 2. This tunnel structure geometry is fairly uniform and is over 1,000 ft (305m) long. An arch roof can be considered to reduce the roof and more importantly wall thicknesses (in order to keep the excavation and shoring system within ROWs). However, the cut-and-cover approach may require building the tunnels in small sections with multiple surface stages; temporary decking for traffic; temporary easement agreements with adjacent properties, or even acquiring adjacent properties (or nearby high-risk facilities). Among these three case studies, this tunnel has similar deep tunnel invert elevations (as Case 1) but this tunnel extends into more competent bedrock with the invert at approximately 70 ft (21m) below existing grade. Therefore, the cut-and-cover approach may not be the most economical solution. For the cut and cover option, sometimes it could become more attractive if the planned tunnel vertical profile can be adjusted (flattened). In this particular case, the allowable adjustment is very limited.

3 COMPARATIVE ANALYSES USING SIMPLIFIED QUALITATIVE RISK

An evaluation of foreseeable potential risks and impacts associated with each case study has been performed and provided in Figures 9 through 11. Seven evaluation criteria including 16 potential risk items are considered. It should be noted that weighting factors or values between each item are not considered and only relative degrees of risk impacts (i.e., “High”, “Medium” and “Low”) between the baseline and alternative tunnel methodologies for each case have been evaluated. This simplified qualitative risk assessment can be a useful tool to compare different alternatives and make a preliminary decision at early planning stages.

3.1 Case 1 Evaluation

Both design alternatives have similar challenges, particularly with potential movements of the existing bridge abutments. The entire tunnel structure will be built in unsaturated overburden soils and hence face stability and ground loss during tunneling can be the most critical concern for the jacked box tunnel option. In addition, the close proximity to adjacent structures can limit the jacking process. Therefore, an intermediate jacking station(s) for the new jacked box, and ground improvement at the existing structure and at the tunneling face during the jacking operation are required for the jacked box option. Considering these risks during construction, the cut-and-cover tunnel option was selected as the recommended and preferred tunneling option in this case.

By selecting the alternative cut and cover option, most of the high risk items are mitigated and the level of residual risk is reduced.

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<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Baseline (Jacked Box)</th>
<th>Alternative (C &amp; C)</th>
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<tbody>
<tr>
<td>Design and Construction Difficulty</td>
<td>Constructability/construction risks</td>
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<td>Design effort</td>
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<td>M</td>
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<td>Geotechnical Constraints</td>
<td>Ground conditions</td>
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<td>Disruption to Communities</td>
<td>Residence/business impact</td>
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<td>Traffic Disruption/impact</td>
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<td>M</td>
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<tr>
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<tr>
<td>Environmental Impacts</td>
<td>Noise/vibration/dust</td>
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<td>Visual/aesthetic issues</td>
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Figure 9. Case1 Risk Impact Comparison (H: High, M: Medium, L: Low)

3.2 Case 2 Evaluation

Along the final tunnel alignment, tunnels need to be constructed within existing ROWs. There are many major utilities to be relocated or supported in-place. Multiple construction stages will be required to enable cut-and-cover tunnel construction. However, with shallow ground cover, a narrow center pillar width, and tunneling in mixed face conditions, it is anticipated that significant ground improvement will need to be performed above and between the twin tunnels. In addition to the cost and
schedule for additional ground improvement, these activities will also require street closure and traffic disruption, which will defeat the main advantage of the bored tunnel option at this site. In addition, several temporary excavation pits with deep shoring systems (or SEM mining sections with ground improvement) are still required for the TBM reception pit and demolition of the existing tunnel and tiebacks. The bored tunnel option is deemed to have higher third party impacts and construction risk due to the mixed face ground conditions with groundwater inflows, and the potential presence of obstructions. Therefore, the baseline cut-and-cover approach is still the preferred solution.

4 RECOMMENDATIONS AND CONCLUSIONS

No tunnel construction approach is risk-free, especially in urban areas, as discussed in this paper. Every tunnel construction carries a certain type and degree of risk for all parties involved. Based on the review of these three design-build tunnel cases, it is evident that although project schedule and cost are two of the more important factors for selection of the tunneling method, they may not be the only governing factors driving selection of the tunneling means and methods. Third-party impacts, such as traffic disruption, ground deformation, damage to existing structures, noise and vibration, and durability considerations (for long term maintenance cost) take a significant role in the decision making process.

It should be pointed out that tunnel ventilation requirements (and also fire, life and safety regulations) could also be one of the important factors when considering feasible tunneling methods. The National Fire Protection Association (NFPA) 130 requires mechanical emergency tunnel ventilation system be installed for rail tunnels with a length greater than 1,000 ft (305m). In urban areas, if tunnel configuration allows the installation of jet fans and/or air plenum, then most of tunneling methods are feasible. If tunnel interior space is limited, and ventilation shafts (and emergency exits) are required for tunnels in excess of 1,000 ft (305m), then cut-and-cover or SEM approach could be more advantageous in urban areas. It should also be noted that mandatory tunnel ventilation study should be performed for tunnel lengths between 200 ft and 1,000 ft. (61m and 305m) to confirm project-specific ventilation requirements (i.e. tunnel space). These criteria should be reviewed during tunnel initial planning stage, and as part of the risk impact analyses.

From these three case studies, cost and schedule are not the only decision making factors. Because of unique, project specific conditions, when determining the tunneling method for short urban tunnels, during the planning stages a comparative analysis using a risk assessment process should be conducted for selection of the tunnel alignment, the vertical profile, and the tunnel construction methods. Some important aspects of the project such as constructability, environmental impacts, third party impacts, cost and schedule, and design/construction risks and their mitigation strategies should be considered throughout the risk assessment process for the selection of the construction methods for the “short tunnels” in urban areas. A third party outreach program should be conducted during this assessment process to bring all parties on the same page.

Finally, durability aspects such as design life and requirements for water and gas tightness, as well as tunnel operation and maintenance costs, should also be considered in the tunnel type selection (i.e. tunnel lining.
Because tunnels usually have a design life in excess of 100 years, urban tunnel repair/rehabilitation will have significant adverse impacts to the public (from a cost and schedule standpoint as well) in future.

5. REFERENCE
