



FINAL DRAFT Geotechnical Design Memorandum #02 - Underground Excavation Methods – Rev A

GPC6, C2012668-02 Task Order #39 Dallas CBD
Second Light Rail Alignment (D2 Subway)

FINAL DRAFT

Dallas, TX
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1 EXECUTIVE SUMMARY

This geotechnical design memorandum (GDM) summarizes feasible underground excavation methods for planned running tunnel and mined station cavern structures for the DART D2 Subway Extension. The evaluation of suitable excavation techniques was based on consideration of ground conditions, tunnel alignment and potential impacts to existing infrastructure obtained from currently available project-specific data, including geotechnical data and as-built construction records.

Subsurface (hydrogeological and geotechnical) conditions are among the deciding factors for selecting an underground construction method. Other considerations include alignment (plan and profile); geometries of underground openings; underground obstructions including overlying and adjacent utilities, facilities, and deep foundations, and overall tunnel alignment length. For shorter tunnels, construction following the principles of the Sequential Excavation Method (SEM) normally has an economic advantage. For

transportation tunnels of one to two miles, and longer, tunnel construction utilizing a Tunnel Boring Machine (TBM) is usually considered advantageous from the economic point of view.

The DART D2 extension project is a planned light rail scheme within the central business district of Dallas, Texas. This area is known for the Austin Chalk formation, which is generally massive in nature with few discontinuities and low compressive strengths. The combination of low compressive strength and massive nature of the formation makes it an ideal medium for a sequential excavation with a road header as demonstrated by recently completed excavations for the DART City Place Station and for the Addison Toll Road Tunnel. Also, the subsurface conditions make it compatible for excavations by TBMs where high advance rates of excavation could be accomplished due to low strengths of the rock provided the alignment in plan and profile is conducive to TBM operation. Thus grades preferably less than 5%, horizontal curve radii greater than 400 feet and sufficient rock cover, usually one tunnel diameter, over the crown of the tunnel.

SEM tunneling is a very flexible construction method with respect to excavation, means of rock support, face support, and required auxiliary measures. Excavation sequences, enlargement of excavation profiles for allowing displacement of the surrounding rock mass, subdivision of headings, amount and means of rock support can be adapted rather easily and quickly to the actual ground conditions encountered. Additional measures built at the heading face (e.g. grouting, dewatering, installation of pipe roof umbrellas or spiles, shotcrete lining with yielding elements) can cope with adverse conditions such as fault zones. Further, using SEM tunneling, the shape of the profile can be adapted to the clearance profile and space needed for future installations (e.g. tunnel ventilation, cable ducts, drainage pipes etc.). SEM tunneling, however, is a multi-pass system; it requires installation of initial support, waterproofing system, and final support (liner).

In TBM tunneling, installation of additional measures at or above the cutter head is possible, but limited due to space constraints and limited openings within the cutter head and shield. Identified fault zones or zones with expected unfavorable rock mass behavior may cause delays to TBM drive if not explored ahead of time and mitigated. Also, TBM tunneling produces a circular shape tunnel and thus produces somewhat of a larger cross section than that of a SEM tunnel and this results in a larger cross-sectional area and thus more muck volume and may require marginally larger horse power requirements for ventilation fans.

On a positive side, TBM could provide one-pass liner system by using precast concrete segmental liner as the final tunnel structure. Waterproofing of the liner is achieved by providing gaskets between the segments that seal the tunnel and permanently preventing the groundwater intrusion in a completed tunnel facility.

In terms of construction schedule features, TBM method is expected to have higher daily advance rates than SEM. The construction schedule, however, needs to allocate TBM procurement time to order, design, manufacture, deliver and assemble a TBM on site. The procurement time for SEM equipment is significantly shorter. All the above considerations would need to be evaluated for advantages and limitations of the different construction methods considered for the DART D2 project. Ultimately, the tunnel construction method should be left to the design build contractor.

Recommendations for 20% preliminary engineering design are provided in Section 8 of this report.

2 INTRODUCTION

The DART D2 extension project is a planned light rail scheme in the center of Dallas, Texas. With planning beginning in 2007, recent developments have resulted in the approval of the 'D2 Subway Locally Preferred

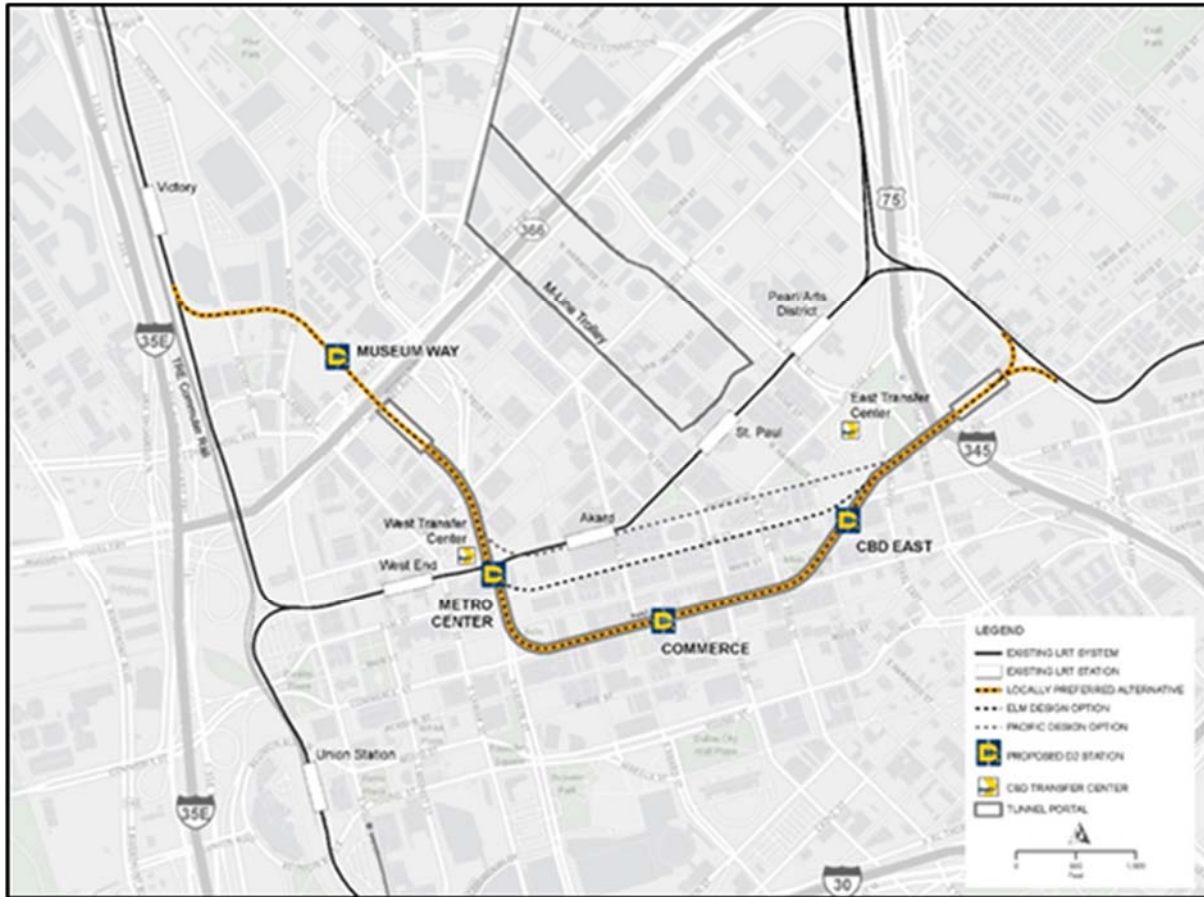


Alignment (LPA)' in September 2017. The LPA alignment runs from Victory Park to Deep Ellum via Commerce Street and downtown Dallas. At the time of this memorandum, the alignment includes at-grade, open cut, cut-and-cover, and mined tunnel construction. The mined tunnel section through downtown Dallas includes at least one underground mined station and twin running tunnels between the open cut sections. It is noted that the configuration of underground openings, and method of their construction may be revised in the future as the alignment profile is being finalized.

2.1 Project Description

The Dallas Central Business District (CBD) DART Second Light Rail (D2 Subway) Locally Preferred Alignment (LPA) which includes east and north portals, twin bored tunnels, one mined cavern station and two cut-and-cover transit stations totaling approximately 6250-ft and was revised March 8, 2019 to include south of Swiss alignment (**Figure 2-1**). The alignment contains at-grade, open cut, cut-and-cover, and mined tunnel construction. The stations are configured as center platform layout.

FIGURE 2-1. DART D2 SUBWAY PROJECT LOCATION PLAN



The purpose of this memorandum is to provide feasible underground excavation methods to be considered for design of running tunnels and mined station cavern structures for the project. Project-specific DART D2 subsurface investigations were performed 2016 and 2019. A draft Geotechnical Data Report was issued by Alliance Geotechnical Group in February 2016.

There are several different construction techniques that can be used for the execution of underground structures, however, several factors must be considered before choosing the most appropriate tunneling method for this project. For instance, the horizontal and vertical alignment, structure configuration, geologic profile, tunneling in soft-ground, mixed face or rock and associated ground behavior, groundwater inflow, underground obstructions, as well as, impacts of underground construction on existing infrastructure all play a role in the decision-making process. This memorandum describes the different construction techniques commonly used for tunneling in dense urban environments and evaluates advantages and limitations of different tunneling methods considered.

2.2 Scope

The scope of this memorandum is a preliminary engineering evaluation of excavation techniques for planned running tunnel and mined station cavern structures to support 20% design level.

2.3 Assumptions

This memorandum has been prepared using the following assumptions and inputs:

- The project alignment is as provided on March 8, 2019 (an updated alignment will be issued by the end of July 2019)
- The project alignment includes consideration of 9 existing adjacent buildings and their foundations (as of July 2019 the effort to identify affected subsurface structures and foundations along the alignment corridor is still undergoing)
- Ground conditions are based on data presented in the February 28, 2019 Draft Geotechnical Data Report prepared by Alliance Geotechnical Group (as of July 15, 2019, the Final Geotechnical Data Report is still pending)
- Commerce Station location is between STA 71+13.15 and STA 77+38.15 (in July 2019 it is expected that the station location will be adjusted to the west by approximately 350 feet as part of an updated alignment that would be issued by the end of July 2019).

2.4 Design Assumptions

This GDM assumes the latest project alignment based on 10% Design South of Swiss Alignment dated March 8, 2019.

Design assumptions include: prohibition on blasting, restrictions on trucking along Commerce Street, running tunnels are undrained, maximum 6% vertical grade at east and west portal approaches.

Construction assumptions: The portal approaches will be U-section structures, portals will be built using cut-and-cover

The current phase of the geotechnical field investigation program has been completed, and the project's Draft Geotechnical Data Report (GDR) dated February 28, 2019 was issued. Laboratory testing of representative samples is currently in-progress. Upon completion of review and verification the laboratory testing results, the GDR will be updated to incorporate the latest testing data results.

3 METHODOLOGY AND GENERAL CONSIDERATIONS

3.1 Approach

The decision-making approach for selecting the most appropriate method(s) for the running, single track tunnels and station construction is dependent on the following factors: knowledge of the ground conditions, the tunnel alignment, and impacts on the existing infrastructure. The evaluation of feasible tunneling methods was based on review of existing available geotechnical investigations, presence of adjacent and overlying structures, existing subsurface obstructions, excavation impacts to the existing infrastructure, and consideration of prior nearby tunneling experience in similar ground conditions.

3.2 Geology

The general subsurface stratigraphy consists of successive layers of surficial fill overlying alluvial materials consisting of sand and interbedded clay. Below the alluvial material, the Austin Chalk is present. Based on the 10% Design South of Swiss alignment dated March 8, 2019, excavation of underground structures will be primarily located within the Austin Chalk. Austin Chalk is generally referred to as a medium hard to hard limestone rock formation. The Eagle Ford Shale underlies the Austin Chalk Formation. A summary of the geologic strata within the project vicinity is provided in **Table 3-1**.

TABLE 3-1. SUMMARY OF SUBSURFACE CONDITIONS

Units: Feet

Ground Class Group	Ground Class	Approximate Thickness (ft)	Description ⁽¹⁾
Fill	F	5	Manmade intermixed stiff to hard clay with varying amounts of sand and silt with traces of gravel, brick, concrete, and limestone fragments (Huitt-Zollars, 1992).
Alluvium	A1	1-30	Low to high plastic clays and sandy and silty clays (Huitt-Zollars, 1992) and sandy clay.
Alluvium	A2	0 - 14	Cohesionless material ranging from silty sands to sand and gravel (Huitt-Zollars, 1992) and clayey sand.
Residual Soil	RS	0	Overlying Austin Chalk; completely decomposed limestone that exhibits a rock-like fabric. All rock material is converted to soil. Recovered with soil sampling equipment; drive samples generally possible. No visible rock fabric or structure.
Weathered Rock	IGM	1 – 10	Highly to completely weathered limestone or shale (ISRM Weathering Grades IV and V). Rock core Recovery < 50%; SPT N-value >50/6". Original rock mass structure largely intact. Includes "Fish Bed Conglomerate, basal pebbly beds, reworked fossils and pebble-to cobble-size fragments of chalky limestone (HNTB, 2016). Includes transitional arenaceous, fossiliferous zone (Collier, 2015). Includes tan, highly weathered limestone of variable thickness; very soft to soft with occasional to frequent interbeds of tan silty clay and clay seams (Huitt-Zollars, 1992). More than half of the rock material matrix is weathered to a soil (Weathering Grade IV) or all rock material is decomposed and disintegrated to soil (Weathering Grade V). Fresh or discolored rock is present either as a discontinuous framework or as corestones (Weathering Grade IV).

Ground Class Group	Ground Class	Approximate Thickness (ft)	Description ⁽¹⁾
III	L-III and S-III	0 – 10	<ul style="list-style-type: none"> • L-III: Predominantly limestone with some shale. • S-III: Predominantly shale with some limestone, mudstone, and sandstone. • RQD = 50% to 90% (typical) • Fracture spacing less than 2 feet ⁽²⁾, or • Multiple sets of slickensided, polished fracture surfaces, or • Multiple planar weakness zones with fillings or disintegrated rock or alteration products less than 6 inches thick, or • A single planar weakness zone with filling greater than 6 inches thick, or • Less than half of the rock material matrix is weathered to a soil • Moderately blocky to very blocky and seamy ⁽³⁾
II	L-II and S-II	0 - 60	<ul style="list-style-type: none"> • L-II: Predominantly limestone with some shale. • S-II: Predominantly shale with some limestone, mudstone, and sandstone. • RQD = 50% to 90% (typical) • Fracture spacing 2 to 6 feet (2), or • One set of slickensided, polished fracture surfaces present within the excavation horizon, or rock or alteration products less than 6 inches. • Moderately blocky ⁽³⁾
I	L-I and S-1	39 – 65	<ul style="list-style-type: none"> • L-1: Predominantly limestone with some shale • S-1: Predominantly shale with some limestone, mudstone, and sandstone. • Generally, RQD > 90% • Fracture spacing greater than 6-ft (2), and • Joint surfaces range from rough or irregular to smooth and planar, and • Fracture surfaces are unaltered to slightly altered, with non-softening mineral coatings, and • No obvious planar weakness zones with alteration products.
Bentonite	B	0 – 1	<ul style="list-style-type: none"> • Bentonite and bentonitic shale in vertical thickness greater than or equal to 6 inches.

NOTES:

(1) ISRM Weathering Grades are from International Society for Rock Mechanics, 1981, "Suggested Methods for the Qualitative Description of Discontinuities in Rock Masses," in ISRM Suggested Methods: Rock Characterization, Testing and Monitoring, E.T. Brown, editor, Pergamon Press, Oxford, p. 31.

(2) For fractures with minimum persistence of 3 feet.

(3) Terzaghi rock mass description from Proctor, R.V. and T.L. White, 1968, Rock Tunneling with Steel Supports, Revised, Commercial Shearing and Stamping Company, Youngstown, Ohio.

3.3 Adjacent and Overlying Structures

Buildings on either side of Lamar Street are low rise frame structures, except for the Rosa Parks Plaza tower between Elm and Main streets, and the Bank of America building and tower between Main and Commerce streets. The latter is connected to a parking lot across Lamar Street by means of a shallow underground pedestrian passageway.

As built building foundation surveys of adjacent structures should be conducted during design to protect adjacent structures from being affected.

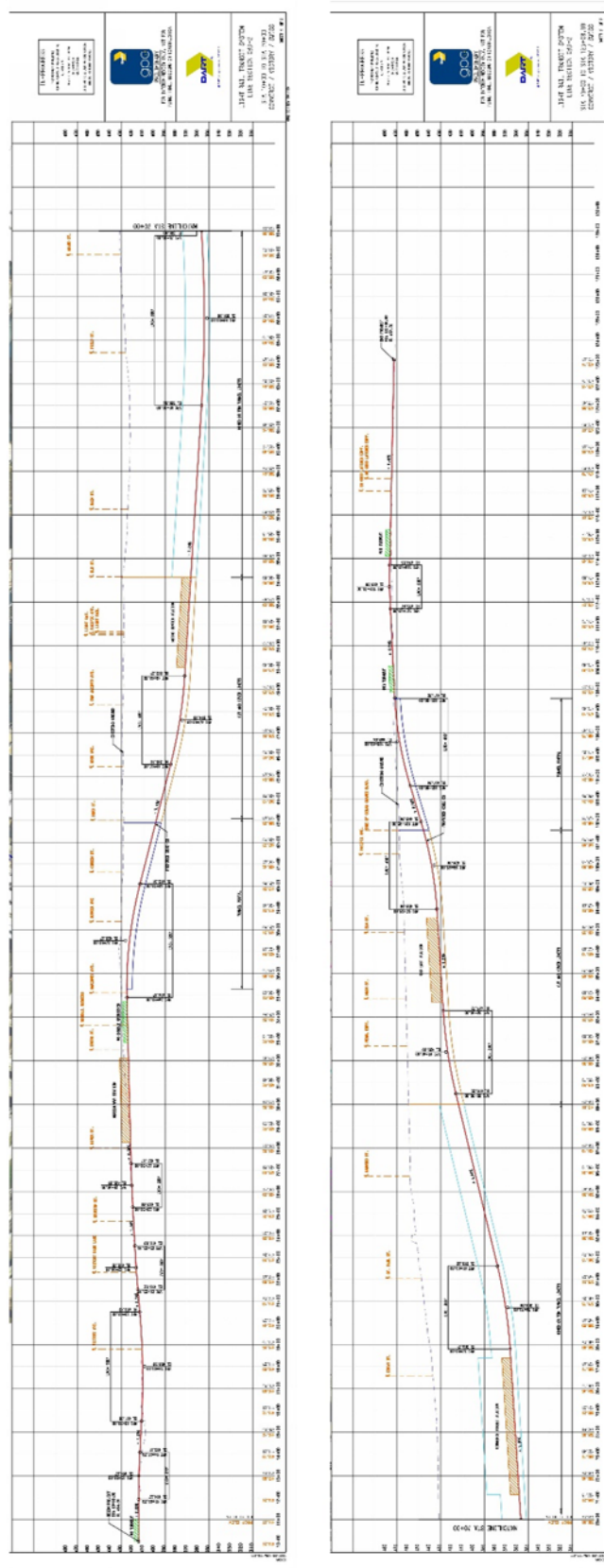
3.4 Project Criteria and Constraints

3.4.1 TUNNEL ALIGNMENT

The tunnel alignment refers to both the plan alignment as well as the longitudinal profile. Key considerations include operational purpose, site characteristics, underground obstacles and ground conditions. A series of alignments have been studied since planning started in 2007 but has since settled on the current LPA with much of the underground section beneath Commerce Street. The LPA was revised March 8, 2019 to include south of Swiss Alignment and to avoid presence of existing Elm Street parking garage pile foundations. The current March 8, 2019 LPA underground section, shown in **Figure 3-1**, extends between Pacific Avenue (approximate Station 100+00) and Elm Street (approximate Station 54+10).

Three underground stations are identified as Metro Center Station, Commerce Street Station and Central Business District (CBD) East Station. The average distance from the surface to track level is 59-ft, with a high of 68-ft and a low of 53-ft. The underground structures are summarized by type and their respective lengths in **Table 3-2**. Specifically, the approximate limits of U-section north and east portal approaches are as follows: Station 35+29 to Station 42+89 (Hord Street) and Station 101+55 (east edge of Cesar Chavez Boulevard) to Station 107+60, respectively. Total length of U-section structures equals 1365-ft. The eastern portion of the underground alignment includes approximately 400 ft of cut-and-cover tunnel sections extend from approximate Station 101+55 to Station 97+54.

FIGURE 3-1. 10% SOUTH OF SWISS LPA TRACK VERTICAL ALIGNMENT FOR UNDERGROUND SECTION



The underground section, as currently depicted, has two pronounced curves in the horizontal alignment on either side of Commerce Station. The radius of the horizontal curve between Commerce Station and CBD East Station is shown in **Figure 3-2**, while the horizontal curve between Commerce Street Station and Metro Center Station is shown in **Figure 3-3**.

As noted before, the configuration of underground openings, and method of their construction is closely related to the adopted project alignment and may be revised in the future as the alignment profile is being finalized.

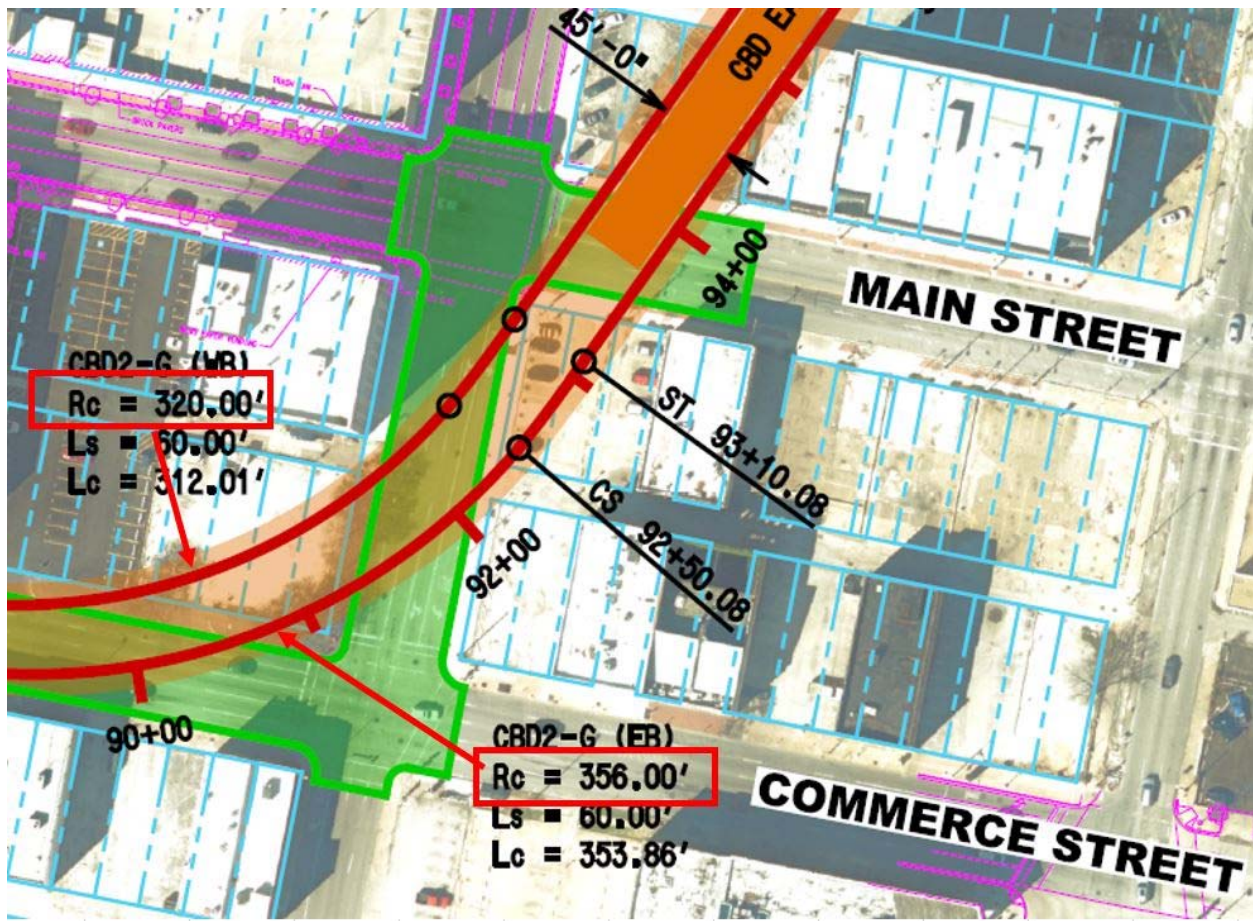
TABLE 3-2. SUMMARY OF UNDERGROUND STRUCTURES

Units: Feet

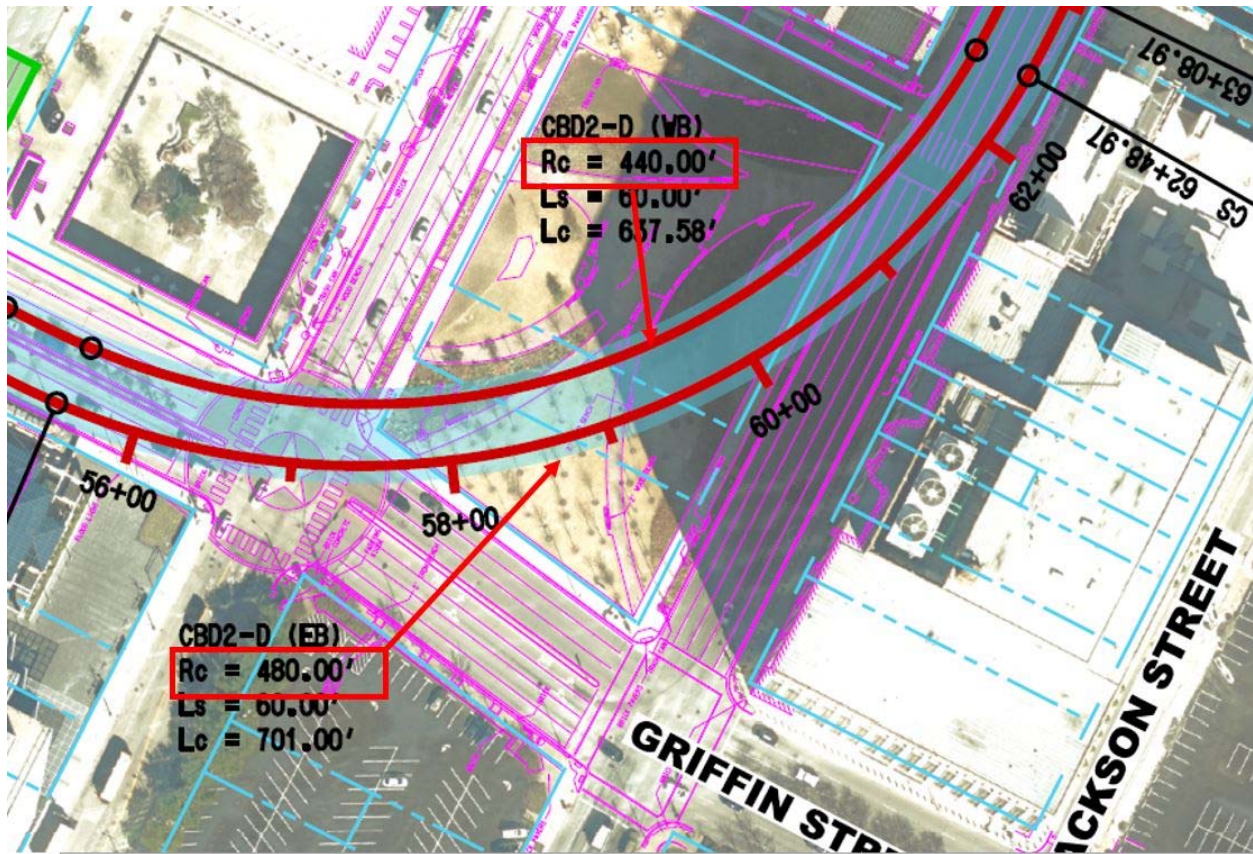
Structure Type (Location)	Station Limits	Approximate Depths (ft)	Total Lengths (ft)
U-section (north portal approach)	35+29 to 42+89	5 to 30	760
U-section (east portal approach)	101+55 to 107+60	0 to 22	605
Cut-and-cover tunnel (north portal)	42+89 to 50+03	30 to 57	714
Cut-and-cover tunnel (east portal)	97+50 to 101+55	22 to 30	405
Cut-and-cover tunnel (west of CBD East Station)	89+00 to 93+69	34 to 45	469
Cut-and-cover box station (Metro Center Station)	50+03 to 54+13	57 to 64	410
Cut-and-cover box station (CBD East Station)	93+69 to 97+54	30 to 34	385
Mined running tunnel	54+13 to 71+13 and 77+38 to 89+00	44 to 74	2862
Mined station cavern (Commerce Station)	71+13 to 77+38	73 to 74	625

For tunnel excavation beneath more densely populated urban areas, the shield TBM tunnel method which employs a single-pass lining system would provide improved ground control and enhanced protection measures for potential presence of gaseous ground conditions. Furthermore, a shield TBM is considered preferable under soft rock conditions because the TBM is driven forward by means of hydraulic thrust cylinders reacting longitudinally against the last segment lining in lieu of gripper pads pushing on the sidewalls of recently bored tunnel (in Austin Chalk). The current 10% South of Swiss Alignment features two pronounced curves in the horizontal alignment of 320-foot and 440-foot as shown in **Figures 3-2 and 3-3**, respectively which will affect the feasibility of mining methods for the running tunnel. The relatively tight radii of these curves which fall within and/or below “Rule of Thumb” limit corresponding to $15 \times (22'6") = 338$ -ft say 350-ft present key constraints for consideration of shield TBM construction. These tight radii also present operational constraints such as reduced train operating speeds on the order of 20 miles per hour.

FIGURE 3-2. HORIZONTAL CURVE BETWEEN COMMERCE STATION AND CBD EAST STATION (RADIUS = 320 FT)



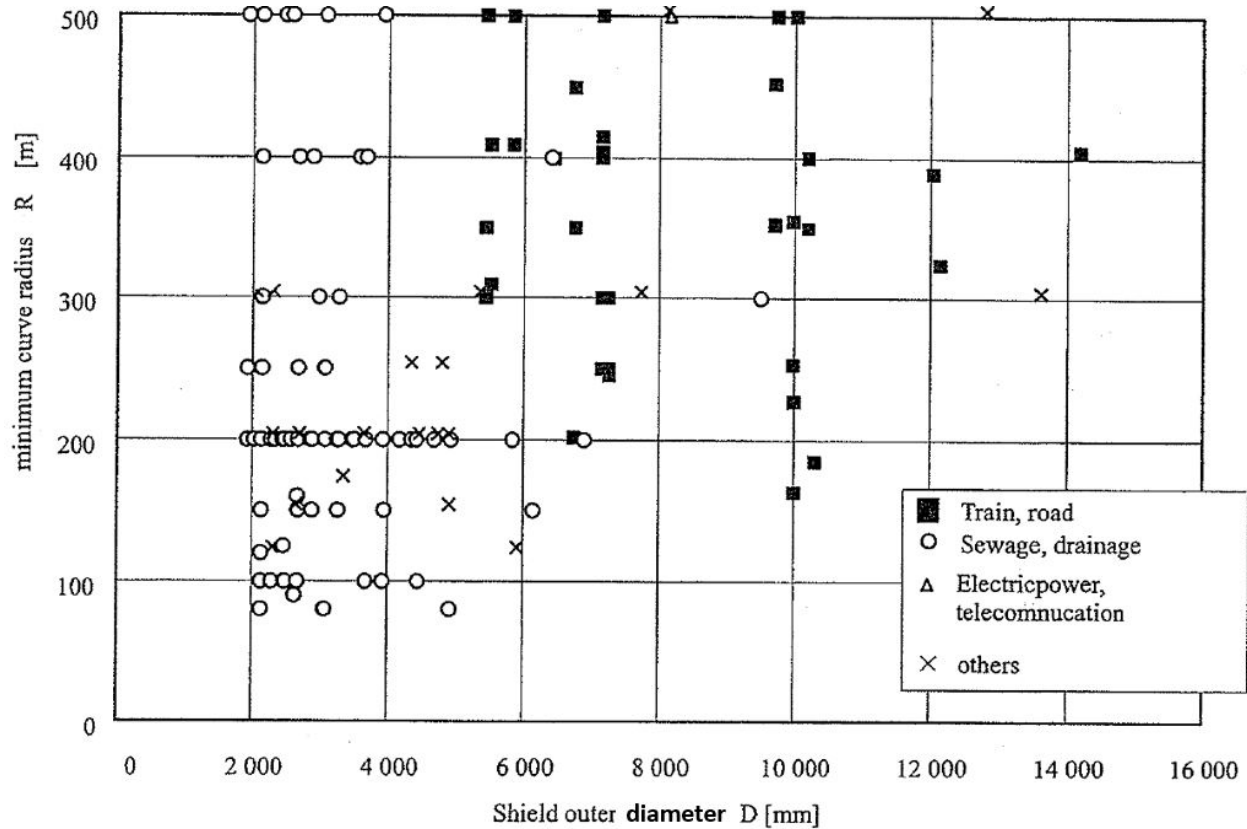
**FIGURE 3-3. HORIZONTAL CURVE BETWEEN COMMERCE STATION AND METRO CENTER STATION
(RADIUS = 440 FT)***



Subject to alignment review and potential revision.

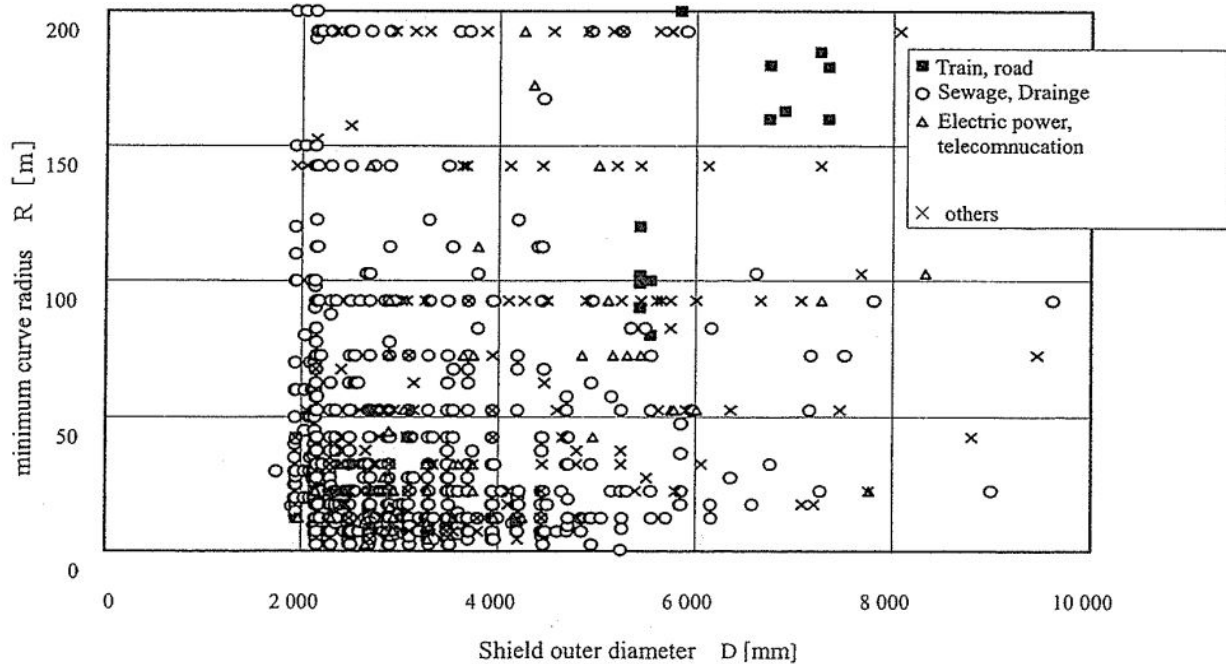
Feasibility assessment of the shield tunnel method for excavation of horizontal curves should consider the type of curve. Specifically, for excavation of ordinary curves, i.e. those with turning radii which can be excavated without using articulated shields or auxiliary methods, the relationship between the minimum radius curve and the outer diameter of the shield is presented in **Figure 3-4**. From this chart, considering a 22'-6" outside diameter equivalent to 6.86 m = 6860 mm would correspond to a minimum curve radius, $R = 200$ m equal to 656-ft.

FIGURE 3-4. RELATIONSHIP BETWEEN MINIMUM CURVE RADIUS AND SHIELD OUTER DIAMETER FOR ORDINARY CURVES (Japan Society of Civil Engineers, August 2007).



For sharp curves, the requirement for ground improvement by chemical grouting, the measurement system for the shield machine, and the type and structure of segments should be carefully studied. "An articulation device may be added in the central portion of the shield to provide flexibility for excavating curved tunnel alignments". **Figure 3-5** provides relationship between minimum curve radius and the outer diameter of shield machines in which articulation has been adopted. As shown for transportation tunnels 160 m corresponding to approximately 524 ft is the minimum curve for anticipated 22'-6" outside diameter shield.

FIGURE 3-5. RELATIONSHIP BETWEEN MINIMUM CURVE RADIUS AND SHIELD OUTER DIAMETER FOR ARTICULATED SHIELDS (Japan Society of Civil Engineers, August 2007).



3.4.2 RUNNING TUNNEL CROSS SECTIONS

The running tunnel cross section has been developed to account for train dynamic and clearance envelopes, construction and mining tolerances, space proofing for future track, rail and facility systems, and operation, maintenance and safety requirements per NFPA 130. The minimum internal diameter is 19'-6", and the tunnel centerlines are spaced at 36'-2". Running tunnels are space-proofed as single-track tunnels.

3.4.3 STATION CROSS SECTIONS

The mined Commerce Station cross section has been developed considering the requirement for a center platform configuration and the respective minimum platform width, vertical circulation elements, and architectural finishes. Station facility systems space-proofing will be developed after the architectural, ventilation/fire life safety systems and rail systems are developed to sufficient level of completion to assure coordinated interdisciplinary review. As of development of this memorandum, the minimum external width to accommodate the track and 26'-10" wide center platform is 61'-4".

Meanwhile, bottom up or top down cut-and-cover construction methods would be considered for shallow alignment conditions at Metro Center Station and CBD East Station. Minimum internal width of the station is 57'-8" to accommodate a 30'-8" wide center platform. This construction method and support of excavation, although disruptive to streets, traffic, utilities, businesses and public, are considered conventional and widely implemented throughout the industry.

3.4.4 TUNNEL PORTALS

The term "Tunnel Portal" refers to both, a location from which a mined tunnel construction may commence and the location where an open or U-section final structure configuration transitions to an underground

alignment. The mined running tunnels will be constructed from a tunnel portal and may commence from either end of the underground alignment in case of the SEM construction, or from a selected portal in case of TBM tunnel construction. The starting location of the mined tunnel is yet to be determined. The portal U-section and cut-and-cover section are contiguous to the mined tunnel (exact locations of differing sections are yet to be determined). For example, the existing DART alignment features a U-section south of Mockingbird Lane Station, shown in **Figure 3-6**, which is immediately adjacent to a mined and final structure portal. By contrast, at the southern end of the DART alignment north of downtown Dallas a mined tunnel transitions into a deep cut-and-cover section and then to a U-section. When determining the location, and depth of the mined tunnel portal, the ground conditions along with the overbuild constraints are primary considerations that need to be considered. Mined tunnel portal considerations are discussed as part of the selection of the tunneling methods.

The limits of the tunnel portal extend from the “headwall” located at the interface between the U-section portal approach and the cut-and-cover portal structure to the beginning of the mined tunnel section. Approximate width and height dimensions at the planned portal headwall locations: 60-ft x 37-ft Hord Street (North Portal) and under Cesar Chavez Boulevard (East Portal) are: 40 ft to 70 ft X 35 ft to 50 ft.

FIGURE 3-6. TUNNEL PORTAL SOUTH OF MOCKINGBIRD LANE STATION

4 TUNNEL CONSTRUCTION METHODS IN URBAN ENVIRONMENTS

There are multiple construction methods available for tunneling in urban settings, each with their respective advantages and disadvantages. The two primary choices for mined tunneling on the DART D2 Subway Extension Project are SEM (by roadheader excavation) and TBM (full-face mechanized tunnel excavation) which minimize surface disruptions and impacts on residents and businesses in dense urban areas. In the past, cut-and-cover techniques were frequently utilized not only for shallow tunneling but also for construction at greater depths. More recently however, surface disruptions and impacts on residents and businesses increasingly deter the use of cut-and cover methods in dense urban areas. Advanced tunneling technology such as conventional – Sequential Excavation Method (SEM) – and full-face mechanized tunneling – Tunnel Boring Machines (TBM) – are more prevalent in urban settings because they allow mining activities to continue while minimizing surface disruption. Generally, access for tunneling is provided from access

points-shafts or from open-cut areas where space for construction staging and support logistics is deemed available.

While full-face mechanized tunneling has made vast advances over the past decades in particular in soft ground and saturated soft ground conditions, it remains predominantly limited to a circular cross section. It is also restrictive in terms of the horizontal alignment configuration, as required minimum horizontal alignment requirements need to be met. For a standard 20-22 feet diameter, TBM the minimum horizontal turning radius exceeds the desired minimum project radius of >400 ft, or so. Special articulation methods and associated demonstration trials would be needed to manufacture a TBM with a turning radius of <400 ft for the desired tunnel diameter.

Meanwhile, conventional or SEM tunneling offers flexibility in tunnel geometry and profile, changes to tunnel support based on in-situ ground conditions, and adaptability when ground cover is limited.

The two choices for mined tunneling for the project are SEM (excavation by drill and blast or roadheader) and possibly TBM (full-face mechanized tunnel excavation) provided 1) minimum required alignment radii for the latter can be provided; 2) maximum practical alignment grade is met (5% or so). Sufficient soil cover must be available over the crown of the tunnel to minimize ground deformations/settlements, and alignment must be positioned to avoid or sufficiently clear underground obstructions including major utilities of adjacent or overlying underground facilities.

Apart from the method of excavation, the tunneling methods are also characterized by the structural lining for temporary and final ground support. Generally, a distinction is made between a temporary (initial) and permanent (final) tunnel support. While SEM tunneling usually features both and include waterproofing system between the two types of supports, a TBM drive may utilize a dual-pass or single-pass system; the latter is more likely to be used and features gasketed pre-cast concrete segmental liner installation.

The initial tunnel support will consist of support measures that are installed directly following the excavation. In the prevalent limestone host formation, initial lining would typically comprise rock dowels or rock bolts and a layer of shotcrete. After completion of the initial tunnel support, the surface of the initial lining is prepared for waterproofing installation with a smoothing layer of unreinforced shotcrete. Once the waterproofing installation is completed, the final tunnel support is installed. This can be considered a dual-pass support system.

Meanwhile, a single-pass support system consists of a pre-cast segmental lining that is installed with select TBMs. Waterproofing of pre-cast segments is achieved with gaskets installed along the perimeter of the individual segments. Water-tightness is achieved by compressing the gaskets between individual segments both in the circumferential and longitudinal directions.

4.1 Sequential Excavation Method (SEM)

The basic principle of SEM tunneling is to develop the maximum self-supporting capacity of the ground by mobilizing the strength of the surrounding ground.

SEM tunneling involves sequential excavation of the ground directly followed by a prescribed installation of the initial support. It consists of limited excavation round lengths and multiple headings.

Initial ground support installation in rock involves grouted rock bolts or rock dowels and shotcrete lining installation. Generally, for rock tunneling, it is the intent to develop a reinforced 'rock arch' above the tunnel

crown by the installation of a regular rock bolt/dowel pattern. A reinforced shotcrete layer (minimum 3 to 4-in) is also installed to bridge between rock bolts/dowels and prevent the formation of rock wedges between the individual bolts/dowels. The standard pattern can also be supplemented with localized (spot) bolts/dowels to stabilize observed rock wedges.

Meanwhile, when the 'rock arch' cannot be achieved, a more passive, soft-ground support system is implemented through the installation of a structural shotcrete lining in the order of 8 to 10-in with an invert ring closure depending on the excavation size and geologic conditions. In such cases, lattice girders are commonly used to provide for control of geometry and assure the creation of a structural lining, both in the circumferential and longitudinal direction. Typical tunnel support and sequencing is shown in **Figure 4-1** and **Figure 4-2**, respectively.

If ground conditions require pre-stabilization ahead of the advancing tunnel face, the lattice girders can be used as an abutment for tunnel pre-support spilling. Limiting the excavation size and length of advance will aid in maintaining the self-supporting capability of the ground. Combined with early support installation, the tunnel opening and ground deformations are positively controlled. Upon completion of the initial support, the waterproofing system and final lining is installed (see **Figure 4-3**).

FIGURE 4-1. SCHEMATIC SEM CROSS SECTION

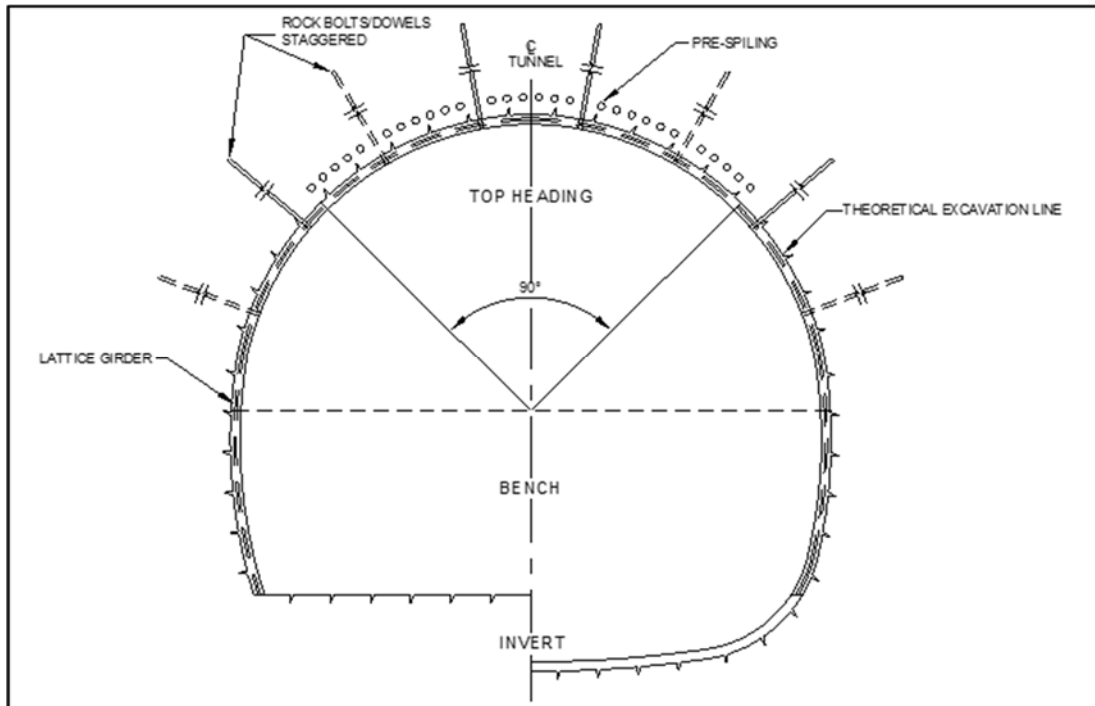


FIGURE 4-2. SCHEMATIC SEM LONGITUDINAL EXCAVATION AND SUPPORT

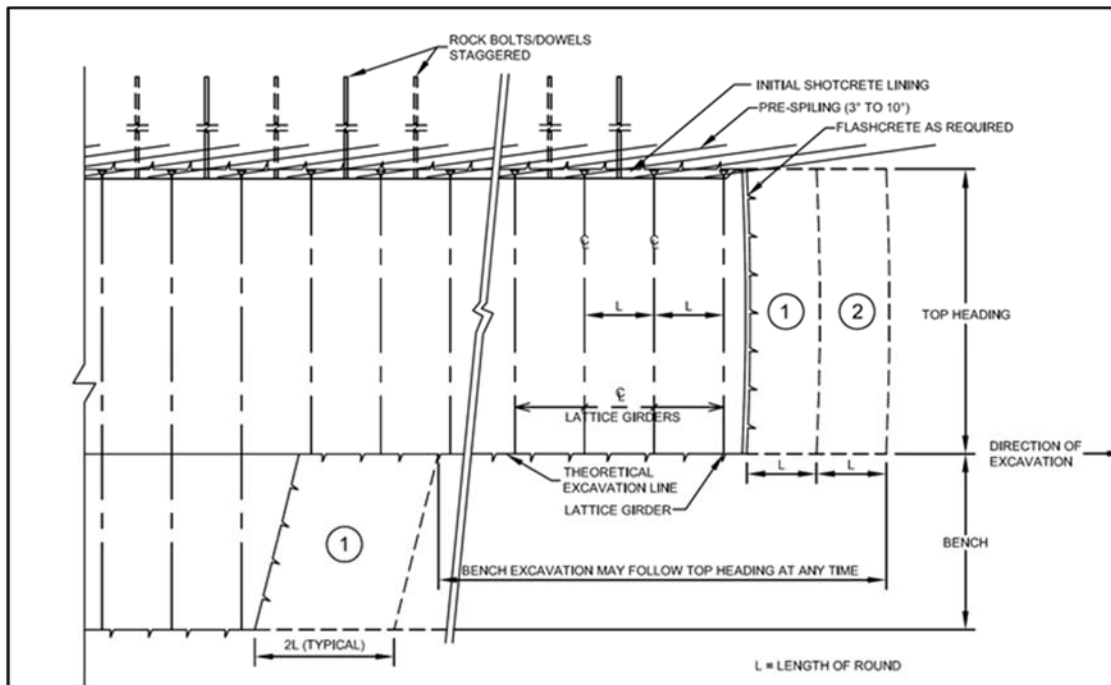
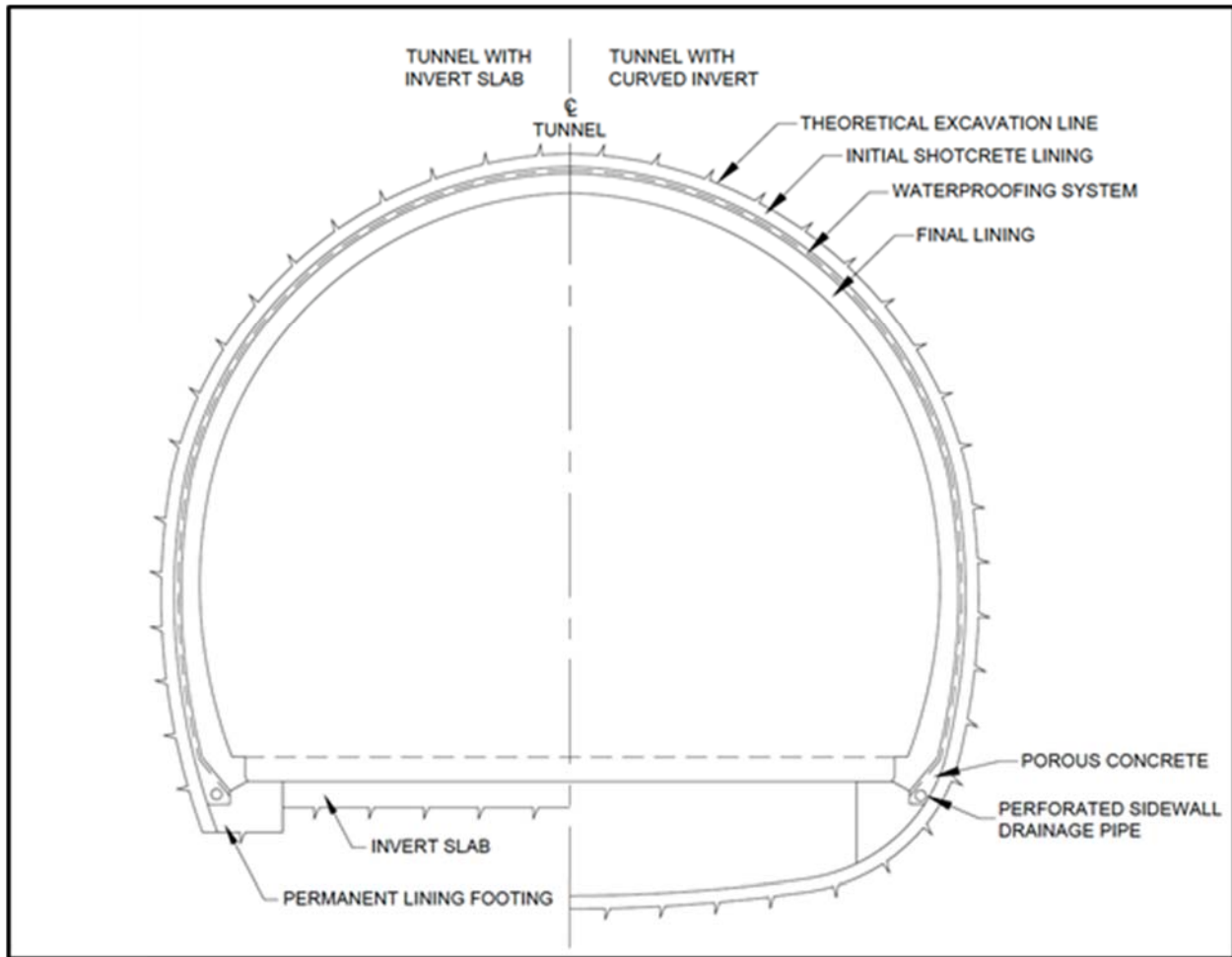


FIGURE 4-3. SCHEMATIC SEM TUNNEL COMPLETED CROSS SECTION



In SEM, tunneling average daily advance rates can reach 30 to 50 ft in favorable rock conditions with peak rates up to 60 ft/day. Even in poor conditions (e.g. in fault zones) 5 to 10 ft/day are possible due to the increased flexibility of the method. Further, SEM tunnel excavation can normally be mobilized within a few months compared to TBM tunneling where machine procurement can take more than one year.

In summary, SEM is a very flexible method with respect to excavation, means of rock support, face support and required auxiliary measures. The amount and means of rock support can be adapted rather easily and rapidly to address the actual ground conditions encountered. Additional measures such as grouting, dewatering, and installation of pipe roof umbrellas can cope with many adverse conditions.

4.2 Tunnel Boring Machines (TBM)

Full-face TBMs utilize a rotary cutterhead to continuously excavate the ground, however, it does not permit direct access to the exposed face as would be available with SEM. TBMs can be designed for excavation in hard-rock, soft-ground or even mixed-faced conditions. For the purposes of this memorandum, only rock TBMs are discussed as these would be utilized for the limestone formation.

Excavation machines can be generally classified into two categories: Gripper and shield based on the machine reaction force. Three common types of rock TBMs are described hereafter:

1. Open Gripper Main Beam TBM (Open Gripper Type)
2. Single Shield TBM (Closed Segment-Shield Type)
3. Double Shield TBM (Closed Gripper/Segment-Shield Type)

It should be noted that these machines would have to be equipped to manage groundwater inflow during construction. Further investigation into the groundwater conditions along the alignment is required as it will have an impact on the TBM selection process.

4.2.1 OPEN GRIPPER BEAM

The open gripper-beam category of TBMs is suited for stable to friable rock with occasional fractured zones and controllable groundwater inflows. Controllable inflows are able to be controlled via pumping through a discharge line to the surface and can be in the thousands of gallons per minute. The major components include:

1. Cutterhead (with disc cutters) and Front Support
2. Main Beam
3. Thrust Cylinder
4. Gripper
5. Rear Support
6. Conveyor
7. Trailing backup system for muck and material transportation, ventilation, power supply, etc.

The front of the gripper TBM is a rotating cutterhead that matches the diameter of the tunnel. The cutterhead holds disc cutters. As the cutterhead turns, hydraulic jacks push the cutters into the rock. The transfer of this high thrust through the rolling disc cutters creates fractures in the rock causing chips to break away from the tunnel face. A floating gripper system pushes on the sidewalls and is locked in place while the jacks extend, allowing the main beam to advance the TBM. The machine can be continuously steered while gripper shoes push on the sidewalls to provide a reaction for the machine's forward thrust. Buckets in the rotating cutterhead scoop up and deposit the muck on to a belt conveyor inside the main beam. The muck is then transferred to the rear of the machine for removal from the tunnel. At the end of a stroke, the rear legs of the machine are lowered, the grippers and propel cylinders are retracted. The retraction of the propel cylinders repositions the gripper assembly for the next boring cycle. The grippers are extended, the rear legs lifted, and boring begins again.

A waterproofing system and cast-in-place final lining can be installed after completion of excavation and initial support.

4.2.2 SINGLE SHIELD TBM

The Single Shield TBMs are fitted with an open shield (unpressurized face) to cope with more brittle rock formations or soft rock. The TBM is protected by the shield and then extended and driven forward by means of hydraulic thrust cylinders on the last completed segment ring. The rotating cutterhead is fitted with hard rock disc cutters, which roll across the tunnel face, cutting notches in it, and subsequently dislodging large chips of rock. Muck buckets which are positioned at some distance behind the discs, carry the dislodged rock pieces behind the cutterhead. The excavated material is brought to the surface by conveyors or skip buckets.

To build the ring within the shield, the external diameter of the segmental lining needs to be smaller than the internal diameter of the shield. This naturally creates a small gap – also known as the annulus – between the two elements. To avoid long-term deformations and uneven load on the segmental lining, this gap is filled with a cement grout. Upon injection of the annulus grout, the TBM can then advance forward 5 to 6-ft (depending on the width of the segment) by pushing against the completed ring with hydraulic rams.

4.2.3 DOUBLE SHIELD TBM

The Double Shield TBM consists of a rotating cutterhead mounted to the cutterhead support, followed by three shields: a telescopic shield (a smaller diameter inner shield which slides within the larger outer shields), a gripper shield and a tail shield. In double shield mode, the gripper shoes are energized, pushing against the tunnel walls to react the boring forces just like the open gripper TBM. The main propel cylinders are then extended to push the cutterhead support and cutterhead forward. The rotating cutterhead cuts the rock. The telescopic shield extends as the machine advances keeping everything in the machine under cover and protected from the ground surrounding it.

The gripper shield remains stationary during boring. A segment erector is fixed to the gripper shield allowing pre-cast concrete tunnel lining segments to be erected while the machine is boring. The segments are erected within the safety of the tail shield. Similar to the single-shield TBM, the annulus grouting would be needed after the completion of the segmental ring.

It is the Double Shield's ability to erect the tunnel lining simultaneously with boring that allows it to achieve high-performance rates. TBM would advance forward in 5 to 6-ft shoves, depending on the width of the segment. The completely enclosed shielded design provides a safe working environment. The precast circular liner section is described in Section 5 of this report.

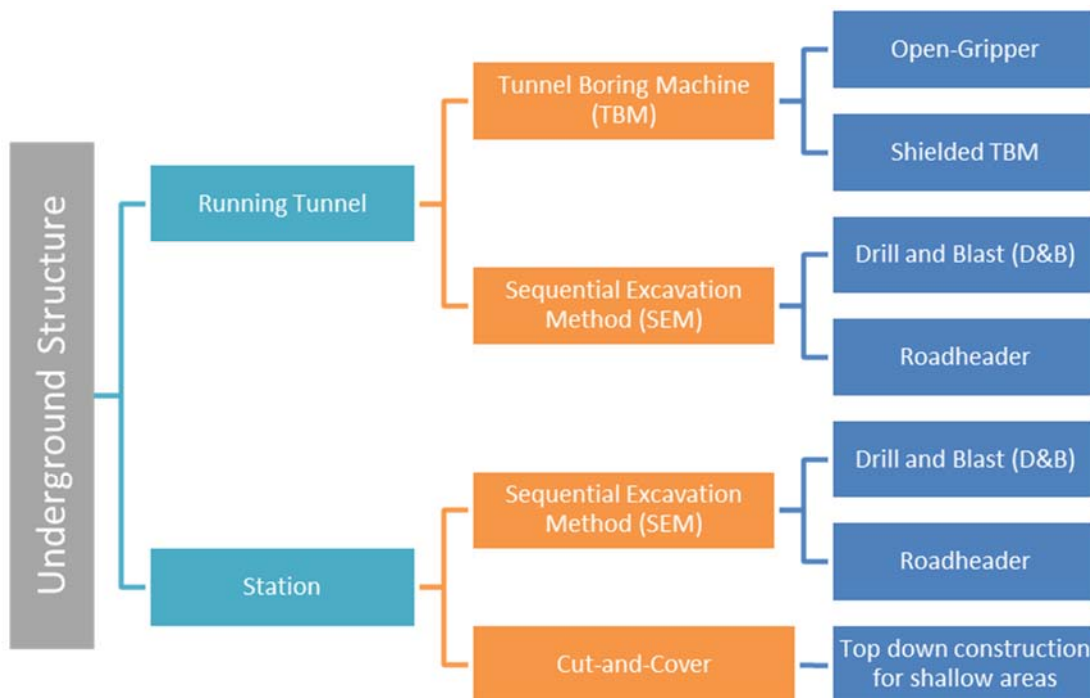
4.2.4 STANDUP TIME

The stand-up time – the amount of time the ground remains stable without the installation of support – is an important element that needs consideration. For instance, the Single/Double-Shield TBM can be used in softer, low quality rock with a short stand-up time whereas the Open-Gripper is generally applied to favorable rock tunneling conditions with medium to long stand-up times.

5 APPLICATIONS OF UNDERGROUND EXCAVATION METHODS FOR DART D2

The mined tunnel section of the LPA includes three stations and twin running tunnels. The construction methods detailed above can be used interchangeably for the station and running tunnels, except for the use of TBMs. A flow chart below (**Figure 5-1**) illustrates the proposed tunneling methods reviewed for applicability for the DART D2 extension project:

FIGURE 5-1. EVALUATED TUNNELING METHODS FOR THE DART D2 EXTENSION PROJECT



5.1 Running Tunnel Construction

The following sections discuss the different tunneling methods considered for the running tunnels. These include full-face mechanized tunneling (Open-Gripper and Single/Double-Shield TBM) and conventional tunneling (Drill & Blast and Roadheader). The tunnel support measures reviewed as part of the evaluation include:

- Initial Support Measures
 - Rock Bolts / Dowels (systematic pattern and spot bolting)
 - Fiber-Reinforced Shotcrete
 - Pre-Cast Segmental Lining (considered both initial and final support)
- Final Support Measures
 - Cast-In-Place Concrete with waterproofing system
 - Pre-Cast Segmental Lining (considered both initial and final support)

5.1.1 TUNNEL BORING MACHINES

The Open-Gripper versus Single/Double-Shield TBM selection process starts with considering their effectiveness in varying degrees of several geomechanical categories. While Open-Gripper and Single/Double-Shield TBMs applicability is very similar regarding Supporting Pressure, Swelling Behavior, Abrasiveness, and Water Inflow, they do perform differently when considering Rock Mass Rating (RMR), Rock Quality Designation (RQD), and Rock Compressive Strength (DAUB Recommendations) with the latter having little impact on the decision-making process for the TBM selection.

Should a rock TBM option be selected, two key limiting factors are the competent rock cover above the tunnel and the minimum radius required for a change in alignment. Based on the rock conditions reviewed it appears that the Open-Gripper TBM would need on the order of some 15-ft of competent rock cover above the tunnel crown and the weathered/fractured limestone layer. While a Single/Double-Shield TBM would be less restrictive, the tunnel crown would still need to be several feet below the weathered/fractured limestone. If minimum rock cover cannot be achieved, alternative TBM tunneling methods to that described herein would need to be assessed.

While TBM excavation is feasible in Austin Chalk with the described cover constraints, the minimum radius indicated on the LPA (400-ft) is outside of the range of a typical ~20-ft diameter Open-Gripper or Single-Shield TBM and would need to be increased greater than 400-ft. However, for completeness and if TBM manufacturing advances smaller radii or the horizontal radii are increased at a later stage, the following sections describe the tunneling approach for Open-Gripper and Single/Double-Shield TBMs. In good to moderate geotechnical subsurface conditions, the average daily advance rates of approximately 60 ft/day (range), are often possible with Shield TBM's (having segmental liner installation, that trails TBM gear, mostly governing daily production). Open-Gripper TBM's have achieved peak advance rates upwards of 200 ft/day.

OPEN-GRIPPER TBM

An Open-Gripper TBM tunneling approach can be applied for DART D2 due to the quality of the unweathered limestone. This material features the self-supporting capacity (medium to long stand-up time). As noted above, utilizing an Open-Gripper TBM will require launching the machine where there is sufficient competent rock cover. An Open-Gripper TBM tunneling was successfully used on the previous DART project. An example of a typical Open-Gripper Configuration is shown in **Figure 5-2**.

This TBM type would include a finger shield behind the cutterhead where the initial support is installed to protect the work force (shown as 'Roof Support in **Figure 5-3**). Likely support requirements would entail 10-ft long rock dowels installed on a systematic pattern. Supplemental support measures (toolbox items) may include grouting for ground improvement, spot bolting, wire mesh, mine straps, shotcrete, and others. Advancing the TBM would be accomplished using gripper shoes (hydraulic jacks) braced against the ground (see **Figure 5-3**). The typical advance length would be 5 to 6-ft and include about 4 to 5 rock dowels per each advance. The next advance sequence can only commence when all initial support has been installed. Based on previous experience, Austin Chalk is prone to desiccation and weathering upon exposure. Therefore, it will be advisable to spray a thin layer of shotcrete behind the TBM to avoid deterioration of the rock mass.

Ground ahead of the machine would be probed to assess the geologic conditions ahead of the tunnel face. If weathered/fractured chalk is unexpectedly encountered along the alignment, ground improvement would be required to advance the machine forward. Such ground improvement would include a systematic grouting from within the TBM to enhance the stand-up characteristics of the ground.

After excavation and initial support installation, the shotcrete surface will be prepared for the installation of the waterproofing system. The waterproofing system is envisioned to be based on the use of a continuous, wrap around PVC waterproofing membrane. The reinforced cast-in-place final support (10 to 12-in) will be accomplished by using a travelling formwork configured for the cross-sectional configuration and the tunnel alignment profiles.

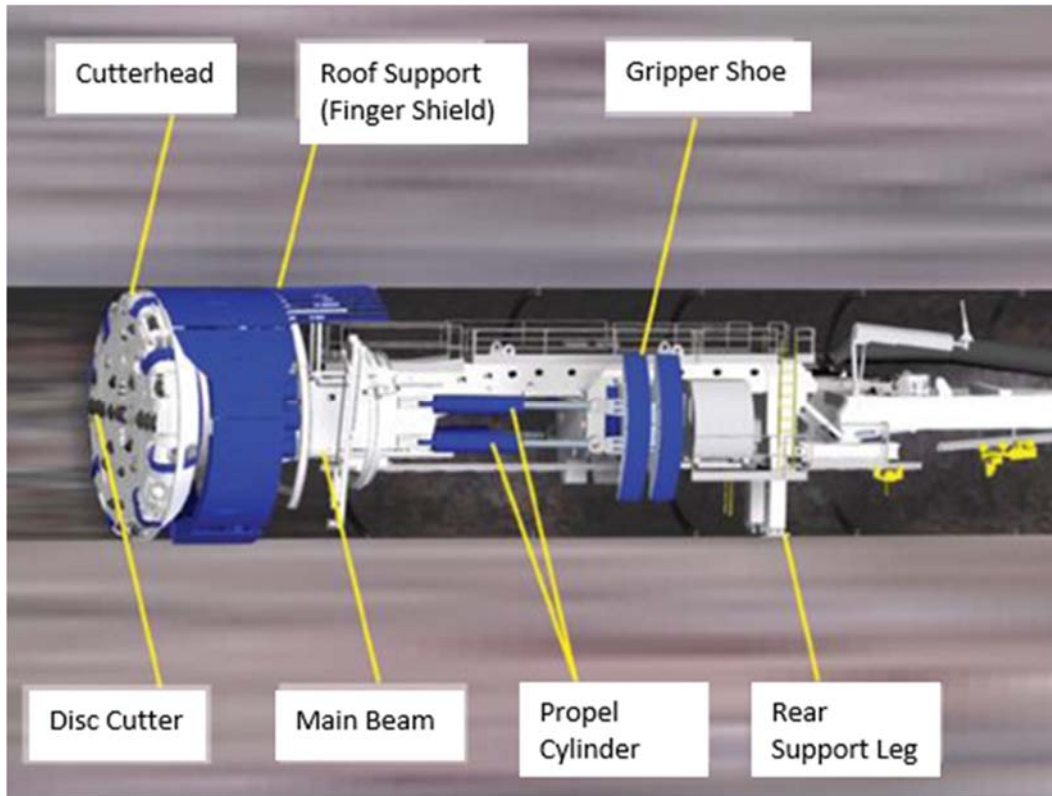
A conceptual running tunnel cross section configuration for an Open Beam Gripper TBM Construction (Dual Pass Cast in Place Concrete Liner) is shown in **Figure 5-4**.

SINGLE-SHIELD TBM

Based on the geological conditions, an alternative to the Open-Gripper TBM is the Single-Shield TBM (see **Figure 5-5**). Utilizing a Single-Shield TBM would require the tunnel crown to be several feet below the weathered and/or fractured Austin Chalk layer. The overburden should be in the order of 10 to 15-ft. If at the portal location, the depth to formation level to meet the vertical alignment does not yield sufficient cover below the weathered and/or fractured rock, a SEM starter tunnel can be constructed following the approach as described above. It should be noted that an Open-Gripper is expected to have higher peak advance rates in the stable chalk, however, the Single-Shield TBM would have a more consistent advance rate if weathered/fractured chalk is unexpectedly encountered along the alignment.

Single-Shield TBM's include a full-round shield to protect the crew and allow for the erection of a reinforced pre-cast segmental lining with an approximate thickness of 12-in for the DART D2 running tunnels. The individual segments are bolted together to form a ring (see **Figure 5-6**). A conceptual running tunnel cross section configuration for a Single-Shield TBM is shown in **Figure 5-7**.

FIGURE 5-2. EXAMPLE OF OPEN-GRIPPER TBM (COURTESY OF THE ROBBINS COMPANY)



Source: The Robbins Company

FIGURE 5-3. TYPICAL HORIZONTAL HYDRAULIC 'GRIPPER' JACKS



FIGURE 5-4. CONCEPTUAL RUNNING TUNNEL CROSS SECTION FOR OPEN-GRIPPER TBM CONSTRUCTION (DUAL PASS CAST IN PLACE CONCRETE LINER)

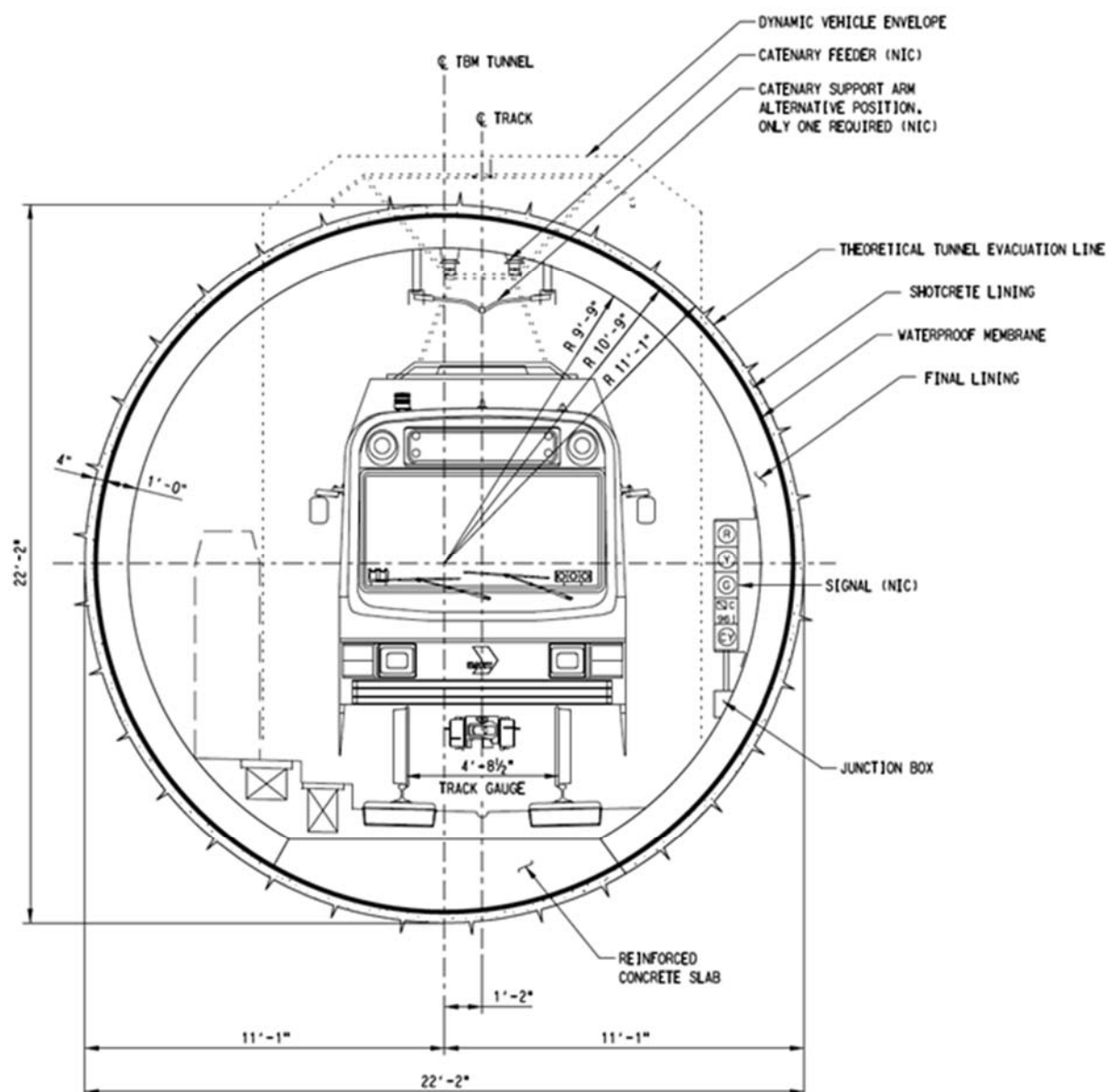
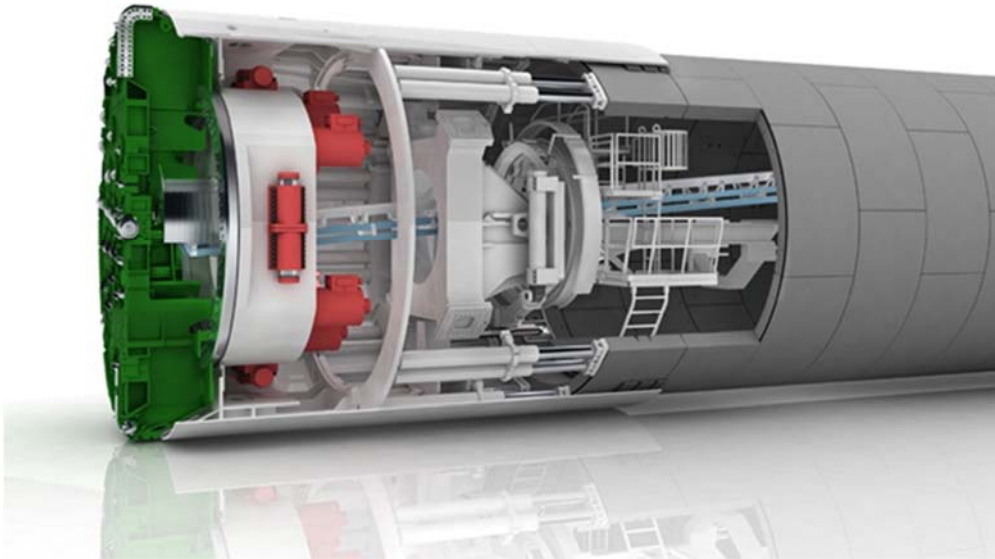


FIGURE 5-5. EXAMPLE SINGLE-SHIELD TBM (COURTESY HERRENKNECHT TUNNELING SYSTEMS)



Source: Herrenknecht Tunneling Systems

FIGURE 5-6. EXAMPLE TBM CROSS SECTION / ISOMETRIC VIEW OF SEGMENTS

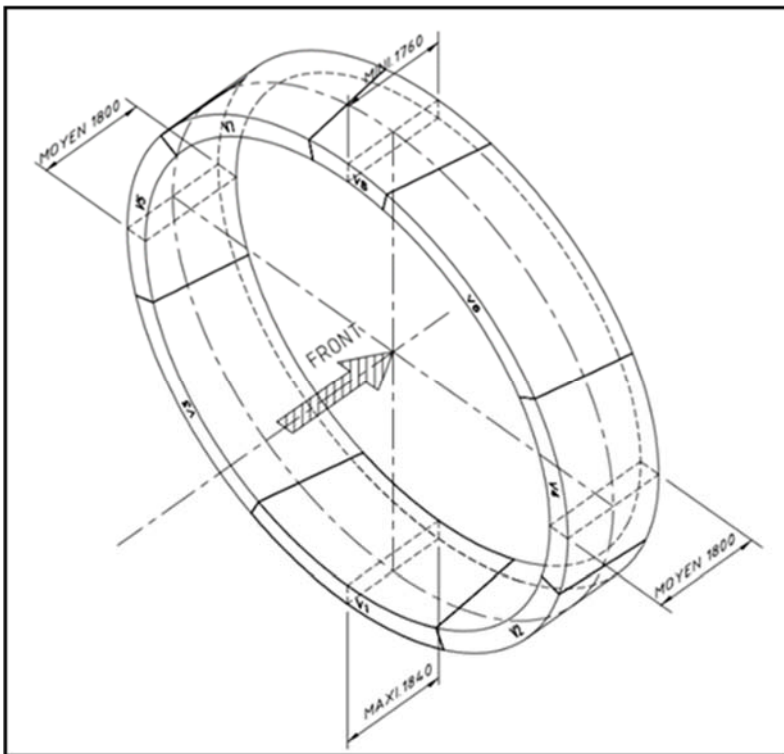
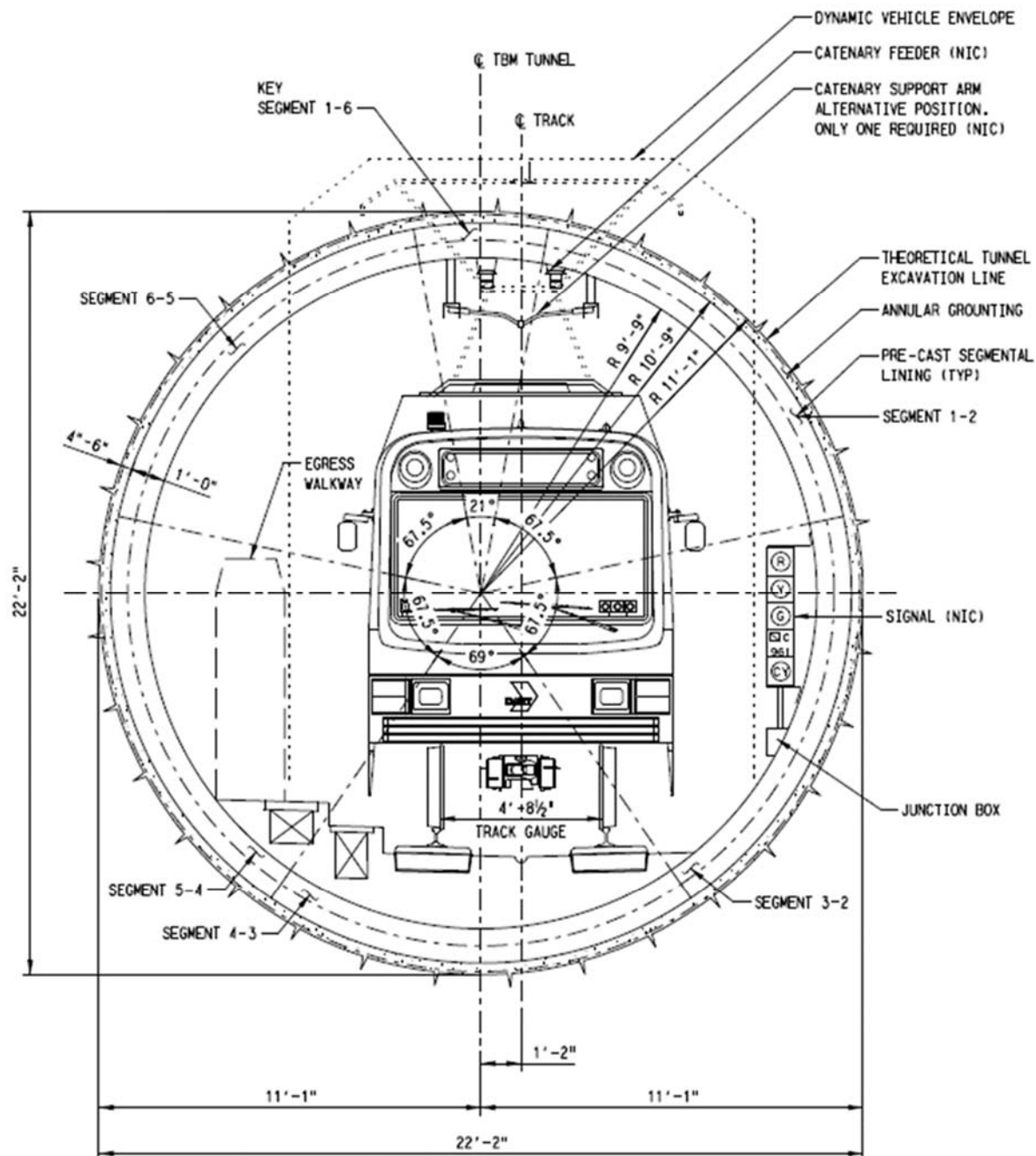


FIGURE 5-7. CONCEPTUAL RUNNING TUNNEL CROSS SECTION FOR SINGLE-SHIELD AND DOUBLE SHIELD TBM CONSTRUCTION



DOUBLE-SHIELD TBM

If the ground becomes too weak to support the gripper shoe pressure, the machine thrust must be achieved another way. In this situation, the Double-Shield machine can be operated in "single shield mode". Auxiliary thrust cylinders are in the gripper shield. In single shield mode they transfer the thrust from the gripper shield to the tunnel lining. Since the thrust is transferred to the tunnel lining, it is not possible to erect the lining simultaneously with boring. In the single shield mode, tunnel boring and tunnel lining erection are sequential operations. It is usually not possible to provide active support to the face and the excavated sides of the tunnel. The rapid advance of the back part of the machine to reposition the grippers after the completion of a boring stroke means that the rock mass must be able stand up without support until the annular gap has been fully grouted. Meanwhile, if excavating in competent ground and operating in "double shield mode", the advancement of the machine and the erection of the lining can occur at the same time. The TBM tunnel cross section for a double shield TBM operating in single shield mode would also be as shown in **Figure 5-7**.

5.1.2 TUNNEL BORING MACHINE EVALUATION

Using a variety of criteria, the gripper and shielded TBMs are compared in Table 5-1.

TABLE 5-1. GENERAL COMPARISON OF GRIPPER ROCK TBM WITH SHIELDED TBM METHODS

No units

#	Criteria	Gripper TBM	Shielded TBM	#
	Rock Conditions	Principle of gripper TBM is to stabilize the rock at the earliest possible point and to introduce substantial automation of work procedures. The gripper machine braces itself at the back with two gripper plates against the rock. In the front, moveable shield components guarantee optimum guidance of the TBM. Spacious working area for installation of rock support in TBM.	When a tunnel runs through solid as well as abrasive or loose rock, a shield and backup is required. This design achieves reliable tunneling performance under heterogeneous rock conditions. Protected within the shield, which is a cylindrical steel construction, most of the excavation and support procedures in the tunnel have been automated. Single shield machines install a tunnel lining with lining segments. To bore forward the machine is supported by hydraulic thrust cylinders pressing on the most recently installed segment ring. The boring and lining installation will take place in sequence. After each boring cycle the machine must stop, and a new tunnel lining ring is installed.	
1	Cost of TBM and auxiliary equipment	Manufacturing cost generally lower.	Additional cost for segment molds, ring erector, grouting equipment, segment delivery, etc.	1
2	Work Site	Minimal Working Area Required	Larger work site area required if it is planned to install segment fabrication hall and storage place on site.	2

TABLE 5-1. GENERAL COMPARISON OF GRIPPER ROCK TBM WITH SHIELDED TBM METHODS

No units

#	Criteria	Gripper TBM	Shielded TBM	#
3	Auxiliary Equipment	Less auxiliary equipment in the portal shaft (less supplying train, with less installed power, less total wagons, lighter portal or tower cranes).		3
4	TBM Assembly	TBM assembly simpler.		4
5	Rock strength	Gripping Force: a minimum of rock quality is required. TBM behavior is difficult to assess with presence of poor rock conditions and faults, which could lead to drastically reduce in excavation performance and uncertainly to this excavation method	Shield machine which uses last built ring as abutment, reducing the risk of geological uncertainly.	5
6	Quality of Ground Support Installation	Quality strongly depends on personnel and working conditions	With segmental lining controlled and supervised conditions in segment plant.	6
7	Fault Zones	Systematic and meaningful temporary support to be installed immediately behind the cutterhead. These possible intensive support measures will result in low production rates per day due to significant delays for the support works	Operation in single shield mode. No stability and gripping problems.	7
8	Operation	Steering problems in poor ground conditions. Gripping in soft or unstable rock mass difficult. Tunneling process demands for flexibility to accommodate tunnel support work and logistics to the actual situation.	Tunneling performance almost independent for a wide range of rock mass conditions, resulting in systematic and continuous approach for tunneling allowing a fast learning curve.	8
9	Operational safety during excavation work	With Gripper TBM ground support dependent on excavation classes. Open rock surfaces during excavation until the ground support is stable.	With shielded TBMs complete ground support by TBM and segmental lining. Very safe as due to the shield and cutter head there are no open rock surfaces, avoiding rock falls through the tunnel.	9

TABLE 5-1. GENERAL COMPARISON OF GRIPPER ROCK TBM WITH SHIELDED TBM METHODS

No units

#	Criteria	Gripper TBM	Shielded TBM	#
10	Initial Lining	Rock bolts/dowels and shotcrete.	Safe and systematic approach for the tunnel lining, no "discussions" about rock support classes. Tunnel lining requires a precast segment factory installation. Location of the factory near the site is important to reduce transport cost.	10
11	Final Lining	Lining is done "in situ" by means of standard formwork, pouring concrete directly in work.	Precast segment support is initial and final lining for shielded TBMs.	11
12	Quality of Lining		Higher quality with precast segment lining.	12
13	Advance rates	Performance rate of a Gripper TBM directly correlates with the effort for rock support measures. In optimum condition, performance rates are higher at peak production, since and advance cycle does not include precast segment erection. Rock support, in optimal conditions, can be executed while excavation is carried out. Compared to shield machines rather low production rates in poor rock masses.	Higher average excavation rates due to continuous operation mode. With segmental lining independent of rock support classes. (Excavation is much more consistent). Small performance variation between different rock types.	13
14	Time Schedule / Completion Deadline	Completion Date generally later, depending on the sequencing of the works. Often, the final lining is executed only after finishing tunnel Excavation with TBM. Execution of lining "in situ" during excavation reduces excavation performance.	Completion date earlier, as final lining is executed at the same time than excavation.	14

5.1.3 SEQUENTIAL EXCAVATION METHOD (SEM)

Two different means of SEM tunnel excavation have been identified for potential application for DART D2. These include the use of a roadheader to excavate by grinding of the rock and the use of drill and blast as permitted, where explosives are charged and detonated to create the opening in a very controlled manner.

ROADHEADER EXCAVATION

A 'Roadheader' is an excavation machine which holds a rotating cutting head at the end of a crane-like boom (see **Figure 5-8**). The rotating picks grind the ground, which is then collected on the apron in front of the machine and transported to its back for haulage via a conveyor system. The Roadheader excavates the SEM headings at a prescribed maximum length and of a prescribed cross-sectional size.

FIGURE 5-8. A TYPICAL ROADHEADER WITH A TRANSVERSE CUTTING HEAD

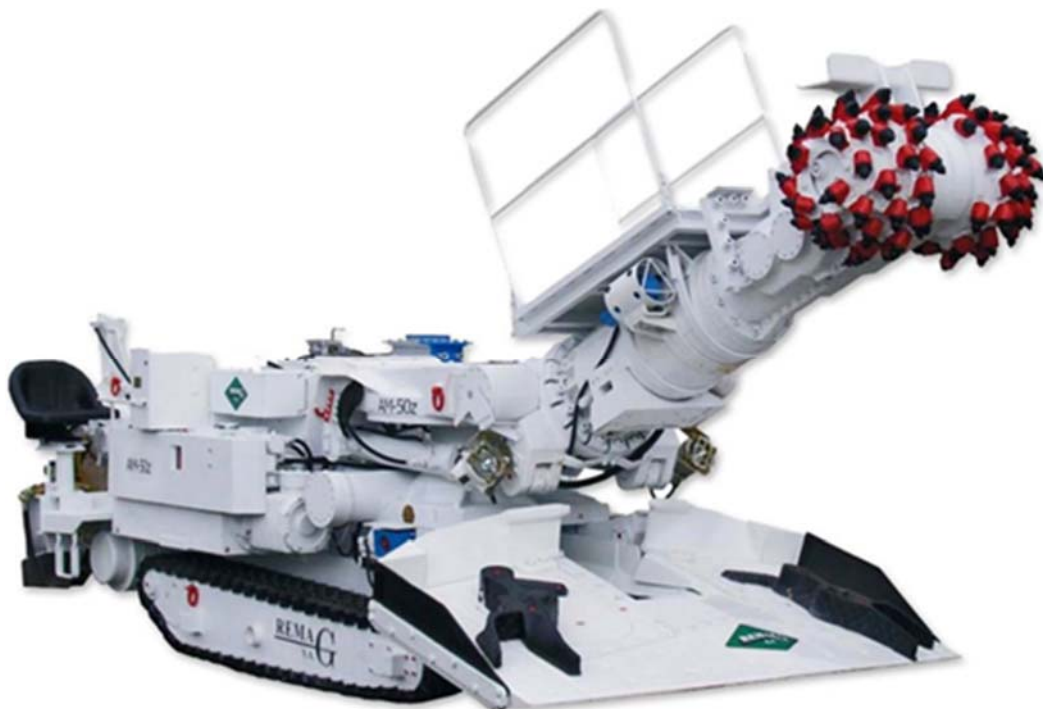
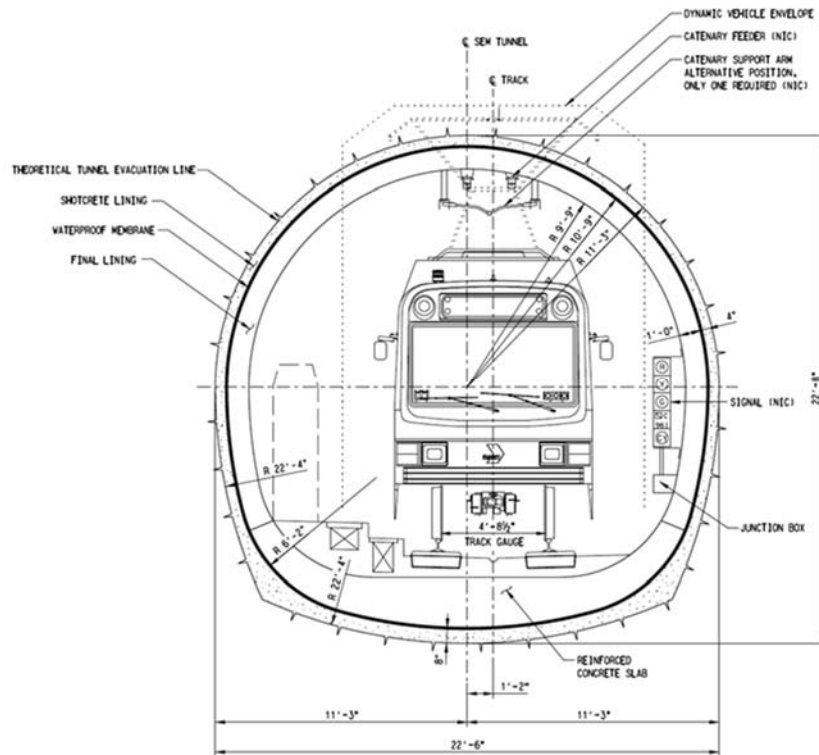


FIGURE 5-9. CONCEPTUAL RUNNING TUNNEL CROSS SECTION FOR ROADHEADER CONSTRUCTION



Roadheaders were used successfully in similar ground conditions throughout the construction of the DART stations, adits, and escalators. Other projects include the Addison Airport Tunnel and the Cole Park Storm Water Detention Vaults. Likely support requirements would entail rock dowels installed in a systematic pattern. Supplemental support measures (toolbox items) may include grouting for ground improvement, spot bolting, wire mesh, shotcrete, and others. A typical cross-section for a roadheader tunnel is provided in **Figure 5-9**. The typical advance length would be 5 to 10-ft depending on the thickness of competent limestone rock cover and include systematic rock dowel installation per each advance. The next advance sequence can only commence when all initial support is installed.

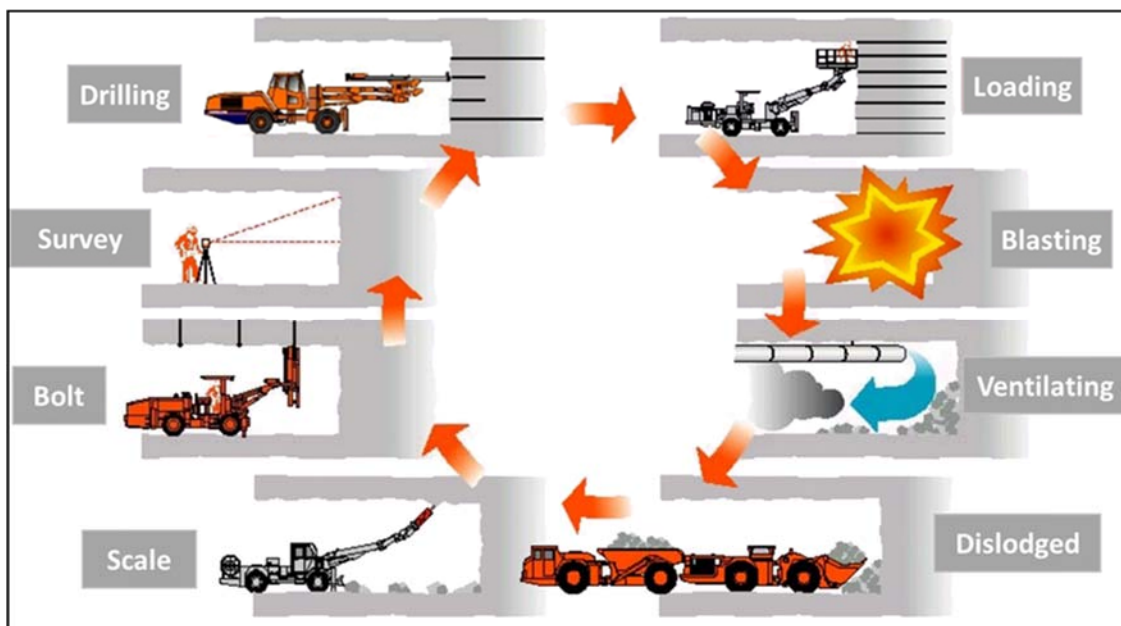
DRILL AND BLAST (D&B) EXCAVATION

Drill and Blast is a method frequently used for the excavation of tunnels, caverns and shaft in hard rock. Full-face and partial-face excavation is possible with Drill and Blast depending on rock conditions and excavation size and geometry. It is noted that per DART Design Criteria Manual Section 18.3.2 "Excavation Methods", drill and blast excavation is not permitted unless authorized by DART. For completeness, drill and blast has been discussed in the event that approval is granted because it is a proven construction method that has been accepted in urban tunneling. However, considering safety concerns, the noise and vibration associated with this method and based on the successful roadheader excavation in Austin Chalk it is generally not a favored method. Further, drill and blast techniques fracture the rock mass to a much greater extent around the opening than the relatively smooth and very low vibration roadheader excavation.

A drill and blast excavation cycle typically includes the following steps as shown in **Figure 5-10**:

1. Drill a pattern of holes.
2. Load the holes with explosives.
3. Detonate the explosives in a timed sequence.
4. Ventilate to remove blast fumes.
5. Excavate the blasted rock.
6. Scale down of the crown and walls to remove loose rock that could pose safety hazards to workers.
7. Install initial ground support.
8. Survey of excavated opening.
9. Repeat the cycle.

FIGURE 5-10. DRILL & BLAST TYPICAL SEQUENCE (COURTESY OF RAIL SYSTEM)



Source: Rail System

Noise and vibration considerations must be addressed when performing drill and blast excavations in urban areas. Blasting imparts energy to the ground that is experienced as vibration levels of varying intensity. The noise from vibration is propagated as air over pressure that can be disturbing to humans and in some instance can cause physical damage. Blast vibrations are typically measured in terms of a vector sum of the peak particle velocity (PPV). Noise and vibration limits as well as drilling and blasting restrictions will need to be incorporated in the design of drill and blast excavation if selected as a suitable method of excavation.

Additionally, drill and blast excavation needs to also consider logistical aspects such as: work restraints related to regulatory controls (fire department, building department), storage and transportation of explosives; on site safety programs specific to blasting; public awareness and education programs to minimize public disturbance and complaints and proper blast round design for optimum muck size for ease of handling

Drill and blast will produce over break in underground excavations. Controlled blasting can be used to help limit the amount of over break. Controlled blasting is the excavation of rock in which the various elements of the blast (perimeter drilling, hole size, depth, spacing, charge size, distribution, delay sequence, etc.) are balanced and controlled to reduce over break, minimize disturbance to the rock beyond the excavation limits and reduce ground-borne noise and vibration associated with blasting. Controlled blasting can include measures such as smooth wall blasting, channel drilling or line drilling.

For DART D2, the running tunnel temporary and permanent support is similar to details provided under the discussion of SEM by Roadheader for running tunnels. Station SEM excavation by drill and blast is also similar to SEM by roadheader, with temporary support consisting of rock bolting and a shotcrete lining and permanent support provided by a cast-in-place concrete lining such as that shown in **Figure 5-11**. To help control noise and vibrations, rock cover should typically be on the order of 15 to 20-ft above the tunnel.

This technical drawing illustrates the cross-section of a station cavern. At the top, it shows the "STATION CAVERN" with two "TRACK" centers spaced 30'-0". Below each track is a "RUNNING TUNNEL" with a width of 1'-2". The main cavern body contains two locomotives facing each other, separated by an "EGRESS WALKWAY". The cavern's interior features concentric circular lines representing different structural layers: a "WATERPROOFING MEMBRANE", "SHOTCRETE LINING", and "C/P CONCRETE LINING". Various radii are indicated, such as R 35'-7", R 18'-2", R 10'-0", and R 20'-0". Dimensions for the overall cavern width at the base are given as 57'-10" and 13'-11". Vertical dimensions on the right side indicate heights of 21'-11 1/2", 13'-11 1/2", 7'-2", and 1'-3 1/2".

5.2 Station Construction

The mined construction methods will be in accordance with the SEM using road header excavation. The tunnel support measures reviewed as part of the evaluation include:

- Initial Support Measures
 - Rock Bolts / Dowels (systematic pattern and spot bolting)
 - Fiber-reinforced Shotcrete
- Final Support Measures
 - Cast-In-Place Concrete with waterproofing system

5.2.1 SEQUENTIAL EXCAVATION METHOD (SEM)

ROADHEADER EXCAVATION

As mentioned above, roadheader excavation was successfully adapted in the similar ground conditions throughout the construction of the DART stations, adits, and escalators (see **Figure 5-12**). For DART D2, the minimum rock cover should be approximately 15 to 20-ft. Anticipated support requirements would include 12 to 16-ft long rock dowels installed in a systematic pattern. Supplemental support measures (toolbox items) may include grouting for ground improvement, spot bolting, wire mesh, shotcrete, and others. The typical advance length would be 5 to 6-ft and include installation of a systematic rock dowel pattern per each advance. The next advance sequence can only commence when all initial support is installed. If a 'rock arch' cannot be achieved because the rock cover is limited, a soft-ground support system will need to be implemented with a structural shotcrete lining in the order of 12 to 14-in with an invert ring closure and likely multiple partial headings. Pre-stabilization ahead of the advancing tunnel face will need to be further developed based on expected conditions.

After excavation and initial support installation, the shotcrete surface will be prepared for the installation of the waterproofing system. The reinforced cast-in-place final support will be accomplished by using a formwork configured for the cross-sectional configuration. The reinforced lining thickness would range between 12 to 18-in depending on station geometry and geologic conditions present at each underground station.

FIGURE 5-12. CITY PLACE STATION CONSTRUCTION, MARCH 1994. AXIAL CUTTING HEAD



DRILL AND BLAST EXCAVATION

Drill and blast for station construction would be similar to that described for the running tunnels, however, due to the larger cross-sectional area typical required for center platform light rail stations, partial-face excavation is typically implemented during construction. When considering the noise and vibration impact from drill and blast construction in urban environments, station construction for DART D2 without impacting the existing infrastructure will be difficult to maintain, therefore it is not recommended.

6 CASE HISTORIES

A key aspect in evaluating suitable tunnel construction options is through comparison with similar projects completed in the past. Below are summaries of similar cases of other subway projects located in urban areas, in particular tunneling for DART. It is anticipated that DART D2 would utilize very similar construction approaches.

6.1 Dallas Light Rail System (DART)

6.1.1 TUNNEL CONSTRUCTION APPROACH (SECTION NC-1B)

DART construction referred to as Section NC-1B included construction of running 18-ft diameter tunnels within the competent Austin Chalk Formation. Both running tunnels were 13,000ft-long and were excavated using open-gripper tunnel boring machines. Rock dowels were used for initial support. The final lining over the clear majority of the tunnels consists of a thin reinforced shotcrete layer. Only occasionally a permanent cast-in-place concrete lining was applied. Despite the larger anticipated tunnel diameters for DART D2, the same construction methods would be highly applicable provided TBM use will not be excluded due to horizontal alignment restrictions. (See **Figure 6-1**)

6.1.2 STATION CONSTRUCTION APPROACH (CITY PLACE STATION)

For the construction of the City Place Station enlargement mined exclusively by SEM utilizing roadheader excavation. This included development of the large station caverns, emergency egress shafts and tunnels and inclined escalator tunnels. Due to the competence and self-supporting capability of Austin Chalk, minimal initial support was required using rock dowels/bolts and lightly reinforced shotcrete lining. (See **Figure 6-2**)

FIGURE 6-1. FINISHED DART RUNNING TUNNEL IN THE BACKGROUND



FIGURE 6-2. CITY PLACE STATION ENLARGEMENT VIA ROADHEADER



6.2 Subsurface gases in DART Tunnel Construction

During the construction of DART in the mid-1990's, on several occasions the Lower Explosive Limit (LEL) for methane gas was recorded during tunnel excavation by a Tunnel Boring Machine (TBM) – which required tunnel construction to cease. The LEL is approximately 20% of the concentration required for explosion ignition. When excavation was stopped, it was found that the gas concentration dissipated quickly.

After this discovery, the project was subsequently halted while an investigation was conducted. This delayed the project by 79 days [1]. It was found that no significant methane concentrations were in the atmospheric air or within the rock itself, but instead the air inside some fractures were found to contain 85% to 97% concentrations of methane gas – with characteristics of that typical to a petroleum source. The investigation concluded that the source is not likely to be local, and that the gas has instead migrated up through the fractures in the ground.

The investigation also noted that the ventilation system may have been inefficient in removing the gas from the heading – allowing methane to 'layer' in the crown. While the amount encountered in DART was low and limited only to fractured areas which could be detected early, there is a potential risk that methane may be present within the tunneling limits of DART D2. This requires further investigation and consideration to confirm the chosen construction method.

6.3 Tyson's Corner Tunnels for Dulles Metrorail (Washington, DC Metro)

The Dulles Corridor Metro project, near Washington D.C. required a 1,700 feet long double tube tunnel through the hilly area of Tyson's Corner. (See **Figure 6-3**) Due to complex geological conditions involving soft alluvial and residual soils and relatively low overburden cover, mechanical excavators were used to advance the tunnel. Supported during construction by a double-grout injected umbrella of approximately 57 feet long pipes, steel supports and lattice girders – with a permanent cast-in-place concrete lining.

6.3.1 DULLES AIRPORT TUNNEL FOR THE AUTOMATED PEOPLE MOVER SYSTEM

Apart from the area of complicated geology at Tyson's Corner, two 21ft-diameter Single Shield TBM's were commissioned for an 1,830 ft. section of running tunnels to connect between airport underground stations. TBM was driven in soft to medium hard rock conditions featuring mainly mudstones, sandstones, and siltstones. Where radii of the horizontal alignment were small, SEM tunneling was utilized for the running tunnels. (See **Figure 6-4**)

FIGURE 6-3. TYSON'S CORNER SEM TUNNELING – SHOTCRETE INITIAL SUPPORT INSTALLED



FIGURE 6-4. DULLES AIRPORT TBM TUNNELS



6.4 East Side Access Project – New York City

6.4.1 TUNNEL

East Side Access (ESA) is one of the most complex, ongoing transportation projects in the United States. The project will connect the Long Island Rail Road's (LIRR) Main and Port Washington lines in Queens to a new LIRR terminal beneath Grand Central Terminal (GCT) in Manhattan. The 25,000ft long running tunnels were constructed using two hard rock TBM's. Because of the extremely hard rock, drill and blast methods were employed for the other underground structures (caverns, cross passages, shafts) which required detailed settlement/ground vibration management. (See **Figure 6-5**)

6.4.2 STATION CAVERNS

The large station caverns measuring 60ft wide by 78ft high, and 1200ft long, were constructed using SEM and drill and blast methods for excavation to enlarge the TBM bores into the station cavern. This method was selected only due to the very hard rock present throughout the project that did not allow for an economic utilization of roadheader technology. (See **Figure 6-6**)

6.5 Riyadh Metro Project

6.5.1 TUNNELS

Aggregate 1.25 miles of SEM tunnels, 10.5 miles of TBM tunnels. Riyadh Metro is a large, new metro project with 6 lines constructed in water-bearing fill, Alluvium, and weathered to fresh limestone breccia. Line 1 (of 6) totals 20 miles of length with 22 stations. The running tunnels (approx. 35ft in diameter) were constructed by a single-shield TBM which installed a segmental lining from within the shield. (See **Figure 6-7**)

6.5.2 ADITS / SHAFTS

Due to the generally favorable limestone rock mass conditions, all adits, shafts, and stations were excavated using the SEM and road header excavation. (see **Figure 6-8**).

FIGURE 6-5. EAST SIDE ACCESS HARD ROCK TBM

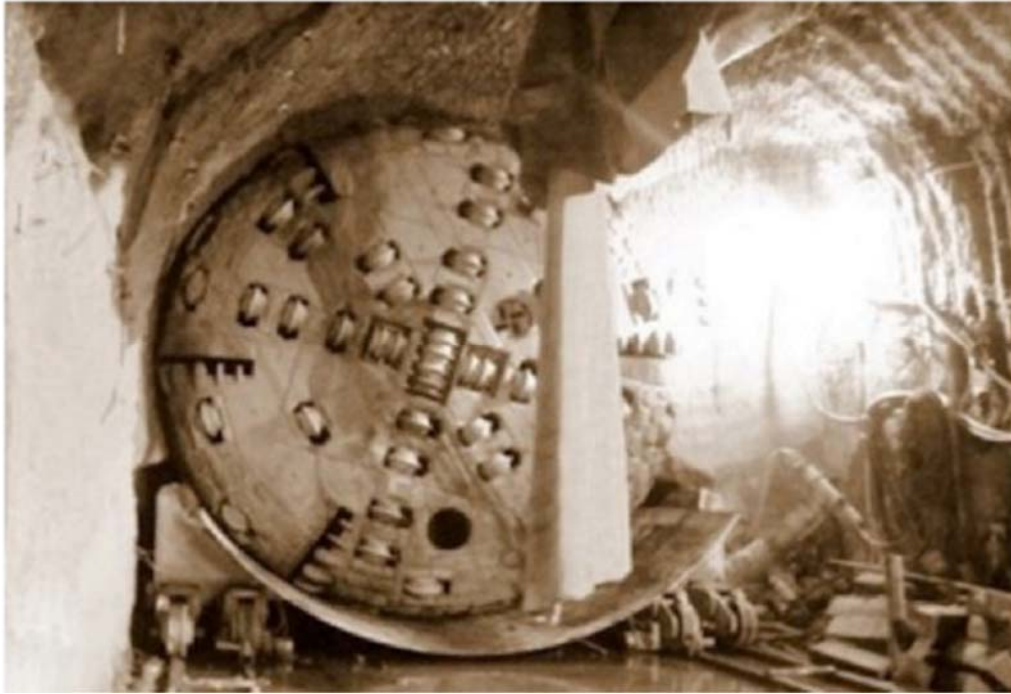


FIGURE 6-6. EAST SIDE ACCESS CAVERNS UNDERNEATH GRAND CENTRAL TERMINAL, NYC



FIGURE 6-7. TBM LAUNCH – RIYADH METRO PROJECT



FIGURE 6-8. RIYADH METRO ADIT CONSTRUCTION VIA ROADHEADER



7 CONCLUSIONS

Many factors have an influence on choosing a technical feasible and economical construction method. On occasion it is difficult to decide which construction method, TBM or SEM, is technologically and economically more advantageous. Using SEM, the shape of the profile can be adapted to the clearance profile and space needed for installations (e.g. tunnel ventilation, cable ducts, drainage pipes etc.). In TBM tunneling, the excavation profile is circular shaped and therefore larger compared to SEM tunneling; however, it could be constructed as a single pass instead of multi-pass system. For the economic comparison of both methods, scheduling and cost estimating analysis would need to be performed.

The DART D2 extension project area is known for the Austin Chalk formation, which is generally massive in nature with few discontinuities and low compressive strengths. The combination of low compressive strength and massive nature of the formation makes it an ideal medium for a sequential excavation with a road header as demonstrated by recently completed excavations for the DART City Place Station and for the Addison Toll Road Tunnel. Also, the subsurface conditions make it compatible for excavations by TBMs where high advance rates of excavation could be accomplished due to low strengths of the rock given the satisfactorily established alignment in plan and profile that is conducive to TBM excavation in terms of maximum grades (< 5%), horizontal curves (>400 feet or so) and sufficient ground cover over the tunnel crown (usually, of one tunnel diameter or so).

SEM tunneling is a very flexible construction method with respect to excavation, means of rock support, face support, and required auxiliary measures. Excavation sequences, enlargement of excavation profiles for allowing displacement of the surrounding rock mass, subdivision of headings, amount and means of rock support can be adapted rather easily and quickly to the actual ground conditions encountered. Additional measures built at the heading face (e.g. grouting, dewatering, installation of pipe roof umbrellas or spiles, shotcrete lining with yielding elements) can cope with adverse conditions in fault zones. Further, using SEM tunneling, the shape of the profile can be adapted to the clearance profile and space needed for future installations (e.g. tunnel ventilation, cable ducts, drainage pipes etc.). SEM tunneling, however, is a multi-pass system; it requires installation of initial support, waterproofing system, and final support (liner) and the sequence of staged construction must be considered in the project schedule.

In TBM tunneling, installation of additional measures at or above the cutter head is possible but limited due to space constraint and limited openings within the cutter head and shield. Identified fault zones or zones with expected unfavorable rock mass behavior may cause delays to TBM drive if not explored ahead of time and mitigated. Also, TBM tunneling produces a circular shape for a tunnel and is a somewhat of a larger cross section than that of a SEM tunnel and this results in a slightly larger cross-sectional area of the tunnel that may require marginally larger horse power requirements of tunnel ventilation fans in order to establish critical velocities of the air being pushed (or pulled) through the tunnel in case of fire emergency. On a positive side, TBM could provide one-pass liner system by using precast concrete segmental liner as the final tunnel structure. Waterproofing of the liner is achieved by providing gaskets between the segments that seal the tunnel permanently preventing the groundwater intrusion in a completed tunnel facility.

In terms of construction schedule features, TBM method is expected to have higher daily advance rates than SEM. The construction schedule, however, needs to allocate TBM procurement time to order, design, manufacture, deliver and assemble a TBM on site. The procurement time for SEM equipment is significantly



shorter. All the above considerations would need to be evaluated for advantages and limitations of the different construction methods considered for DART D2 project.

Construction time and completion of a project is crucial for each infrastructure project. Therefore, the estimated construction time is an important factor in the selection of the construction scheme (number of construction lots, intermediate construction accesses) and construction method (excavation method, lining system). SEM tunneling normally has an economic advantage for shorter tunnels. For transportation tunnels in rock longer than 2-3 miles a TBM drive could be considered from the economic point of view.

During further design, the technical and economic feasibility of adequate construction methods must be evaluated by a risk analysis. The risk analysis for possible construction methods serves to identify scenarios (events) to be considered in the design and forms the basis for selecting an adequate construction method. For occupational health and safety during construction, TBM tunneling might provide an advantage over SEM. Shielded TBMs with segmental lining ensure a higher safety for the miners. The crew is always working in the protection of the TBM shield or the installed segmental lining. Ventilation requirements could be different for each of the construction methods. In general, more fresh air must be supplied to the headings of a SEM tunnel.

For the valid comparison of both methods, all above considerations must be contemplated, along with scheduling, cost estimating and risk analysis, to finally select a preferred method of construction.

8 RECOMMENDATIONS FOR PE 20% DESIGN

8.1 Design Recommendation #1

8.1.1 DESIGN RECOMMENDATION

Tunnel excavation for the DART D2 running tunnels can be implemented by the SEM tunnel excavation method. Alternatively, if desired by the contractor, a TBM method can be selected for running tunnel excavation.

8.1.2 BASIS OF RECOMMENDATION

10% South of Swiss Alignment, March 9, 2019.

GDM #3 Ground Characterization

8.1.3 SOURCES OF UNCERTAINTY

Underground obstructions may be present that will increase the risk of mining operations by TBM method of tunneling. If presently unknown underground obstructions are encountered by the TBM during excavation, the costs of tunneling by the TBM method may be driven upward by downtime and TBM recovery efforts.

The current south of Swiss 10% alignment may ultimately not be accepted by DART. Subsequent alignment changes may lead to alternate mining method requirements.

The further development of the design during preliminary engineering and the presence or lack of project constraints on the alignment may affect whether the roadheader or TBM methods will ultimately be used for excavation.

Additional boring data could indicate less or more severe geotechnical conditions than those presently available. Changes in geotechnical conditions could alter the recommended mining methods.

8.2 Design Recommendation #2

8.2.1 DESIGN RECOMMENDATION

The Commerce Station can be constructed with the SEM underground mining method.

8.2.2 BASIS OF RECOMMENDATION

10% South of Swiss Alignment, March 9, 2019

GDM #3 Ground Characterization

8.2.3 SOURCES OF UNCERTAINTY

The current south of Swiss 10% alignment may ultimately not be accepted by DART. Subsequent alignment changes may lead to alternate mining method requirements.

Additional boring data could indicate less or more severe geotechnical conditions than those presently available. Changes in geotechnical conditions could alter the recommended mining methods.

8.3 Design Recommendation #3

8.3.1 DESIGN RECOMMENDATION

The Metro Center Station and CBD East Station can be constructed by the Cut and Cover Method.

8.3.2 BASIS OF RECOMMENDATION

10% South of Swiss Alignment, March 9, 2019

GDM #3 Ground Characterization

8.3.3 SOURCES OF UNCERTAINTY

The current south of Swiss 10% alignment may ultimately not be accepted by DART. Subsequent alignment changes may lead to alternate mining method requirements.

Additional boring data could indicate less or more severe geotechnical conditions than those presently available. Changes in geotechnical conditions could alter the recommended mining methods.

9 CONSTRUCTION CONSIDERATIONS

9.1 Constructability Issues

The DART D2 extension project area is known for the Austin Chalk formation, which is generally massive in nature with few discontinuities and low compressive strengths. The combination of low compressive strength and massive nature of the formation makes it an ideal medium for a sequential excavation with a road header as demonstrated by recently completed excavations for the DART City Place Station and for the Addison Toll Road Tunnel. Also, the subsurface conditions make it compatible for excavations by TBMs where high advance rates of excavation could be accomplished due to low strengths of the rock given the satisfactorily established alignment in plan and profile that is conducive to TBM excavation in terms of maximum grades (< 5%), horizontal curves (>400 feet or so) and sufficient ground cover over the tunnel crown (usually, of one tunnel diameter or so).

For the economic comparison of both methods, scheduling and cost estimating analysis would need to be performed.

9.2 Spatial and Geometry Requirements

Spatial and geometry requirements (grades and dimensions) are as discussed in the sections above.

Using SEM, the shape of the profile can be adapted to the clearance profile and space needed for installations. In TBM tunneling, the excavation profile is circular shaped and therefore larger compared to SEM tunneling.

9.3 Environmental Considerations

Environmental considerations for the TBM, SEM, and Cut and Cover excavation methods will be incorporated into the Performance Specifications as the project develops.

9.4 Availability of Materials

Numerous vendors of excavation equipment and materials are readily available on the market.

9.5 Use of Non-Standard Materials, Construction Equipment, or Construction Means and Methods

Contractors are expected to use their own means and methods for excavation, to obtain an optimal solution. The use of non-standard equipment and methods to obtain an optimal solution is not discouraged.

9.6 Special Monitoring Requirements

Special monitoring requirements for the TBM, SEM, and Cut and Cover excavation methods will be incorporated into the Performance Specifications as the project develops.

9.7 Potential Causes for Delays

In TBM tunneling, installation of additional measures at or above the cutter head is possible but limited due to space constraint and limited openings within the cutter head and shield. Identified fault zones or zones with expected unfavorable rock mass behavior may cause delays to TBM drive if not explored ahead of time and mitigated.

In terms of construction schedule features, TBM method is expected to have higher daily advance rates than SEM. The construction schedule, however, needs to allocate TBM procurement time to order, design, manufacture, deliver and assemble a TBM on site. The procurement time for SEM equipment is significantly shorter. All the above considerations would need to be evaluated for advantages and limitations of the different construction methods considered for DART D2 project.

Construction time and completion of a project is crucial for each infrastructure project. Therefore, the estimated construction time is an important factor in the selection of the construction scheme and construction method. SEM tunneling normally has an economic advantage for shorter tunnels. For transportation tunnels in rock longer than 2-3 miles a TBM drive could be considered from the economic point of view.

9.8 Potential Hazards

TBM tunneling might provide an advantage over SEM. Shielded TBMs with segmental lining ensure a higher safety for the miners. The crew is always working in the protection of the TBM shield or the installed segmental lining.

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