

FINAL DRAFT Geotechnical Design Memorandum #04 - Waterproofing and Drainage for Underground Excavations – Rev A

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

FINAL DRAFT

Dallas, TX
August 12, 2019



This Report was Prepared for DART
General Planning Consultant Six Managed by HDR



Document Revision Record

FINAL DRAFT Geotechnical Design Memorandum #04 -Waterproofing for Underground Excavations	HDR Report Number: Click here to enter text.
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Revision Number: A	Date: August 12, 2019
<i>Version 1</i>	<i>Date: Click here to enter text.</i>

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SUMMARY

Subject/Objective

This memorandum describes systems, materials, and methods of execution that are currently implemented in tunnels and related underground space for preventing intrusion of groundwater from adversely affecting the structural and functional integrity of these structures, and to make recommendations for the DART D2 Subway.

Conclusions

Considering the geological characteristics and groundwater elevations along the DART D2 subway alignment, and the proposed profile of this alignment, DART previous experiences as reported in their Interoffice memorandum of August 24, 2016, and evaluating the benefits and disadvantages of various currently available systems, the use of a synthetic waterproofing membrane completely encapsulating the tunnel and related underground structures is found to be appropriate for this project. However, it is recommended that, as design progresses, the possibility of employing a drained system, where found beneficial be evaluated from an aspect of maintenance and operations constraints over the design life of the project.

1 INTRODUCTION

1.1 Purpose

The purpose of this memorandum is to examine and evaluate waterproofing methods currently implemented in tunnels and similar underground structures and to recommend a system that would be appropriate for protecting the tunnel and associated underground facilities of the proposed DART D2 subway from groundwater.

1.2 Scope

The study conducted for this memorandum covers the following structures comprised in the portal-to-portal 7,200 foot long tunnel segment of the DART D2 subway project;

- Single track, twin bore tunnels
- One mined cavern station at Commerce Street
- Two cut and cover stations at Metro Center and Central Business District (CBD) East
- Possibly one mined double crossover cavern near Commerce Station
- Several cross passageways
- Several adits for station entrances.

1.3 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 August 2019)
- The project alignment includes consideration of 9 existing adjacent buildings and their foundations (as of August 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 August 15, 2019, the Final Geotechnical Data Report is still pending)
- Commerce Station location is between STA 71+13.15 and STA 77+38.15 (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 in August of 2019).

2 BACKGROUND

2.1 Project Description

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 'DART D2 Subway Locally Preferred Alignment (LPA)' in September 2017. The LPA alignment (**Figure 2-1**) 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 one underground mined station, two cut-and-cover stations and a twin-bore running tunnel between the cut-and-cover portal sections. The configuration of underground openings, and method of their construction has been revised per the new alignment profile of March 8, 2019 designated as '10% South of Swiss Street'.

It is of paramount importance to protect underground facilities, including tunnels and stations, from the effects of groundwater seeping into these facilities and their internal structures. If left untreated and/or uncontrolled, water infiltrating through final liners or inverts of the completed underground structures would create an uncomfortable environment for its users, accelerate structures deterioration, reduce their service life, and possibly lead to further damages to the surrounding rail and facility systems equipment, including system and electrical cables, as well as to the architectural finishes. Such damages would not only reduce service life of structural components of underground facilities but would significantly increase long term maintenance costs of these facilities and negatively impact long term life cycle costs of the entire project.

This memorandum has been developed to respond to the "10% South of Swiss Street" alignment dated March 8, 2019, which was developed subsequently to a shallower baseline alignment considered for the 10% design level studies. For this new alignment, the excavation of



the single-track tunnels is assumed to be accomplished either by the conventional tunneling methods (Sequential Excavation Method or SEM) with a roadheader, or by tunnel boring machine (TBM) supplemented, where necessary, by SEM. The SEM scheme for the tunnel section of the D2 project will require a construction shaft midway between the portals. The acceptability of the construction shaft in the urban environment of the Project, however, is questionable; in addition, it would require provisions for ground improvement and initial excavation support. Therefore, a mechanized tunneling method via tunnel boring machine (TBM) is presently considered to be more plausible. The tunnel excavation could be accomplished continually from the west portal with implementation of one-pass system (gasketed precast concrete segmental liner), or using a cast-in-place reinforced concrete liner without any intermediate construction shaft. For this reason, a deeper alignment suitable for TBM tunneling was developed, which can be found in the document titled "10% South of Swiss Street, March 8, 2019".

This memorandum identifies types of waterproofing systems commonly used for mined tunnels and underground structures in urban environments; it outlines watertightness considerations and requirements; describes the main components and the benefits of compartmentalization for a soft, unreinforced continuous membrane waterproofing systems for SEM and TBM tunnels and other underground structures with cast-in-place reinforced concrete walls or liners; describes the way in which watertightness is achieved for one-pass TBM tunnels with precast concrete segmental liners; highlights the importance of adopting stringent watertightness criteria to achieve dry tunnels and stations, and recognizes the need for qualified waterproofing installers and rigorous inspection. Moreover, the memorandum provides a recommendation for the DART D2 project in terms of both approach to watertightness criteria and approach to waterproofing for the underground facilities.

Two types of waterproofing systems have been considered, drained (open) and undrained (closed). Open waterproofing systems would allow controlled groundwater inflow into a tunnel drainage system, whereas a closed system features all structures that would be fully wrapped "tanked" in a recommended waterproofing membrane system and would not allow groundwater inflow into the finished underground structures.

An open system would usually have a higher long-term maintenance requirement to avoid potential clogging of the drainage system and would generally not be recommended for shallower alignments where groundwater leakage (including fine soil materials) into the underground structures may cause surface settlements; whereas a closed system (still with a need for regular inspections), would be more appropriate for shallower alignments, where ground cover over the tunnels and the stations is in a range of up to one diameter of each underground opening, respectively, but can also be used at greater depths if groundwater pressures do not necessitate designing excessively heavy structures. As the design progresses with the recommended deeper alignment profile, if an open system is recommended for benefits in terms of initial cost of construction, it would be important to understand, directly from DART maintenance and operations personnel, performance of similar underground drainage and watertightness systems already installed in the existing DART tunnels and stations, and incorporate those lessons learned into the design of the new system along with considerations for life cycle costs.

For long-term structural durability the selection of the waterproofing membrane material needs to be based on environmental considerations, specifically chemicals that can be detrimental to the water proofing or gasket materials, and presence of potentially corrosive subsurface conditions. Therefore, the final selection would depend upon completion of the project subsurface investigation program, including related laboratory testing.

2.1.1 RUNNING TUNNEL CROSS SECTIONS

The running tunnel cross section has been developed to account for the size and length of train consist, the catenary system, the dynamic car offsets for curvature, the anticipated requirements for utilities within the tunnel and personnel clearances for maintenance and emergency egress. At the early stage of development of this memorandum, excavation of the single-track tunnels was assumed to be accomplished along a baseline alignment that was relatively shallow and via conventional tunneling methods (Sequential Excavation Method or SEM) with a roadheader, with required ample provisions for localized ground improvement and support for all excavated openings. With the currently (March 8, 2019) adopted deeper vertical (profile) alignment, the tunnel excavation will be accomplished via mechanized tunneling method using tunnel boring machine (TBM) and implementation of either one-pass system (gasketed precast concrete segmental liner), or a two-pass (double lining) system requiring installation of temporary and permanent liners, supplemented with SEM excavation where necessitated by alignment constraints (**Figure 2-2**); therefore, the recommendations of this memorandum will be revisited in the future, after the selection of tunneling method.

2.1.2 STATION CROSS SECTIONS

The mined Commerce Street Station cross section (**Figure 2-3**) has been developed considering the preference for a center platform configuration and requirements for minimum platform width, architectural finishes, and passenger flow through the station. Similar to the running tunnels, it is envisioned that excavation of the mined station will utilize SEM principles with a roadheader. This excavation methodology is compatible with the use of tunnel boring machine for tunnel excavation. Cut-and-cover construction (**Figure 2-4**) is currently envisioned for the shallower Metro Center Station and CBD East Station.

2.1.3 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-Wall section (**Figure 2-5**) final structure configuration transitions to an underground alignment. The waterproofing principles discussed herein are tailored to mined tunneling but can be adopted for tunnel portals. Specific details will need to be developed to transition from the tunnel portal waterproofing to the tunnel waterproofing system. Waterproofing elements for the tunnel to portal transition section would have to be tailored for the tunnel construction method chosen. Specifically, a SEM-mined tunnel would have different waterproofing requirements than that of TBM approach.



FIGURE 2-1. DART D2 SUBWAY LPA ROUTE (SOUTH OF SWISS ALIGNMENT, MARCH 8, 2019)

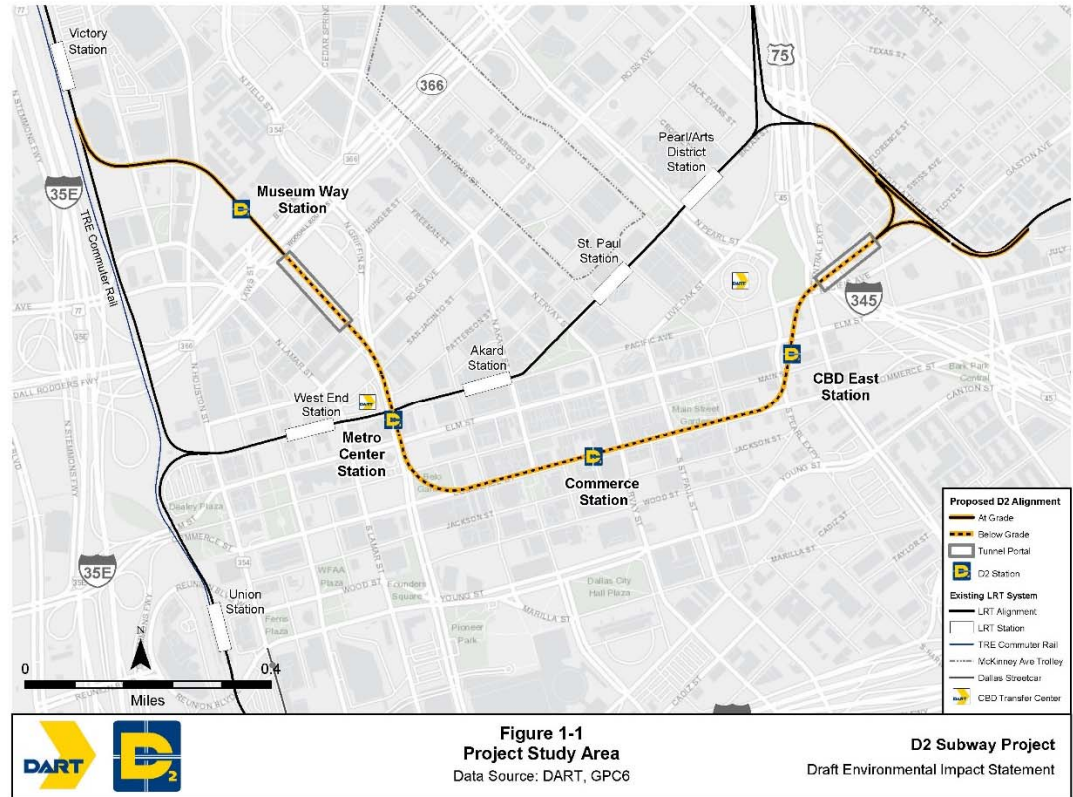
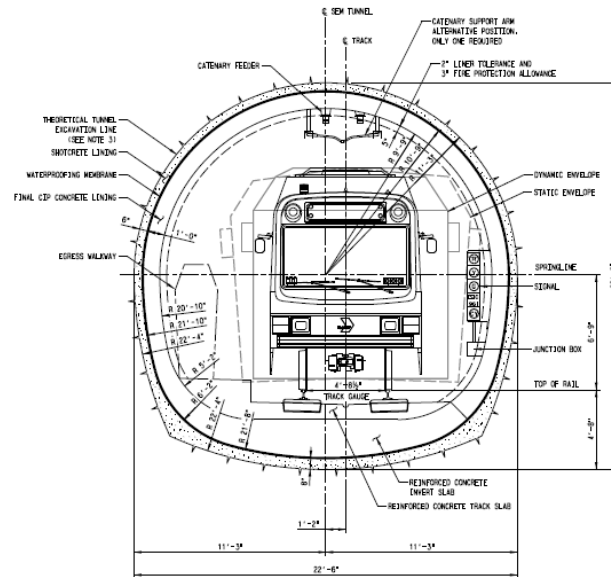
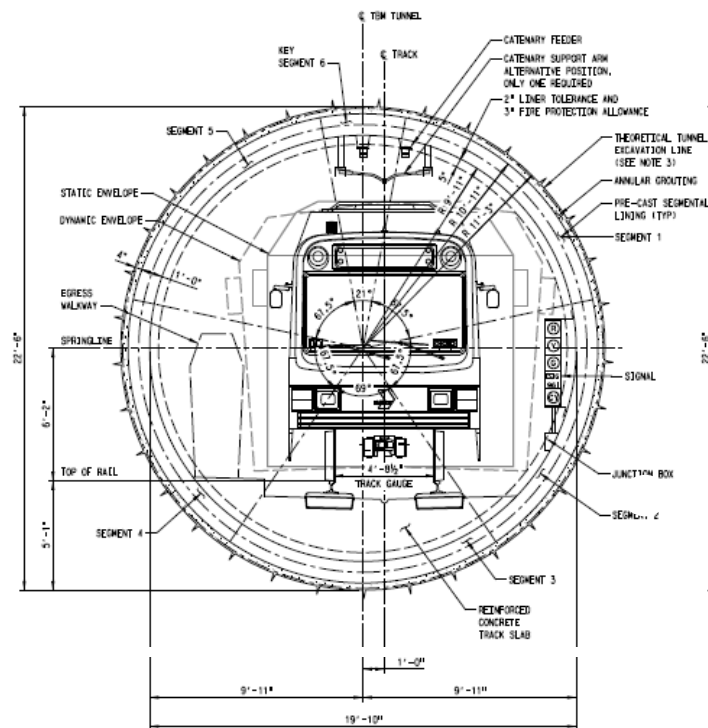


FIGURE 2-2. CONCEPTUAL RUNNING TUNNEL CROSS SECTIONS

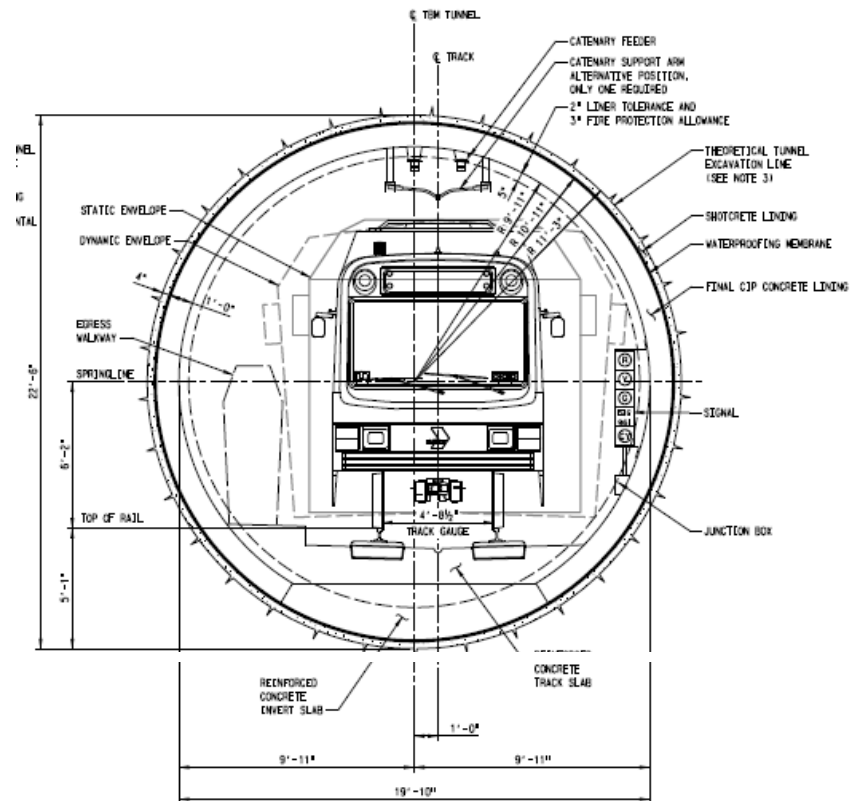


(a) SEM BY ROADHEADER CONSTRUCTION



(b) MECHANIZED (TBM) ONE-PASS SYSTEM

FIGURE 2-2. CONCEPTUAL RUNNING TUNNEL CROSS SECTIONS (CONTINUED)



(c) MECHANIZED (TBM) TWO-PASS SYSTEM

FIGURE 2-3. CONCEPTUAL STATION CROSS SECTION FOR ROADHEADER CONSTRUCTION

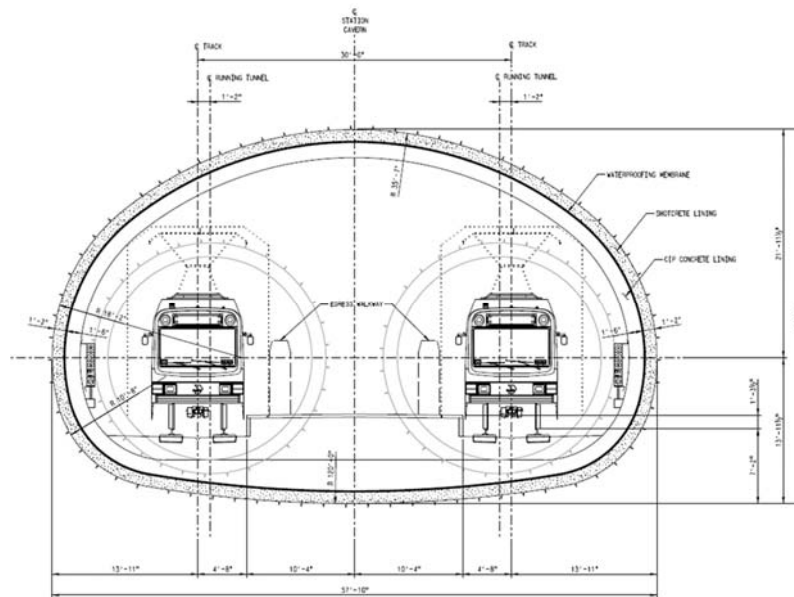


FIGURE 2-4. CONCEPTUAL STATION CROSS SECTION FOR CUT-AND-COVER CONSTRUCTION

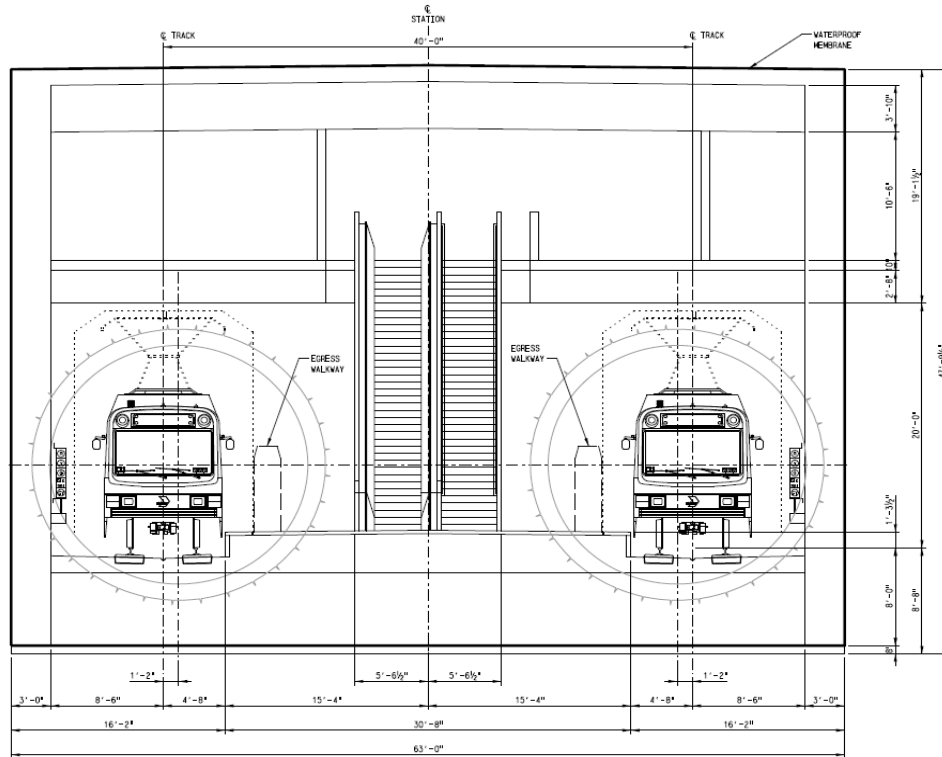
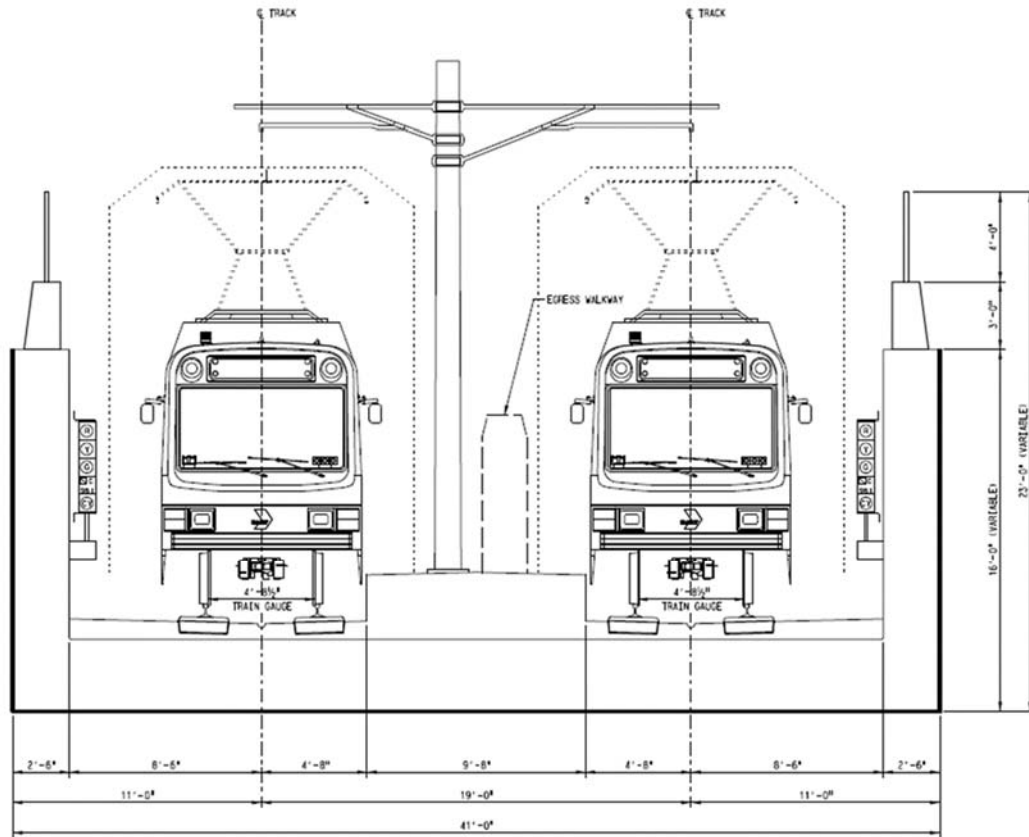


FIGURE 2-5. CONCEPTUAL U-WALL CROSS SECTION



3 WATERPROOFING SYSTEMS

3.1 General

Tunnel waterproofing systems are used to prevent groundwater inflow into an underground opening. They consist of a combination of various materials and elements. The design of a waterproofing system is based on an overall understanding of the critical geotechnical and hydrological conditions, geometry and layout of the structure and construction methods to be used. A waterproofing system should always be an integrated system that considers intermediate construction stages, final conditions of structures and their ultimate usage that includes maintenance and operations.

There are two basic types of waterproofing systems: drained (open) and undrained (closed). Various waterproofing materials are available to form these systems.

Open waterproofing systems allow controlled groundwater inflow into a tunnel invert drainage system. The tunnel vault area is typically equipped with a waterproofing system forming an umbrella-like protective membrane. A drainage fleece adjacent to this membrane drains the water seeping towards the cavern into the invert drainage system, which is typically located at the bottom of the tunnel sidewalls.

Open systems are commonly installed in new tunnels with double lining, between the temporary tunnel support (initial lining) and the permanent support (final lining).

The open waterproofing system is commonly used in deeper tunnels in rock where:

- low water infiltration rates prevail
- design for groundwater hydrostatic pressures would be uneconomical.

Groundwater inflow for open systems is typically confined to distinct locations including:

- joints
- fractures
- areas where permeability is such that draw-down in overlying soil layers and resulting ground deformations would be minimal.

Open systems generally enable designing an economical permanent liner and invert, as it allows considering reduced hydrostatic loads.

Closed waterproofing systems are often referred to as 'tanked' systems. Such systems extend around the entire tunnel perimeter and aim at completely excluding the groundwater from flowing into the tunnel or cavern. Groundwater drainage is not provided. The permanent lining, therefore, must be designed for full hydrostatic water pressures. Such systems feature, depending on hydrostatic loads, substantial lining and invert thicknesses. Closed waterproofing systems are typically employed in shallow alignments in rock where:

- overlying soils are permeable
- groundwater discharge would be large

- ground water discharge would otherwise cause a lowering of the groundwater table and consequent surface settlements
- contamination of the groundwater is an issue
- sensitive urban settings cause associated discharge costs to be high.

3.2 Waterproofing System Requirements and Compatibility Considerations

When designing a waterproofing system for new structures (tunnels with double lining systems, stations, portals), it must be acknowledged that the structure and its surrounding ground are not a static system but constantly undergo changes over time. Stress redistributions, groundwater elevation and flow changes, temperature changes, sedimentation, erosion and other factors continuously affect the path of water in the geologic host formation surrounding the underground structure. The structure itself exhibits changes in temperature, moisture and internal and external time-dependent loadings that in turn cause movements in structural joints and existing cracks, and potentially cause new cracks.

Knowledge of these facts has led to the acceptance and application of flexible, continuous membrane-type waterproofing systems. These systems, in particular when loosely laid, bridge the above-mentioned openings, dislocations and other strain-related movements. Such membrane waterproofing systems have these minimum requirements to make it successful:

- The waterproofing system must be continuous.
- The membrane must be able to adapt to irregularities of surfaces it is attached to.
- The membrane must remain permanently impervious despite rheological or structurally caused movements (long term behavior of ground and structure).
- The waterproofing system must be able to bridge small cracks in the constructed surface. It must be able to absorb discontinuous stress variations and, to certain extent, provide sufficient tensile strength.
- The waterproofing system must be resistant to corrosive subsurface conditions, whether from natural sources or contaminated ground, and to biological attacks. Special attention must be paid to the presence of hydrocarbons in liquid or gaseous state, in the ground surrounding the structure.
- The waterproofing system must be suitable for installation on damp or wet surfaces. It must be easy to handle and to install. Installation must be possible in large quantities with the help of reliable, mechanized methods at acceptable costs.
- The material must be self-extinguishing in case of a fire during installation.
- It must be possible to check the waterproofing system for potential damage and repair it easily, before placement of the concrete elements of the final structure and/or backfilling.
- For enhanced reliability, provisions must be made for testing watertightness during the installation stage and/or for post construction remedial work, should leakage occur.

3.3 Continuous Membrane-Type Waterproofing Systems

The main component of a continuous membrane-type waterproofing system involves a flexible, synthetic, impermeable waterproofing membrane, with thickness commonly ranging between 2.0 and 3.0 mm (80 and 120 mil). The thickness is selected depending on installation requirements and specific construction conditions. For example, an increased strength will be required for application in large station cavern structures and in areas that also require a higher degree of resistance against puncture due to the follow-on activities involving reinforcement installation and pouring of cast-in-place concrete.

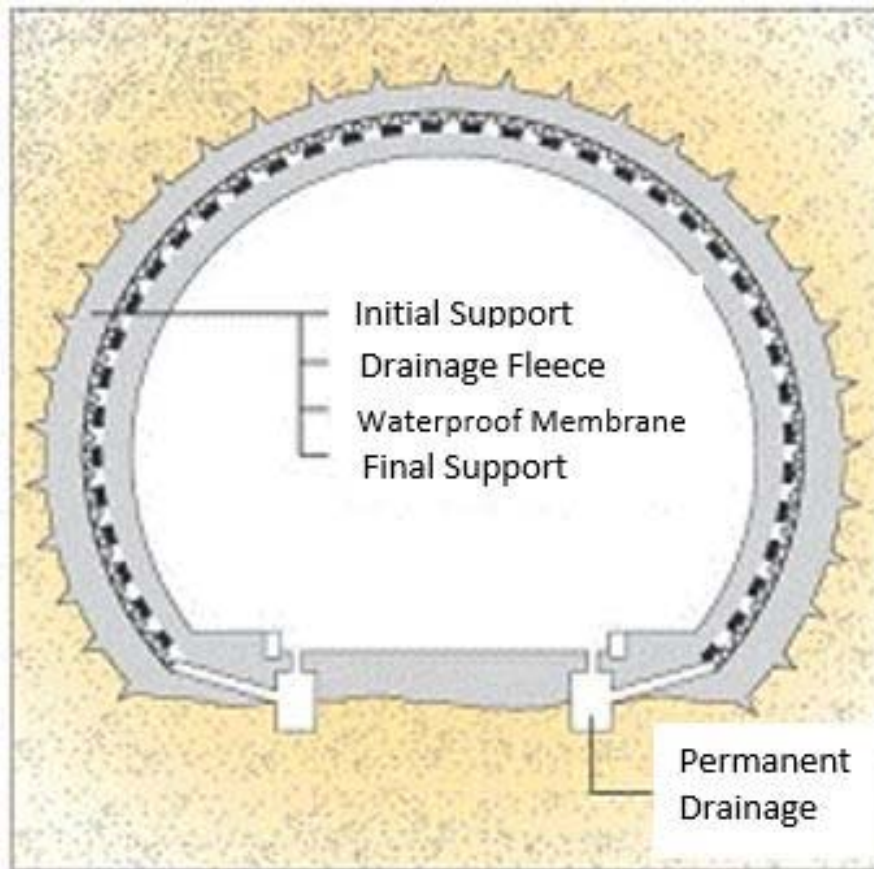
The waterproofing membrane is supplied in sheets, typically six (6) feet wide. These sheets are welded together using double weld seams, which are tested for air tightness, thereby establishing a continuous membrane. The impermeable membrane shields the cast-in-place concrete permanent lining from any water infiltration and protects the reinforcing steel from water-induced corrosion.

The membrane is installed against a mat that commonly consists of a non-woven geotextile. This layer serves as a drainage layer (in drained systems) and as a protective barrier for the membrane against irregularities or sharp edges of the substrate (for both drained and undrained systems). Depending on application to different structures of the DART D2 project, the drainage layer may consist of different materials based upon its intended purpose, i.e. whether it will serve as a protection and drainage layer or as a protection layer only.

In a drained system, the groundwater, which infiltrates into the drainage layer, is conveyed behind the impervious waterproofing membrane around the structure. The collected groundwater is transferred to a perforated sidewall drain-pipe located in a drainage course at the bottom of the sidewall and in the invert. Water collected in these perforated sidewall drains is discharged into the tunnel main track drain at regular distances via non-perforated transverse pipes.

A typical drained waterproofing system is shown in **Figure 3-1**.

FIGURE 3-1. SCHEMATIC DRAINED WATERPROOFING SYSTEM (FOR DEEP ALIGNMENTS)



3.3.1 MEMBRANE AND DRAINAGE LAYER

The preliminary recommended waterproofing system will consist of a flexible, impermeable membrane and a drainage layer between the membrane and the initial shotcrete lining. The thickness of the synthetic membrane may be 80 to 120 mil (2.0 to 3 mm) depending on the size of the underground structure and the area of application. For example, a 100 or 120 mil membrane can be applied to the station caverns considering the cavern size and potential construction sequence. and an 80-mil membrane can be applied to the single-track running tunnels. The drainage layer for single-track running tunnels may consist of a non-woven polypropylene geotextile, supplied in thickness of 285 mil or 400 mil, with corresponding weights of 22 oz/square yards or 28 oz/square yards. The geotextile also provides protection to the membrane when applied to the substrate. Where enhanced protection against substrate may be needed, a heavier geotextile can be used. If structural requirements dictate the need for maximum ground /structure interaction, non-woven polypropylene geotextile reinforced with HDPE drainage grid are available to minimize potential liner deformations and achieve a practical final lining thickness.

Final selection of the waterproofing membrane material will be based on long-term durability and environmental considerations, pending evaluation of updated subsurface data and laboratory testing results.

3.3.2 DRAINAGE SYSTEM

If the drainage system for DART D2 is designed as a combined system to collect groundwater in addition to water from other sources, pending final alignment selection, (water brought into the tunnels by trains, wash water, fire extinguishing, etc.), the key features of the drainage system for a deeper alignment may include:

- Perforated side wall drain pipes: These are perforated pipes which collect the groundwater conveyed through the drainage layer and conducted to these drain pipes. Depending on the size and length of the underground structure, the sidewall drain pipe diameter will range from 6" to 8". Typically, the perforated sidewall drain pipe is laid on a leveling concrete pad and covered with specially mixed porous concrete or gravel. The concrete leveling pad is designed to place the pipes at their desired elevation and depending on application, may be laid out in a way that provides a slope in longitudinal direction.
- Porous concrete: This is a low cement content, coarse aggregate concrete mix, which covers the perforated sidewall drain pipes. Waterproofing membrane and drainage layer are placed on top of and around the porous concrete. The termination of waterproofing is secured to the invert by shot fired fixing nails.
- Transverse drain pipes: These are non-perforated pipes ranging in diameter from 6" to 8" depending on the size of the sidewall drain pipes. These transverse pipes connect to the sidewall drain pipes at regular intervals and convey the collected water into the main track drain. The transverse pipes are placed within the invert slab or within the gravel drainage layer.

- **Drainage Layer:** The drainage layer consists of gravel material to facilitate the collection of groundwater within the invert section. Groundwater within this layer is collected and drained to the main track drain via perforated drain pipes.
- **Main Track Drains:** These drains are typically located along the centerlines of tracks within the drainage layer and collect water from the sidewall drain pipes at regular intervals and from the drainage layer. Their sizing depends on factors including the anticipated groundwater inflow volumes, fire extinguishing related water, length and size of the tunnel, etc.
- **Manholes:** Manholes are located over drain pipes at regular intervals at the locations of connecting transverse pipes.
- **Cleaning Niches and Cleanouts:** These provide direct and indirect accesses to the drain pipes and are used for maintenance of the drainage system by means of inspection and a regular cleaning.

When considering the use of a drained waterproofing system it is important that the design incorporates provisions to address calcification of drainage systems within tunnel/station final linings. The size and angle of the perforated sidewall drain pipe and the laterals to the main track drains are designed to keep both pipes submerged to reduce calcification. Further, at these intersections, manholes are generally installed to provide a means for cleaning and unclogging blockages in accordance with the maintenance schedule. A typical sidewall drain is shown in **Figure 3-2**. Typical details are provided in **Figure 3-3** and **Figure 3-4** showing the sidewall drainage pipe (with cleanout) and connection to the main track drain, respectively.

FIGURE 3-2. TYPICAL SIDEWALL DRAINPIPE



FIGURE 3-3. TYPICAL PERFORATED SIDEWALL DRAIN-PIPE WITH CLEANOUT AND LATERAL PIPE

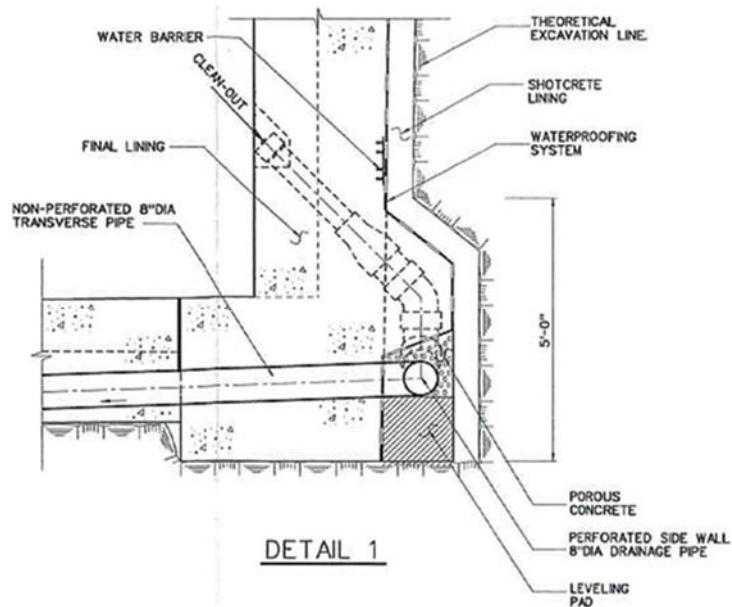
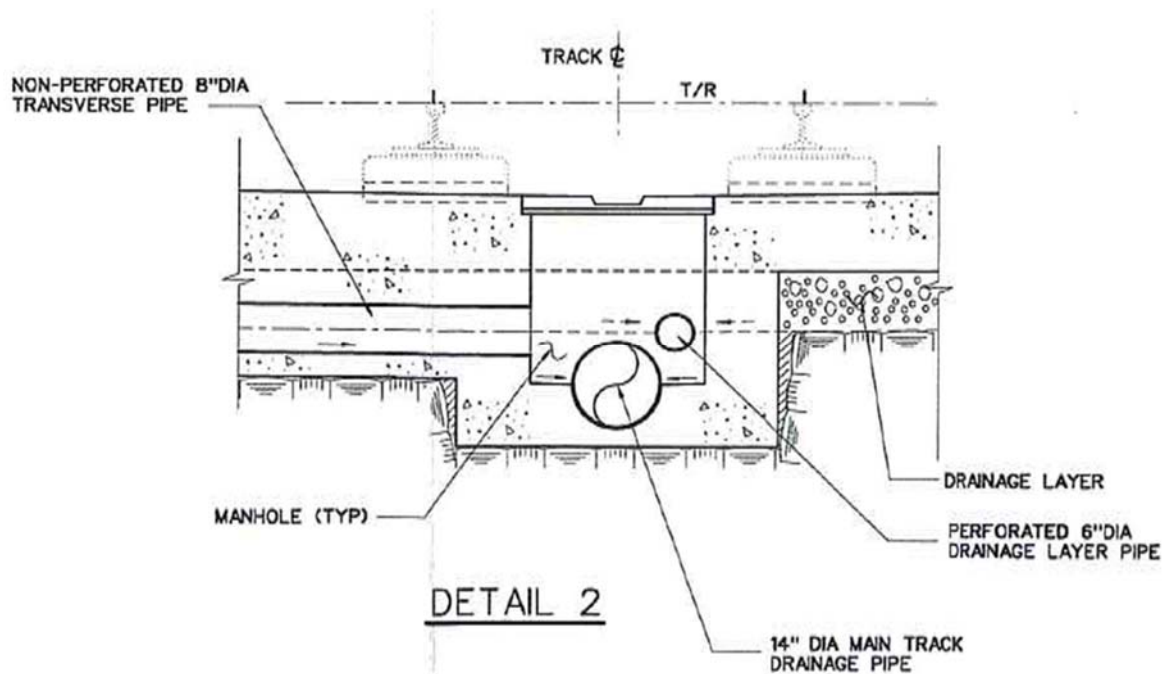
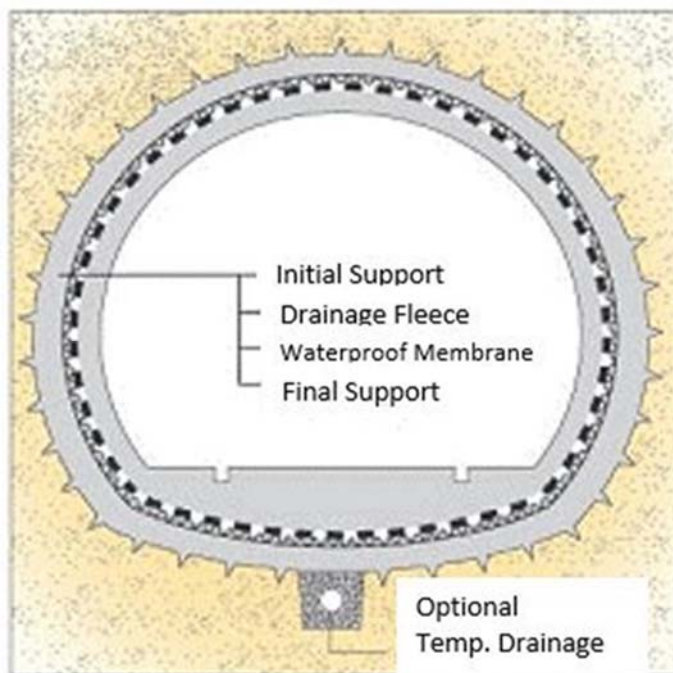


FIGURE 3-4. TYPICAL LATERAL CONNECTION TO CENTER (MAIN) TRACK DRAIN



In an undrained system, the impermeable membrane fully encapsulates the permanent (secondary) concrete lining and prevents all groundwater from infiltrating the structure. This system does not include any drainage pipes to convey groundwater away from the tunnel lining and, therefore, the groundwater equilibrates after coming to a steady-state condition. Since there is no groundwater flow path, eventually hydrostatic water pressure builds up behind the lining and imposes groundwater loads on the tunnel lining which must be resisted. A typical undrained waterproofing system is shown in **Figure 3-5**.

FIGURE 3-5. SCHEMATIC OF UNDRAINED WATERPROOFING SYSTEM



3.3.3 WATERPROOFING SYSTEM COMPONENTS

A continuous flexible membrane waterproofing system typically includes the installation of the following main components:

1. Membrane: Synthetic waterproofing membrane specifically formulated for sealing underground structures against intruding groundwater.
2. Geotextile: Non-woven polypropylene filter fabric protection of the synthetic membrane from sharp projections on the surface to which the membrane is applied, and in drained waterproofing systems, to provide a groundwater channel.



3. **Geodrain:** Composite panel consisting of a rigid HDPE geonet drain core and filter fabric bonded on both sides and held in place by nailed attachment disks. It provides a protection of the synthetic membrane and channeling of groundwater where a drained system is to be used.
4. **Water Barrier:** A base seal waterstop welded to the membrane and applied at construction joints.
5. **Remedial Grouting Pipes:** Pipes typically installed near water barrier intersections to control the watertightness of individual membrane sections. If leakage occurs, the pipes are used for remedial grouting. Pipes are either rigid or flexible.
6. **Concrete Grout Tubes:** Tubes used for contact grouting the voids that typically occur at the crown of the underground structures between the permanent tunnel lining and the membrane waterproofing system attached to the temporary rock support system.
7. **Re-groutable Hose:** Grouting hoses made of synthetics equipped with a valve system, which excludes grout return flow from outside into the grouting hose. The grouting hose must allow multiple grouting passes.
8. **Terminal Box:** Synthetic or metallic box with watertight feed-through connections for re-groutable hoses or remedial grouting pipes to house the grouting and venting ends of the re-groutable hoses or ends of remedial grouting pipes.
9. **Attachment Disk:** Disk made of membrane-compatible material, incorporating a cushioned washer that is nailed to the substrate through the geodrain/geotextile.
10. **BA Anchor:** Rigid plastic shell with an inside thread and membrane flange used for creating watertight penetrations through the membrane.

It is good practice in underground construction to select a synthetic membrane with a 'signal layer'. The membrane is manufactured with two different color materials which are fused together, typically with a thin, bright colored layer to be installed on the side which is exposed during construction and a thicker dark colored layer on the substrate side. When the membrane is damaged during the construction process (such as when punctured by rebar or struck by other objects) the bright colored layer is damaged and the dark colored layer is exposed to identify the damage. A typical signal layer is shown in **Figure 3-6**.

FIGURE 3-6. TYPICAL SIGNAL LAYER CONFIGURATION

Various materials can be used for the synthetic membrane, dependent on the ground, groundwater, substrate, and project conditions. Materials could include:

- Polyvinyl Chloride (PVC)
- High-Density Polyethylene (HDPE)
- Flexible Polyolefin (FPO)

3.3.4 POLYVINYL CHLORIDE (PVC) MEMBRANES

PVC membranes are the most commonly used synthetic waterproofing membranes for underground construction due to their high workability, flexibility, durability and relative economy. Typical membrane thicknesses for use in tunneling projects are between 80 mil and 120 mil, with higher thicknesses used where higher resistance to damage and/or greater durability are desired.

PVC membranes are not used in underground environments that are considered 'gassy' due to degradation under hydrocarbon gas attack. Also, while the membranes are self-extinguishing, they will release toxic fumes when ignited, so proper ventilation and safety equipment is required while the materials are exposed.

3.3.5 HIGH-DENSITY POLYETHYLENE (HDPE) MEMBRANES

HDPE membranes are commonly used in underground construction which exhibits 'gassy' environment, as the HDPE material is more resistant to hydrocarbon attack. These membranes are also commonly used in surface containment applications such as landfill liners, reservoirs, lagoons, etc. where they are exposed to the elements for an extended period. These membranes are typically more expensive and are much stiffer than PVC membranes and, therefore, harder to install in the field, particularly in non-planar overhead applications such as tunnel arches.

3.3.6 FLEXIBLE POLYOLEFIN (FPO) MEMBRANES

Flexible Polyolefin membranes are the newest addition to the waterproofing membrane market and offer a high degree of chemical resistance, including resistance to hydrocarbons, and high strength. They are somewhat stiffer and more expensive than PVC membranes. These membranes are commonly used as replacements to much stiffer HDPE membranes, where high chemical resistant and strength are required.

ADVANTAGES OF FPO (SIKA, 2019)

- Thermal and chemical, including hydrocarbon resistance.
- Service life.
- Low smoke behavior.
- High resistance to permanent pressure.
- Good welding properties due to advanced FPO-recipes.
- Environmental stress corrosion cracking resistance.
- Better fire behavior.

DISADVANTAGES OF FPO

- Ageing through thermal oxidation process.
- Less flexibility in comparison to PVC.
- Costlier than other synthetic membranes

3.4 Compartmentalization

It is recommended that the design of the waterproofing system incorporate a built-in repair system by means of compartmentalization. Compartmentalization refers to the concept of subdividing the waterproofing membrane into individual areas or self-contained grids (compartments) by means of base seal water barriers. These water barriers are specifically formulated for creating these compartments. They feature 1.5-inch high ribs to properly key into the concrete, which is cast against the barriers. Should water leakage occur through punctures that have gone undetected prior to concreting, then the water infiltration will be limited to the individual compartment, thus preventing uncontrolled water migration beyond the compartment. Within this compartment, control and grouting pipes are installed at corners. These pipes penetrate through the concrete lining and are in contact with the membrane (**Figure 3-7** and **Figure 3-8**). They serve a dual purpose. Should leakage occur, then water would find its path to these pipes and exit there, thus signaling a breach within the compartment. Once detected, the same pipes may be used for injection of low viscosity, hydro-active grouts. The injection of grout, as the water migration previously, will be limited to the leaking section only. Once cured, the grout layer provides a secondary waterproofing layer similar to a membrane and acts as a remedial waterproofing layer.

required.

FIGURE 3-7. SCHEMATIC COMPARTMENTALIZATION OF WATERPROOFING SYSTEM

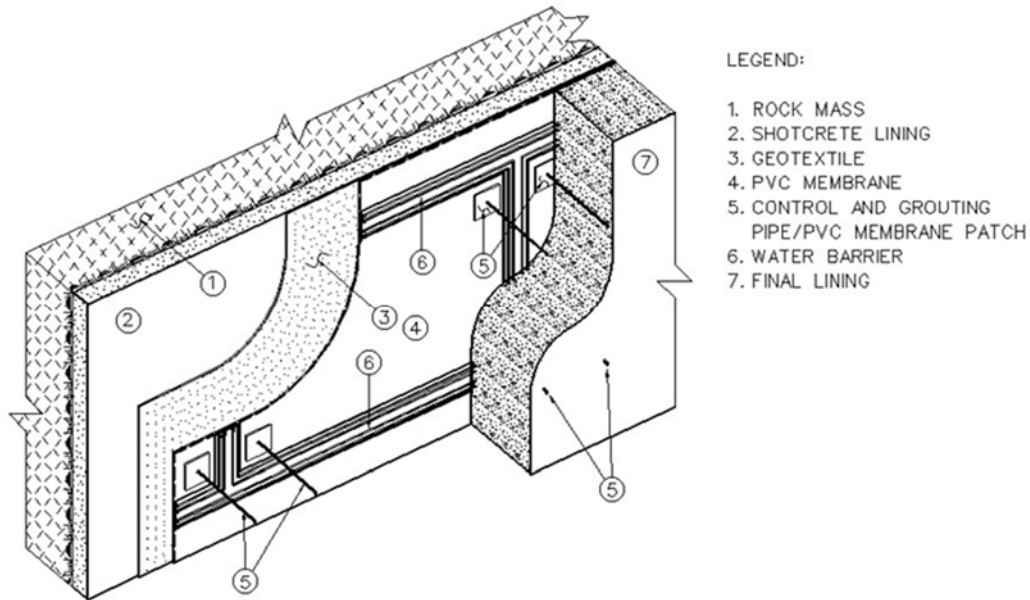


FIGURE 3-8. TYPICAL CONTINUOUS WATERPROOFING (POLYVINYL CHLORIDE - PVC) MEMBRANE COMPARTMENTALIZED SYSTEM (COURTESY OF MTACC FOR EAST SIDE ACCESS PROJECT)



3.5 Waterproofing System Installation

The following summarizes typical waterproofing system installation considerations for a dual lining system with cast-in-place concrete final lining and synthetic membrane suitable for the DART D2 Project.

Prior to waterproofing application, the substrate must comply with a set of specified surface qualities. All loose surface materials and, as applicable, shotcrete and debris must be removed prior to installation. In the case where rock bolts/dowels are installed as part of the initial support, generally, all projecting portions of rock bolt and dowel hardware must be cut off and patched flush with the face of the substrate surface. Temporary supports and hangers installed for construction purposes must be also removed. Any protrusions of more than 1/2 inch must be covered with shotcrete, quick setting grout, or mortar such that no sharp edges remain. All embedded elements of a shotcrete lining should be covered by at least 1 inch of shotcrete or mortar prior to installation of the drainage layer and membrane. Steel fiber-reinforced shotcrete must be covered with a layer of plain shotcrete with a minimum thickness of 1 inch.

The surface of the substrate (initial support) must meet smoothness criteria, which are dependent on the waterproofing material to be installed. It is typical to specify smoothness criteria ranging between 1:10 and 1:20, which relates to the ratio between depression depth and wavelength as measured with a 10/20-foot-long straight edge in random direction.

The drainage layer is attached to the substrate of the initial tunnel support by fired nails and plastic disks. Attachments should be distributed such that they are applied at surface depressions in the initial support to ensure a tight fit of the waterproofing system. The membrane is subsequently welded to the plastic discs (**Figure 3-9**). **Figure 3-10** shows the drainage layer as typically installed for the arch. For invert installation, fewer fixing discs are required.

FIGURE 3-9. FIXING DISC FOR MEMBRANE ATTACHMENT)

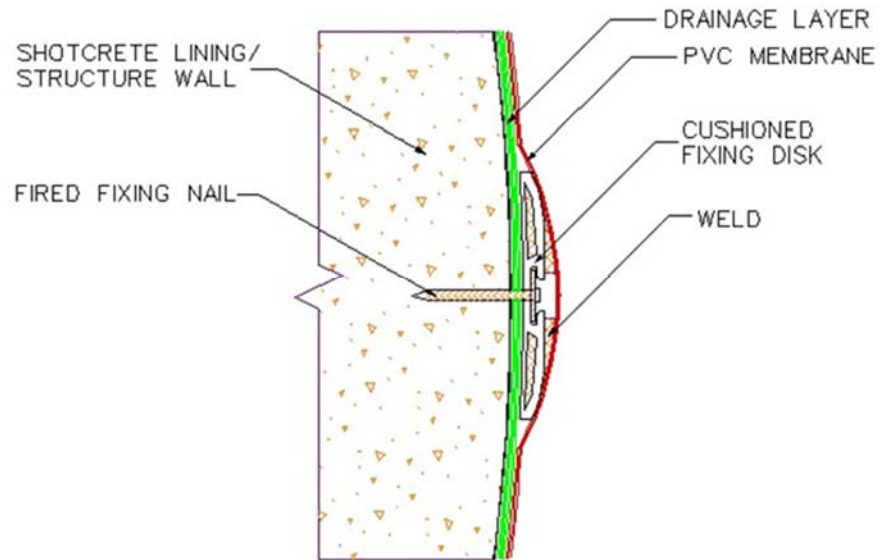


FIGURE 3-10. DRAINAGE LAYER ARCH INSTALLATION



Once the individual membrane sheets are attached to the plastic discs (**Figure 3-11**) they are welded using continuous double weld seams to form a continuous waterproofing membrane system. For an undrained system, the invert waterproofing installation is generally followed by the installation of the invert permanent support, which provides protection during continued construction activities and also acts as a working slab for the installation arch waterproofing and permanent works (**Figure 3-12** and **Figure 3-13**, respectively). Prior to acceptance, the double weld seams are tested with pressurized air to demonstrate tightness.

In a drained system, the membrane covers the entire tunnel vault and sidewall, and terminates at the longitudinal perforated sidewall drain pipes in the invert (**Figure 3-2**). These are embedded in porous concrete or other porous layers. The membrane and drainage layers wrap around this porous layer so that the drainage layer may discharge collected water into the drainage pipe. Inside of the structure, the membrane is fixed in the invert to the concrete footing or mud slab using fired nails at intervals not to exceed usually 1 foot distances.

A skilled installation is required for application of this waterproofing system. Minimum installer qualifications and experience in the installation of this waterproofing system in underground construction is needed. Furthermore, during construction, a detailed quality assurance program must be incorporated that combines checklists, approval procedures and a thorough dedicated inspection.

FIGURE 3-11. LOOSE WATERPROOFING (PVC) MEMBRANE WELDED TO FIXING DISCS

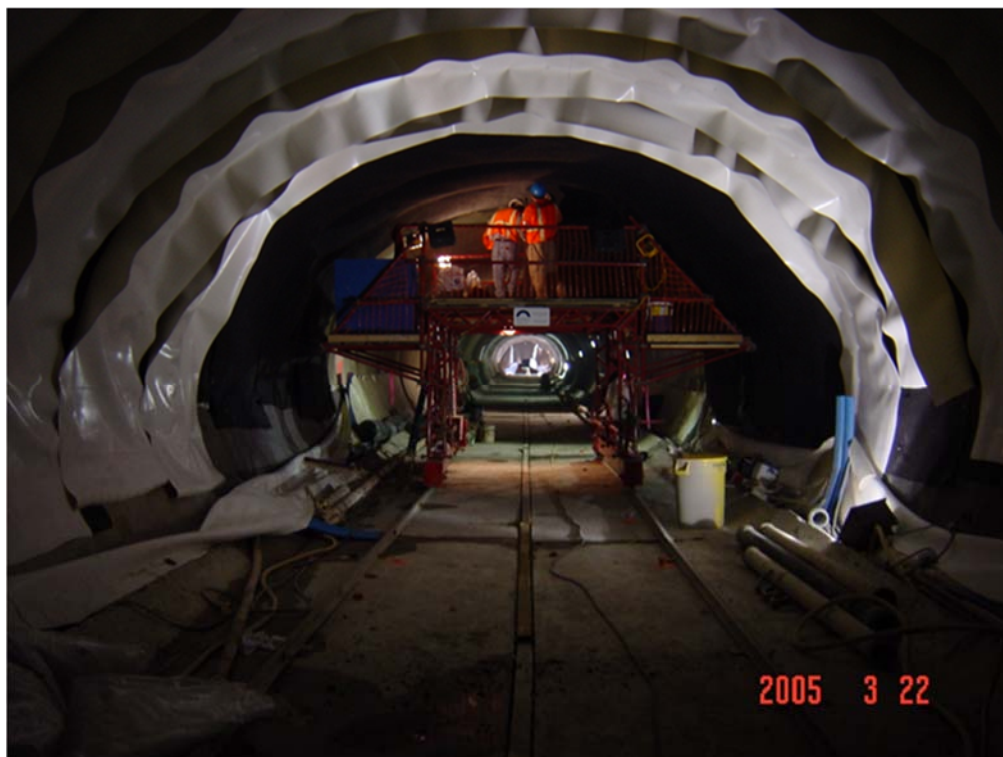


FIGURE 3-12. INSTALLED WATERPROOFING (PVC) MEMBRANE AT TUNNEL INVERT

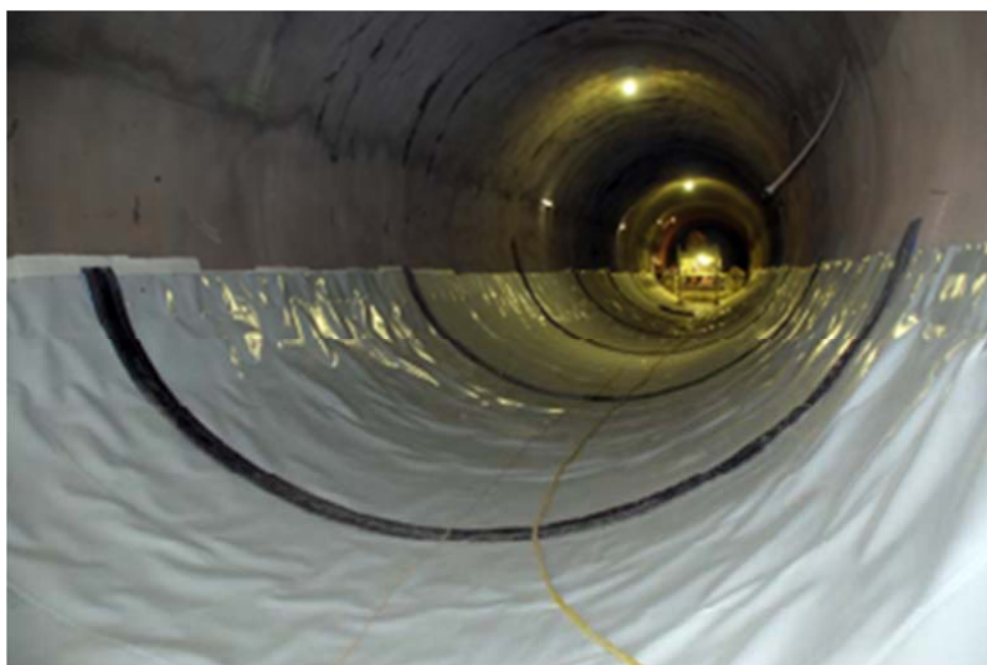


FIGURE 3-13. INSTALLED WATERPROOFING (PVC) MEMBRANE ALONG TUNNEL ARCH



3.6 Other Waterproofing Systems

Other waterproofing systems that may be used in underground structures include:

- Sprayed-on waterproofing membranes
- Water-impermeable concrete.

3.6.1 SPRAYED-ON WATERPROOFING MEMBRANES

Sprayed-on membranes are liquid polymers that are directly sprayed onto substrates like shotcrete or steel. Polymerization is initiated either by chemicals, air or moisture. To facilitate adherence of the spray-on membrane, the substrate must be clean of loose particles, foreign materials (such as oil) and also meet smoothness criteria to enhance thickness control during application. Any water inflow must be either plugged prior to the installation or diverted by means of half-pipes, drain mats, etc. to prevent damaging penetration of water through the freshly applied, soft membrane.

Despite improvements of sprayed-on materials and spray-on membrane systems in recent years, their demands on surface preparation and applications are very constricting, making preparatory work time-consuming and sometimes costly. The demand for practically dry substrate is, unfortunately, contrary to applications where waterproofing is needed. Commonly, much more sprayed-on membrane is applied than anticipated, to accommodate the rough substrate surface

and to achieve the minimum specified membrane thickness, drastically increasing the material and installation costs of the system. Difficulty of adhering to the strict surface preparation requirement makes the sprayed-on membrane vulnerable, thus increasing the risk for malfunction.

3.6.2 WATER-IMPERMEABLE CAST-IN-PLACE LININGS

When constructing water-impermeable cast-in-place (CIP) concrete linings, attention must be paid to the crack limitation and to the sealing of construction joints. For this purpose, CIP concrete must be sufficiently reinforced to limit flexural and shrinkage cracks. The concrete mix should be designed such that the development of excessive heat of hydration is suppressed. Temperature and humidity-conditioned formwork systems and post-treatment devices as well as curing agents contribute to heat and drying control. Chemical admixtures, such as those manufactured by XYPEX and Penetron, that reduce permeability of the concrete by clogging its pores upon contact with seeping water may be effectively used for enhancing impermeability of CIP concrete walls and liners.

Abrupt changes in lining thickness, and excessive roughness of the surfaces against which the concrete lining is being poured, should be avoided. Abrupt changes in thickness lead to the concentration of stresses that frequently lead to the development of cracks at these locations. Increased surface roughness around the tunnel perimeter may result in an interlocking effect between the concrete lining and the surrounding temporary support or ground, thus impeding the free shrinkage of the concrete lining during curing. This process fosters the development of high tensile stresses within the concrete section, which frequently result in cracked linings. Elements of the temporary tunnel support (e.g. steel sets, rock bolts end hardware, steel channels and mine straps) should not protrude into the concrete lining.

An appropriate arrangement of construction joints and their positively controlled sealing is a vital element in water-impermeable concrete applications. Water barriers/stops arranged along the construction joints, either on the outside (towards the ground) or in the middle of the concrete section inhibit the groundwater from flowing into the tunnel opening. In complex applications, water barriers combined with re-groutable grouting hoses, preferably targeting specific problematic sections, are typically used for additional safety against water leakage.

These additional requirements in connection with a sprayed-on application and construction of water-impermeable concrete can result in increased cost and increased installation complexities. Therefore, these two waterproofing methods are not further considered for the DART D2 project. When considering the waterproofing requirements and compatibility considerations described above, the flexible membrane waterproofing system provides a significantly more adaptable and reliable product. It should also be noted that if a unified waterproofing system is used for both the tunnels and stations the implementation of a unified set of surface preparation guidelines, construction materials, installer qualifications and rules of installation QA/QC becomes advantageous.

3.6.3 GASKETED PRECAST SEGMENT LINERS OF TUNNEL BORING MACHINE (TBM) TUNNELS

As mining by one-pass TBM is currently envisioned for DART D2, gasketed precast segments are considered as an alternative to CIP-lined TBM or SEM tunneling whose watertightness is achieved by means of membrane waterproofing systems. In this respect, a single shield tunnel boring machine would be capable of accommodating the constrictions of the alignment. When a Single Shield TBM is used for the tunnel construction, the temporary and permanent supports consist of, respectively, the shield of the TBM and precast concrete segments that are delivered to the TBM, through the excavated part of the tunnel, and assembled, in their final configuration, within the TBM shield. Each precast segment is provided with a specifically designed surrounding gasket, along its four sides, that once pressed together during the concrete lining installation, creates an effective barrier against water intrusion.

4 WATERPROOFING SYSTEMS CONSIDERATIONS FOR DART D2

The tunnel waterproofing systems discussed herein, can also be adopted for portal U-wall sections and/or cut-and-cover construction to be implemented for the project.

At the 10% design level, two types of continuous membrane-based waterproofing system (drained and undrained) were considered for the DART D2 tunnels and stations, depending on the project alignment to be adopted (deeper or shallower, respectively).

4.1 Continuous Flexible Membrane Drained Waterproofing System

A continuous flexible membrane drained waterproofing system for a double lining system, which typically includes a synthetic membrane and drainage layer is generally used for deep rock tunnels and caverns where the water pressures are high, but permeability of the rock medium restricts the flow rate. It reduces the hydrostatic pressure that must be resisted by the structure, and in this respect has an advantage in eliminating the need to design excessively thick walls. Thus, with the use of a drained system, a construction with lower initial cost is achievable. In circular tunnels and arched tunnels and caverns, this advantage is less pronounced, as the loads are resisted in majority by compression in the liner.

Conversely, the drained system incurs added life-cycle cost in terms of maintenance and operation of the water discharge system. In addition, in calcareous formations, such as the Austin Chalk limestone at the DART D2 site, the drainage piping is prone to clogging with time due to calcification.

Although the March 8, 2019 alignment adopted for the DART D2 project is deeper than the baseline alignment considered for the 10% design level, groundwater elevation being 19 to 22 feet below grade, hydrostatic pressures acting on the tunnel and station structures are at

moderate levels; the tunnel will be mined by TBM, which in the case of a one-pass liner does not require externally applied waterproofing and in the case of a tunnel with CIP liner or a tunnel and cross passages excavated by SEM, the circular and arched configurations of these options will not require excessively thick liners to resist the prevailing water pressures.

With regards to the stations, the deep Commerce Street station will be a cavern with an arch configuration, therefore, as explained above, its liner will be resisting external pressures in greater part by axial compression and will not require to be unusually thick. The two cut-and-cover stations will have vertical walls and plane roof and invert slabs resisting external pressures predominantly by bending and, therefore, be susceptible to the effect of these pressures. However, these structures will be situated at the shallower ends of the alignment, therefore, the effect of full water pressure would not necessitate very thick walls and slabs.

Based on these considerations, a drained membrane waterproofing system is regarded as an unnecessary and somewhat objectionable solution to ensure watertightness for the DART D2 tunnel and facilities.

4.2 Continuous Flexible Membrane Undrained Waterproofing System

For the current baseline alignment, the undrained waterproofing system was recommended, involving the use of a flexible synthetic membrane which completely wraps the structure. An additional membrane or protective layer must be used as protection for the waterproofing system installed in the invert area and a non-woven geotextile fabric to protect the waterproofing membrane over the remaining part of the structure. A closed system eliminates the continuous pumping of groundwater volumes and restores the natural groundwater regime practically to near pre-construction levels. Therefore, surface settlements often associated with groundwater drawdown are minimized. This system also eliminates the need for treatment costs of potentially contaminated groundwater, if present.

4.3 Groundwater Infiltration Leakage Criteria

Water leakage can contribute to long-term structural deterioration, increased corrosion, damage to Mechanical-Electrical-Plumbing (MEP) equipment, damages to architectural finishes, which typically result in increased maintenance efforts and cost during the design service life of underground structures. Groundwater infiltration can also cause slippery conditions which may result in potential hazards on walkways for the public and maintenance personnel.

Therefore, it is recommended that stringent watertightness criteria and the use of a continuous membrane waterproofing system are implemented for dual linings in the DART D2 project. This will provide a friendlier and safer environment to the user and reduced maintenance efforts and associated cost to the owner. This agrees with the latest national and international trends where watertightness is an established requirement by agency standards. The information provided below is by no means exhaustive, but it does indicate the infiltration criteria adopted worldwide.



4.3.1 INTERNATIONAL PROFESSIONAL ORGANIZATIONS

The following Information obtained from international professional organizations has been summarized in **Table 4-1**:

- The International Tunneling Association (ITA) (adapted from (VTU, DS 853))
- Singapore's Land Transport Authority (LTA, 2002)
- Hong Kong's Mass Transit Rail Corporation (MTRC, 1997)
- The German Cities Committee (Kienberger, 1999)

Locations of previous tunneling projects by national owner organizations reviewed are as follows:

- Washington
- New York
- San Francisco
- Atlanta
- Boston
- Baltimore
- Buffalo

TABLE 4-1. ALLOWABLE INFILTRATION RATES FROM SELECT INTERNATIONAL PROFESSIONAL ORGANIZATIONS

Organization	Structure Type	Allowable Infiltration (gals/sq.ft./day)
Singapore LTA	Running Tunnel	< 0.001 to 0.003
Hong Kong MTRC	Running Tunnel	< 0.003
ITA Working Group	Running Tunnel	< 0.002
	Cavern (storage/ public use)	< 0.001
German Cities Committee	Running Tunnel	< 0.0002
	Cavern (storage/ public use)	< 0.00002

4.3.2 GERMAN CITIES STANDARDS

In addition to studying case histories and national and international standards, it is necessary to understand the use of the underground structure. For example, the German Cities Committee has sub-categorized their allowable infiltration rates into usage of the underground structure, which is presented in **Table 4-2**.

TABLE 4-2. ALLOWABLE INFILTRATION RATES FROM GERMAN CITIES COMMITTEE (KIENBERGER, 1999)

Category of Tightness	Leakage Criteria	Underground Structure Usage	Allowable Infiltration (gals/sq.ft./day)
1	Completely Dry	Storage & Public Areas	< 0.00002
2	Dry	Subways & Light Rail	< 0.0002
3	Localized Damp Spots due to Capillary Action	Highways & Pedestrian	< 0.002
4	Slightly Dripping	Railway	< 0.012
5	Dripping	Sewerage	< 0.025

While these tables clearly indicate that groundwater infiltration requirements depend highly on the use of the underground structure it must be noted that long-term maintenance considerations play an equally important role when adopting certain water infiltration criteria.

While the trend indicates adaptation of more stringent inflow criteria, it also signifies a trend in the willingness of the owner and operator towards initial investment costs for waterproofing systems, thereby controlling long-term maintenance and operation costs.

Following these international and national trends and for the reasons of passenger comfort, protection of sensitive equipment and significant reduction of long-term maintenance (repair cost), the recommendation for adopting stringent waterproofing criteria for the DART D2 project is justified.

4.3.3 AASHTO RECOMMENDATIONS

The American Association of State Highway Transportation Engineers has provided the following recommendation for highway tunnels (AASHTO, 2017) :

C6.10.2 Criteria generally include a measured infiltration of volume/ft²/day and a maximum flow at any single point. Typical criteria range from 0.0002 to 0.01 gals/ft²/day, with 0.02 gallon per minute of flow from any single leak. The Owner shall establish the required leakage criteria. Factors to consider when establishing permissible leakage include the long-term management of the incoming water, the selected structural system and associated number of joints, and constituent components of the groundwater including groundwater chemistry and contaminants.

5 CONSTRUCTION CONSIDERATIONS

5.1 Constructability Issues

A waterproofing system must be selected and planned to represent the optimal solution regarding the given requirements pertaining to its intended use on the one hand, and the technically and economically acceptable possibilities on the other.

Standards for tunnel construction must be high, in particular those involving sealing and waterproofing systems. There are several constructability issues associated with waterproofing membranes as indicated in the following sections.

5.2 Spatial and Geometry Requirements

Sharp corners are not conducive to waterproofing membranes.

Waterproofing membranes must occupy the space between the initial lining with smoothing layers and the final lining.

5.3 Environmental Considerations

One hazardous materials site rated as a high-risk site is located within the designated location for the roadheader tunnel construction or TBM launch site. The LG Magnolia LP property, located at 1100 McKinney Ave., Map ID 174, was listed in the Activity and Use Limitations (AUL), Voluntary Cleanup Program (VCP), Municipal Setting Designation (MSD), and Groundwater Contamination Cases (GCC) databases. According to the database report, the earliest known date of detected contamination was 2007. The property received a certificate of completion through the VCP in 2007 for addressing soils and groundwater affected by volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), metals, total petroleum hydrocarbons (TPH), polychlorinated biphenyls (PCBs), and solvents. During the VCP process, the applicants agreed to accept an AUL, with MSD institutional controls. The site's proximity to the corridor and the nature of the database listings resulted in a High-Risk ranking.

As stated above, PVC membranes are not used in underground environments that are considered 'gassy' due to the threat of degradation due to hydrocarbon gas attack. The selection of lining material must be carefully determined during final design. Also, while the membranes are self-extinguishing, they will release toxic fumes when ignited so proper ventilation and safety equipment is required while the materials are exposed.

5.4 Availability of Materials

Waterproofing membrane is available from the following sources;

- Sika

- Wisko America Inc.
- UTT Mapaei

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

Due to the sensitivity and service life requirements of the waterproofing membrane, use of non-standard materials, construction equipment, or construction means and methods should not be permitted. Manufacturers' recommendations should be followed at all times.

5.6 Special Monitoring Requirements

5.6.1 TESTING WITH COMPRESSED AIR (SIKA, 2019)

Double-wedge machines produce two welded seams at once. The channel between the seams is then tested for initial and final pressure over the test duration period.

5.6.2 VISUAL INSPECTION OF SEAMS

All seams should be visually inspected after welding for good workmanship. Special attention should be paid to T-joints, penetrations, and flashings.

5.6.3 MECHANICAL TESTING OF SEAMS

All hand-welded seams should be mechanically tested once they have completely cooled. This test helps detect seams that are not fully welded.

5.6.4 MAINTENANCE OF PUMPING SYSTEM

If a drained waterproofing system is employed, the pumping system must be perpetually monitored to ensure water pressure does not redevelop on the final lining.

5.6.5 WATERPROOFING REDUCES MONITORING REQUIREMENTS

Special maintenance due to untimely deterioration of the structure is virtually eliminated by waterproofing systems, and, more importantly, the structure can function as designed over long periods of time. (Wisko, 2019)

5.7 Potential Causes for Delays

Shotcrete surfaces must be prepared so as to achieve the smoothness and regularity required to preserve the membrane integrity. Additional shotcrete may be necessary where required to smooth surface irregularities and meet the smoothness and installation criteria. If not carried out in the first place, this may be a potential cause for delays.

Forms may be required for waterproofing membrane installation.

5.8 Potential Hazards

Water seeping into an underground structure endangers shotcrete and cast in place concrete, especially through freeze/thaw action. (Wisko, 2019) Spalling concrete or shotcrete, icicles, and efflorescence or stalactites are all evidence of a tunnel with either no waterproofing or an inadequately designed system. All necessary precautions should be taken during design and construction to prevent these potential hazards.

Safety is increased by effective waterproofing systems because water seeping through the structure and freezing on the road or track surfaces is eliminated. Additionally, falling of shotcrete or concrete due to freeze/thaw action, is avoided, thereby allowing traffic to pass and routine maintenance work to be performed with greater security. This not only allows road and track beds to function as designed, but also permits the proper operation of electrical, lighting, and ventilating systems contained within the structure. The long-term effects of water incursion, such as leaching of lime and minerals from concrete and mortar and the corrosion of reinforced elements are likewise avoided.

While the waterproofing membranes are self-extinguishing, they will release toxic fumes when ignited. Proper ventilation and safety equipment are required while the materials are exposed.

Undrained lining systems require that the installation of the membrane be designed to cope with water pressure. Permanently drained lining systems must be designed and maintained to carry off the prevailing underground water so that the tunnel shell is relieved. Failure to maintain pumping and/or plugging of the drainage system can lead to the failure of the lining of an undrained system.

6 RECOMMENDATIONS

6.1 Design Recommendation

1. Based on the current alignment and longitudinal profile, the station caverns and the connecting running tunnels for the DART D2 project are anticipated to be constructed primarily within the Austin Chalk and Eagle Ford Shale Formations, under the water-table and excavated by tunnel boring machine (TBM), possibly, combination with conventional sequential excavation method (SEM) of tunneling with a roadheader.

This recommendation is based on the south of Swiss 10% alignment dated March 8, 2019, with steep running tunnel grades and tight radius of curvature west of the CBD East station, where tunneling by TBM would not be possible and would be instead achieved by cut-and-cover excavation or by SEM excavation. It is expected that the remaining length of tunneling will be achieved by one-pass TBM system (gasketed precast concrete segmental liner). If the alignment changes and the tight curve is eliminated, the tunnel excavation by SEM or by cut-and-cover method would be eliminated, however, SEM excavation will still be used for the Commerce Street station and cross passages. Therefore, these recommendations for waterproofing concerns structures constructed by both TBM and SEM excavation.

Considering the geologic and hydrologic conditions, type and configuration of the structure, possible underground tunneling methods to be utilized, the need to provide a dry and functional structure with a design life of a minimum of 100 years and reduced maintenance cost, it is recommended that an undrained synthetic membrane waterproofing system is implemented into the design of the project.

2. As the design progresses further coordination with DART is recommended to evaluate anticipated life cycle cost in conjunction with maintenance and operations requirements for the possibility of incorporating into the design a drained waterproofing system if deemed beneficial.
3. Further investigation into the geologic and hydrologic conditions is needed to investigate the compatibility of various types of synthetic membrane described in Section 3 within the local environment for final selection of an appropriate membrane material.
4. It is also recommended that a compartmentalized system as described in Section 3.4 be implemented to localize leaks and prevent spreading of water along the exterior face of the structure's liner/walls, and to facilitate detection and repair of such leaks.
5. As it is important that the DART D2 structures follow state-of-the-art tunneling practices to provide dry underground space that is pleasant and safe for the public and that operation and maintenance costs are kept to a minimum, we recommend the waterproofing performance requirements be established that do not allow water leakage and that all structures should be completely watertight. The watertightness of the waterproofing system is recommended to be less than 0.001 gal/ft²/day, with 0.02 gallon per minute of flow from any single leak, in accordance with AASHTO, 2017, LRFD Road Tunnel Design and Construction Guide Specifications, First Edition.

6.2 Sources of Uncertainty

6.2.1 DESIGN-RELATED UNCERTAINTIES

These recommendations are based on the south of Swiss 10% alignment dated March 8, 2019, with steep running tunnel grades and tight radius of curvature west of the CBD East station.

With the current alignment and longitudinal profile, the Commerce Street station cavern and the connecting running tunnels for the DART D2 project are anticipated to be constructed primarily within the Austin Chalk and Eagle Ford Shale Formations, under the water table. The station cavern will be excavated by the conventional sequential excavation method (SEM) and the tunnel will be excavated by tunnel boring machine (TBM), possibly, in combination with SEM tunneling with a roadheader or by cut-and-cover excavation at the portion adjacent to the CBD East station, where the horizontal curve of the alignment is not favorable to the advance of TBM tunneling. The Metro Center and CBD East stations will be constructed by the cut-an-cover method.

It is expected that the remaining length of tunneling will be achieved by a one-pass TBM system (gasketed precast concrete segmental liner). If the alignment changes and the tight curve is eliminated, the tunnel excavation by SEM would be eliminated, however, SEM excavation will still be used for the Commerce Street station and cross passages. Therefore, these

recommendations for waterproofing concerns structures constructed by both TBM and SEM excavation.

Considering the geologic and hydrologic conditions, type and configuration of the structure, possible underground tunneling methods to be utilized, the need to provide a dry and functional structure with a design life of a minimum of 100 years and reduced maintenance cost; it is recommended that an undrained synthetic membrane waterproofing system is implemented into the design of the project.

The current south of Swiss 10% alignment may ultimately not be accepted by DART. However, it is not anticipated that subsequent alignment changes would lead to alternate waterproofing requirements and these recommendations. Nonetheless, if the depth of the Commerce Street station at its currently envisioned location or associated with any revised alignment proves to be under excessively high hydrostatic pressures resulting in an unreasonably heavy permanent liner, a drained waterproofing system may be selected during future design development stages.

This recommendation, although not preferred, would be consistent with national and international tunneling practices in urban settings. For example, tunnels with drained continuous waterproofing membrane systems have been used in the following projects:

- MTACC East Side Access Project, New York, New York
- MTACC No. 7-Line Extension, New York, New York
- MTACC 2nd Avenue Subway, New York, New York
- Weehawken Tunnel Project, North Bergen, New Jersey
- Dulles Airport Automated People Mover System, Dulles, Virginia
- Dulles Corridor Metrorail Project, Vienna, Virginia
- DART, Dallas, Texas
- Caldecott Tunnel 4th Bore, Oakland, California
- Crossrail London, London, United Kingdom
- Riyadh Metro Project, Riyadh, Saudi Arabia

6.2.2 CONSTRUCTION-RELATED UNCERTAINTIES

If the contractor cannot meet the watertightness criteria stated above with its design, means, and methods of construction, the underground space may fail to meet a pleasant, safe, low maintenance cost environment. A rigorous QC program is to be implemented to ensure that production, delivery, handling and installation of all the components of the waterproofing system are carried out in accordance with the design specifications and manufacturer's procedures.

6.3 Basis of Recommendation

An undrained continuous membrane waterproofing for SEM tunnel, station and cross passages featuring CIP liners is the preferred method of ensuring watertightness because:

1. Elimination of drainage system prone to clogging due to calcification .
2. Reduced life-cycle cost due associated with low operation and maintenance.
3. Circular and vaulted configuration of tunnel, station cavern and cross passages amenable to resist elevated water pressure.
4. Relatively low water pressures acting on cut-and-cover station structures located at shallower depths of the alignment.
5. Elimination of complex design details and potentially ensuing construction deficiencies.

These recommendations are based on the south of Swiss 10% alignment, which is deeper than the originally proposed baseline alignment and features 20 to 50 feet of unweathered Austin Chalk rock cover. A drained synthetic waterproofing system can also be considered for the CBD station cavern, as surface settlements due to groundwater drawdown will be limited. This option is recommended only when structural analyses during subsequent design development would result indicate the need of an excessively thick liner for the station cavern.

7 REFERENCES

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