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| **Subject:** | **Tunnel Excavation and Drive Assessment (Final Draft)** |
| **Project feature:** | Tunnels and Shafts |
| **Prepared for:** | California Department of Water Resources (DWR) / Delta Conveyance Office (DCO) |
| **Prepared by:** | Delta Conveyance Design and Construction Authority (DCA) |
| **Copies to:** | File |
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# 1. Purpose

This technical memorandum (TM) discusses preliminary findings and considerations involved with determining feasible tunnel excavation and drive lengths for the Delta Conveyance tunnels. This TM supersedes the Viability of Long Tunnel Boring Machine Tunneling Drives TM (DCA, 2020). The current proposed alignment alternatives include single-heading tunnel boring machine (TBM) tunnel drives up to approximately 15 miles long and the finished inside diameter could range from 26 to 40 feet. The preliminary findings contained in this TM would be used to establish shaft spacing, drive length, tunnel/shaft footprint, assist in logistical support, cost estimates and traffic impact studies. Several factors that will impact drive lengths and have been taken into consideration and are discussed in this TM, including:

- Geotechnical and groundwater conditions.
- Tunnel construction maintenance needs.
- Safety considerations.
- Past precedence of long tunnel drives in soil and rock.
- Recommended measures to support long tunnel drives.

At the time this TM was prepared, the bulk of the geotechnical investigations had not yet begun, and there is very little project-specific geologic data available, especially along the Eastern alignment corridor. This TM is expected be modified and refined as additional geotechnical information becomes available, including the optimization of the horizontal and vertical tunnel alignments.

# 2. Geotechnical and Groundwater Conditions.

## 2.1 Ground Conditions

Based upon information provided in the WaterFix 2018 Conceptual Engineering Report (CER) (DWR, 2018), it is anticipated that the tunnel and shafts would be excavated in saturated soft ground conditions., It is expected that the soil deposits at tunnel depth consist of clays, silts, silty and clayey sands, and clean sands based on the data previously collected along the potential tunnel alignments.

## 2.2 Soil Abrasivity

Soil Abrasion Tests (SAT) values provide valuable information about areas of higher abrasion and areas where more frequent TBM cutterhead tool inspections are recommended, which is very useful for planning these inspections. Based on recent SAT results from project borings drilled between 2009 and

2018, the Delta Conveyance Tunnel alignment will be excavated through soils of low to medium abrasivity (DCA, 2021a). It is recommended that Soil Abrasion Testing (SAT) be performed on soil samples along the proposed tunnel alignments during subsequent phases of the geotechnical exploration program.

For comparison, on the San Francisco Public Utilities Commissions (SFPUC) Bay Tunnel project SATs were conducted on a range of soil types that were expected to be encountered during tunnel excavation. In general, the sands and gravels of the San Antonio Formation resulted in classifications of medium to high abrasivity and the clays and silts very low to low abrasivity (SFPUC, 2009). Even though the tunnel had a smaller diameter of 15 feet, during construction the entire 5-mile drive was successfully excavated with no intermediate shafts in ground conditions similar to those expected for the Delta Conveyance tunnels.

## 2.3 Groundwater Conditions

Along the tunnel alignments, the groundwater level ranges from 5 to 10 feet below ground surface (bgs), and the groundwater at any location is connected vertically within a single aquifer. The external hydrostatic pressure on the tunnel could range between 2.7 bar at the tunnel crown up to 4.2 bar at the tunnel invert (bottom of the tunnel) for the 36-foot ID tunnel.

Based on the current drawings, the tunnel would be excavated at a depth ranging from approximately 98 to 119 feet bgs to the tunnel crown (top of the tunnel) for the 36-foot ID tunnel. Reducing the depth of the tunnel will reduce the water and earth pressures acting on the face of the TBM resulting in fewer stoppages for maintenance and improved safety for workers during interventions.

# 3. Tunnel Construction

## 3.1 Horizontal and Vertical Alignment

### 3.1.1 Horizontal Alignment

The tunnel will be kept as straight as possible and with a minimum radius of 1,000 feet. These criteria have been set to accommodate tunnel boring machine steering capabilities and to allow for efficient and safe transport of labor and construction materials. The conceptual horizontal alignment was developed to meet the following design parameters:

- Minimize easement acquisition as much as possible and avoid future developments as much as possible.
- Avoid curves a and maintain tunnel alignments straight when going through all shafts.
- Minimize the construction duration in areas that would affect nearby communities.
- Avoid alignments that will create excessive noise, dust, traffic congestion and restricted access.
- Shaft sites should avoid being in areas of sensitive habitat, such as wildlife preserves or refuges.
- Choose alignments that will have the least negative impact on existing utilities.
- Shafts should be ideally accessible and in close proximity to existing road\highways and rail roads.
- Alignment to connect the shaft locations selected in the Shaft Siting Study TM (DCA, 2021b).

Refer to the Shaft Siting Study TM for further details used in the evaluation for each of the alignment alternatives.

### 3.1.2 Vertical Alignment

The vertical alignment of the tunnel would be chosen based on geotechnical investigations, associated analysis and results, to avoid conflict with existing underground utilities, and to provide proper vertical clearance under specific features (i.e., Stockton Deep Water Ship Channel and East Bay Municipal Utility District Mokelumne Aqueduct). Vertical alignment would be chosen to:

- Stay within favorable ground conditions for construction and seismic performance.
- Be as shallow as possible with respect to the local groundwater table to minimize impacts of hydrostatic pressures on the design and construction.
- Maintain a minimum depth so that surface structures are not impacted.
- Maintain a minimum clearance not less than 75 feet below the current Stockton Deep Water Ship Channel bottom at EL 35 feet Mean Lower Low Water (MLLW).

The vertical alignment shown in the engineering concept drawings was developed for general conformance with the considerations listed above. The final vertical alignment would be further refined as future geotechnical, topographic, and related information becomes available.

### 3.1.3 Tunnel Diameter

Results from the hydraulic and capacity analysis, as described in the Capacity Analysis for Preliminary Tunnel Diameter Selection TM (DCA, 2021c), indicate an inside diameter of 36 feet is recommended for the main tunnels based on that the maximum tunnel flow velocity be limited to 6 feet per second (fps) for the maximum design flow capacity of 6,000 cfs. Results also indicate a minimum 28-foot inside tunnel diameter would be needed to convey the anticipated flows for the northern tunnel located between intakes C-E-3 and C-E-5. However, it is recommended for planning purposes that the tunnel inside diameter be increased to 36 feet to match the main tunnels since the extra cost associated with a larger 36- foot inside diameter tunnel would be offset by the elimination of an intake area launch shaft with ancillary tunnel infrastructure, an additional TBM (28-foot ID), and mobilizing another tunneling operation near the intakes.

To facilitate segment erection, steering tolerances and shield thickness, the excavated diameter would be slightly larger than the outside diameter of the precast segments. Refer to the Tunneling Effects Assessment TM (DCA, 2021d) for excavated diameter details.

## 3.2 Tunnel Excavation Method

State-of-the-art pressurized-face TBMs will be required to excavate the Delta Conveyance tunnels due to the presence of high groundwater pressures combined with the varying permeability of the soil units. There are two basic types of pressurized-face tunneling machines that could be used effectively in these conditions—Earth Pressure Balance (EPB) TBMs and Slurry TBMs. Recently, Variable Density TBMs (hybrid TBMs) can excavate in various types of soils and have been developed to operate as either EPB or Slurry TBMs, although some effort is required to switch from one mode to the other.

In addition to the contractor’s experience the choice between EPB and Slurry TBM excavation methods is influenced by several geotechnical factors, including grain size distribution, strength, ground permeability, occurrence of boulders or obstructions, hazardous gases and contaminants, feasibility of soil separation and muck disposal, and settlement considerations. EPB TBMs are typically used in cohesive soils such as silts and clays, while Slurry TBMs are used in cohesionless soils such as sands and gravels. Based on data collected to date, it is expected that an EPB TBM would be the most suitable method for excavating the fine grain soils. However, further studies as to the specific type of pressurized TBM to be used for each of the tunnel reaches will need to be evaluated in future phases once additional geotechnical investigations have been performed.

## 3.3 Major TBM Design Components

When discussing the longevity of the TBM cutterhead it is useful to distinguish between primary and secondary wear. Primary wear is the wear expected on the replaceable cutting tools, while secondary wear is the wear on the supporting structures of the cutterhead. Secondary wear can lead to major overhauls on the TBM and, if not repaired, could cause major structural failure to the cutterhead; thus, stopping the tunneling operations. Principal factors affecting primary and secondary wear are:

- The nature of the soil including its mineralogy, grain sizes and abrasiveness.
- Face confinement or support pressure.
- The type and style of cutting tools chosen.
- Thickness of cutterhead and all moving/rotating elements which are in direct contact with the soil.
- The opening area and the geometry of the openings on the cutterhead.
- The wear protection (special alloys) fitted to the cutterhead.
- Ground conditioning and the volume and type of ground conditioning agent used.

Minimizing wear is important because interventions required to perform maintenance can be risky and represent significant delays to tunnel progress. During tunnel excavation, control of primary wear and minimization of secondary wear should be addressed by regular inspection of the cutterhead and especially the primary wear elements like the tools.

Before tunneling operations begin, a thorough ground conditioning test program should be carried out to optimize conditioner application. Consistent ground conditioning combined with regular cutterhead inspections would be expected to minimize delays due to clearing blockages, changing worn out tools, or repairing damage to the cutterhead. Injection of the soil conditioning agents can be introduced at various points along the tunneling system through the cutterhead, TBM shield, within the cutting chamber and also at the screw conveyor.

A brief description for some of the major TBM components that will require continuous monitoring and maintenance are discussed below.

### 3.3.1 Cutterhead

To reduce the amount of maintenance to be performed on the cutterhead, the use of high -strength materials having abrasion resistant properties to protect the cutterhead structure will be required to minimize wear. On the cutterhead face and rim, the use of chromium carbide wear protection plates is advisable. This overlay surface is welded to the steel and has a hardness up to five times greater than unplated steel. Figure 1 depicts various cutterhead features, wear detection devices, and cutting tools.

### 3.3.2 Cutting Tools

The spacing of cutting tools affects the durability of the cutterhead. The quantity of cutters should be designed for efficient material removal at the working face with a sufficiently dimensioned tool gap and cutting tool penetration depth.

The bucket lip tools allow for a smooth flow of the muck into the excavation chamber. Having an adequate bucket size that can hold an appropriate quantity is important to avoid excessive wear in the cutterhead periphery. The bucket lips should be made of high-strength material and be replaceable. The cutterhead design should consider that the cutterhead tools need to be exchanged from the backside of the cutterhead. Therefore, cutterhead tools that are proposed to be welded to the front of the cutterhead structure or can only be changed from the front of the cutterhead, should be avoided. If such tools cannot be replaced from the inside of the cutterhead, their use should be minimized as much as possible and be of materials to withstand abrasion.

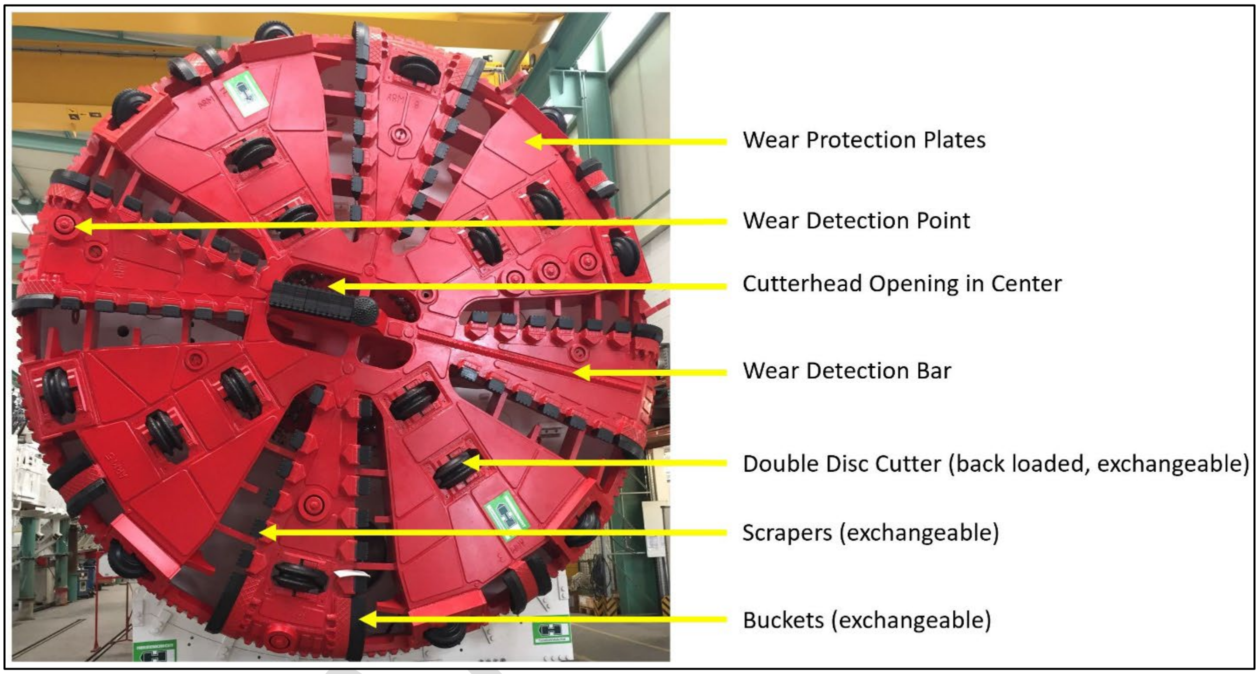


**Figure 1. Cutterhead, Features and Tools (BabEng 2018)**

### 3.3.3 Main Bearing

The main bearing is a crucial part of the TBM. On extended tunnel drives it must have a long design life, with a robust structure and high safety factor. A bearing life of at least 20,000 operating hours is regularly achievable by manufacturers (only the time the cutterhead rotates counts as operating time).

If a main bearing prematurely requires replacement, it is possible to do so without the construction of a shaft in front of the TBM; however, the main bearing would need to be designed to be exchangeable from within the TBM. Such a replacement would require at least several months of delay to tunneling operations. Due to long lead times involved, it is highly recommended that a spare main bearing be ordered with the TBM and remain stored in close proximity to the project site during tunneling.

### 3.3.4 Main Bearing Sealing System

The main bearing seals are another crucial part of the TBM. These seals are the barrier between the excavation chamber and the main bearing and protect the main bearing from water and material ingress from the excavation chamber. Common designs include several rows of seals to increase reliability. To provide an additional level of security, an inflatable emergency seal can be implemented into the design. Also, it is possible to equip the main bearing seals with temperature sensors to provide early indication of potential problems. Other preventive methods include sampling of the main bearing lube oil on regular intervals to check for foreign materials such as soil particles or metal residue caused by premature wear of the bearing.

## 3.4 Interventions for Maintenance

Another important issue for tunnels excavated with pressurized TBMs is access for cutterhead maintenance and for changing cutters. The contractor will need to inspect the cutterhead and change cutters periodically, probably about once a week or every other week depending on the ground conditions and advance rates. For the construction schedule estimate, one hyperbaric intervention occurring once every two weeks for a duration of 20 hours was assumed.

In stable, low permeability ground conditions, it may be possible to attempt free-air interventions (I.e., perform maintenance on the TBM at atmospheric conditions or very low pressures). When this is not possible, groundwater pressures have to be balanced by applying an air pressure approximately equal to the hydrostatic head. Work performed in a compressed air environment above 3 bars requires the use of mixed gases and/or saturation diving techniques. Typical working ranges as noted by Dubnewych, et al. (2007) for use of compressed air, mixed gas, and saturation diving are summarized in Table 1.

**Table 1. Recommended Pressure Working Range for Hyperbaric Interventions on TBM**

| Intervention Type | Recommended Working Pressure Range (bara) |
|---|---|
| Compressed Air | 0 to 3.6 |
| Mixed Gas | 3 to 8 |
| Saturation Conditions (with mixed gases) | 4.5 to > 45 |

[a] 1 bar is equal to 14.5 psi

It should be noted that Cal/OSHA Tunneling Safety Orders do not cover compressed air work above 3.5 bars. This is to discourage the use of compressed air tunneling and to control the safety of operations by reviewing each job under a variance request. However, it is recommended for worker safety, every attempt should be made in the future to try to reduce the vertical profile of the tunnel so that working pressures are kept below 3.5 bar.

When major intervention cannot take place at predetermined maintenance shaft location, TBMs should be designed and equipped to perform ground treatment ahead of the face to facilitate cutterhead maintenance. Usually this involves a systematic program of drilling and pre-excavation grouting or ground freezing ahead of the advancing TBM. This allows for interventions to be undertaken at atmospheric pressure or at reduced pressures, which is safer than personnel working in hyperbaric conditions. Incorporating these design features into the TBM ahead of time will allow for flexibility and ensure the work be performed more safely and with less delays.

## 3.5 Safety Considerations

To maintain safe underground working conditions during construction, the contractor must comply with all the safety regulations documented by Cal/OSHA Subchapter 20 Tunnel Safety Orders. Many of these safety issues could be mitigated by selecting an appropriate excavation method and implementing precautionary or proactive measures. For the construction of the Delta Conveyance tunnels, considerations for gassy ground and emergency response time are two key safety issues.

### 3.5.1 Gassy Soil Conditions

The project corridors pass through areas of the Delta that are underlain with gas fields that extend more than 1,000 feet below the ground surface. Though the tunnel classification has not yet been provided by Cal/OSHA, it may receive a “potentially gassy” or “gassy” classification due to the presence of gas wells and fields in the region. Appropriate mitigation measures will need to be in place, and the contractor will need to comply with Cal/OSHA’s Tunnel Safety Orders (CCR, 2018a) so that the tunnel can be excavated in a safe manner. Under “potentially gassy” or “gassy” classification, the TBMs are required to be equipped with gas monitoring equipment that automatically shut down the TBM if gas is detected. It is also likely that special access and egress requirements may be imposed by Cal/OSHA. Additionally, if a particular reach of tunnel is classified as “gassy” then all equipment used in the tunnels needs to be intrinsically safe (I.e., equipment and associated wiring not capable of causing an explosion) for that reach. Additional safety requirements can be found in Cal/OSHA Tunnel Safety Orders.

### 3.5.2 Emergency Response

A detailed emergency plan for use in time of emergency will need to be prepared by the contractor prior to any work being performed in the tunnel. The plan will need to comply with all the requirements stipulated by Cal/OSHA Tunnel Safety Orders Article 9 (CCR, 2018b) and shall include such items as ventilation controls, firefighting equipment, rescue procedures, excavation plans and communications. The plan will also outline the duties and responsibilities of each key person if a fire, explosion or other emergency were to occur. Due to the remote shaft locations Cal/OSHA also requires the contractor to provide (or make arrangements in advance with locally available rescue services to provide) at least two 5-person rescue teams, one on the jobsite or within one-half hour travel time from the entry point, and the other within 2 hours travel time. A complete list of regulations that pertain to rescue crews and breathing apparatus requirements are documented in Cal/OSHA Tunnel Safety Orders Article 10 (CCR, 2018c).

## 4. Feasibility of Long Tunnel Drives

A literature review was performed to study existing industry experience with long tunnel drives and focused on tunnel projects with varying drive lengths in soil and rock. Tables A1 and A2 in Attachment 1 summarize some of the longest tunnel drives in soil and rock that have been excavated with a single heading. The results of this literature review indicated that the lengths of a tunnel drive were determined by multiple factors. For example, use of multiple shorter tunnel drives of less 2 miles were used for the following types of installations:

- Wastewater tunnels with interim manholes for maintenance or drop shafts to facilitate connections at relatively short separation distances.
- Transit tunnels with transit stations at relatively short separation distances.
- Water conveyance facilities that were primarily constructed using cut-and-cover methods or placement of the pipelines on the ground surface, and the tunnels were only used for short distances to cross utilities, major roadways, streams, or other above ground features that could not be disturbed.
- Tunnels that were constructed using concurrent multiple TBMs to reduce the total project delivery time.

Longer tunnels (greater than 4 miles) have been used for water conveyance and transit tunnels that do not have limitations related to other infrastructure or features. The longer tunnels have been excavated in both soil and rock, including:

- Soft ground and hard rock geology.
- Sub-aqueous tunnels (underwater).
- Under urban environments with limited shaft site availability.
- In remote areas with limited surface access due to geography or the presence of protected environmental habitat.

Two of the longest drives identified in the literature review included a 5.6-mile-long section of the 51-ft diameter Tokyo Outer Ring Road tunnel and the 5.8-mile-long, 41-ft diameter Central Circular Route Shinagawa North Line road tunnel located in Japan. One of the longest undersea TBM drives occurred in rock for the Channel Tunnel between France and the United Kingdom with the longest single heading drive of approximately 13.9 miles. Another example of a long drive in rock is the Deer Island Outfall in Boston, Massachusetts which extended approximately 9.4 miles without any intermediate shafts. The Districts of Los Angeles County Sanitation Districts' Joint Water Pollution Control Plant Effluent and Outfall Tunnel is under construction and is planned to be 7 miles long with a single Slurry TBM with no intermediate access. Even though some of these tunnels include rock segments the mechanical component requirements for a hardrock TBM need to be much more robust compared to soft ground TBMs and that is why these project examples have been included in this discussion.

Based on precedence and today's technology it appears that excavating tunnels in soils up to 6-miles long is readily achievable. The reason why there are not many more examples of long soil tunnels is not related to TBM performance but for other reasons as stated above. In order to extend single tunnel drives up to approximately 15 miles in length, intermediate maintenance shafts will be required at intervals not exceeding 6-miles. The maintenance shafts will allow the TBM to be totally refurbished, if needed, to a "like new "condition and provides opportunity to have the TBM and its components recertified to meet manufacturer's specifications and standards. Maintenance shafts also provide additional benefits, such as means for egress and ingress and logistic support to make tunneling operations more efficient.

# 5. Recommended Measures to Support Long Tunnel Drives

## 5.1 Accessible Cutterhead Spokes

Manufacturers have developed special cutterheads with ports that can be used to replace the cutters from inside the spoke of the cutterhead under atmospheric conditions. The concept allows for access to some important cutterhead tools without the need for compressed air entry into the excavation chamber. Access is provided to the most important cutterhead tool type (discs or rippers), but there are other cutterhead tools that still require compressed air interventions for change-outs (scrapers and buckets). Therefore, this feature reduces the number of compressed air interventions, but does not eliminate them completely.

The Herrenknecht Slurry TBM used on the Bosporus Crossing in Turkey incorporated accessible spokes into the cutterhead design as shown in Figure 2. The concept of accessible cutterhead spokes was first used on the Elbe River 4th Bore in Hamburg, Germany completed in 2000 with a 46.5-foot diameter pressurized face TBM.

**Figure 2. Cutter change within Accessible Cutterhead Spoke in Atmospheric air (Herrenknecht, 2019).**

## 5.2 Wear Sensors

The cutterhead should be designed so that the cutterhead tools are in contact with the soil to cut and excavate the ground. The cutterhead tools protrude from the cutterhead structure. However, when cutting tools wear out beyond acceptable limits, there is a risk of wear and structural damage to the cutterhead structure, which is secondary wear as described above. This wear needs to be prevented because of the long and very costly stops required for repair work that may include welding in the excavation chamber under compressed air.

Wear detection systems are a state-of-the-art technique to indicate excessive wear of the cutterhead tools and to prevent secondary wear. Wear sensors protrude from the cutterhead steel structure, but not as much as the cutterhead tools. The intention is that the wear indicators detect problems before there is a risk of damaging the cutterhead structure. Alarms from the wear indicator systems are shown on a monitor located in the operator's cabin. The two types of designs used on the cutterhead are wear detection points and wear detection bars and as shown on Figure 3. Both designs are based on the same principle. They contain an oil line with a pressure sensor inside the TBM. When the wear causes damage in the indicator at the cutterhead, the oil discharges, causing the pressure inside the line to drop. This indicates wear to the detection system.

## 5.3 Remote Cameras – Excavation Chamber and Cutterhead Backside

To get better and early information about the cutterhead tools and structure, even before or without an intervention, TBM manufacturers are currently experimenting with improved wide-angle cameras lenses mounted on a cylinder that extends into the excavation chamber to provide video and picture feed of the status (see Figure 3). The setup also includes a water nozzle that can clean the camera and the backside of the cutterhead and cutterhead tools.

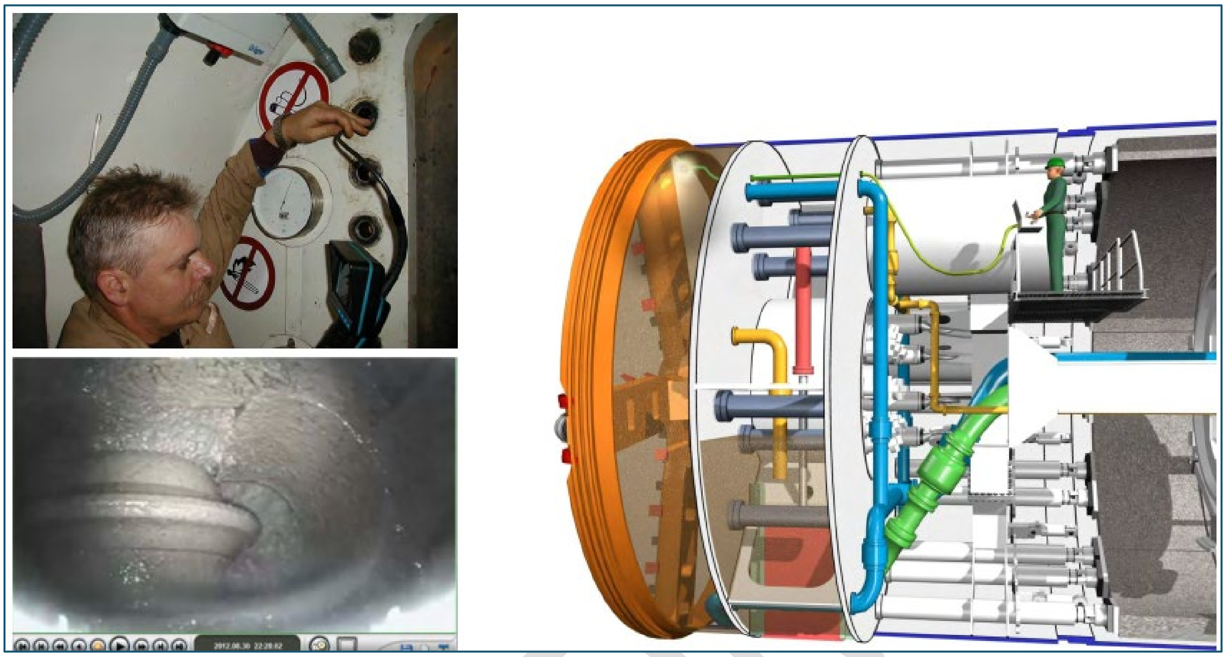

**Figure 3. Camera Extending into the Excavation Chamber for Inspection (Ozdemir, 2015)**

## 5.4 Soil Conditioning

Soil conditioning is an important aspect of soft ground tunnel construction to improve TBM performance and to modify the ground to provide better control of the tunneling operation and RTM material. Suitable conditioning agents may be introduced at various points in the tunneling process, including at the cutterhead/ground interface, within the cutterhead chamber, in the muck removal system (screw conveyor), and around the outside of the tunneling shield. Soil conditioning agents improve EPB TBM performance in several ways:

- Reduced wear of cutterhead face plate and tools, and all parts of the RTM removal system.
- Reduced torque and cutterhead power requirements.
- Reduced friction and heat buildup along the TBM shield.
- Improved flow of excavated material through the cutterhead.
- Improved handling of excavated material because it is formed into a suitably plastic-like mass.
- Improved stability of tunnel face and better control of surface settlement.

It is far more cost effective to treat the soil being excavated with appropriate conditioners than to implement time-consuming maintenance tasks for equipment during tunnel excavation. In general, soil conditioning would be required for EPB TBMs in all ground types.

# 6. Maintenance and Inspection During Operations

Access into the tunnel for inspection and maintenance during operations would be provided at the launch, maintenance and reception shafts. Having shaft intervals at a spacing not exceeding 6 miles would not only meet construction needs but also comply with operation and maintenance requirements. Refer to Tunnel Inspection and Maintenance Considerations TM (DCA, 2021e) for further details.

# 7. Conclusions

The constant development of TBM technology and increasing working life of components allow for larger and longer tunnel drives. Planning for the Delta Conveyance tunnels to have single drives extending up to approximately 14 to 15 miles in length is considered achievable if the following measures are implemented.

- Spacing of maintenance shafts should not exceed 6 miles over the length of tunnel between launch and reception shafts. Based on research, current state-of-the-art soft ground TBMs have successfully completed or are in the planning stage to excavate single tunnel drives up to 7 miles long.
- TBMs should be fully refurbished at maintenance shaft locations and recertified to manufacturers standards.
- Key TBM components, including the main bearing should be guaranteed by the manufacturer for the minimum operating hours needed to excavate 15 miles.
- A spare main bearing should be provided by the manufacturer with the TBM and stored throughout the duration of tunneling.
- The design of the TBM should allow for the replacement of the main bearing and seals from within the tunnel.
- Maintenance shafts should be used for tunnel ventilation and tunnel egress and ingress, if feasible.
- During tunnel excavation, control of primary wear and minimization of secondary wear should be addressed by regular inspection of the cutterhead which will increase the longevity of the TBM.
- Cutterhead tools should be designed to be exchangeable from the backside of the cutterhead.
- TBM should be designed and have the capability to perform ground treatment ahead of the face. This would allow the development of underground safe havens if needed.
- Sensors should indicate excessive wear of the cutterhead tools and prevent secondary wear
- Remote camera systems should be located in the cutterhead structure to monitor the condition of the cutterhead structure and cutting tools.
- Consistent ground conditioning should be used to maximize EPB TBM performance and minimize unexpected delays due to blockages, worn out tools, or damage to the cutterhead structure.
- Experienced TBM operators that have constructed long tunnels in similar ground conditions.

This is not a complete list but includes some of the major considerations that should be implemented to ensure the longevity of the TBM components to achieve drive lengths up to approximately 15 miles. As mentioned previously, this TM needs to be updated once additional geotechnical information becomes available and as TBM technologies improve over time.

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# 9. Document History and Quality Assurance

Reviewers listed have completed an internal quality review check and approval process for deliverable documents that is consistent with procedures and directives identified by the Engineering Design Manager (EDM) and the DCA.

| Approval Names and Roles | | | |
|---|---|---|---|
| **Prepared by** | **Internal Quality Control review by** | **Consistency review by** | **Approved for submission by** |
| Steve Dubnewych / EDM Tunnels and Shafts Lead | Robert Marshall / EDM QC Reviewer | Gwen Buchholz / DCA Environmental Consultant<br>Phil Ryan / EDM Design Manager | Terry Krause / EDM Project Manager |

This interim document is considered preliminary and was prepared under the responsible charge of Steve Dubnewych, California Professional Engineering License C66922.

**Note to Reader**

This is an early foundational technical document. Contents therefore reflect the timeframe associated with submission of the initial and final drafts. Only minor editorial and document date revisions have been made to the current Conformed Final Draft for Administrative Draft Engineering Project Report version.

# Attachment 1
# Long TBM Drives

**Table A1. Examples of Long Pressurized-Face TBM's tunnels**

| Project and Location | Length (mi) | TBM Diameter (feet) | Country | Status Tunnelling | TBM Type | Application | Comment |
|---|---|---|---|---|---|---|---|
| Tokyo Outer Ring | 2 x 5.6 | 52 | Japan | Ongoing | 2 x EPB | Road | Hydrostatic head up to 7 bar |
| Albvorland Tunnel | 2 x 4.9 | 36 | Germany | Complete | 2 x EPB | Rail | |
| Galleria Santa Lucia | 4.69 | 52 | Italy | Complete | 1 x EPB | Road | |
| Changjiang Yangtse River Crossing | 2 x 4.4 | 50 | China | Complete | 2 x Slurry | Road | Water pressure up to 6.5 bar |
| Yangtze River Tunnel | 4.4 | 51 | China | Complete | 1 x Slurry | Road | |
| Bei Heng Motorway | 4.0 | 51 | China | Complete | 1 x Slurry | Road | |
| Westerschelde Tunnel | 4.1 | 37 | Netherlands | Complete | 2 x Slurry | Road | Water pressure up to 6.2 bar |
| Central Circular Route Shinagawa North Line | 5.0 | 41.2 | Japan | Complete | 1 x EPB | Road | |
| Deep Tunnel Sewerage System (Contract T-02) | 4.8 | 20 | Singapore | Complete | 1 x EPB | Wastewater | |
| Deep Tunnel Sewerage System (Contract T-04) | 4.5 | 14 | Singapore | Complete | 1 x EPB | Wastewater | |
| SFPUC Bay Tunnel | 5.5 | 15 | USA | Complete | 1 x EPB | Water | |
| Thames Tideway | 5 | 29 | UK | Completed | EPB | Water/Waste water | Total Length 16 miles |
| HS2 Chilterns Tunnel | 2 x 10 | 34 | UK | Starting 2021 | 2 x Variable Density | Rail | Hybrid – EPB\Slurry combination |
| BART Silicon Valley Phase II | 5.0 | 55 | USA | Under design | Pressurized Face | Transit | |
| JWPCP Effluent Outfall Tunnel | 7.0 | 21 | USA | Starting 2021 | 1 x Slurry | Effluent | Shafts have been constructed and TBM is procured. |

**Table A2. Examples of Long Hard Rock TBM's tunnels**

| Project and Location | Length (mi) | TBM Diameter (feet) | Country | Status Tunnelling | TBM Type | Application | Comment |
|---|---|---|---|---|---|---|---|
| Inland Feeder – Arrowhead East Tunnel | 4.2 | 19 | USA | Completed | Single Shield | Water | |
| Chattahoochee Tunnel (North Drive) | 4.9 | 18 | USA | Completed | Main Beam | Wastewater | |
| Nancy Creek Tunnel (Southern Drive) | 5.0 | 18 | USA | Completed | Main Beam | Wastewater | |
| Second Manapouri Tailrace Tunnel | 6.2 | 33 | New Zealand | Completed | Main Beam | Water | |
| Deer Island Outfall | 9.4 | 27 | USA | Completed | Double Shield | Wastewater | |
| Gotthard Base Tunnel (Bodio to Faido) | 10.3 | 29 | Switzerland | Completed | Gripper | Rail | |
| Channel Tunnel (Marine Tunnel South - UK Side) | 11.1 | 27 | UK/France | Completed | Double Shield | Rail | Weak rock |
| Channel Tunnel (Marine Tunnel North - UK Side) | 11.5 | 27 | UK/France | Completed | Double Shield | Rail | Weak rock |
| Channel Tunnel (Marine Tunnel North - French Side) | 12.0 | 29 | UK/France | Completed | EPB | Rail | Weak rock |
| Channel Tunnel (Marine Tunnel South - French Side) | 12.5 | 29 | UK/France | Completed | EPB | Rail | Weak rock |
| Channel Tunnel (Marine Service Tunnel – French Side) | 13.9 | 19 | UK/France | Completed | EPB | Rail | Weak rock |