Subject:	**Shaft Conceptual Design (Final Draft)**
Project feature:	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
Date/Version:	December 23, 2021
Reference no.:	EDM_SH_CE_TMO_Shaft-Conceptual-Design_000942_V03_FD_20211223

1. Introduction

1.1 Purpose

This technical memorandum (TM) defines the conceptual design, and operational and construction requirements for shaft structures associated with the Delta Conveyance Project (Project) tunnel conveyance system. Key factors affecting the sizing of shafts are identified for each usage type.

Potential construction methods are described and compared considering the shaft's ground supporting lining structure, as well as the base slab and internal linings required for the launch and receiving of tunnel boring machines (TBMs) and the long-term permanent loading condition. A comparison of the methods considers the benefits and disadvantages for a range of factors, including safety and environmental aspects. The ultimate choice of methods would need to consider detailed ground investigations and groundwater studies; but also, since the permanent structure requirements would not generally dictate the method, the contractor should be able to choose a method that suits their expertise and proposed construction sequencing.

The work site requirements associated with construction of the shaft structures and for the servicing of the associated main tunnel drives are identified, and potential arrangements of work site areas are discussed. Details of the shaft locations are shown on the engineering concept drawings and included in a separate Shaft Siting Study TM (DCA 2021a)

1.2 Summary of Proposed Planning Assumptions

The following sizing and methodology assumptions are considered suitable as a basis for planning purposes.

1.2.1 Shaft Sizing

The following shaft sizing has been assumed in the conceptual design:

- Launch shaft sizing of approximately 115-foot internal diameter (ID)
- Retrieval shaft sizing of approximately 70-foot ID
- Maintenance shaft sizing of approximately 70-foot ID

The shaft sizing is broadly based on a 36-foot-ID tunnel. Section 5 provides shaft dimensions for different tunnel diameters. Shaft sizes may vary at specific interface structures such as intakes and forebay inlets/outlets where other hydraulic requirements may dictate the diameter of the shafts.

1.2.2 Methods of construction

Method of construction assume a circular diaphragm wall shaft lining with excavation underwater and a tremie base slab. An internal lining would be installed at the tunnel and would include framing of the tunnel openings. This method is subject to further study of ground investigation data.

1.2.3 Worksite Arrangements

The following worksite arrangements have been assumed in the conceptual design (please refer to Section 4 for detailed descriptions):

- Tunnel servicing work sites at a launch shaft would be approximately 25 acres per drive, excluding segment storage and reusable tunnel material (RTM) stockpiles. Part of the work site would consist of an elevated pad for construction of the shaft with approximately 4 acres for single drive and 6 acres for double drive site. The surrounding area would be used for support facilities water treatment and topsoil material stockpiles.
- Maintenance and reception shaft construction work sites would require an area of approximately 12 acres with 1.5-2.5 acres for an elevated pad and the surrounding area needed for support facilities and excavated material stockpiles.
- Segment storage is subject to the logistics approach employed and has been assumed at 7 acres for each tunnel drive to provide 4 months supply.
- RTM storage is considered as a separate site area connected by a surface conveyor and road system. The layout and areas required are the subject of a separate TM (DCA, 2021b)

2. Shaft Requirements

2.1 Operational Requirements

2.1.1 Drop and Riser Shafts

Shaft structures at the beginning and end of the tunnels form part of the conveyance systems and transfer water from the surface intake structures down to the tunnel level and then return the water via pumping to the surface facilities at the terminus. Also these shafts in their final configuration assist the system in surge mitigation since they provide a cushion when the system is shutdown quickly for any reason. Figure 1 shows a possible arrangement of a drop or riser shaft. The inlet and outlet structures would be placed on top of the shaft structure at a level dictated by the associated intake, forebay, or pumping plant arrangement.

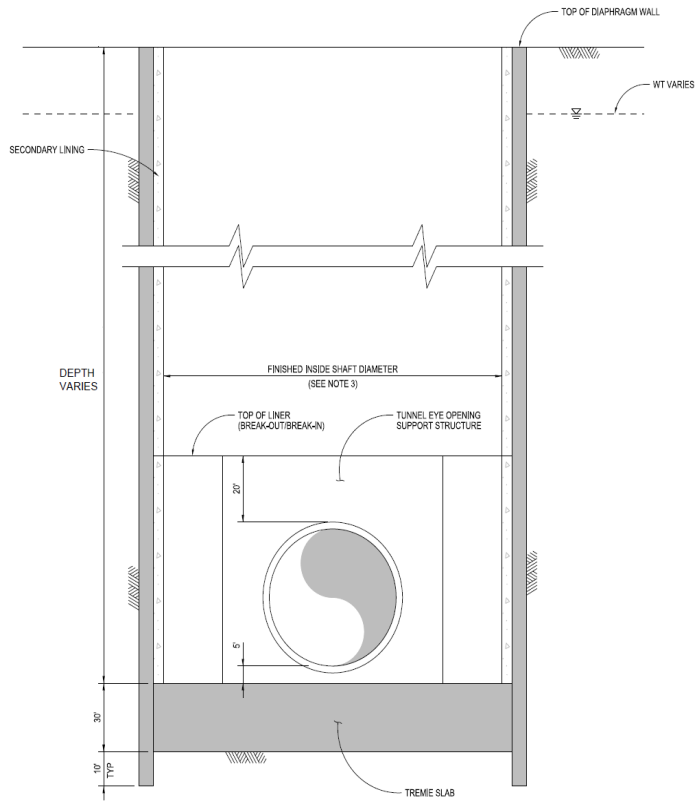


Figure 1. Potential Arrangement for a Drop and Riser Shaft

The interface between the top of the shaft and the inlet or outlet structure would be designed to minimize the potential for disruption between the surface work contractor and the tunnel and shaft contractor. The internal diameter of the shaft would connect to the near surface hydraulic structures.

Shaft located at the low point of each tunnel would need to include a facility to dewater or drain the tunnel and remove sediment for maintenance. These maintenance requirements are likely to be infrequent, considering the anticipated tunnel water velocity, but it would be necessary to include direct access from the surface and the ability to lower pumping equipment or grab buckets from an opening at the top of the shaft. The depth of the shaft could extend below the level of the tunnel opening so that a sump area could be formed for dewatering and removing sediment.

2.1.2 Maintenance Access and Surge Control

Access for maintenance of the tunnel is the subject of the Tunnel Inspection and Maintenance Considerations Technical Memorandum (DCA, 2021c). Access for maintenance would be provided at all of the shafts used for the construction of the tunnel which would be at spacing of up to 6 miles. Under the final configuration the access pad surrounding the shaft would be to a level similar to the surrounding levee system and the shaft walls would extend up to the 200-year flood plus sea level rise elevation.

Access shafts will be provided with a framed cover to include removable panels arranged to provide an access opening as well as ventilation and security. Panels should be removable from the top of the shaft collar using a mobile crane positioned on the shaft pad.

All shafts used for access would have a final lining of the minimum diameter required for construction as described in the following section. This final internal diameter would also be used for the control of transient pressure (surge) variations, helping to dampen the effects of such events and reduce the maximum hydraulic pressures in the tunnel. Details of the surge analyses are included in a separate hydraulic analysis TM (DCA 2021d)

2.2 Construction Requirements and Sizing

2.2.1 Launch Shaft

A tunnel launch shaft would be used to launch the TBM into the ground and to service the tunnel excavation process. It should be large enough to facilitate the following key phases for the construction of the tunnel:

- **Assemble TBM** – Initially, the launch shaft would be used for TBM assembly. Safe assemblage would require adequate space around the perimeter of the machine for its construction. As a minimum, this should include space for a scaffold structure to provide a safe work platform on all sides, as well as a laydown area at the back of the machine for delivery of internal parts after completion of the TBM's skin.
- **Launch TBM** – During the TBM's launch, the machine would be pushed against a flattened, prepared face of the shaft wall with a ring seal to enable it to operate under pressure. Behind the TBM, a thrust frame would be needed so the TBM could push against the wall or base of the shaft as it drives into the ground. There should be enough space for the TBM, the thrust frame, and for sections of the TBM backup to be lowered into position behind the thrust frame. During the launch, hydraulic power and other services would be supplied to the TBM though umbilical cords extending up the shaft walls. Figure 2 includes a plan layout for the TBM launch phase with a proposed ID of 115 feet.

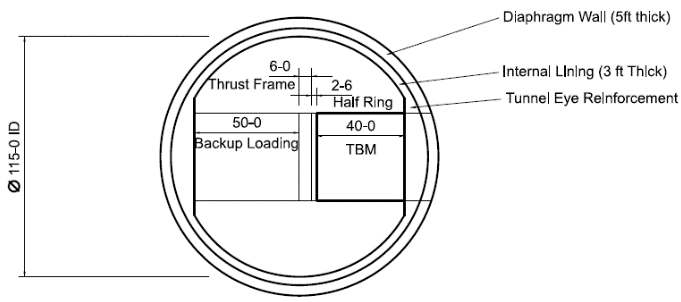


Figure 2. Launch Shaft Sizing

- **Shaft Breakout** – As the TBM excavates through the wall of the launch shaft into the surrounding ground, it would be necessary to prevent groundwater and the surrounding ground from flowing into the shaft under high pressure. This could be achieved by providing a block of ground that would be ground-treated or cut off from the surrounding groundwater for approximately 1.5 times the length of the TBM. A mechanical double ring seal could also be used so the face could be pressurized during the breakout.
- **Service Drive** – During the excavation of the tunnel, the base of the shaft would be a logistical hub to supply and remove all necessary materials and labor

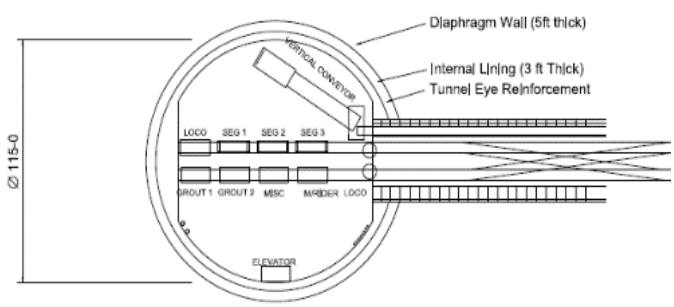


Figure 3. Launch Shaft Operation

needed to support tunnel excavation. The key space requirements for the launch shaft are shown on Figure 3 and include:

- **Segment delivery systems** – Sized to deliver segments at a rate to support the TBM's maximum advance rate. This rate could be several times faster than the average advance rate. The cycle time required to maneuver segments from the top of the shaft down to segment transport vehicles at the tunnel level would include the crane winch time, as well the time it takes to maneuver vehicles at the base of the shaft to receive their segment loads. The base of the shaft must have enough space to safely handle segments and move them onto the transport vehicles.
- **Excavated reusable tunnel material (RTM) removal system** – A number of systems could be used to remove excavated material with the launch shaft, including skips, conveyors, and slurry pumps (with a slurry TBM). For planning purposes, vertical conveyor systems are assumed because they are suited to the very high rates of removal that could occur during an excavation cycle and would link naturally with a conveyor system used in the tunnel. For a slurry TBM, the space requirements inside the shaft would be less than for a conveyor system.
- Other material handling and service requirements include:
  - **Grout** – Could be delivered using vehicle-mounted remixers that would be filled at the base of the shaft. One or two remixers per tunnel ring would be required. For longer tunnel drives, it could be less economic to pump grout, so transporting dry mix for preparation at the TBM heading could be preferred by the contractor.
  - **Soil Conditioners** – used to improve the TBM excavation rate, reduce wear to the cutter head and maintain face stability. Solutions would be prepared with supply plant in close proximity to the shaft and piped or transported to the faces in a similar manner to the grout.
  - **Ventilation air** – Would be needed as a continuous supply throughout tunneling operations. Two or more ventilation ducts would be required within the shaft and then along the length of the tunnel. These ducts could be 6 feet in diameter or more.
  - **Compressed air** – Pipes fixed to the walls of the shaft would supply air for use of pneumatic tools.
  - **Water supply and discharge** – Pipes fixed to the walls of the shaft and the tunnel would supply and return water used by the TBM.
  - **Power** – Cables and transformers fixed to the walls of the shaft and tunnel would supply power.
  - **Communications** – Fiber, cable, and other systems would be required for safe communications within the tunnel.
- **Labor access** – An elevator system and an emergency stair would be provided for personnel to access the tunnel.

2.2.2 Tunnel Boring Machine Retrieval Shaft

The minimum shaft size required for TBM retrieval would be based on the space required to dismantle the TBM after it has driven into the shaft. Figure 4 includes a plan layout for the TBM retrieval phase with a proposed ID of 70 feet. This size is based on having a minimum 5 foot access around the perimeter of a 40ft diameter by 40ft long TBM at the base of the shaft. The length of the TBM may vary with different manufactures and some may require additional provision to ensure the TBM can be serviced in the space available.

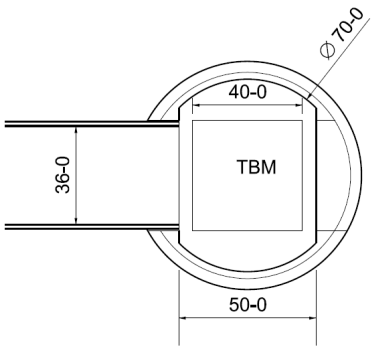


Figure 4. Receiving Shaft Sizing

At locations where a tunnel is driven toward an end that does not otherwise launch or receive a TBM from the opposite direction, it could be more economic to drive the TBM completely through the shaft and abandon it in the ground. This potentially could accelerate the completion of the Project due to the time savings associated with removing a TBM.

2.2.3 Maintenance Shaft

Where conditions could be particularly abrasive or where tunnel drives could be very long, a maintenance access shaft would be provided, at up to 6-mile spacing (to be verified by soil abrasion testing results), to maintain the TBM cutterhead and other major components of the TBM. This is consistent with the maximum spacing proposed for inspection and maintenance access during operation of the facility. The size of the maintenance shaft would need to be sufficient to install the tunnel opening frames around the shaft break-in and break-out walls, and then depending on how much of the TBM needed to be accessed, there would be a safe area to work around the TBM. It would also be necessary to ensure the shaft would be fully sealed around the opening, which would be overcut by the cutterhead, providing a flow path for the pressurized water-bearing ground. This could be achieved either by driving far enough into the shaft to ensure a lining ring would be fully grouted into the opening, or by providing a jet grout block or cutoff wall separate to the shaft structure.

For planning purposes, it is recommended to assume the full TBM would need to be accessed; therefore, the shaft would be the same size as the receiving shaft. However, if it could be determined that only the cutterhead part of the TBM would need to be replaced, the shaft could be 10 to 20 feet smaller in diameter. The maintenance shafts could also be used during tunnel construction to provide fresh air for ventilation and an exit in case of an emergency, to improve safety for the workers.

3. Shaft Construction Methods

3.1 Wet Excavation Methods

Shaft construction using wet excavation methods means the ground within preconstructed shaft lining walls would be removed underwater. This method does not try to exclude the groundwater until the complete structure has been installed, which includes the shaft lining and the base tremie slab. Figure 5 shows the cross-section arrangement for a shaft constructed using the wet method.

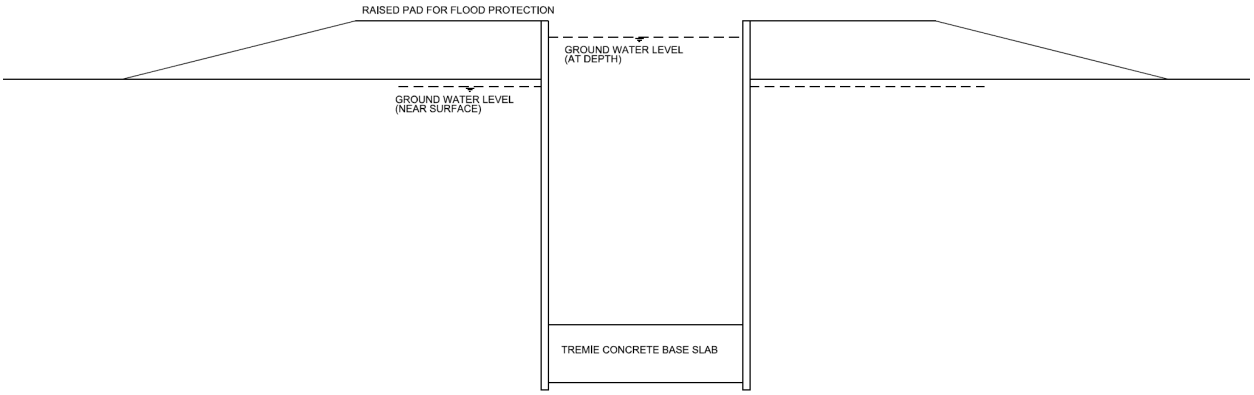


Figure 5. Typical Cross-section of Wet Excavation Method

3.1.1 Diaphragm Walls Wet Method

Diaphragm walls would be cast-in-place concrete, constructed before the shaft excavation. These walls would serve as an initial ground support lining and could also perform as a permanent lining (if needed), depending on the design.

The walls would be constructed by excavating interlocking (water-tight) primary and secondary panels, approximately 10 feet wide and 3 to 5 feet thick to the full depth of the shaft below the underside of a base slab. In suitable ground, the primary panel could be excavated with two or three overlapping trenches to form a wider primary panel.

The panels would be typically excavated with a clamshell bucket (for softer soils and shallower depths) and/or with a rotating cutterhead known as a hydrofraise (for more difficult conditions, including rock, greater depths where verticality is a constraint, and for secondary panels between two primary panels). For the proposed shaft depths on this project a hydrofraise would be used for most of the trench excavation although a clamshell may still be used to start trenches more efficiently. The panel excavation requires a cast-in-place concrete guide wall at the surface. The panel trenches would be stabilized with bentonite slurry, which would need to be to a level approximately 10 feet above groundwater level within the trench during its excavation. Once the excavation reaches the desired depth, a reinforced steel cage (or H-pile as reinforcement) would be lowered into the trench, and concrete tremied into the bottom of the trench to displace the slurry and cast the wall.

Diaphragm walls are an established method of shaft lining construction and have been installed to the depths proposed for this Project of approximately 180 feet. In weak soils, it could be necessary to undertake some ground improvements to help control the position of the excavation and to maintain stability of the slurry trench. There are reported case histories of slurry construction reaching a depth of 260 feet (Stockhausen and Goodenow 2013). The diaphragm wall wet method were also used for three of the Blue Plains Tunnel shafts in Washington, DC, which were installed up to 60 feet diameter and 120 feet deep.

A base slab would be required to resist uplift forces from the ground and the groundwater beneath the shaft structure. With the diaphragm wall wet method, the base slab would be placed underwater by tremie concrete methods. Construction of a tremie slab for large-diameter shafts requires formation of blockout keys into the diaphragm walls, heavy reinforcement steel, and a thick concrete slab. An elaborate temperature control cooling system would also be required during the casting and curing period to

prevent cracking and durability issues caused by the heat of hydration. Extensive use of divers would be needed to prepare and check conditions at the base of the shaft prior to placement of concrete.

Following the completion of the diaphragm wall shaft and base slab, the water within the shaft would be removed. An internal lining would be constructed over the height of the future tunnel opening and designed to transfer the loading from the diaphragm walls when the TBM breaks through the walls on launching or receiving the tunnel drive.

This section of internal lining would also serve to distribute the thrust loads from the TBM as it pushes itself into the ground from the shaft.

A secondary lining could be required, depending on the ultimate design philosophy for the diaphragm walls. The walls would be designed to take either short- or longer-term loads, and when combined with the hydraulic requirements, may affect the need for a secondary lining.

3.1.2 Secant Pile Wall Wet Method

Secant pile walls would be constructed by overlapping drilled shafts to construct a continuous wall supporting the earth and water pressure. Secant pile walls were successfully installed in many projects; they are typically not used beyond a depth of 120 feet, especially with the use of casing; however, in favorable ground conditions, they could be used (Stockhausen and Goodenow 2013) and could also work in combination with ground improvement to achieve the required depths.

If secant pile walls were used, the structural section dimensions of a secant piles would be approximately 6 feet in diameter to achieve a continuous shaft wall thickness of 5 feet, accounting for the pile overlapping. Boxout sections in the secondary piles would also be required as a key for the tremie base slab.

The excavation and installation of the base slab and other internal structures would use the same approach as the diaphragm walls method described.

3.1.3 Cutter Soil Mixing Wet Method

The cutter soil mixing (CSM) method mixes in situ soil with cement and water to form rectangular soil-cement panels. The individual panels would be interlocked to provide a water-tight structural ring for a circular shaft. The CSM panels could be excavated using a modified trench cutter “hydro mill” type machine. The cutters for the CSM method would be mounted on a horizontal axis and turn on a vertical axis. The construction of a guide wall would not be required. The mixing tool would be driven into the ground at a continuous rate. The soil matrix is broken up by the cutting wheels, and at the same time, a fluid would be pumped to the nozzles, in between the cutting wheels, where it is mixed thoroughly with the loosened soil.

The penetration speed of the cutter and the volume of fluid pumped into the soil would be adjusted by the operator to create a homogeneous, plastic soil mass, which permits easy penetration and extraction of the machine. After reaching the design depth, the mixing tool would be slowly extracted while cement slurry is continuously added and mixed. Reinforcing elements, typically steel beams, could be inserted into the completed wall before the cement in the mixed soil is set. Currently, equipment can achieve depths of 240 feet (Stockhausen and Goodenow 2013).

Quality control of CSM walls would be more difficult to achieve and it could be necessary to provide additional panels to guarantee the strength capacity of the soil-cement mix, which would be critical for the required large shaft diameter.

CSM was previously used to construct shafts for Old River Crossing in the Delta (Lindquist 2010) (Figure 6).

It would not be possible to include blockout keys into the walls of a CSM shaft because the panels would be mixed in the ground; therefore, an alternative structural system would be needed to resist the uplift forces on the slab. These could include tension piles or ground anchors through the slab.

On completion of the shaft and after draining it, the internal structure required for TBM breakout would be similar to the diaphragm wall method described.

A secondary lining would be required for the CSM shaft because the walls would not be of sufficient quality to meet long-term structural design objectives. It would be necessary to install the secondary lining before the shaft could be used as a working shaft for tunnel drives, and this could be achieved using cast-in-place or shotcrete methods.

Source: Lindquist (2010)

Figure 6. Cutter Soil Mixing Equipment used on the Old River Crossing, Sacramento Delta

3.1.4 Caisson Sinking Method

Caisson sinking methods involve constructing sections of the shaft structure at ground level and then excavating from within them, allowing the structure to sink into the ground as it is undermined. Sunken caissons are not common for shafts greater than approximately 14 feet in diameter or shafts greater than 80 feet deep, as the surface area of the shaft is proportional to the (skin) friction force that must be overcome to sink the shaft. This method has not been considered further at this planning stage.

3.2 Dry Excavation Methods with Groundwater Cutoff

Shaft excavation in the dry means that the ground is removed in a free air environment with just localized dewatering of the excavation area. For the expected conditions in the Delta for this Project, special measures would be required to manage the groundwater pressures around the excavation to make this method possible.

Measures to control groundwater include either using a pre-installed shaft lining to provide a suitable groundwater cut-off or using separate cut-off measures, dewatering, or both to enable more conventional shaft construction measures to be used.

3.2.1 Groundwater Cutoff using Shaft Lining

The following methods use the pre-installed lining to extend beyond the depth of the shaft to provide cut-off of the surrounding groundwater. The required depth of these walls below the base of the shaft would depend on the actual ground and groundwater conditions. While the lining would form a cut-off around the perimeter of the shaft, it would not cut off the vertical flow of groundwater from directly

below. If necessary, the flow of water from below could be reduced to a manageable level using a number of methods, including:

- Extend the cutoff length of the pre-installed lining
- Extend the cutoff length using a grout curtain
- Operate dewatering wells within the cutoff zone
- Permeation grout the cutoff zone to reduce permeability

In addition to providing a groundwater cutoff, this method also needs to consider the hydrostatic forces on the ground plug within the cutoff zone. This block of ground needs to be of sufficient mass to resist the uplift forces. Figure 7 shows a cross-section arrangement of the shaft structure constructed using the dry excavation method, with the lining walls extended to provide groundwater cutoff.

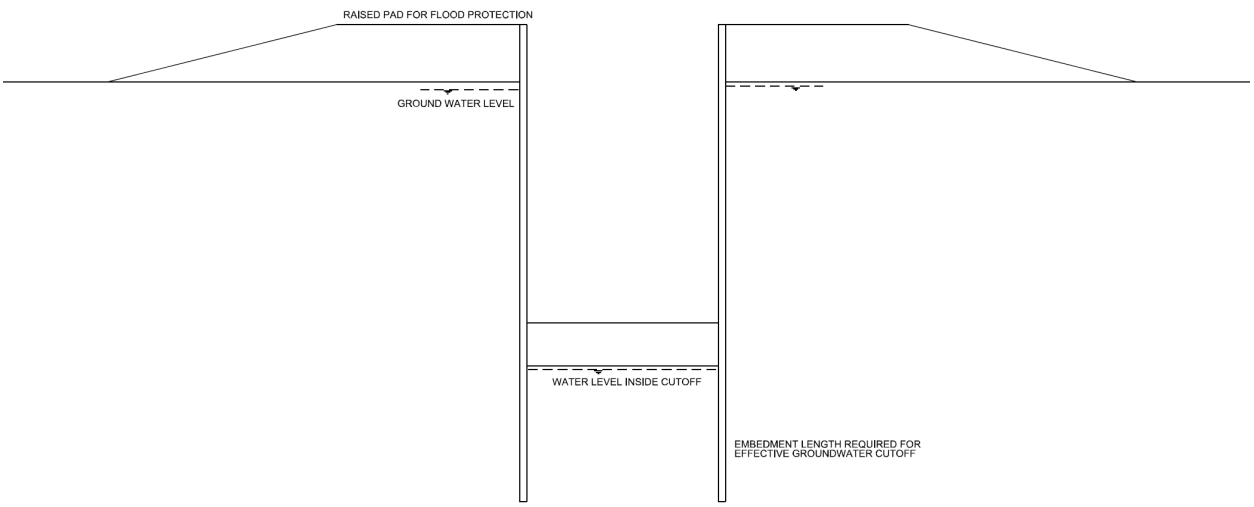


Figure 7. Typical Cross-section of Dry Excavation Method with Shaft Lining Cutoff Walls

3.2.1.1 Diaphragm Walls Cutoff Method

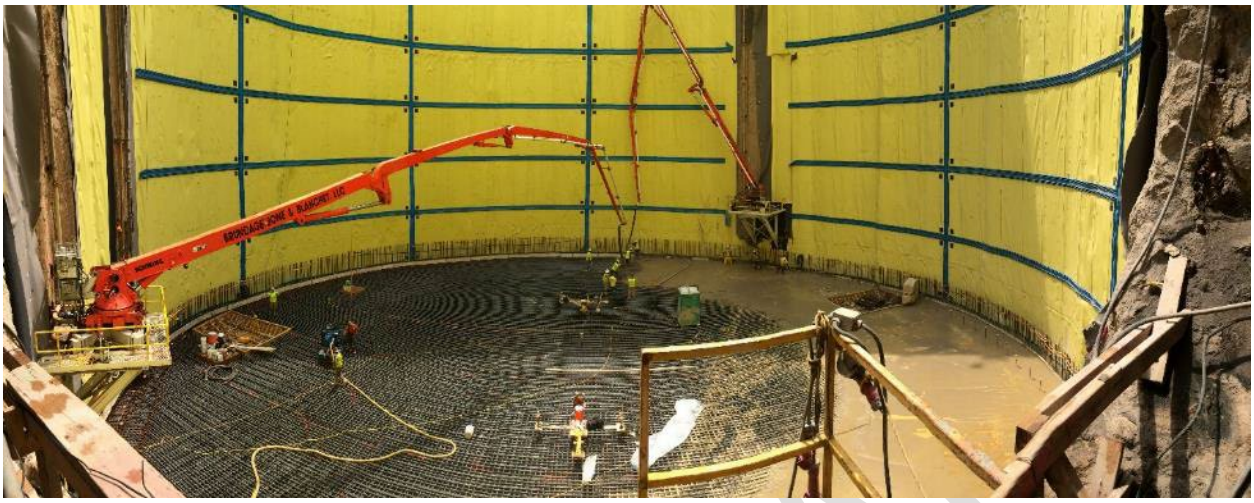
The diaphragm wall shaft lining for the dry method would be constructed in a similar way to the wet method described, except the walls would be significantly longer. Subject to the actual ground conditions, the embedment depth required to form a cut-off could be significant.

The design of the wall panels would be sized for the ground loads at the base of the shaft. Below the base slab, the wall panels would only be required for groundwater cut-off and would only have minimal reinforcement in these lower sections. It would also be possible to install drill casings in the wall panels so that ground treatment could be continued below the base of the diaphragm walls to improve groundwater cut-off. This technique was used in Portland for the Swan Island Pump Station shaft (Luongo and St-Amour 2005) and in London for the Lee Tunnel Pump Station shaft (Jewell et al. 2014).

Construction of the base slab in the dry could be completed at the base of the shaft without special measures other than the constraints of the shaft walls. Some underdrainage could be required to maintain a dry work area, but this could be sealed after the slab would be complete and achieves design strength.

Concrete placement would require active cooling measures if completed as a single pour. Alternatively, it could be placed in layers, with additional dowel connectors between the layers. This method was used for

the 132-foot-diameter base slab for the Blue Plains pumping plant shaft in Washington, DC (Blanchard et al 2017) (Figure 8).



Source: Traylor Bros Inc. (2014)

Figure 8. Base Slab Construction for the Blue Plains Dewatering Shaft, Washington, DC

Following completion of the base slab, the internal structures would be completed using the same methods as for the wet method previously described.

3.2.1.2 Secant Pile Wall Cutoff Method

The secant pile wall shaft lining for the dry method would be constructed in a similar way to the wet method described, except the walls would be significantly longer. Subject to the actual ground conditions, the embedment depth required to form a cut-off could be significant. This method could be used in combination with other methods such as jet grouting to provide adequate cut off depth.

The design of the secant piles would be sized for the ground loads at the base of the shaft. Below the base slab, the piles would only be required for groundwater cutoff and would only need minimal overlap and reinforcement in these lower sections. This method was used for the construction of shafts on the Thames Tideway Project in the United Kingdom (UK) (Figure 9).

Source: Jacobs (2014)

Figure 9. Secant Pile Shaft Thames Tideway Project, UK

3.2.1.3 Cutter Soil Mixing (CSM) Cutoff Method

CSM could be used as a dry method provided the soil mix walls could be installed to an adequate depth. There is limited experience with installation to the likely depths required, so careful assessment of the ground conditions and consideration of current technology would be needed to confirm the feasibility of this method.

Construction of the base slab would be the same as for the diaphragm wall shaft, except that the secondary lining would be required before the slab can be exposed to the uplift forces associated with groundwater.

3.2.2 Groundwater Cutoff Separate to Shaft Lining

The methods described in this section are more conventional for sinking shafts but rely on separate measures to be able to dewater or depressurize the water in the ground where the shaft would be constructed. A number of methods or a combination of methods could be used to achieve these conditions. These could include the following:

- Cutoff slurry wall
- Dewatering

- Ground treatment
- Ground freezing

Figure 10 shows the cross-section arrangement of cutoff walls relative to shaft structure.

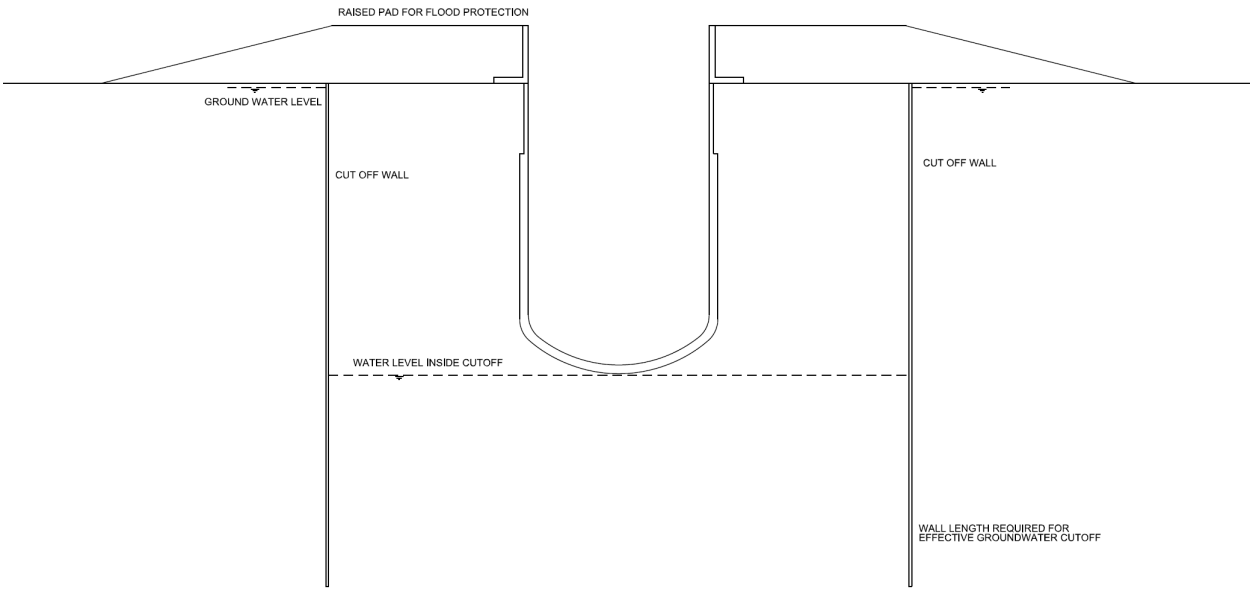


Figure 10. Typical Cross section of Dry Excavation Method with Separate Cutoff Walls

3.2.2.1 Cutoff Slurry Wall

This would be a relatively thin (2-foot) but deep (300-plus-foot) slurry trench backfilled with a soil, bentonite, and cement mix to provide an impermeable barrier. This wall would be constructed as an early works activity at a nominal distance away from the proposed shaft location to form an enclosed zone within the area of the shaft pad. Once constructed, the cut-off zone would be dewatered to check inflow from beneath; and, if necessary, additional permeation grouting could be used to reduce inflow. On successful dewatering, the shaft excavation would proceed using conventional shaft sinking methods.

3.2.2.2 Dewatering

In some ground conditions, the groundwater levels can be reduced by pumping from deep wells located around the perimeter of the site. However, for the anticipated conditions in the Delta (to be confirmed by the pending geotechnical investigation), this method would not likely be feasible due to the highly permeable ground and the excessive volumes of groundwater that would need to be extracted. The potential impacts to existing wells could also make this method unacceptable.

3.2.2.3 Ground Treatment

Ground improvement methods could be used to reduce the permeability of the ground surrounding the shaft. Typically, a zone twice the diameter of the shaft and one diameter deeper than the shaft would need treatment to achieve adequate groundwater cut-off.

3.2.2.4 Ground Freezing

This method freezes the groundwater to provide a cut-off. Water must be present in the soil for the ground freezing method to work. A coolant, usually calcium chloride brine, would be introduced into closed-end freeze pipes circulated into casings within holes drilled in a pattern consistent with the shape of the area to be stabilized. As the brine moves through the system, heat would be extracted from the soil, freezing the earth around the pipes in the shape of vertical, elliptical cylinders. The brine would be returned to the refrigeration plant through an insulated header and, after re-cooling, would be recirculated within the closed system. The frozen ground cylinders gradually enlarge with time until they intersect to form a continuous wall of the desired thickness.

The ground freezing technique can be used for the full range of soils; however, it is typically used in fine sands and silts or coarser soils as long as the groundwater velocity is less than a limiting threshold, typically up to 6 feet per day. Ground freezing would be less favorable in clays, which take longer to freeze for a given spacing of pipes. This method was used for the South Bay Ocean Outfall shaft in San Diego, CA (Robinson & Jatczak 1999).

3.2.3 Excavation Methods used with a Separate Cutoff

When an effective groundwater cutoff has been provided, the excavation of the shaft could commence at the same time as the lining installation. Depending on the actual ground conditions present in the dewatered zone, the excavation and lining installation could proceed in increments that expose a section of ground below the previously installed lining section. These increments could range from 3 to 6 feet or more, depending on the ground.

In very poor ground, it could be necessary to install sheets, pipes, or mini-piles around the perimeter of the excavation as a pre-support before excavation for each increment. The following lining system types could be used subject to the contractor's preference and cost considerations:

- CSM
- Sprayed concrete lining
- Ribs and lagging
- Base slab for the invert

3.2.3.1 Cutter Soil Mixing

The CSM method described in Sections 3.1.3 and 3.2.1 could also be used in combination with a separate groundwater cutoff. The absence of groundwater loading would reduce reliance on the quality of mixing, and this method could be suited to poor ground conditions near the top of the shaft. The depth that could be achieved with this method could be a limitation for achieving groundwater cutoff, although it could be used in combination with other methods described in this section for the deeper parts of the shaft.

3.2.3.2 Sprayed Concrete Lining

This method uses sprayed concrete to incrementally install the lining in the shaft excavation. This method could be much quicker than other lining methods and could use robotic spraying machines to place the required concrete lining thickness. Steel reinforcement bars would be placed in advance or fiber reinforcement could be included in the sprayed mix to provide the necessary design strength. The thickness of the sprayed concrete could also be varied as the excavation deepens to optimize the quantity

used. It would also be possible to include the additional structure needed for the tunnel eye within the concrete thickness during the lining installation.

This method has been used on large-diameter tunnel launch shafts on the CrossRail project in London and included the 30-meter (100-foot) diameter Limo Auxiliary shaft used to service two parallel TBM drives (Newhouse 2019).

The sprayed concrete method could also be used to form a dome shell base slab that can be substantially thinner than required for a flat disc slab structure used in the other methods (potentially less than 5 feet thick compared to 30-plus-feet). This base slab structure could also be designed to resist permanent uplift pressures, if necessary.

With the tunnel eye reinforcement already provided in the shaft lining, the sprayed concrete lining method could also be used to excavate starter tunnels as far as the groundwater cutoff zone. A stub tunnel could be used to further reduce the size of the shaft because the TBM would be pushed into the stub, leaving space to install the necessary backup in the shaft. Furthermore, a back-shunt stub tunnel could be formed to improve the maneuvering and loading of segments during TBM operations.

The initial sprayed concrete lining could be sufficient as a permanent structure and could include a sprayed waterproof membrane if necessary. A second permanent sprayed concrete lining could also be included after completion of the tunnel works, as could an in-situ lining using methods similar to the other wet and dry methods described.

3.2.3.3 Ribs and Lagging

Ribs and lagging is a method that uses circular steel rib sections placed at regular intervals around the shaft, with timber lagging spanning between them and grouted against the ground. In poor ground conditions, the timbers can be installed below the last completed steel rib, using the ground at the base of the excavation to support the timbers until the next steel rib is installed.

3.2.3.4 Base Slab

The base slab would be constructed in a way similar to the diaphragm wall dry method described. Following the completion of the base slab, the internal structures would be completed using the same methods as for the wet method. A secondary lining would be required before the groundwater pressures were allowed to return to provide resistance to the uplift forces.

3.3 Discounted Shaft Excavation and Lining Methods

The following shaft construction methodologies have been discounted based on the current understanding of the likely ground conditions and current limits of technology:

- Vertical shaft sinking machine – This method uses a mechanical excavator with a caisson sinking method to construct the shaft but has been discounted due to the maximum size, which, based on current technology, is limited to around 40 feet.
- Groundwater lowering (outside the confines of a cutoff barrier) – This dewatering method to facilitate one of the dry excavation methods has been discounted because of the likely far-reaching impacts it would have on the surrounding groundwater conditions and its users. It would also be unlikely that the required depth of groundwater lowering could be achieved in the Delta's anticipated ground conditions.

3.4 Comparison of Methods

The shaft methods described in the previous sections have a number of features that are either beneficial or a disadvantage relative to the other methods, depending on the particular circumstances for their construction. It could also be beneficial to use a combination of these methods. The ultimate choice would need to consider detailed ground investigations and groundwater studies; also the contractor should be able to choose a method that suits their expertise and proposed construction sequencing provided the permanent lining structure meets the project requirements.

To assist in making a comparison of methods, the following considerations have been applied to each method to identify key benefits or disadvantages over the other alternatives:

- **Safety** – The construction operations should be safe for the construction workers to perform.
- **Environmental** – Some methods could have the potential to adversely affect the natural environment, such as groundwater and air quality impacts.
- **Quality** – The proposed construction methods should allow for good control of the process to produce a reliable, quality product that would meet the required specifications and service life.
- **Schedule** – The method could affect the project schedule in terms of its overall impact to the critical path.
- **Cost** – Relative cost differences could be a factor where schedule does not dictate.
- **Other risk factors** – These could include known factors that adversely affect the assumed method and adversely affect the outcome.

A table identifying the potential benefits and disadvantages of the shaft construction methods considered in this report is included as Attachment 1.

4. Work Site Requirements

The tunneling contracts would require several work sites to complete the works. The main site would be for the construction of a launch shaft and then for the servicing of the main tunnel drive. Additional sites could be required for retrieval shafts and maintenance shafts. Potentially, a launch site could be used for two tunnels driving in opposite directions. For this double drive site scenario, there could be a different arrangement if both tunnels were part of a single contract compared with having separate contracts, as discussed in the following subsections. This section describes the features needed for each stage of the construction and these have been used as minimum worksite area requirements. Typical worksite layouts are illustrated in Attachment 2 and these would be developed for specific sites to minimize the areas of disturbance and associated impacts.

4.1 Tunnel Launch Shaft Work Site

The tunnel launch shaft work site would be used to service the tunnel drives and would be the largest site required for each tunnel contract. The following subsections discuss the requirements for key areas of the work site at different stages of construction.

4.1.1 Site Development

Development of the work site includes clearing, setting up access and facilities and construction of the shaft pad in preparation for shaft construction. It is assumed that these activities would be part of the main tunnel and shafts works contract, although they could be undertaken as early works contracts if schedule constraints became a factor.

Access arrangements would be required for the start of any work and would need to be suitable for the anticipated level of usage for each stage of the works. Construction activities that require high-volume reliable delivery include the concrete works in the shafts, as well as the segment and material delivery for the main tunnel drive. The access arrangement would also need to manage the RTM's removal from the work site area if that became necessary. The site would include security fences and a guarded entry point to control access.

Many of the potential sites would require significant preparation due to the soft ground conditions, including some removal and replacement or improvement of underlying material that would likely be required before the temporary facilities can be established. This could include methods such as deep soil mixing, installation of vertical wick drains, or other techniques.

Protecting the open shaft from potential flood needs to be considered because the existing ground level could be as much as 18 feet below sea level and up to 40 feet below flood level. Existing levees protect the sites to regular flood levels, but the life safety consequences of a levee failure or overtopping would be much higher for tunnel operations than normal agricultural activities. Figure 11 shows potential options including that could be used to prevent flooding. The provision of a raised pad, ring levee, shaft collar or a combination could be used to prevent the shaft and tunnel from flooding. Potentially, for use with the conventional dry excavation shaft sinking methods, a cutoff wall could also be installed as early work. This would facilitate the use of borrow from within the cutoff zone to construct the ring levee without the need to import material.

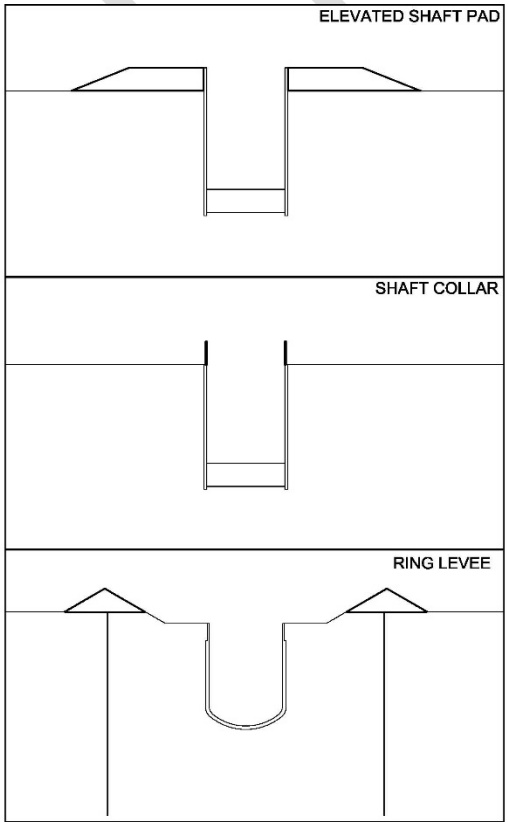


Figure 11. Shaft Flood Protection Options

The operational requirements discussed in Section 2.1 include an elevated pad to existing levee levels with a shaft collar extending to the 200-year flood level. Therefore, the elevated shaft pad approach has been used as a basis for the concept design since the ground treatment and pad construction can all be undertaken in a single early phase.

4.1.2 Shaft Construction Work Area

For construction of the shaft, the largest work area would be needed for the diaphragm wall method. Outside the area of the shaft, the following key work areas are needed as a minimum:

Diaphragm Wall construction

- An area for cranes and slurry trenching equipment to service the shaft during excavation
- A laydown area for the fabrication of wall panel reinforcement cages
- A slurry processing plant and settlement ponds for use during diaphragm wall construction
- Access for ground improvements activities as may be required.

Shaft Excavation

- Crane for excavated material removal by skip
- Muck hopper
- Access for haulage trucks

Shaft and lining

- Cranes for handling reinforcement and formwork.
- Reinforcement layout and fabrication area
- Access for concrete mixer and pump trucks

General facilities (not required to be on shaft pad)

- Workshops and materials supply yard
- Office facilities
- Parking
- Topsoil stockpiles
- Shaft excavation material stockpiles

4.1.3 Work Site Arrangement during Tunnel Excavation

During excavation of the tunnel drive the layout of the shaft work site would be arranged so that the necessary supply and removal of materials, labor, and equipment can be performed at a speed to support the maximum operating capacity of the TBM. The details of these movements within the shaft are described in Section 2.2.1 with their impact on the sizing of the shaft.

Operations at the top of the shaft would require several facilities either directly adjacent to the shaft or farther away. The operations adjacent to the shaft would be elevated to a level above the 100 year flood level and would be protected from a possible levee breach as described in Flood Risk Management TM (DCA, 2021e). These work facilities and areas are identified in the following subsections, and a typical tunnel launch shaft layout is illustrated in Attachment 2.1

4.1.3.1 Near Shaft Facilities

The key facilities considered critical to the operation of the TBM and safety of staff are as follows:

- Craneage needed to supply the segments and other materials to the transport cars at the base of the shaft
- An access road arrangement that enables the safe delivery of tunnel lining segments and other materials to areas accessible to the shaft cranes
- Electrical substations, transformers, and distribution equipment
- Ventilation equipment needed to supply continuous clean air to the TBM and tunnel
- Conveyor system (or other excavated material removal system), which could include a cassette system used to feed additional length of conveyor belt as the tunnel progresses
- Tunnel grout batching plant and associated stockpiles
- Soil conditioner preparation plant to supply foam or other conditioning agents to the TBM
- Water storage tanks for return water to the TBM
- Fuel supply needed for equipment working in the tunnel system
- Key staff offices, workshop and equipment storage buildings

4.1.3.2 The minimum area needed for these near shaft facilities would be approximately 3 acres, and this area should be given some level of protection from a potential flooding. Other Site Facilities

Other site facilities that could be further from the shaft and that could be recovered from a flood event more easily include:

- Workshops, and storage and supply yards to support the TBM, ventilation, conveyors and other general utilities needed for construction of the tunnel
- Water treatment units/ponds to receive and return water to the TBM
- Project office buildings and parking
- Helicopter Pad for emergencies, if required for a remote site

These would be located adjacent to the near shaft area to minimize servicing vehicle movements and to provide a nearby safe zone for evacuation in the event of a flood. The space needed for the surrounding area would be approximately 6 acres.

Additional areas that could be further from the shaft depending on logistics and existing ground conditions include:

- Topsoil/peat stockpile area for material from initial site clearance (varies based on site conditions). This material would be spread over areas of the site not required for operational reasons and would likely be located close to the worksite area.
- Tunnel segment storage area (see details below). The location of this area would be to suit the delivery method which could be by road or rail. The area would be sited relatively close to the shaft and the segments would be by transferred by truck to the gantry crane for lowering into the tunnel during construction.

- RTM handling equipment and storage areas (refer to separate TM Resuable Tunnel Material (DCA, 2021g). The location of the RTM areas would be to suit local topography so it is protected from flooding risk and also taking into consideration transport logistics for removal at a later date for reuse if required.

4.1.3.3 Segment Storage Areas

The number of segments that would be stored at the launch shaft work site would depend on a number of factors, including:

- Location and distance to the segment manufacturing factory
- Storage capacity at the manufacturing factory
- Available space at the work site
- Ground conditions and improvements needed to be able to stack segments
- The height of the segment stacks
- The risk to TBM production if the supply of segments to the site was interrupted
- The environmental impact of transporting segments that could restrict the amount of truck traffic and potentially limit the times of day that could be used for hauling

The number of available segments should allow for approximately 4 months of tunnel production. It is estimated that this would require up to 7 acres per tunnel drive, assuming average tunnel production rates and four high segment stacks. A number of factors would affect the actual area required, including: ground conditions, site preparation, and logistical arrangements for segment deliveries. Further details of logistical considerations and potential sites for segment production are discussed in a separate TM (DCA, 2021f)

4.2 Double Drive Work Site

Driving the main tunnel in opposite directions from one work site has the potential to reduce impacts to the Delta by reducing the number of sites that need significant new infrastructure. Depending on the length of the drives and the potential limit on the size of contract that a single contracting organization can deliver, these double drives could be completed either by one or two contracts.

The double drive site could also use one or two shafts to service the two tunnels. While it would be feasible to use a single shaft for two tunnel drives, it could be more suited to a single contractor due to the challenges of coordinating TBM launches. This would place constraints on both drives until they were fully launched with all their trailing backup, and the shaft could be physically divided.

If two shafts were provided, the short section of tunnel between them would still need to be completed by one contract. Potentially, the first contract could launch the TBM from a first shaft and, initially, drive it through the second shaft to form the connection between the shafts. The first contract would then transfer operations to the second shaft, releasing the first shaft to the second contractor. Thereafter, each contractor could continue in opposite directions with separate shafts and associated work sites.

An alternative to two shafts could be a double-cell shaft arrangement that could be constructed to provide separate access arrangements for two contractors working side by side. Similar arrangements have been used at on the Northeast Interceptor Sewer in Los Angeles and Blue Plains Tunnel shafts (Allam et al 2013) (Figure 12). The additional space provided by this arrangement can also be used to assist the initial TBM launch, enabling multiple sections of the TBM backup to be installed at the same time.

The currently proposed tunnel drive locations result in only one double drive site at Twin cities. It is assumed that this will be a double-cell shaft and included in the first tunnel contract. Upon completion of the shaft construction a second tunnel contractor would take control of the adjacent cell. The operational facilities and site area requirements for the double shaft would effectively be double those for the single launch shaft, except the shared area on the raised pad would increase from approximately 3 acres to 4 acres.

Source: Dubnewych (2005)

Figure 12. Double-cell Shaft Concept, Northeast Interceptor Sewer in Los Angeles

4.3 Retrieval Shaft Work Site

A retrieval shaft work site would be like that required for the shaft construction phase of the launch shaft work site described.

The requirement for flood protection would consider the reduced time that the shaft is exposed to flooding and impacts during shaft excavation. Therefore, the supporting facilities may not need to be protected by being elevated. On breakthrough of the tunnel, alternative protection measures could include structurally extending the shaft walls, and, ultimately, a shaft cover or raised pad would protect the tunnel from flooding.

Development of the site and activities for construction of the shaft would be similar to the launch shaft construction discussed above. The area of the elevated shaft pad would be sized for the retrieval of the TBM with sufficient space to accommodate large mobile cranes together with laydown areas for the dismantling and loading of TBM parts onto trucks. The working area at the top of the shaft pad required for this operation would be approximately 1.7 acres.

Other facilities surrounding the shaft pad would require an additional area of approximately 8 acres and would include for:

- Stockpiling of topsoil and shaft excavation material
- Water treatment areas for slurry wall and shaft excavation and dewatering activities
- Contractors offices and support facilities (these would be smaller than the launch shafts and only accommodate the site staff without the support staff who will be located close to the launch shaft for each tunnel contract)

Overall, the worksite area for a retrieval shaft site would be approximately 12-15 acres depending on the specifics of the site location and soil conditions. A typical reception shaft worksite layout is shown in Attachment 2.2.

4.4 Maintenance Shaft Work Site

A maintenance shaft work site would be similar to the retrieval shaft work site. The working area at the top of the shaft pad could be slightly smaller with an area of approximately 1.0 acres needed for the shaft construction activities. Mobile cranes would be needed to support TBM maintenance activities and they could be smaller depending on the parts needed for the maintenance or repair. A typical maintenance shaft worksite layout is shown in Attachment 2.3.

5. Summary and Recommendations

5.1 Shaft Sizing

The proposed launch, reception, and maintenance shafts sizes of 115-foot and 70-foot ID would be based on a proposed 36-foot-ID shaft with an associated TBM of 40 feet of length and diameter. This size would change for different sizes of tunnel, as defined in Table 1. Shaft sizes would also meet the requirements for surge control and may increase at inlet and outlet structures where other hydraulic considerations dictate.

Table 1. Summary of Shaft Sizes Based on Tunnel Diameter

Tunnel ID (feet)	Launch Shaft ID (feet)	Reception and Maintenance Shaft ID (feet)
40	120	76
38	115	70
36	115	70
31	110	63
26	110	53
20	90	45

The size and location of the shaft structures for this Project make them unique in terms of finding experience with equivalent successful structures. Many of the methods associated with the project's size and conditions have been demonstrated, although the combination in a single structure has not. For example, the diameter of a diaphragm wall shaft has been achieved on the Blue Plains project (Allam et al, 2013) but not in such potentially weak water-bearing ground. Similarly, tremie base slabs have been successfully constructed at these depths but not at the diameter of these shafts. As more information comes available on the location and conditions of potential sites, one of these methods could become more or less favorable.

5.2 Methods of Construction

This TM has considered wet and dry methods of shaft construction. The main differences between these approaches would be the excavation phase and the base slab construction. While excavation under water for the wet method would likely be suited to the anticipated potentially poor ground conditions, the construction of a wet method base slab of the thickness and strength needed for the proposed shaft sizes would be very challenging.

To use a dry method for shaft construction, an effective means of controlling groundwater down to the full depth of the shaft would be required. This has been considered either using a shaft lining method extending to a depth to provide an effective groundwater cutoff, or by using a separate cutoff installed before shaft construction.

Using a dry method that extends the shaft lining below the base of the shaft would rely on controlling the water within the shaft as excavation proceeded, whereas a separate cutoff outside the shaft limits could control the water from within the cutoff, but outside the shaft excavation.

Potential benefits of the extended lining cutoff would be that it would allow the shaft walling system to serve a dual purpose as a cutoff and would require a smaller base area over which to control groundwater inflow through dewatering or ground improvements.

The separate cutoff has the benefit of being an early works activity that could be separate from the main tunnel contract, providing the potential to prove the effectiveness of the cutoff and make further ground improvements, if necessary, without affecting the main contract's critical path. It also would require a narrower wall with less expensive slurry-type infill, together with potential schedule advantages associated with a thinner base slab and integrated tunnel eye construction without the need for a separate jet-grouted block.

5.3 Work site requirements

Work site areas considered in this TM identify critical tunnel support facilities and the shaft opening that should be protected from a risk of flooding, which would be catastrophic if flooded during tunnel construction. The means of protecting the work site could include extending a shaft collar to prevent flooding of the tunnel as well as raising the site area for construction of the shaft and tunnel or providing a flood protection embankment around the critical work. Raised working areas would also be required for shaft methods involving slurry trenches, because the slurry level must be approximately 10 feet above the groundwater level which could be hydraulically connected to the river at depth.

Less critical facilities and segment storage areas have been considered separately to reduce the size of protection works that would require substantial quantities of imported fill at the start of the project, potentially before RTM would be available from tunnel excavation. Table 2 summarizes the areas needed for the phases of construction and their associated flood protection requirements.

Table 2. Summary of Approximate Work Site Area Requirements

Site Purpose	Flood Protected Area (acres)	Raised Pad Area (acres of base)	Support area (acres)	Segment Stockpile Area (acres)
Launch	3	4 to 6	6	7
Double Launch	3.5	4.5	12	14

Table 2. Summary of Approximate Work Site Area Requirements

Site Purpose	Flood Protected Area (acres)	Raised Pad Area (acres of base)	Support area (acres)	Segment Stockpile Area (acres)
Maintenance	1[a]	1 to 3.5	2	-
Retrieval	1.7[a]	1 to 3.5	2	-

[a] Alternative shaft flood protection measures could reduce the need for raised worksite area.

Notes:

Additional area required for RTM processing and stockpiling not shown.

Additional stockpile area required for topsoil clearing and shaft excavated material not shown.

Raised pad area based on 2:1 H:V side slopes and maximum anticipated heights.

H:V = horizontal to vertical

5.4 Recommendations

The shaft construction methods and work site arrangements considered in this TM have the potential to be used on this Project based on the range of ground conditions and delivery schedules currently envisaged. At this time, the diaphragm wall wet method is proposed for all shaft sites, using a raised work pad to ensure the top of the slurry trenches is safely above the maximum deep ground water level taken to be equivalent to the existing river levee levels. Under the final configuration the shaft wall levels would extend up to the 200-year flood plus sea level rise elevation.

During the final design phase and following receipt of more geotechnical information, the following items should be analyzed further.

- Site investigation – Each potential site design layout would be developed based upon site-specific geological conditions, groundwater regime, and land use on adjacent properties.
- Structural sizing calculation – Sizing of key structural elements like the diaphragm wall and base slab thicknesses would be developed based upon additional geotechnical information at the shaft sites.

6. References

Allam I., J. Diiulio, and H. Leiendecker. 2013. Blue Plains Tunnel: Design and Construction of Large Diameter Diaphragm Wall Shafts. *In Proceedings of the Rapid Excavation Tunneling Conference (RETC).*

Blanchard R., E. Ross, H. Leiendecker, and R. Aradas. 2017. Large Diameter and Deep Shafts: Unique Design and Construction Challenges. *In Proceedings of the Rapid Excavation Tunneling Conference (RETC)*.

Delta Conveyance Design and Construction Authority (DCA). 2021a. Shaft Siting Study Technical Memorandum. Final Draft.

Delta Conveyance Design and Construction Authority (DCA). 2021b. Reusable Tunnel Material Technical Memorandum. Final Draft.

Delta Conveyance Design and Construction Authority (DCA). 2021c. Tunnel Inspection and Maintenance Considerations Technical Memorandum. Final Draft.

Delta Conveyance Design and Construction Authority (DCA). 2021d. Hydraulic Analysis of Delta Conveyance Options–Main Tunnel System Technical Memorandum. Final Draft.

Delta Conveyance Design and Construction Authority (DCA). 2021e. Flood Risk Management Technical Memorandum. Final Draft

Delta Conveyance Design and Construction Authority (DCA). 2021f. Preliminary Precast Yard Study Technical Memorandum. Final Draft Delta Conveyance Design and Construction Authority (DCA). 2021g. Reusable Tunnel Material Technical Memorandum. Final Draft

Feldsher T., G. Boyce, D. Tsztoo, M. Cash, and D. McMaster. 2014. New Irvington Tunnel Meets the Challenges. *In Proceedings of the 2014 North America Tunneling Conference (NAT)*.

Jewell P., A. Barker, M. Bellhouse, C. Matta, and A. Sefton. Innovation Shaft and Tunnel Linings for Thames Water Lee Tunnel. *In Proceedings of the 2014 North America Tunneling Conference (NAT).*

Lindquist, E. 2010. Construction Of Two Microtunnel Access Shafts Using The Cutter Soil Mix (CSM) Method In The San Joaquin Delta, California Deep Foundations Institute.

Luongo, V. and Y. St-Amour. 2005. Construction of Deep Shafts and Ground Improvement for the West Side CSO Tunnel Project, Portland, Oregon. *In Proceedings of the Rapid Excavation Tunneling Conference (RETC).*

Newhouse, J. 2019. Ground Movement due to Shaft Construction. In Proceedings of the 27th European Young Geotechnical Engineers Conference.

Robinson, B. and M. Jatczak. Construction of the South Bay Ocean Outfall. *In Proceedings of the Rapid Excavation Tunneling Conference (RETC)*.

Stockhausen, S. and N. Goodenow. 2013. Shaft Construction Methods. In Proceedings of the Rapid Excavation Tunneling Conference (RETC).

Wong, J., R. Mues, and L. McVicker. 2011. Shaft Design and Construction Considerations. *In Proceedings of the Rapid Excavation Tunneling Conference (RETC).*

7. 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
Martin Ellis / EDM Shafts Engineer	Steve Dubnewych / EDM Tunnel Lead	Gwen Buchholz / DCA Environmental Consultant Phil Ryan / EDM Design Manager	Terry Krause / EDM Project Manager

This interim document is considered preliminary and was prepared under the responsible charge of Martin Ellis, California Professional Engineering License C83803.

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
Shaft Methods Comparison Table

Table A-1. Comparison of Shaft Methods

Criteria	Wet Excavation Methods				Dry Excavation Methods					
					Shaft Lining Cut-Off a			Separate Cut-Off b		
	Diaphragm Walls (~200 feet deep)	Secant Piles (~200 feet deep)	CSM (~200 feet deep)	Caisson Sinking	Diaphragm Walls (~300 feet deep)	Secant Piles (~300 feet deep)	CSM (~300 feet deep)	Ribs and Lagging	Sprayed Concrete	CSM (~200 feet deep)
Safety	Underwater base slab construction requires extensive use of divers▼				Secure pre-supported walls for open excavation and base slab construction▲		-	Manual installation of timber lagging▼	-	Additional stability of excavation in poor ground▲
Groundwater impact	No removal of groundwater for shaft installation▲				Inflow through base area of shaft▼			Inflow through base area of cut-off zone▼		
Concrete quantity GHG impact	-	-	-	Largest mass of structure to overcome floatation and friction▼	-	-	-	Lightest structure; may require additional ballast concrete to resist floatation▼	Least structural thickness lining and base slab▲	-
Quality	Control of verticality and concrete quality is critical to every element▼		Difficult to control soil mix properties in variable ground▼	-	Control of verticality and concrete quality is critical to every element▼		Difficult to control soil mix properties in variable ground▼	-	-	-
Schedule	-	Need for secondary lining▼	Need for secondary lining▼	-	-	-	Need for secondary lining▼	Need for secondary lining▼	Time savings for shaft lining, base slab, and tunnel eye installation▲	-
Relevant examples	Blue Plains DC, (Blanchard 2017) SFPUC Bay Tunnel CA (Wong 2011)	New Irvington Tunnel, (Feldher 2014) SR99 Alaska Way WA	Old River Crossing Port of Miami Tunnel		Blue Plains Lee Tunnel project London UK, (Jewell 2014) Swan Island PS Portland (Luongo 2005)	Transbay Transit Center secant pile shaft test program (240 feet deep)	Old River Crossing	-	Limo Launch shaft, CrossRail London, UK (Newhouse 2019)	Old River Crossing Port of Miami Tunnel
Other risk factors	Formation of base slab keys is difficult underwater▼		Walls subject to leakage and instability with incomplete soil mixing▼	Caissons can get held up if ground friction cannot be overcome▼	Incomplete cut-off if walls separate at depth▼	Incomplete cut-off if piles separate at depth▼	Incomplete cut-off if mix zone is incomplete at depth▼	Excessive pumping needed if cut-off depth is insufficient▼		

[a] Assumes dewatering within shaft walls.
[b] Assumes dewatering inside a cut-off wall zone, or ground freeze, or ground improvement.

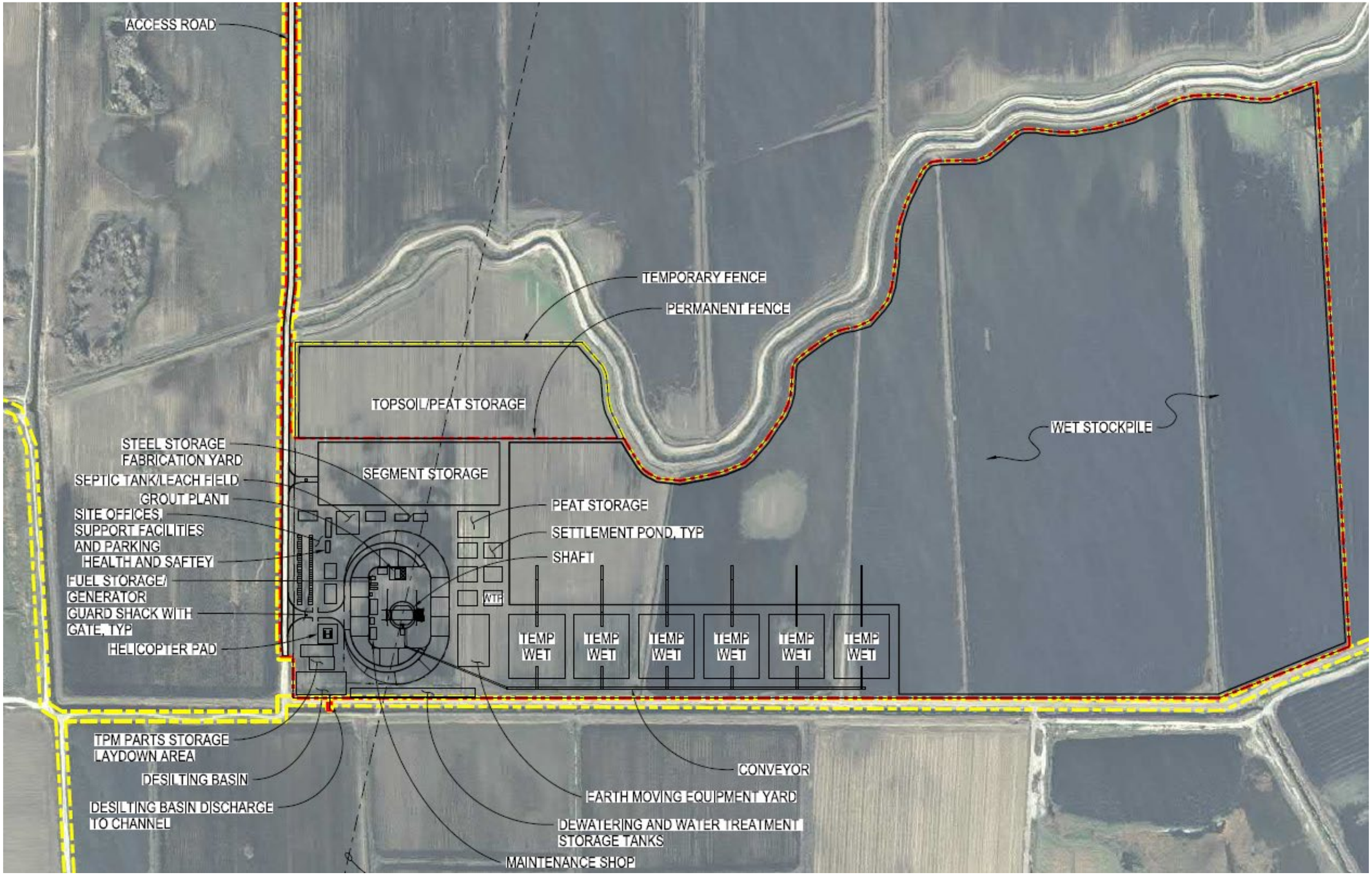
Notes:

Red shading with▼ indicates potential disadvantage over other methods.

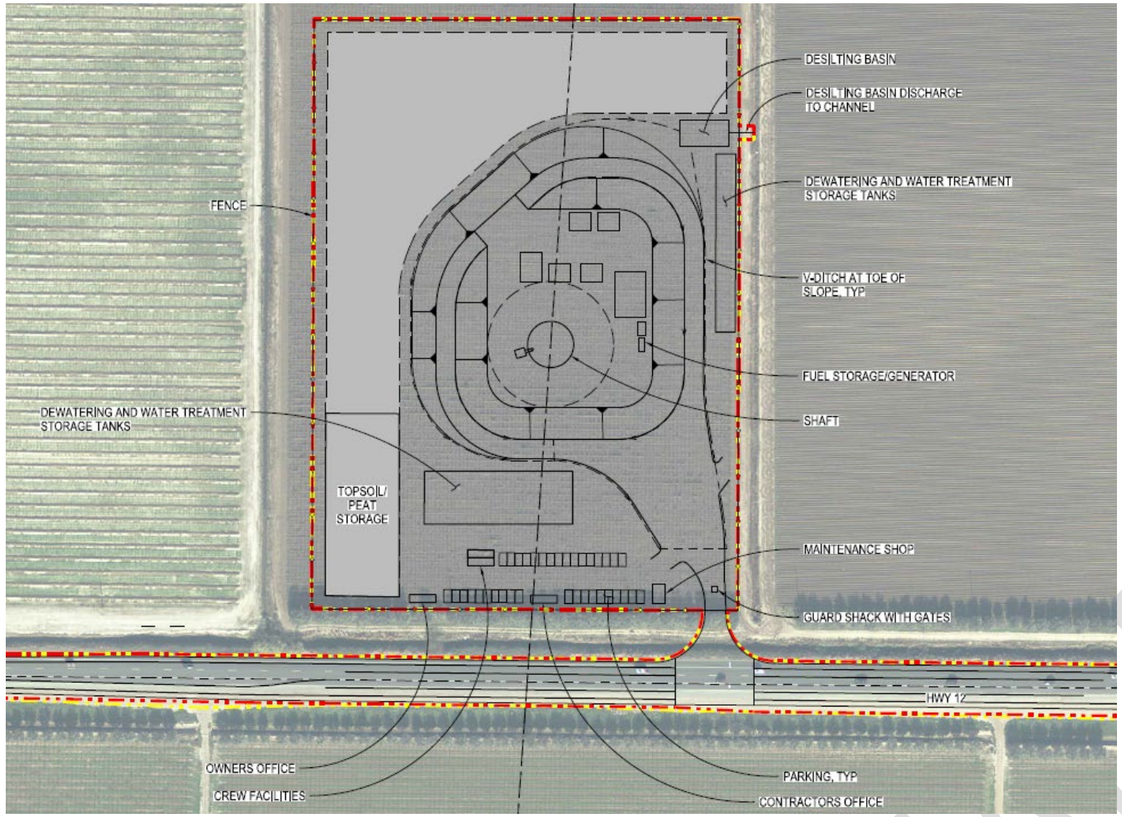
Green shading ▲indicates potential advantage over other methods.

– = not applicable
~ = approximately
CSM = cutter soil mixing
GHG = greenhouse gas
PS = pump station
SFPUC = San Francisco Public Utilities Commission
SR = State Route
UK = United Kingdom

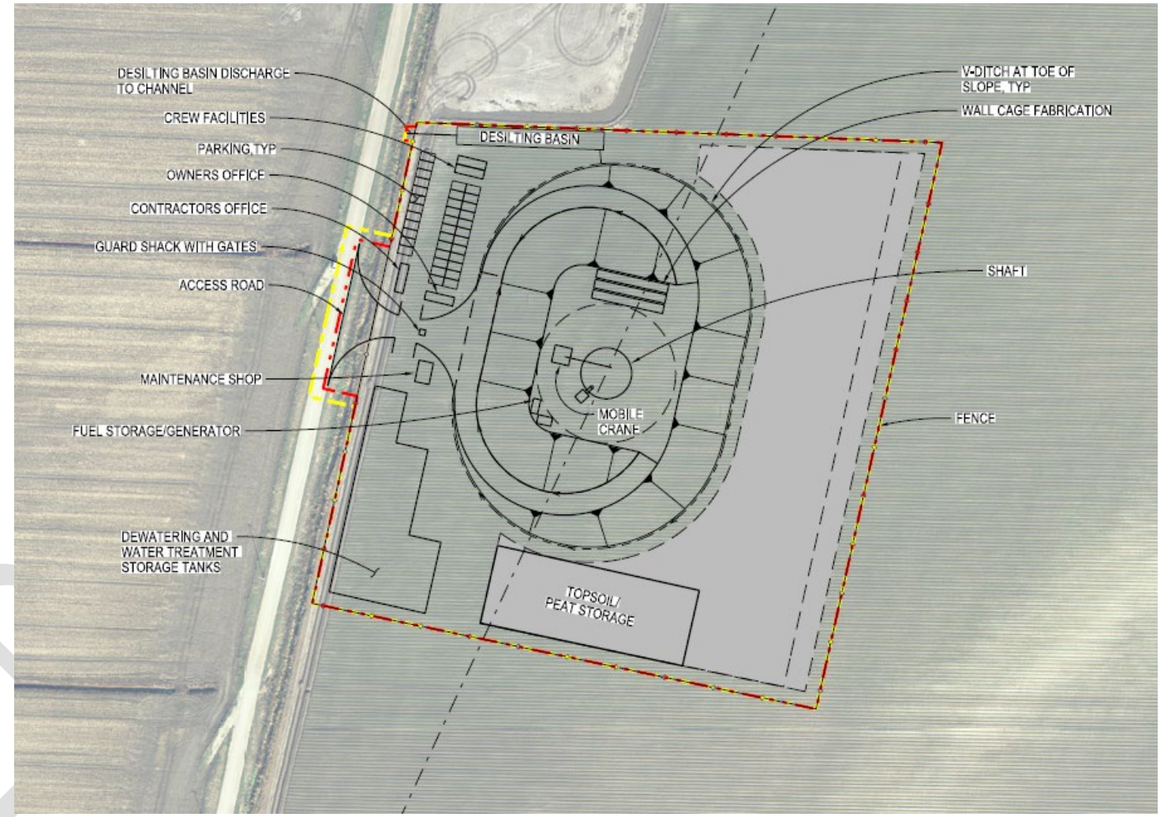
Attachment 2
Typical Worksite Layouts



Attachment 2.1 - Tunnel Launch Shaft Worksite Layout



Attachment 2-3. Maintenance Shaft Worksite Layout



Attachment 2-2. Reception Shaft Worksite Layout