

Design Considerations and Evaluation Process for a New Tunnel and Ocean Outfall Project

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ABSTRACT

The Joint Water Pollution Control Plant, operated by the Sanitation Districts of Los Angeles County, treats wastewater generated by over three million people. A new tunnel and ocean outfall is being considered to meet future hydraulic demands and provide long-term redundancy for the Districts' existing tunnels, portions of which were constructed as early as the 1930s.

The detailed process used to evaluate the feasibility of various tunnel and outfall locations is described. Challenges include a geologic profile with mixed face and squeezing ground conditions; high water pressures; active fault crossings; gassy and contaminated ground conditions; and liquefaction, slope stability, and lateral spreading concerns in the area of the riser and diffusers.

INTRODUCTION

The Sanitation Districts of Los Angeles County (Districts) are 24 independent special districts serving approximately 5.3 million residents in Los Angeles (LA) County. Seventeen of the districts that furnish sewerage services to metropolitan LA are signatory to a Joint Outfall Agreement that provides for a regional, interconnected system of facilities known as the Joint Outfall System (JOS). The JOS serves an area that encompasses 73 cities as well as unincorporated territory and parts of the City of LA. The JOS provides wastewater collection, treatment, reuse, and disposal for residential, commercial, and industrial users, and it includes seven treatment plants, the largest of which is the Joint Water Pollution Control Plant (JWPCP), located in the City of Carson. Currently, secondary effluent from the JWPCP is conveyed through two parallel tunnels 2.4 and 3.7 m (8 and 12 ft) in diameter. The tunnels interconnect at a manifold structure at Royal Palms State Beach on the Palos Verdes (PV) Peninsula, from which two operational seafloor outfalls extend offshore. Both tunnels are required to be in service at all times and have not been inspected since 1958. The new tunnel and ocean outfall system, if constructed, will provide additional capacity and long-term redundancy, and will allow inspection, maintenance, and repair of the existing tunnel and outfall system.

In June of 2006, feasibility studies and preliminary engineering for this project was awarded to the Parsons Corporation in association with Jacobs Associates, which is leading the underground design efforts. Currently, the team is undertaking an alternative selection process to choose the alignment alternatives to consider during the preliminary engineering phase of this project.

STUDY AREA

The new tunnel will commence with a shaft at the JWPCP. From the JWPCP, an onshore tunnel will be constructed in a southward direction to a shaft at the shoreline and then will continue offshore. The offshore alignment will begin with a tunnel that will either continue to a diffuser as a tunnel or as a seafloor pipeline.

The onshore study area (Figure 1) includes multiple alignments from the JWPCP to the shoreline—from Royal Palms State Beach on the PV Peninsula to the far eastern boundary of the Port of LA. The offshore study area extends from the shoreline, southwards to the San Pedro and PV Shelves.

[Insert Figure 1 here; exact caption follows.]

FIGURE 1. Project study area

AREA SITE CONDITIONS

Geologic and Seismic Setting

The study area lies on the southwest boundary of the LA Basin and straddles the paleo-LA River and two prominent geomorphic features—the PV Hills and the Newport-Inglewood Uplift (Figure 2). The dominant structural feature is the PV fault, which forms the northwest-trending Gaffey syncline and anticline. The Cabrillo fault, a splay of the PV fault, although not as pronounced, is nevertheless a significant geomorphic feature (Figure 2). Another pervasive feature of the area is that it is underlain by the Wilmington Oil Field, a well-developed, northwest-trending anticline structure of oil-bearing rock.

[Insert Figure 2 here; exact caption follows.]

FIGURE 2. Geologic structures in the project area

The stratigraphy of the LA Basin and the PV Hills is generally characterized as follows:

- Quaternary age: Surficial deposits include Holocene sediments consisting of fill, alluvium, sand dunes, and terrace deposits underlain by Pleistocene sediments, including the Lakewood and the San Pedro formations. The Lakewood Formation contains the PV sand member. The San Pedro Formation contains the San Pedro sand, the Timms Point silt, and Lomita marl members. These formations range from primarily unconsolidated sediments to strong soil and very weak rock.
- Tertiary age: Pliocene sediments include the Fernando Formation, consisting of the Pico and oil-bearing Repetto members, which are underlain by the Miocene-age Malaga Mudstone and the Monterey Formation. The Monterey Formation consists of Valmonte Diatomite, and Altamira Shale. These formations range from strong soil to weak and moderately strong rock.
- Jurassic age: Basement rock is Catalina Schist, metamorphic hard rock that varies from moderately strong to very strong.

Generally, the onshore tunnel alignments west of the PV fault and toward the PV peninsula are primarily Tertiary-age ground, with the possibility of encountering Jurassic-age rock at depth and Quaternary-age sediments as the tunnel alignments drift/trend away toward the east flanks of the peninsula. The onshore alignments east of the PV fault are entirely in Quaternary-age sediments.

Offshore, the tunnel would be mostly west of the PV fault to reach the proposed diffuser areas. These portions of the alignment are located in Tertiary-age ground. Where the offshore tunnel alignments are east of the PV fault (primarily within the Port of LA Harbor area), the tunnel alignments will encounter Quaternary-age sediments before transitioning to Tertiary-age ground.

Example geologic profiles for alignments both east and west of the PV Fault are shown in Figure 3. The differences in the onshore geology, as noted above, can be seen in these two alignments.

A significant earthquake is expected within the next 30 years within Southern California, and there is significant risk of a M7. Palos Verdes fault offset is also a major concern, for which mitigation measures are discussed in “Design Considerations,” below.

[Insert Figure 3 here – on full page if possible; exact caption follows.]

FIGURE 3. Geologic profiles illustrating differences in subsurface conditions on either side of the PV Fault.

Groundwater Conditions

Groundwater onshore varies from sea level near the shoreline and rises toward JWPCP to 17 m (55 ft) below the ground surface. The Gaspur Aquifer represents runoff down the Los Angeles River from the San Bernardino Mountains and into deep aquifers and is a source of groundwater. A series of deep injection wells prevent seawater intrusion into this aquifer. Between the ground surface and the permanent groundwater level, perched water or trapped virgin water is expected to be encountered in lenses or pockets. At tunnel depth, however, groundwater pressure conditions are expected to reflect those of the permanent groundwater table. Groundwater offshore and pressure head are expected to be consistent with sea level.

PROJECT COMPONENT AREAS

To aid in establishing and evaluating the preliminary alternatives for a potential tunnel and ocean outfall system, five component areas were developed and independently analyzed. These include JWPCP shaft sites, coastal shaft sites, onshore alignments, marine alignments, and diffuser areas. For each area, preliminary options were developed based on a set of initial criteria, as described below.

Shafts

Shafts will be necessary to construct the tunnel; however, the total number of shafts is dependent on the alignment alternative selected and whether it is feasible to construct additional intermediate shafts. Regardless of the alternative selected, at least one mining shaft will be necessary, and additional shafts may be used for access and/or retrieval. The proposed shafts range in depth, depending on where they are located along the alignment alternatives, with potential depths of 75 m (245 ft) below the ground surface. Additionally, the proposed diameters of the shafts range from approximately 9 to 18 m (30 to 60 ft), depending on the expected use for each shaft. Working shafts are expected to be at least 12 m (40 ft) in diameter and up to 18 m (60 ft) if a shaft supports two headings. For example, a shaft at the shoreline may be used to mine both onshore and offshore headings. The diameter of access shafts is expected to be approximately 9 m (30 ft).

Given that these shafts could be excavated in a range of geologic materials, several shaft excavation and temporary support systems are discussed. For excavations in soil below the groundwater table, watertight excavation methods will be used. The watertight methods of excavation support that are considered most feasible include both slurry diaphragm walls and ground freezing. Two nonwatertight methods include sequential excavation and soldier piles with lagging. The nonwatertight methods are expected to be used for shafts in sedimentary rock.

JWPCP shaft sites. Two potential shaft sites at the JWPCP have been identified and are being evaluated—they are known as the JWPCP West and East Shaft sites. A location at the JWPCP is

necessary to house the permanent structure, which will connect the existing treatment facilities to the new tunnel and could also be used for mining. Location criteria for the JWPCP shaft site are that the site must be within the confines of the JWPCP property boundaries; avoid conflicts with current facilities or planned future facilities; have a minimum area of 1.6 ha (4 acre); be roughly rectangular to square in shape and relatively flat; and have access for equipment, ventilation systems, and personnel, as well as long-term access for excavated material removal on a continuous basis.

Coastal shaft sites. The remaining potential shaft sites are considered coastal shaft sites and fall into one of three categories: working shafts, retrieval shafts, or access shafts. Locations near the coast along the different alternatives could be used to mine the offshore portion of the tunnel. A shaft close to the shoreline will reduce the length of the tunnel drives if it could be constructed and used as a mining shaft. An intermediate shaft site not used for mining could still be beneficial for maintenance and ventilation and other access needs. A site of 1.6–2 ha (4–5 acre) was determined to be the minimum size necessary for a working shaft, but a 2.4-to-3.2-ha (6–8 acre) site is preferred.

Retrieval shafts require approximately 0.8 ha (2 acre). This is adequate for routine access for personnel ingress and egress, as well as for the removal of salvageable portions of the tunnel boring machine (TBM) at the project's conclusion. Retrieval shafts will not be used to remove excavated material during the tunneling operations.

Access shafts will require the least area and are limited to personnel ingress and egress, as well as connection with the overall tunnel's ventilation system. Public land is preferred over private land for the selection of coastal shaft sites. The site has to be relatively flat and near rectangular or square in shape. Based on these criteria, locations were identified as potential coastal shaft sites (Figure 4).

[Insert Figure 4 here; exact caption follows.]
FIGURE 4. Proposed alignments and shaft sites

Onshore Alignments

Initial evaluations of construction methods indicated traditional open-cut construction was not a viable option due to the disruption that would occur to the surrounding communities and the depth of excavation required—in excess of 18 m (60 ft). Therefore, the onshore alignments must be built by tunneling methods. Using long, continuous public streets between the JWPCP and Pacific Ocean or existing easements, and a minimum radius of 305 m (1,000 ft), criteria were established for developing the onshore alignments. Twenty-two potential tunnel alignments were identified for further analysis (Figure 4).

Tunnel drives up to 10.7 km (6.6 mi) in length are being considered for the onshore drives. The excavated diameter of the tunnel could be up to 7 m (23 ft). Tunnel excavation may require a combination of soft ground and rock excavation methods due to the variable soil conditions that may be encountered. Challenges include long tunnel drives under very high groundwater heads. Groundwater pressures up to 6 bar could be encountered, depending on the alignment alternative selected. A pressurized-face TBM is ideally suited for this project due to the expected presence of high groundwater pressures combined with the varying permeability and strength of the soil units, including mixed-face conditions (i.e., both rock and soil in the excavation face) along the proposed alignment corridors.

A significant factor that helps differentiate which type of TBM to select is the geology expected along the alignment. With the data currently available, a definitive conclusion cannot be made on the most suitable tunnel excavation method. Nevertheless, the advantages and disadvantages of using Slurry TBMs, earth pressure balance (EPB) TBMs, or hybrid TBMs are discussed under “Design Considerations,” below.

Independent of machine type, there are other geotechnical considerations that also must be evaluated, including the potential for ground squeezing, naturally occurring hydrocarbons, and faults in the project area that must be crossed. Given the expected ground and groundwater conditions, a watertight bolted gasketed liner system will be required for ground support and for advancing the TBM. This initial support also could be used as the final lining of the tunnel, or a two-pass lining could be used.

Marine Alignments

The marine alignments, which consist of an offshore tunnel, a seafloor pipeline, or a combination of the two, connect the onshore alignments and the diffuser areas to create complete viable alternatives for further evaluation. The vertical connection from the tunnel to the seafloor pipeline or diffuser site will be made with a riser. The establishment of preliminary options for the marine alignments was deferred until after the establishment of preliminary options for the other four component areas.

Tunnel and pipeline. Similar tunneling conditions, tunnel diameter, TBM types, and geotechnical and liner considerations are required for offshore tunnel alignments, except the maximum drive lengths are generally longer than onshore alignment drive lengths—the offshore drives could be as long as 17 km (10.5 mi). Additionally, external hydrostatic pressures could approach 10 bar.

Fundamental to the selection of the preferred offshore tunnel alignment is the consideration of feasible seafloor pipelines based on geotechnical considerations, ship-traffic considerations, and constructability. Based on a review of case histories, the design team developed constraining criteria for layout of deep marine pipelines (Table 1).

TABLE 1. Marine Pipeline Constraints		
	<i>Reinforced Concrete Pipe ID</i>	<i>Pipe Laying Depth</i>
State of Practice	1.5 to 3.7 m (5 to 12 ft)	<60 m (<200 ft)
State of Art	>4.3 m (>14 ft)	>60 m (>200 ft)

Riser. The design of offshore structures is largely driven by construction considerations; this applies particularly to a riser that connects a tunnel to the seabed portion of the outfall system. Among the major considerations for offshore shafts and risers are:

- Seabed bathymetry and water depth
- Riser height and diameter
- Geologic conditions
- Offshore waves and currents
- Shipping and navigation patterns
- Construction equipment limitations

Tunnel construction constraints directly affect design of the riser, as riser height is controlled by the elevation of the tunnel relative to the seabed, and the depth of water at the riser is a function of the tunnel length and alignment. Water depth, riser diameter, and riser height are perhaps the most important factors affecting the riser design, construction costs, and risks, particularly for the potentially large-diameter structures being considered on this project. As the tunnel length increases to extend under deeper water, the associated costs of the shaft and riser increase, along with construction risks.

Construction of a large riser in the ocean is delicate and risky. Generally, the construction of the riser proceeds independently of and prior to tunnel construction. When both the riser and tunnel are completed,

the connection between the two is made from the tunnel. This is the riskiest part of the operation, and its success is determined largely by the accuracy of the planning during the design. The design has to address all that could go wrong with the different methods as applied to the specific site geology, and a procedure that has built-in safety redundancy must be selected. Based on a review of case histories, the design team developed the constraining criteria for layout of deep marine risers (Table 2).

TABLE 2. Marine Riser Constraints		
	<i>Maximum Depth</i>	<i>Maximum Diameter</i>
State of Practice	30 m (100 ft)	5 m (16 ft)
State of Art	60 m (200 ft)	5 to 6 m (16 to 20 ft)

Diffuser Areas

An underlying criterion for the proposed diffuser is that the system must perform equal to or greater than the existing outfalls. To achieve this, initial parameters of distance from shore, discharge depth, and bathymetry profile were established. In addition, the diffuser area had to avoid the existing outfalls. Three diffuser areas were identified as meeting these initial parameters (Figure 5): Area A (off Point Fermin on the PV Shelf and adjacent to the existing outfalls), Area B (east of the San Pedro Sea Valley), and Area C (on the southern edge of the San Pedro Shelf).

[Insert Figure 5 here; exact caption follows.]
 FIGURE 5. Proposed diffuser areas

A conventional diffuser in either a “Y” or “T” configuration is being considered for this project. The diffuser will likely have two legs of equal length separated by an angle of 120–180°. The diffuser will start either at the top of the tunnel riser or at the seafloor pipeline. If the JWPCP outfall system were designed for the larger spectrum of design flows, sea-floor pipelines and conventional diffusers would need to have very large diameters to accommodate the larger-than-average flows. The diameters that would be required are not standard sizes in the pipe and marine industry.

DESIGN CONSIDERATIONS

Tunnel Construction Considerations

High groundwater head. Depending on the alternative selected, the maximum groundwater head to be experienced could be up to 10 bar. Excavating a tunnel under pressures of this magnitude presents health and safety hazards as well as challenges in designing a machine and initial lining to withstand the pressure. While tunneling under pressures of 4 bar are routinely performed, pressures of 8–10 bar will require state-of-the-art techniques.

Interventions will need to be performed both routinely (planned interventions), and when the progress of the TBM is slower than expected (due to worn cutters). To access the cutterhead for maintenance while tunneling in closed mode, the interventions will need to be performed under free air, compressed air, a mixed-gas environment, or by using saturation diving techniques.

In locations where interventions need to occur under high pressures in soil (e.g., onshore near the coast), compressed air using a mixed gas environment may be required; however, for interventions under high head in rock, there is a potential that the rock will be stable enough to perform interventions in free-air. Additionally, ground improvement methods could be employed to reduce or eliminate the need for compressed air by making the surrounding ground more stable.

Depending on the pressures expected, the TBM may need to be fitted with a decompression chamber. Due to space limitations, the minimum TBM diameter could be dictated by the size of the chamber. This becomes especially critical with an EPB TBM, where the screw conveyor may interfere with the decompression chamber - airlock interface.

Long tunnel drives. A literature review was performed that focused on tunnel projects with varying drive lengths in soil, weak rock, and hard rock. Generally, it was found that many long tunnels in soft ground and weak rock have been excavated in multiple drives of less than about 3 km (2 mi) for a variety of reasons that are not necessarily related to TBM performance. Examples include:

- Wastewater tunnels with drive lengths determined by the spacing of drop shafts or maintenance holes
- Transit tunnels with drive lengths set by the distances between stations
- Water conveyance tunnels with drive lengths influenced by the need to maximize the amount of cut-and-cover or surface pipelines
- Tunnels requiring multiple drives to reduce the total project delivery time

However, some very long tunnels have been excavated in soil and rock as a single heading without the use of intermediate shaft sites, including:

- Submarine tunnels
- Tunnels in urban environments with limited shaft-site availability
- Tunnels in remote areas with difficult terrain or limited surface access

Based on a review of case histories, the design team developed the constraining criteria for layout of long tunnels (Table 3). Some long tunnel drives in soil include the Westerschelde Tunnel in the Netherlands and the South Bay Ocean Outfall in California, which had drives of approximately 6,600 m and 5,900 m (21,650 ft and 19,500 ft), respectively. In rock, some of the Channel Tunnel drives between the United Kingdom and France were over 22,000 m (72,000 ft) in length. An example of a long outfall tunnel in rock is the Deer Island Outfall in Boston, which is just over 15,000 m (49,500 ft).

The maximum external pressures for the case histories reviewed ranged from 7 to 11 bar. Also, the lengths provided in Table 3 are approximate within 10% of what is feasible/practical.

TABLE 3. Tunnel Length Constraints		
	<i>Maximum Length in Soil</i>	<i>Maximum Length in Rock</i>
State of Practice	4,600 m (15,000 ft)	7,600 m (25,000 ft)
State of Art	6,700 m (22,000 ft)	15,900 m (52,000 ft)

Depending on the alignment selected, both the onshore and offshore tunnels are considered at the State of the Art (SOA) for tunnel length. Preliminary onshore tunnels could be over 10,700 m (35,000 ft), with the preliminary offshore portion being over 16,800 m (55,000 ft). Both the onshore and offshore tunnel alignments will likely be excavated in a single heading because of the lack of intermediate shaft site availability onshore and the subaqueous nature of the offshore portion. In all alignment alternatives being considered, there is at least one intermediate shaft site near the coast, which will separate the onshore and offshore tunnel drives.

Long tunnel drives increase the amount of design difficulty because the entire drive must be excavated with the same TBM. For example, the geology is extremely variable within the project area of the JWPCP

tunnel and ocean outfall, and due to the lack of intermediate shafts, each entire drive (onshore and offshore) will need to be mined with one TBM. Additionally, as tunnel length increases, ventilation requirements become greater. Lastly, TBMs may need to be outfitted with special provisions to provide for stopping in potentially bad ground conditions for cutterhead maintenance.

Geological considerations. Geotechnical considerations that also must be evaluated include the potential for ground squeezing, naturally occurring hydrocarbons, and faulting. Squeezing ground occurs when ground slowly advances into the tunnel excavation, which could occur in both cohesive soils and weak rock. In areas where the alignments cross either the PV or Cabrillo fault, squeezing conditions could be encountered if they are not designed against or mitigated properly.

Additionally, alignments passing through the Tertiary-age formations could encounter naturally occurring hydrocarbons during excavation. Both methane gas and hydrogen sulfide gas may be encountered in these formations. In these conditions, a Slurry TBM would be advantageous since it operates in a “closed circuit,” minimizing workers’ exposure to gas underground. Also, a Slurry TBM provides more safety for the expected high pressures, especially in cohesionless soils. It is costlier, however, to separate the bentonite slurry, especially in cohesive soils.

An EPB TBM would discharge the excavated material into muck cars underground and transport it by rail to the surface. During transport, gases could be released and could be dangerous. A number of provisions would need to be in place to mitigate dangers, such as increased ventilation and restrictions on electrical equipment. An EPB TBM could be outfitted with a “closed circuit” muck-removal system similar to a slurry system to prevent discharge of gas into the tunnel environment. An EPB TBM can offer economic tunneling in cohesive soils and weak rock/strong soils, although safety is compromised in cohesionless soils, especially in pressures over 3 bar. In recent years in Japan, the use of EPB has greatly outpaced that of slurry machines except where safety issues are overwhelming (controlled face tunneling in cohesionless soils under high head over 3 bar).

A hybrid TBM may offer the best compromise between slurry and EPB methods. They are equipped with slurry pumping injection and removal systems and a screw conveyor for removal of muck. Hybrid TBMs have been most common in Japan and Europe for over 15 years. To the authors’ knowledge, two small projects have been completed using hybrid TBMs in the U.S.: one in Miami Dade County, Florida, and one in San Mateo County, California. The Southern Nevada Water Authority’s Intake Pump Station No. 3 Tunnel will be excavated by a Hybrid TBM. Hybrid TBMs may excavate in slurry mode when required for safety reasons to prevent the uncontrolled inflow of ground and groundwater. When in good ground, a Hybrid TBM may operate using EPB open-mode tunneling for efficient and economical tunneling.

Seismic considerations. Another design challenge is the crossing of active faults. Fault crossing strategies are being evaluated, including:

- Specially designed one-pass tunnel lining in fault zone (with joints able to withstand some displacement while retaining their water-tightness).
- Two-pass tunnel lining in fault zone (may reduce cross-sectional area if excavated diameter is kept constant). This could accommodate more displacement by leaving an annular gap between the two linings.
- Shallow tunnel profile in fault zone would make repair in the event of rupture more feasible and economical.

Shaft Construction Considerations

Soil and groundwater conditions. Deep shafts excavated in soils with high groundwater heads will be the most challenging ground conditions for shaft construction. Potential shaft sites at the coast in and around the Port of Los Angeles could be excavated more than 50 m (165 ft) below grade entirely in soil. In these locations, the groundwater table is at or just below the existing grade, making for large groundwater pressures at the bottom of the excavation. Additionally, lateral pressures exerted on the shafts excavated in soil will be higher than those excavated in rock because the rock shares some of the load. Shaft excavation in saturated soils is fairly routine at depths of 30 m (100 ft) or less; however it becomes challenging at depths of greater than 45 m (150 ft).

Achieving tight construction tolerances needed to obtain a watertight structure with a deep shaft will be an issue when installing slurry wall panels or ground freeze pipes. Maintaining verticality during installation of both slurry walls and ground freeze pipes becomes more difficult with depth. Potential horizontal deviations of 0.5–1.0% of the vertical distance (depth) could occur. Practical construction tolerances also may be an issue when improving ground for break ins or break outs (e.g., with jet grouting).

While slurry walls and ground freeze walls are effective in controlling groundwater seepage through the shaft walls, groundwater also can enter the excavation from the bottom. With groundwater heads as high as those expected at shafts near the coast, shaft bottom seals become a critical consideration in shaft design. Some methods being considered to mitigate this include establishing groundwater cut off by extending the shaft wall below the base of the excavation, shaft excavation in the wet followed by the construction of a tremie concrete bottom slab designed to resist the hydrostatic pressures at the bottom of the shaft, and temporary aquifer depressurization (if acceptable).

Sensitive receptors and land use. The current land use of the potential shaft sites is important because some sites are being used for recreational purposes and some are already in industrial areas. Construction traffic, noise, light, and dust can create bad public relations with the surrounding community if not properly mitigated. Even when mitigated, these issues may affect a shaft being selected in close proximity to sensitive receptors. Additionally, a site located adjacent to a major freeway or truck route would decrease impacts on the community and traffic flow in general.

Postconstruction access is desirable to allow maintenance and inspection and to house any permanent structures. Because it will be desirable to have permanent access to the tunnel via the shaft sites after construction, it is also important to consider the future land use of the sites.

Outfall Construction

Just as the threat of an earthquake provides design challenges to the tunnel fault crossings, it also adds challenges to the riser and diffuser design and site selection. The seismic hazards are those due to wave propagation damage (shaking) and permanent ground deformation (PGD). Shaking produces higher tunnel liner or pipe liner stresses and strains (hoop, axial, curvature bending, buckling, and racking). Shaking also may produce hydrodynamic forces, which create a water-hammer effect (overpressure) on the system components. In loose or soft-to-medium dense soils like those at some of the potential diffuser locations, PGD consists of liquefaction-induced settlements and liquefaction-induced lateral spreading and slope failure. Differential settlements at the seafloor surface or an entire slope failure could have catastrophic effects for either a seafloor pipeline or a riser and diffuser structure.

The potential for seismic-induced slope instability and liquefaction-induced lateral spreading will have a significant impact on the location of the marine facilities, which will in turn impact the location of the tunnel alignment. The challenge is to be able to predict the potential for PGD in the large offshore study area with limited geotechnical and geophysical data.

CONCLUSIONS

During the preparation of the feasibility studies and screening of alternative alignments (which is underway), evaluations and review of construction case histories of tunnels and marine pipelines, risers, and diffusers were conducted. Criteria were developed by the design team for maximum length, depth, and diameter of constructible alternatives. These criteria may be useful for the planning of other mega projects.

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