Lining Design Solutions to Seismic Fault Offsets on the JWPCP Effluent Outfall Tunnel

2017 NZSEE Conference

Y. Sun, J. VanGreunen, R. Geraili Mikola & J.M. Stolz

McMillen Jacobs Associates, San Francisco, California, U.S.A.

J.Y. Kaneshiro

Parsons, San Diego, California, U.S.A.

M. Vanderzee

Sanitation Districts of Los Angeles County, Los Angeles, California, U.S.A.

ABSTRACT: The Sanitation District of Los Angeles County is planning to construct a 5.5 m inside diameter (18 ft), approximately 11.3-km-long (7 mi) effluent outfall tunnel, to be excavated by TBM and lined with precast concrete segments. This new tunnel will be located in a seismically active region and will cross several seismically active fault zones. These fault zones are potentially capable of generating fault offset displacements, ranging from 0.1 to 0.5 m (0.3 to 1.6 ft), during the design basis earthquake event with a 10% probability of exceedance in 50 years (return period of about 475 years) during the tunnel design life of 100 years. Two lining systems are proposed to accommodate two levels of fault offset displacements: the first is the medium high hazard level up to 0.1 m and the second the high hazard level up to 0.5 m. The tunnel sections subjected to the medium high hazard level will have a one-pass lining system consisting of only the segmental lining installed during tunnel excavation, with special measures considered at the circumferential joints to minimise the potential shear and angular displacements. The tunnel sections subjected to the high hazard fault displacement level will have a two-pass lining system, consisting of the segmental concrete lining for initial and permanent tunnel support and a steel pipe secondary lining for ductility to accommodate the estimated fault displacements, maintain operations, and minimise leakage after an earthquake. This paper describes the approach used to address the tunnel seismic design challenges to meet the Sanitation District's seismic performance objectives.

1 INTRODUCTION

The Sanitation Districts of Los Angeles County (Sanitation Districts) is planning to construct a new 18-foot-diameter (5.5 m), approximately 7-mile-long (11.3 km) tunnel from the Joint Water Pollution Control Plant (JWPCP), located in the City of Carson, to the existing White Point outfall manifold structure at Royal Palms State Beach (RPSB) (Figure 1). The project is part of the Sanitation Districts' Clearwater Program, which will improve overall system reliability through the repair and replacement of the existing aging infrastructure. The existing system includes two 6-mile-long (9.7 km) tunnels, 8- and 12-feet in diameter (2.4 and 3.7 m), and four ocean outfall pipes with a maximum capacity of approximately 675 million gal/day (MGD) (2.6 million m^3/day). Addition of the new parallel tunnel will increase overall capacity to accommodate peak wet weather wastewater flows of up to 1,262 MGD (4.8 million m^3/day) and will allow inspection and repair of the existing tunnels. The new outfall tunnel will be excavated using a pressurized face tunnel boring machine (TBM). Shafts at the north (JWPCP Shaft) and south (RPSB Shaft) ends of the proposed alignment will connect the tunnel to the existing wastewater treatment plant and existing ocean outfalls manifold and during construction act as launch and receiving shafts for the TBM. The tunnel will be excavated from north to south as a single heading.

This paper describes the tunnel lining design approach and methods used to address the challenges during design to meet the Sanitation Districts' seismic performance objectives.

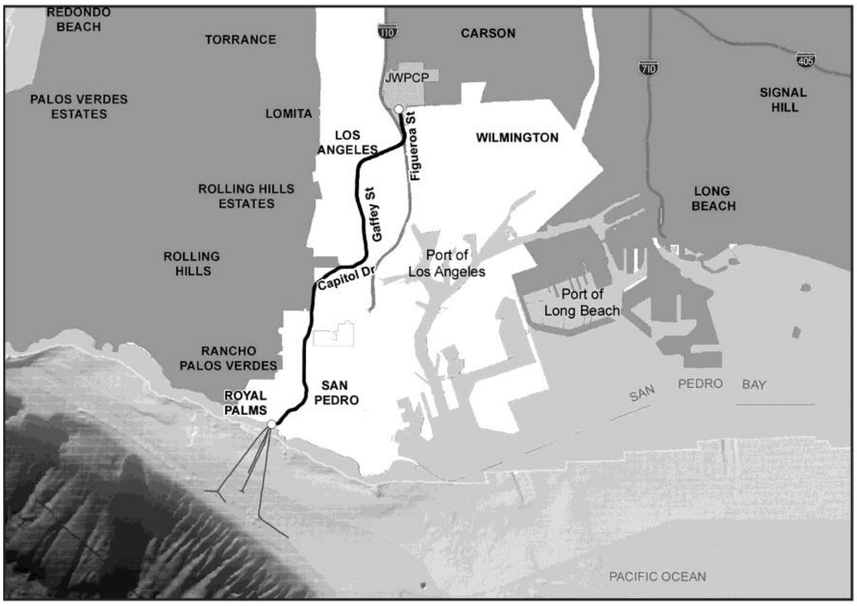


Figure 1. Plan of tunnel alignment (after Haug et al., 2015)

2 TUNNEL PROFILE AND GEOLOGIC CONDITIONS

The new outfall tunnel will slope upward at 0.1% from Station 0+00 at the JWPCP Shaft (El. -62 feet [-19 m]) to Station 367+43 near the RPSB Shaft (El. -26 feet [-8 m]) (Figure 2). The ground cover above the tunnel (measured from the ground surface to the tunnel crown) varies along the alignment, ranging from approximately 45 feet (13.7 m) near Station 75+00 to over 460 feet (140 m) near Station 325+00. Groundwater levels along the alignment vary from El. -21 to +260 feet (-6.4 to 79.3 m) (NAVD88).

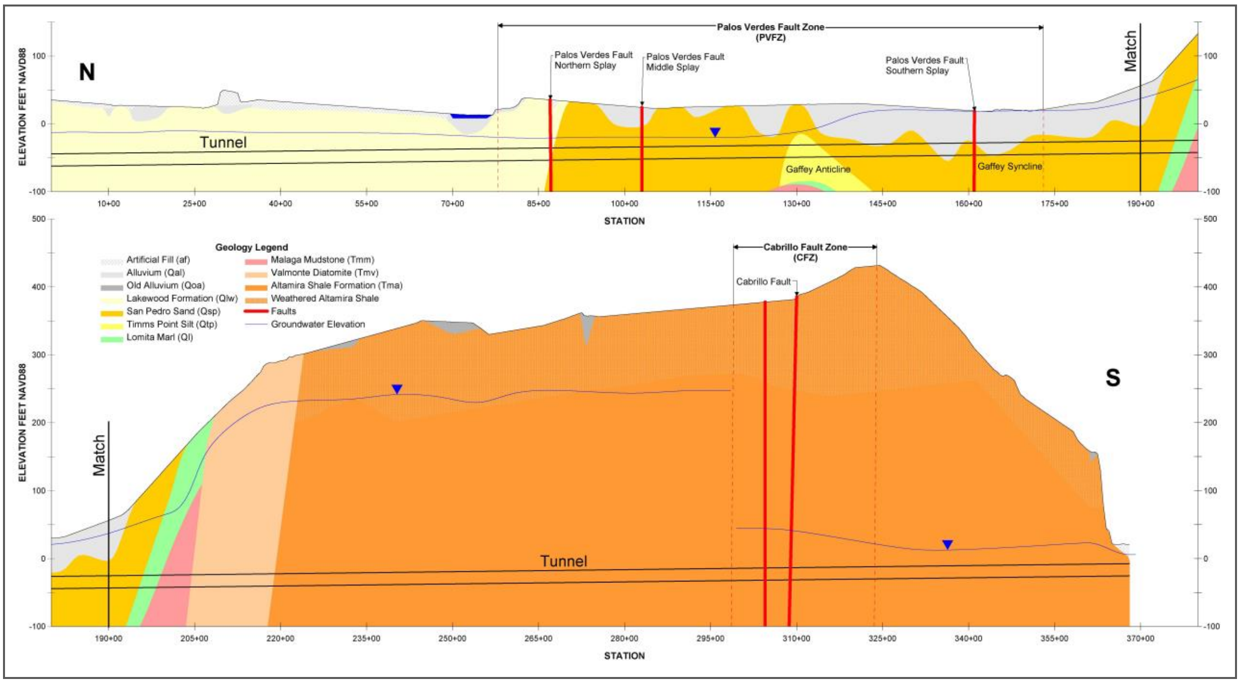


Figure 2. Geologic profile along tunnel alignment

Along the alignment two distinct geological formations will be encountered: alluvium and rock

(Figure 2). The northern part of the alignment will be located within Quaternary-age deposits that include Holocene sediments consisting of fill, alluvium, and terrace deposits. These are underlain by the Pleistocene-age Lakewood Formation and San Pedro Formation, which are primarily consolidated sediments. The southern part of the alignment within the Palos Verdes (PV) Hills will be located in Miocene-age sedimentary formations, which include Malaga Mudstone, Valmonte Diatomite, and Altamira Shale. In the heterogeneous lithology of the latter formation, ground behaviour is expected to vary greatly. The extremely weak material such as claystone will be subject to ravelling and squeezing, while stronger layers such as dolomite will act more competently.

The new tunnel is located in a seismically active region and crosses the active Palos Verdes Fault Zone (PVFZ) and the Cabrillo Fault Zone (CFZ) (Figure 2). The PVFZ is located in the central part of the alignment and consists of two primary (middle and south) splays, which are right-lateral strike-slip and oblique-slip faults, and one secondary (north) splay. The CFZ is located in the southern part of the alignment and considered a secondary fault. These faults are potentially capable of generating fault offset displacements.

3 DESIGN EARTHQUAKE AND SEISMIC PERFORMANCE CRITERIA

The Sanitation Districts adopted a design earthquake event with a 10% probability of occurrence within 50 years (return period of about 475 years) during the facilities' design life of 100 years. The Districts specified that the facilities may experience some distress, such as cracking and minor leakage, but are required to remain operational at full capacity after the design earthquake event.

Based on the seismic hazard analysis (Fugro, 2014), the design earthquake could generate the following two fault displacement hazard levels in the PVFZ and CFZ along the tunnel alignment:

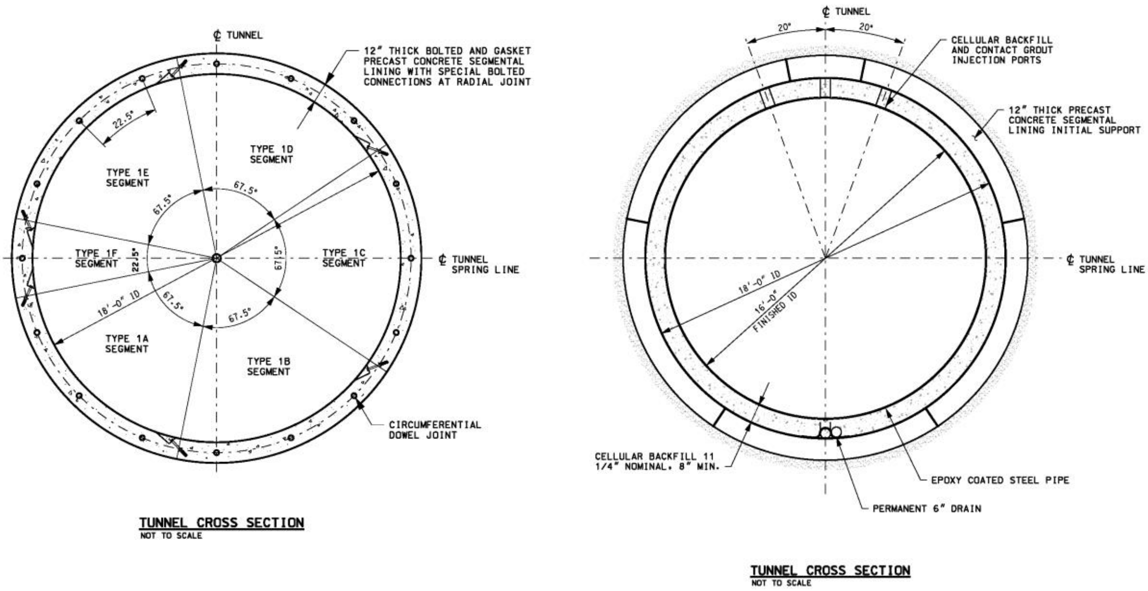
- **High hazard level**. Locations with known fault or fold features with highest potential for discrete localized displacement or deformation hazard to the tunnel with maximum displacement amounts estimated to range from 6 inches to 20 inches (150 to 500 mm)
- **Medium-High hazard level**. Locations with known fault or fold features with lessor amounts of expected discrete localized displacement or deformation hazard to the tunnel with maximum displacement amounts estimated to range from < 2 inches to 4 inches (< 50 to 100 mm)

4 LINING SYSTEMS FOR FAULT CROSSINGS

The lining systems proposed to accommodate the two levels of fault offset displacements are described below.

One-pass Lining System. Reaches of the tunnel will be subjected to medium-high hazard fault displacement level of up to 4 inches (100 mm) over a 1-foot-wide (0.3 m) fault zone (Fugro, 2014). These reaches fall within the CFZ and parts of the PVFZ for a total aggregate length of about 2,650 feet (808 m) of fault crossing. The tunnel lining for these reaches will consist of a 18-foot (5.5 m) ID, 12-inch-thick (305 mm) precast concrete segments. Through the PVFZ (where cover to the tunnel is low) the segmental lining has a post-tensioning system consisting of two-2.5-inch-diameter (65 mm) tendon ducts, each carrying four 0.6-inch-diameter (15 mm) strands, to handle the high internal pressure. This proposed system is designed to balance (with zero resultant stress) a net internal head of 96 feet (29 m) (42 psi [290 kPa]) over ambient groundwater pressure and is being used for the tunnelled section in soil and low cover areas for a total aggregate length of 21,523 ft (6,560 m). This poste tensioned lining system has been used elsewhere (e.g. Kohler and Rupp, 2008 and Saitou et al., 1999). Through the CFZ the cover is high and the segmental lining without the post-tensioning is adequate to support all loads. At the circumferential joints in these reaches of tunnel, measures are being considered to minimize the potential shear and angular displacements. Figure 3a presents the proposed one-pass lining system.

Two-pass Lining System. Tunnel sections subjected to the high hazard fault displacement level will experience maximum offsets of up to 20 inches (500 mm) over a 1-foot-wide (0.3 m) fault zone (Fugro, 2014). These sections occur at the middle and southern primary splays of PVFZ (PVFM and PVFS) for a total aggregate length of about 800 feet (244 m) of fault crossing. The tunnel within these sections will be designed with a two-pass lining system (segmental concrete lining for initial and permanent tunnel support and a steel pipe secondary lining for ductility). The proposed two-pass lining system incorporates a 16-foot ID (4.9 m) steel pipe with a 0.75-inch (20 mm) thickness inside the 18-foot (5.5 m) ID precast concrete segmental lining. It will accommodate the estimated fault displacements and minimize leakage after an earthquake. The annular space between the concrete segments and the steel pipe will be backfilled with low strength grout or crushable concrete. Figure 3b illustrates the proposed two-pass lining system.



a. One-pass lining system b. Two-pass lining system

Figure 3. Proposed lining systems for fault crossings

5 SEISMIC DESIGN EVALUATION AND RESULTS

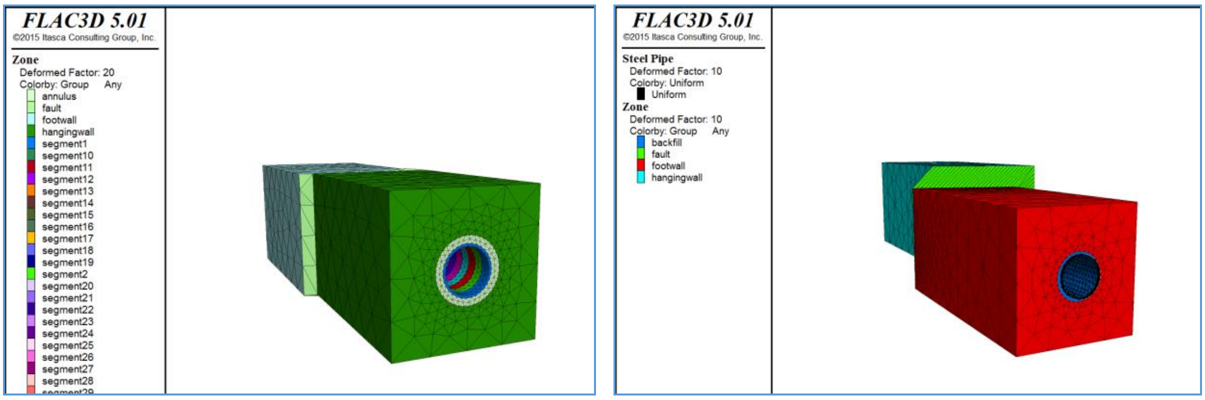
The design evaluation has been undertaken using 3D numerical analyses to assess the effect of fault offsets on the two lining systems proposed for the fault crossings. The 3D analyses were performed using finite-difference program FLAC3D Version 5. Separate numerical models were developed for evaluating the performance of the one-pass and two-pass lining systems (Figures 4a and 4b). Key assumptions used in the analyses include the following:

- The fault offset can be represented by the relative shear offset of two adjacent blocks of ground separated by a fault strand of sheared, crushed ground with a specified width. A 1-foot (0.3 m) fault width was considered as the design basis while widths of 5 and 10 feet (1.5 and 3.0 m) were also used for sensitivity studies. To simulate the fault offset, the two blocks of ground on either side of the fault strand were prescribed to move with the same amount of offset but in opposite directions along the fault plane (Figures 4a and 4b).
- The zone of ground surrounding the tunnel is of poor quality prior to the fault offset and would experience large plastic deformation (compressible) during the fault offset. The thickness of compressible annulus is assumed as 3 feet (0.9 m).
- The fault offset is a dominant event and thus the effects of in situ stresses, groundwater pressures, and ground shaking were not considered for these evaluations.

5.1 Evaluation of one-pass lining system

The maximum shear displacement and maximum joint opening (separation) at the circumferential joints of the lining were computed for the design upper bound fault offset of 4 inches (100 mm) occurring over a fault width of 1 foot (0.3 m). Three design concepts were evaluated for connections at the circumferential joints: (1) no connections, (2) typical segment dowels, and (3) continuous steel rods. Figure 4a shows the FLAC3D model used for the fault offset analyses for the one-pass lining system. Additional assumptions associated with this model include:

- The backfill grout material located between segmental lining and excavated ground is compressible (Young's modulus of 30 ksi [207 MPa]) with a thickness of 4 inches.
- The segmental lining behaves as an elasto-perfectly plastic material, and its behavior is governed by the equivalent Mohr-Coulomb strength parameters. It is not perfectly bonded to the ground and the contact is controlled by an interface.
- The circumferential joints are simulated using interface elements assigned with a friction angle representing expansion joint materials.
- A locked-in stress of 300 psi (2.1 MPa) exists along the circumferential joints, which represents residual forces developed in the segmental lining caused by the TBM thrust forces developed in advancing the TBM.



a. One-pass lining system b. Two-pass lining system

Figure 4. Configurations of 3D models for one- and two-pass lining systems

Table 1. Maximum shear displacement and opening on circumferential joints for one-pass system [1]

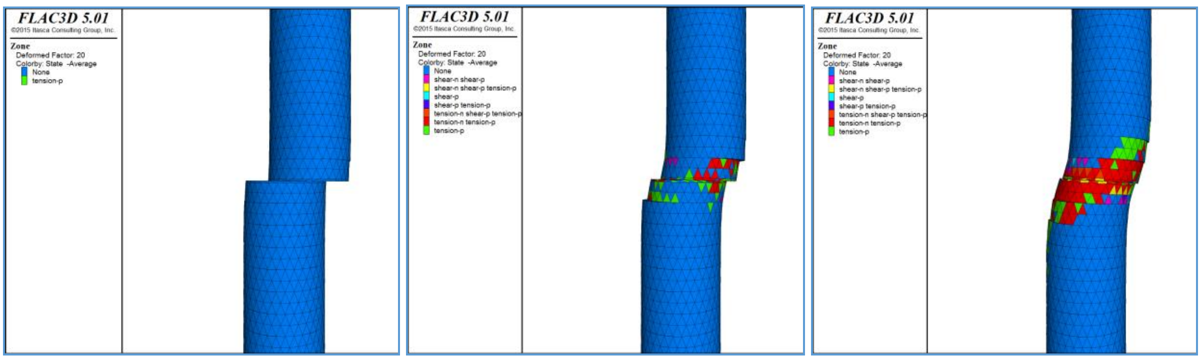
Fault Width, ft (m)	Type of Connection on Circumferential Joint	Max. Shear Displacement, in. inches (mm)	Max. Opening / Separation, inches (mm)
1 (0.3 m)	None	3.03 (76.9)	0.06 (1.4)
	Dowels	1.74 (44.1)	0.07 (1.9)
	Steel Rods	0.68 (17.2)	0.05 (1.3)

[1] Calculated based on a 4-inch (100 mm) offset over a fault width of 1 foot (0.3 m).

The results of the fault offset analyses for the one-pass lining system as represented by the maximum shear displacement and maximum joint opening are summarized in Table 1. Segmental lining performance can be assessed by comparing the maximum shear displacement and joint opening computed at the circumferential joints to the performance of a gasket designed to meet the leakage criteria. Typical gasket performance allows a maximum offset of 15 mm and a total gap opening of 7 mm for the water pressure envisaged on this project. Typical construction tolerances for segment-to-segment offsets and openings at the circumferential joints are 10 mm and 3 mm, respectively. The performance of the tunnel lining, evaluated against these criteria, is discussed below.

- Figures 5a, 5b, and 5c show three deformed shapes (magnified 20 times) of the tunnel lining without connectors, with dowel connectors, and with continuous steel rod connectors, respectively, resulting from a 4-inch (100 mm) fault offset on a 1-foot-wide (0.3 m) fault. The computed maximum shear displacements ranged from 17.2 to 76.9 mm (Table 1), exceeding the gasket capacity. In permeable ground significant leakage could occur. The effect of the connector type on the joint openings was small. It varied from 1.3 to 1.9 mm.

- Figures 5a, 5b, and 5c also illustrate the zones of plasticity or damage that segments would sustain during the fault offset utilizing the connection types being considered. The least amount of damage occurs when there is no connection (Figure 5a). However, offset is primarily concentrated at a single circumferential joint. When dowel connectors are used, damage is restricted to two rings either side of the fault zone (Figure 5b). When steel dowels are used, the damage zone extends to four rings on either side of the fault zone (Figure 5c). Damage would consist of cracking and spalling of the concrete lining.
- If the fault offset occurs over a wider zone (e.g., 5 or 10 feet), shear displacements are much smaller. The effect of the fault zone width is insignificant on the joint openings. Based on the FLAC3D analyses, it can be concluded that there will be leakage, but no significant lining failure or tunnel collapse. Longitudinal segment connections consisting of either a dowel or steel rod would assist in limiting shear displacements and joint openings at the circumferential joints when fault offset occurs. The level of damage depends on the longitudinal restraint and would be repairable following an earthquake with local concrete repairs or a secondary steel lining.



a. No connection b. Dowel connection c. Steel rod connection

Figure 5. Deformed segmental lining (deformation magnified by 20 times) and plasticity in segments after 4-inch offset over 1-foot fault width

5.2 **Evaluation of two-pass lining system**

To assess performance of the secondary steel lining, the maximum tensile and compressive stresses and strains developed in the steel pipe were computed for a fault offset of 20 inches (500 mm) occurring over a fault width of 1 foot (305 mm). Figure 4b shows the FLAC3D model used for the fault offset analyses for the two-pass lining system. Additional assumptions associated with this model include the following:

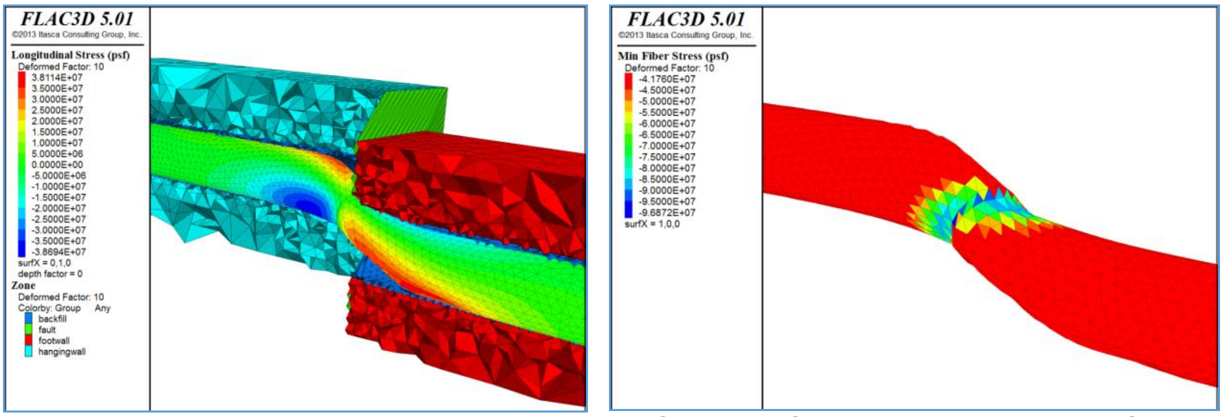
- The 8-inch-thick (200-mm) minimum backfill cellular concrete between the segmental lining and the steel pipe is compressible. Two cellular concrete strengths were evaluated with a Young’s modulus of 30 ksi and 50 ksi (207 and 345 MPa) associated with compressive strength of 300 psi and 500 psi (2.1 and 3.4 MPa), respectively, based on a correlation of E = 100 × f‘c (Nehdi et al., 2002).
- The steel pipe behaves elastically and is not fully bonded to the backfill cellular concrete. Their contact is controlled by the interface shear stiffness, varied to study the effect of the bond.

Table 2 summarizes results of the fault offset analyses represented by the maximum tensile and compressive strains. Performance of the steel lining was assessed by comparing computed maximum tensile and compressive strains to industry-recognized limits. To prevent damage caused by rupture or buckling, tensile and compressive seismic strains for steel pipe should not exceed 5% and 1%, respectively (ASCE, 1984; ALA, 2005).

Table 2. Maximum tensile and compressive strains in steel pipe for two-pass system across PVFZ [1]

Fault Zone	Backfill Concrete Strength, psi (MPa)	Max. Tensile Strain (%)	Max. Compressive Strain (%)	Approximate Total Influence Length, ft (m) [2]
Middle Splay	300 (2.1)	1.71	2.32	26 (8)
	500 (3,4)	2.09	3.01	36 (11)
South Splay	300 (2.1)	1.00	1.58	26 (8)
	500 (3.4)	1.16	1.90	26 (8)

[1] Calculated based on a 20-inch (500 mm) offset over a fault width of 1 foot (0.3 m).
[2] Estimated based on the length of steel pipe section where compressive strains exceed 1%.



a. Longitudinal stress

b. Section where compressive strains exceed 1%

Figure 6. Longitudinal stress and compressive stress contours showing where compressive strains exceed 1% in steel pipe after 20-inch offset over 1-foot fault width (deformations magnified 10 times)

Performance of the secondary steel lining was evaluated against these seismic criteria and discussed below.

- Analysis indicated significant deformation and high inelastic strains in the secondary steel lining in the vicinity of the fault offset. Figure 6a shows a deformed shape (magnified 10 times) of the steel lining following a 20-inch (500 mm) fault offset on a 1-foot-wide (0.3 m) fault. Maximum tensile strains in steel pipe were estimated to range from 1.0% to 2.1% (Table 2). These strains are below the tensile limit of 5% specified above. At these strain levels rupture of the steel pipe is considered unlikely, as it has been observed that a steel pipe can develop tensile strains larger than 20% before it ruptures (Mason et al., 2010).
- Maximum compressive strains ranged from 1.6% to 3.0%. They exceed the compressive limit of 1% specified above. At these high compressive strain levels, local buckling or wrinkling and rupture of the steel pipe could be expected.
- The sections of the steel lining where the maximum strains are developed are adjacent to the fault zone (Figure 6b). The approximate length of the steel pipe affected (defined as the pipe section where the compressive strains exceed the limit of 1%) is estimated to be less than 40 feet (12 m) (about 20 feet [6 m] on either side of the assumed fault plane).
- The reduction in cross-sectional area of the steel pipe affected by the fault offset is estimated to be about 5% for the worst-case fault offset.
- The amount and extent of damage to the secondary steel lining are expected to be less for a smaller fault offset or for a fault offset occurring over a wider fault width.

Based on the FLAC3D analyses, it is expected that tunnel collapse or a significant breach of the tunnel lining will not occur during and following a major earthquake with fault offset up to 20 inches. However, the secondary steel lining adjacent to the fault zone will undergo large inelastic deformations, resulting in local buckling or wrinkling, and possible rupture. Inspection of the tunnel will be required following a major earthquake. The need for post-earthquake repairs would depend on the magnitude of the actual fault offset and the distribution of ground movement in the fault rupture zone.

6 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations resulting from the design approach for the new outfall tunnel lining system are:

- For the tunnel reaches anticipated to experience up to 4 inches (100 mm) of fault offset, a longitudinal connection at the circumferential joints consisting of either a dowel or steel rod will limit shear displacements and joint opening at these joints at the expense of increased lining damage.
- For tunnel reaches anticipated to experience up to 20 inches (500 mm) of fault offset, use of a secondary steel lining will prevent major tunnel damage and collapse. However, the secondary steel lining adjacent to the fault zone is expected to undergo large inelastic deformations, resulting in a reduction in its cross-sectional area and local buckling or wrinkling and rupture due to compression strains above 1%. The approximate length of the steel pipe affected is estimated to be less than 40 feet (12 m) (20 feet [6 m] on either side of a fault).
- Inspection of the tunnel will be required following a major earthquake. The need for post-earthquake repairs would depend on the magnitude of the actual fault offset and the distribution of ground movement in the fault rupture zone.

7 ACKNOWLEDGMENTS

The authors acknowledge the contributions of Parsons Corp., McMillen Jacobs Associates, Fugro, and the Sanitation Districts in the design of this project. This paper’s contents reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the Sanitation Districts.

8 REFERENCES

American Lifelines Alliance (ALA). 2005. *Seismic Guidelines for Water Pipelines*.

ASCE. 1984. *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*.

Fugro. 2014. *Technical Memorandum No. 4 DRAFT—JWPCP Effluent Outfall Tunnel Project Assessment of Fault Rupture Displacements*, October 16, 2014. Revised Draft Table—Fault Displacements and Hazard Categories for Technical Memorandum No. 4, December 5, 2014.

Haug, D., Yankovich, D., Kaneshiro, J., and Dubnewych, S. 2015. Digging to the beach: The final design of the JWPCP effluent outfall tunnel project. *Proc. 2015 Rapid Excavation Tunnel Conference*. 450–461.

Kohler, D., and Rupp, B. 2008. *Thun Flood Relief Tunnel,* Part 1—The hydro-shield method. Tunnel, July, 27–37.

Mason, J.A., O’Rourke, T.D., Jones, S., and Tutuncu, I. 2010. Compression performance of steel pipelines with welded slip joints. *J. Pipeline Systems Engineering and Practice,* 1(1):2–10.

Nehdi, M., Khan, A., and Lo, K.Y. 2005. Development of deformable protective system for underground infrastructure using cellular grouts. *ACI Materials Journal,* Sept.–Oct., 490–498.

Saitou, S., Kaneko, M., Sagara, T., Sugimoto, M., and Kondou, J. 1999. *Construction Report on Prestressed Precast Concrete Segmental Lining Method*. Tunnel Engineering Thesis Collection of Reports 9: Nov. 1999.