SOIL-STRUCTURE INTERACTION AND FAILURE ANALYSES OF STEEL WATER PIPELINES WITH WELDED JOINTS – SAPL2 LOCKBAR REPLACEMENT

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Background, Seismic Deformation Demand, and Global Analysis

Performance Goal and Acceptance Criteria

Nonlinear Finite Element Analyses

Numerical Results

Conclusions
Peninsula Pipeline Seismic Upgrade (PPSU) project consists of seismic upgrades to three Hetch Hetchy regional water delivery pipelines located in San Mateo County.

San Andreas Pipeline 2 (SAPL2) Lockbar Replacement Project consists of replacement or improvement of approximately 1.2 miles of the water transmission pipeline SAPL2 that runs from the Harry Tracy Water Treatment Plant in Millbrae to Sunset Reservoir.
Project Site Aerial View
The project site is particularly susceptible to landslide triggered by a major seismic event. Based on the soil-structure-interaction analysis performed by ARUP/TERRA, permanent slope displacements are expected along Segment 1 of the SAPL2 pipeline, which is 2,425 feet long. The maximum expected permanent slope displacements vary from 6 to 15 inches in a transition zone of 300-feet (displacement-span ratio of 1/96 to 1/240).
Transition zones between areas of different seismic displacements are estimated to be at least 150-ft wide.

\[
RD = \frac{1}{11250} x^2 \quad \text{For } X = 0' \text{ to } 75'
\]

\[
RD = 1 - \frac{1}{11250} (x - 150)^2 \quad \text{For } X = 75' \text{ to } 150'
\]
Global Analysis

- A SAP2000 global model using linear elastic beam elements was created for SAPL2 Segment 1. Soil springs with properties recommended by the geotechnical engineer are used in the model.
Soil Spring Supports

- Upper and lower soil springs with gap elements and different spring constants are used to model the asymmetrical behavior in the vertical direction.
- The nodal lateral displacements are constrained by transverse and tangential soil spring supports at the nodes located along the pipeline.

[Diagram showing upward and downward gap elements and lateral soil springs with constrained lateral displacement.]
Global Analysis to Identify Critical Sections

- High and excessive stress concentrations are observed at sharp bends, i.e., bends with deflection angle more than 15°, and around its corresponding inflection points.
Critical Pipe Joints

NOT FOR CONSTRUCTION

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ELEVATION DATUM: NAVD 88

NOTES:

1. Location of existing pipelines and utilities shown in the drawings are approximate and shall be verified in field by the contractor prior to construction.

2. Existing pipelines and utilities shown on this plan are for information only. Contractor is responsible for determining the location of all existing pipeline and utilities. Contractor shall perform underground utility survey and survey the existing pipelines to verify the alignment prior to developing and submitting the plan and any grading, trenching or tunnel excavation.

3. Contractor shall notify underground service agency (USA) by calling 1-800-227-2500 prior to Trenching.

4. Trench width at each utilities to accommodate utilities to section thicknesses to be determined based on economical conditions.

1/2" THICK STEEL PIPE, TYPICAL U.O.N.
5/8" THICK STEEL PIPE
3/4" THICK STEEL PIPE
7/8" THICK STEEL PIPE
1" THICK STEEL PIPE
1-1/4" THICK STEEL PIPE

7/11/2017
Critical Pipe Joints

**NOTES:**

1. LOCATION OF EXISTING PIPELINES AND UTILITIES SHOWN IN THE DRAWINGS IS APPROXIMATE AND SHALL BE MODIFIED IN FIELD PRIOR TO CONSTRUCTION.
2. EXISTING PIPELINES AND UTILITIES SHOWN ON THIS PLAN ARE FOR INFORMATION ONLY. CONTRACTOR IS RESPONSIBLE FOR DETERMINING THE LOCATION OF ALL EXISTING PIPELINE AND UTILITIES. CONTRACTOR SHALL PERFORM UNDERGROUND UTILITY SURVEY AND PHOTOLOG OF THE EXISTING PIPELINES TO VERIFY THE ALIGNMENT PRIOR TO DEVELOPING AND SUBMITTING DRAINAGE PLAN AND CONTRUCTING ANY GRAVING, TRENCHING OR TUNNEL EXCAVATION.
3. CONTRACTOR SHALL NOTIFY UNDERGROUND SERVICE ALERT (USA) BY CALLING 1-800-276-2800 PRIOR TO DIGGINGS.

**LEGEND:**

1. 1/2" THICK STEEL PIPE
2. TYPICAL U.O.N.
3. 5/8" THICK STEEL PIPE
4. 3/4" THICK STEEL PIPE
5. 7/8" THICK STEEL PIPE
6. 1" THICK STEEL PIPE
7. 1-1/4" THICK STEEL PIPE

**CONTRACT NO. WO-2029**

PUBLIC UTILITIES COMMISSION
INFRASTRUCTURE DIVISION
ENGINEERING MANAGER TYPICAL
SAN ANDREAS PIPELINE, 2 TYPICAL REPLACEMENT
54" # REPLACEMENT SPP2 SEGMENT 1 PLAN AND PROFILE

7/11/2017

50% SUBMITTAL

Five Critical Pipe Joints Identified

1. STA 7+80_8+15 Type 4 Bent
2. STA 10+70_11+00 Type 4 Bent
3. STA 15+30_15+50 Type 2 Bent
4. STA 17+00_17+30 Type 3 Bent
5. STA 19+50_19+70 Type 2 Bent
• Background, Seismic Displacements, and Global Analysis

• Performance Goal and Acceptance Criteria

• Nonlinear Finite Element Analyses

• Numerical Results

• Conclusion
Performance Goal and Acceptance Criteria

- Per San Francisco Public Utilities Commission (SFPUC) General Seismic Requirements (GSR), the pipeline shall meet Seismic Performance Class III (SPC III) performance goal.

- SPC III is defined as “capable of restoration to a level of service consistent with adopted post-earthquake Level of Service goals within 24 hours”, basically continuous operation.

- SPC III pipelines and tunnels should use the 975-year return period earthquakes

- SFPUC have agreed that as long as the ability to deliver water is maintained, structural yielding in the pipeline without rupture is acceptable
  
  a) The maximum stress, including the welding-induced residual stress, could be greater than the yielding stress of A572Gr50 steel.
  b) The maximum plastic strain should be limited to 0.17, the rupture strain for A572Gr50 steel
Performance Goal and Acceptance Criteria

- Based on the performance goal, evaluate the standard pipe joint details recommended by American Water Works Association (AWWA)
- Design pipe wall thickness and pipe joint type to meet the performance goal

**TYPE 1 BEND**
SCALE: 3/8” = 1’-0”
\[ \Delta \text{ OVER 5° TO 22 1/2°} \]

**TYPE 2 BEND**
SCALE: 3/8” = 1’-0”
\[ \Delta \text{ OVER 22 1/2° TO 45°} \]

**TYPE 3 BEND**
SCALE: 3/8” = 1’-0”
\[ \Delta \text{ OVER 45° TO 67 1/2°} \]

**TYPE 4 BEND**
SCALE: 3/8” = 1’-0”
\[ \Delta \text{ OVER 67 1/2° TO 90°} \]
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Pipe segments are simulated using A572Gr50 steel material properties. To account for effects of welding heat, temperature-dependent material properties are employed, per Eurocode 3, Part 1.2 (ECS, 1993).
Soil Springs

- To account for soil-pipe interactions under permanent ground deformations, which are considered as quasi-static loads in the analyses, linear springs are utilized per the method proposed in the ALLA (2005) guideline document. This guideline suggests defining soil springs in three directions—namely, vertical, horizontal, and tangential. The springs were distributed at four equally-spaced points around the circumference at each station along the pipe.

(reproduced from ALLA, 2005)
Welding processes may have significant effects on the performance of a pipeline, especially in regions close to the bends. The vicinity of the welded joint is exposed to severe heat, as a result of which transient thermal gradients are developed within the pipe that will lead to residual stresses/deformations.

A transient heat conduction/diffusion problem with heat flux values is imposed onto the finite element nodes corresponding to the welded joints (along with some body flux). The magnitude of this flux is adjusted so that the immediate edges reach a 1000 °C.

The segment is exposed only to the ambient environment (here 25 °C) until a thermal equilibrium is reached.
Displacement Directionality

- Based on the results from global SAP2000 analyses, several critical segments are identified and chosen to be analyzed using FEM. Displacements are prescribed in the 3D finite element models at stations spaced at transition intervals along the pipe.
  
  a) The direction of the prescribed load displacement variation along the pipe is prescribed as shown in the Figure below.
  
  b) The displacement function along transition zone is shown in the Figure below.

Figure: Angle of movement is measured in degrees from the horizontal as shown.
Based on the results from global SAP2000 analyses, several critical segments are identified and chosen to be analyzed using FEM. Displacements are prescribed in the 3D finite element models at stations spaced at transition intervals along the pipe.

a) The direction of the prescribed load displacement variation along the pipe is prescribed as shown in the Table and Figure below.

b) The displacement function along transition zone is shown in the Figure below.

\[ RD = \frac{1}{11250} x^2 \]

\[ RD = 1 - \frac{1}{11250} (x - 150)^2 \]
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Station 13+50 (Straight Joint)

Plastic strain magnitude contours for straight joint

Residual Mises stress contours for straight joint

Total Mises stress contours for straight joint

Mises stress versus plastic strain magnitude for the most critical four nodes of the most critical finite element in the computational domain for straight joint (300ft-long segment).
Station 19+50 (24.0° Joint)

Bend type 1

Plastic strain magnitude contours for bend type 1

Residual Mises stress contours for bend type 1

Total Mises stress contours for bend type 1

Bend type 2

Plastic strain magnitude contours for bend type 2

Residual Mises stress contours for bend type 2

Total Mises stress contours for bend type 2
Mises stress versus plastic strain magnitude for the most critical four nodes of the most critical finite element in the computational domain for bend type 1 (300ft-long segment).

Mises stress versus plastic strain magnitude for the most critical four nodes of the most critical finite element in the computational domain for bend type 2 (300ft-long segment).
Station 17+10 (42.5° Joint)

Bend type 2

Plastic strain magnitude contours for bend type 2

Residual Mises stress contours for bend type 2

Total Mises stress contours for bend type 2

Bend type 3

Plastic strain magnitude contours for bend type 3

Residual Mises stress contours for bend type 3

Total Mises stress contours for bend type 3
Station 17+10 (42.5° Joint)

Bend type 2

Mesh configuration for bend type 2

Mises stress versus plastic strain magnitude for the most critical four nodes of the most critical finite element in the computational domain for bend type 2 (300ft-long segment).

Bend type 3

Mesh configuration for bend type 3

Mises stress versus plastic strain magnitude for the most critical four nodes of the most critical finite element in the computational domain for bend type 3 (300ft-long segment).
Station 10+90 (52.07° Joint)

Bend type 3

Plastic strain magnitude contours for bend type 3

Residual Mises stress contours for bend type 3

Total Mises stress contours for bend type 3

Bend type 4

Plastic strain magnitude contours for bend type 4

Residual Mises stress contours for bend type 4

Total Mises stress contours for bend type 4
Station 10+90 (52.07° Joint)

**Bend type 3**

Mesh configuration for bend type 3

Mises stress versus plastic strain magnitude for the most critical four nodes of the most critical finite element in the computational domain for bend type 3 (300ft-long segment).

**Bend type 4**

Mesh configuration for bend type 4

Mises stress versus plastic strain magnitude for the most critical four nodes of the most critical finite element in the computational domain for bend type 4 (300ft-long segment).
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Conclusions

- The coefficients and positions of the soil springs should be carefully determined and then applied, which may significantly affect the results. Sensitivity analysis is imperative.

- Welding processes may have crucial effects on the performance of pipeline joints, especially in regions close to bends.

- The recommended pipe joint connection at bends per AWWA may be inadequate for high seismic zone, particularly regions vulnerable to landslides, fault movements, and liquefaction-induced lateral spreading.

- Avoid pipe miter joint along bisect angle line of a bend.

- Reduced miter angle and increased bend segments will help reduce plastic strain and increases structural redundancy.

- However, considering that the angle between the direction of the permanent ground displacement and the longitudinal direction and geometry of the pipelines change case-by-case, stress concentrations may not be significantly reduced by simply adding additional bend segments.