Design and Installation of Distributed Fiber Optic Sensing Technology to Monitor HDPE Pipelines at an Earthquake Fault Crossing

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ABSTRACT

The Summit Pressure Zone South Pipeline Replacement, Phase 1 project included approximately 5,000 linear feet (LF) of 24-in. steel pipeline in various streets in Berkeley, California, in addition to 700 LF of 36-in. high density polyethylene (HDPE) and 500 LF of 22-in. HDPE pipelines to cross the Hayward Fault in Claremont Avenue on the Oakland/Berkeley border. The transmission pipelines cross the Hayward Fault in an area which experiences significant ground movement resulting in several previous pipeline failures. East Bay Municipal Utility District (EBMUD) worked with researchers at University of California, Berkeley (UCB), to develop a system that would be able to monitor and measure pipeline strain in a robust, sensitive, distributed, and accurate way. The team explored various technologies and applications to determine which were most viable. The distributed fiber optic sensing (DFOS) system was selected as the most appropriate method to achieve the goals. Installation of the HDPE pipelines in this area was difficult due to field conditions, and installation of the fiber optic cables in the trench presented further challenges. A collaborative contractor and an adaptable team from EBMUD and UCB allowed the project to overcome these challenges and install a successful project. The system was brought online in summer 2022, and the team has already received some interesting data about the pipeline behavior at the Hayward Fault crossing.

INTRODUCTION

East Bay Municipal Utility District (EBMUD) provides water and wastewater services to the eastern region of the San Francisco Bay Area in California. EBMUD's potable water system provides drinking water to 1.4 million customers within a 332-square-mile service area. The service area spans portions of Alameda and Contra Costa Counties and contains approximately 4,200 miles of distribution pipelines and 340 miles of transmission pipelines.

EBMUD's Summit Pressure Zone (PZ) South Pipeline Replacement Project is a multiphase project that will replace undersized transmission pipelines in the Summit PZ to improve the hydraulic connectivity, realign critical pipelines outside of the Hayward Fault Zone, and replace portions of these pipelines within the Hayward Fault Zone. Construction of Phase 1 was completed in 2022. Phase 2 is currently in design, and Phases 3 and 4 will follow.

A segment of the original 16- to 20-inch Summit PZ transmission pipeline near Clark Kerr Campus, a student housing complex for the University of California, Berkeley (UCB), was identified in EBMUD's Large Diameter Pipelines Master Plan as the number one priority for replacement based on likelihood and consequence of failure. The original alignment closely followed the Hayward Fault. The Summit PZ South Pipeline Replacement, Phase 1 project included approximately 5,000 linear feet (LF) of 24-inch steel pipeline to replace the original transmission pipeline in a new alignment in various streets west of Clark Kerr Campus, outside of the Hayward Fault Zone. Additionally, the project included 700 LF of 36-inch high density polyethylene (HDPE) and 500 LF of 22-inch HDPE pipelines to replace portions of two existing parallel transmission pipelines that cross the Hayward Fault in Claremont Avenue on the Oakland/Berkeley border. The project scope is summarized in Figure 1.

PROJECT DESIGN AND DEVELOPMENT

The transmission pipelines in Claremont Avenue cross the Hayward Fault in an area which experiences significant ground movement. The fault is a right-lateral strike-slip fault which experiences fault creep at a rate of about 4 to 5 mm per year (Lienkaemper et al. 2012). The pipelines cross the fault at a bend as shown in Figure 2.

The US Geological Survey estimates that there is a 33% chance of a 6.7 magnitude or greater earthquake on the Hayward Fault before the year 2043 (Aagaard et al. 2016). Pipeline performance at these fault crossings is a significant concern due to the risk of pipeline leakage or break as a result of permanent ground deformations (PGD). The original pipelines had a history of leaks resulting in service disruptions and costly repairs. Future breaks have the potential to cause damage to adjacent utilities and private property. Both long-term PGD (due to fault creep) and short-term PGD (due to earthquake fault rupture) are expected at the installation site.

EBMUD selected the use of HDPE pipe at the fault crossings due to its ability to withstand deformation, thus expanding EBMUD's use of HDPE as a seismically resilient pipeline material. The pipelines were embedded in imported sand rather than the cement slurry typically used for EBMUD large diameter pipelines. The sand embedment reduces the soil-pipe friction when ground deformations occur in the vicinity of the pipeline. Due to the high level of seismic activity at the site, EBMUD explored the implementation of a system to monitor pipeline performance under long-term fault movement.

EBMUD partnered with UCB to develop an innovative method for utilizing fiber optic technology on this project to monitor and measure pipeline strain. UCB researchers considered various technologies and applications such as conventional strain-gauge sensors and wireless underground sensors, and the team ultimately selected the distributed fiber optic sensing (DFOS) system as the superior option to meet the project goals. DFOS technology offers unparalleled capabilities for large-scale high-resolution strain and temperature sensing. The selected DFOS system can monitor distributed strain and temperature changes along the buried pipelines with a 1 m (3 ft) spatial resolution and 20 microstrain ($\mu\varepsilon$) maximum strain resolution every 2 cm (0.8 in) along the DFOS-instrumented pipe. The strain and temperature data can then be used to determine axial displacement and lateral deflection experienced by the pipeline within the fault zone. After selecting this DFOS system, the team conducted extensive testing of various cable configurations and attachment techniques to ensure collection of the optimal data. The test results were used to finalize design details and specifications for installation.

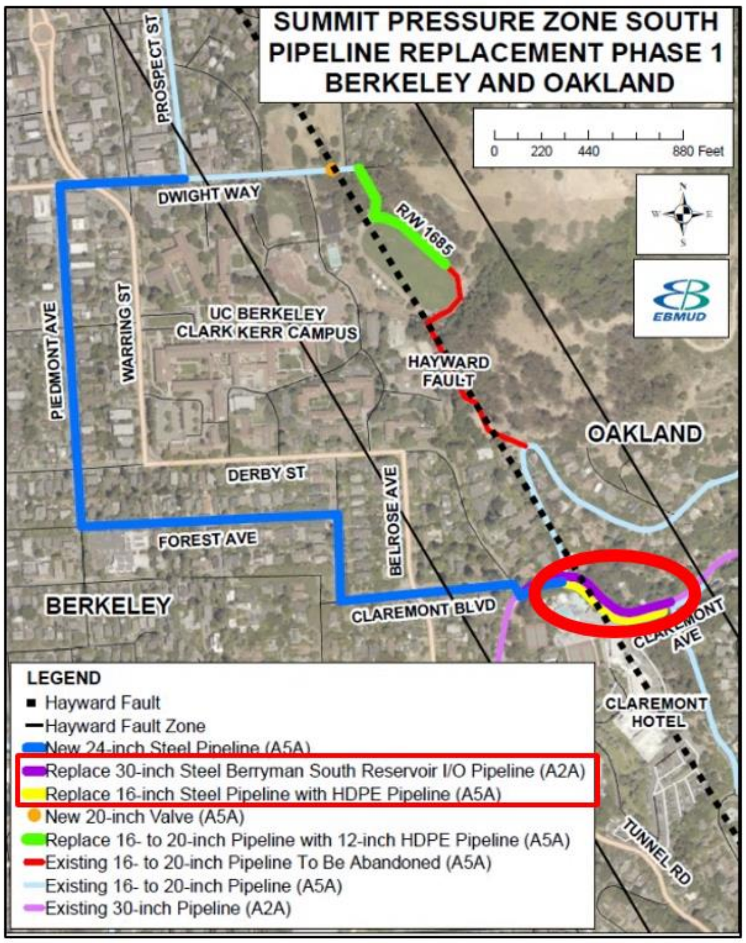


Figure 1. Project Location Map and Scope

The proposed system included installation of four strain sensing cables and one temperature sensing cable with each HDPE pipeline. Three of these strain sensing cables were installed directly on the pipe, parallel to the pipe longitudinal axis. Figure 3 shows the design detail for the cable configuration on the pipe. One cable length was attached at the crown of the pipeline and two additional lengths were placed at 45 degrees from the crown in either direction for adequate bending measurement. The cables were not to deviate more than five degrees from their prescribed orientation and not more than two-and-a-half degrees over any 20-foot length of pipe. The fourth strain sensing cable and the temperature sensing cable were laid loose longitudinally within the pipe trench. This strain sensing cable is to measure trench soil strain and the temperature sensing cable measures soil temperature in order to quantify the contribution of temperature-induced strain to the measured pipeline strain data (Hubbard, et al., 2021).

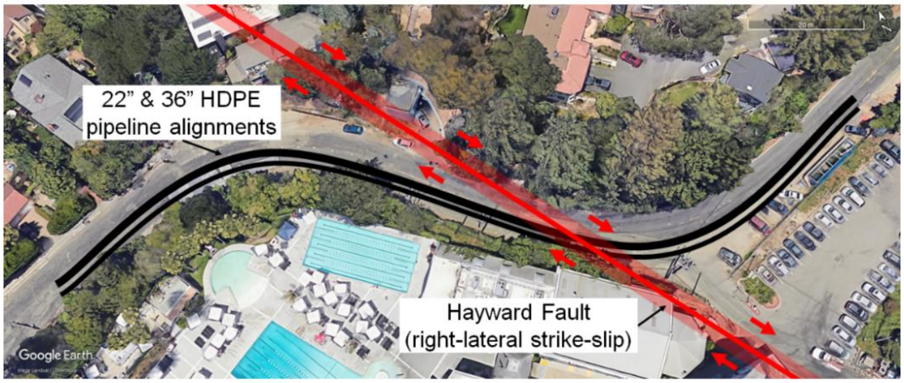


Figure 2. Fault Crossing Geometry for Parallel Pipelines in Claremont Avenue

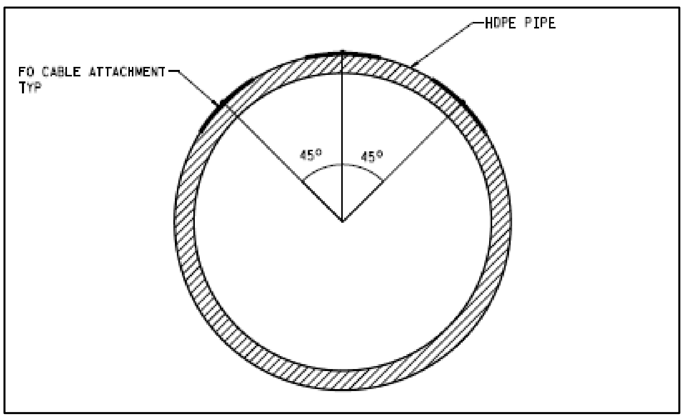


Figure 3. Cable Orientation on Pipe

Figures 4 and 5 show the design details for the attachment methods used. The cables were attached to the pipelines using a combination of Tapecoat H35 cold applied tape in 6-inch widths and 3M Scotch-Weld DP8010 Structural Plastic Adhesive. The tapecoat H35 was specified to be continuous along the length of the pipe and fiber optic cable. At the end of each roll of Tapecoat H35, the new roll was specified to have a one-inch overlap where the previous roll ended. The DP8010 adhesive was specified to be injected underneath the tape with a 3M EPX 490mL Manual Applicator and 3M Scotch-Weld EPX Mixing Nozzle at intervals of 5 feet on center.

Directions for installation along the pipe included the following:

1. Cut a slit in the Tapecoat H35 at 0.5 inches away from the sensing cable. The slit shall be 0.5 inches long and perpendicular to the sensing cable.
2. Insert the nozzle into the slit and inject two pumps in each direction of the pipe, totaling four pumps per injection site. The nozzle shall remain in the slit for five seconds until the pressure dissipates, so that the epoxy remains under the tape without leaking out.

3. Remove the nozzle and then spread the epoxy by manually pressing on the outside of the tape to fill the space between the Tapecoat, cable, and pipe along a length of twelve inches.

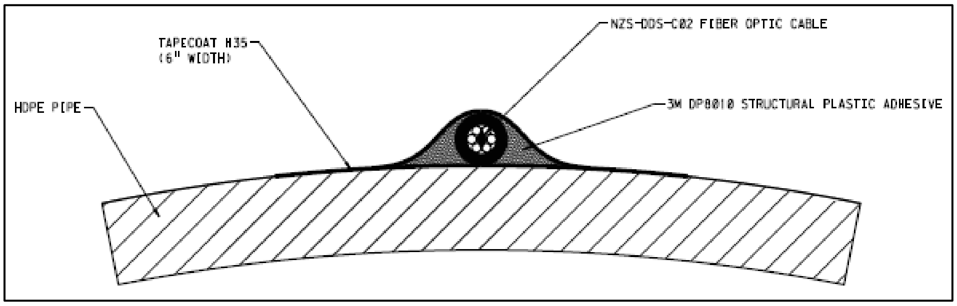


Figure 4. Cross Section of Attachment Method Along Pipe

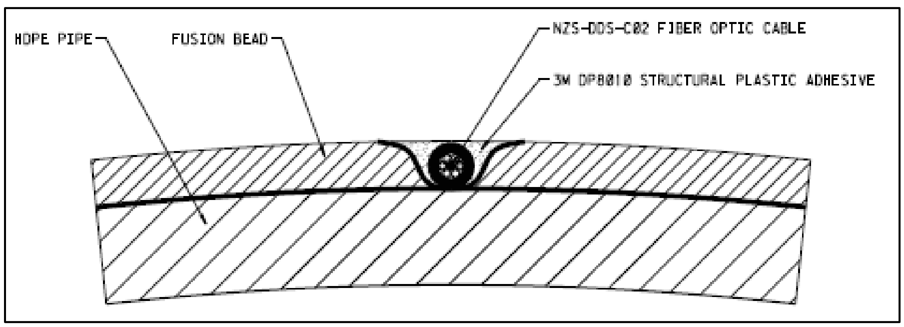


Figure 5. Cross Section of Attachment Method Across Fusion Bead

Directions for installation across fusion joints included the following:

1. Install cables up to 8 feet away from a fusion location.
2. Conduct the fusion and allow the pipe to cool for the rough handling time prior to attachment across the fusion joint,
3. Grind a notch into the fusion bead.
4. Lay the cable in the notch and apply epoxy in place.

Surface preparation of the exterior of the pipe included cleaning the HDPE pipe surface where the Tapecoat H35 will be in contact with the pipe with 70% or greater concentration of isopropyl alcohol, sanding the pipe surface with 80-grit sandpaper, and then flame treating the roughened surface with a propane torch at a rate of 12 inches per second.

INSTALLATION

The new HDPE pipelines were installed by contractor. The contract drawings included the details shown in Figures 3 through 5. Fiber optic cables were installed longitudinally at the top of pipe and at 45 degrees offset from the top on each shoulder as designed. The temperature cable and a strain cable were laid longitudinally in the trench. The contract specifications included details for pipe surface preparation to ensure a good bonding of the cables as well as the specific tolerances allowed for the cable installation. The specifications also included a requirement to complete a mock installation prior to the actual installation, since this is work not typically performed by pipeline contractors.

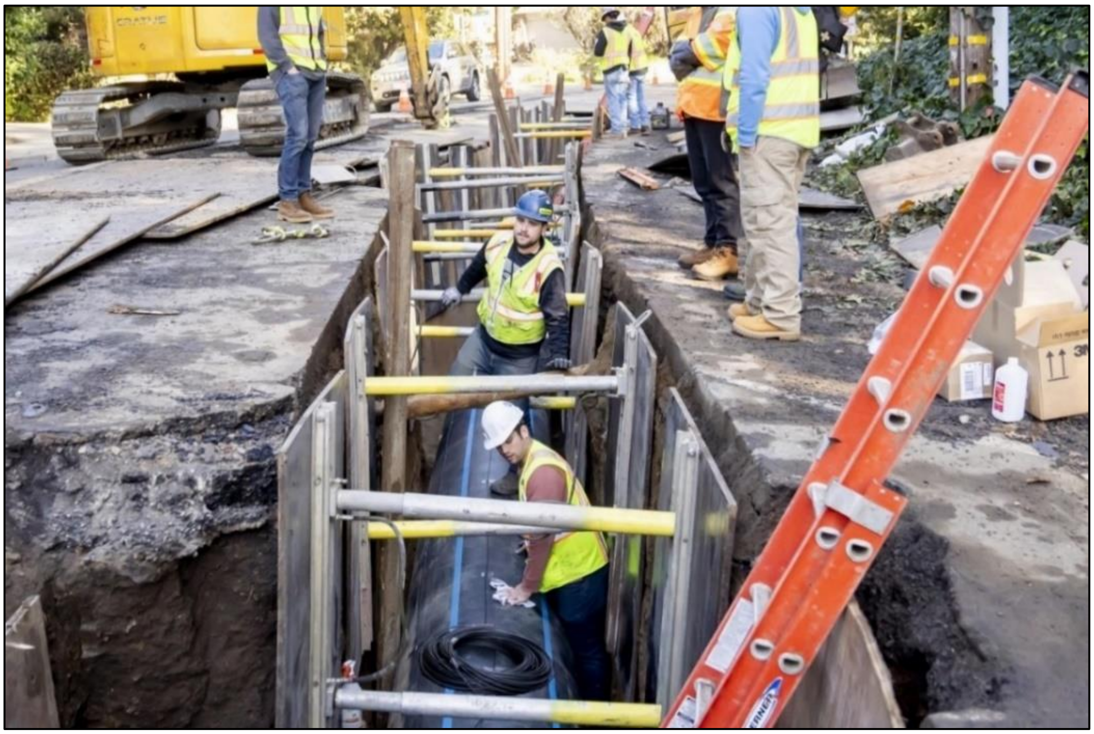
UCB furnished the fiber optic cables as well as the epoxy and tape. UCB also provided field inspection of the cable installation for adherence to the specified tolerances and pipe preparation.

The HDPE pipeline was fused above-ground, then moved to one end of the trench to be pushed and pulled into place. Figure 6 shows excavators "walking" the fused HDPE pipe to be pulled in, and Figure 7 shows the pipeline being pushed into the trench.

Figure 6. Walking the 36-inch HDPE Pipeline into Position

Figure 7. Pushing the 36-inch Pipeline into the Trench

Installation of the HDPE transmission pipelines on Claremont Avenue was challenging due to underground utility congestion, bicycle and vehicular traffic, slope of the roadway, and the presence of significant groundwater. Beyond the difficult installation conditions, there was additional work required to install the fiber optic cables under field conditions. There were more personnel onsite than typical for support. The cables were damaged a couple of times during the installation. In one case, shoring was dropped on the fiber optic cable. The fiber optic cable was able to be successfully repaired in place without needing to splice new cables. Figure 8 (Lau, 2022) shows the cable installation, including contractor installation crew and UCB inspectors.



Source: Adam Lau
Figure 8. Installation of Fiber Optic Cables with 36-inch HDPE Pipe

A high quality, collaborative contractor and an adaptable team from EBMUD and UCB worked together to overcome challenges and install a successful project. This system will be used to measure and monitor future pipeline strain and fault-soil-pipeline interactions to better understand pipeline performance at the fault crossing.

DATA COLLECTION

The DFOS-embedded pipelines were brought online in summer 2022. UCB has since periodically measured the distributed temperature and strain along the DFOS-instrumented alignment for both the 22-inch and 36-inch pipelines (Jasiak, et al., 2023). This paper focuses on the 36-inch pipe data, since this pipe was fully instrumented across the entire fault zone crossing and has demonstrated representative trends.

Distributed Temperature Sensing (DTS) captures the seasonal groundwater temperature cycle (which approximately corresponds to the seasonal air temperature cycle). Figure 9 shows the distributed trench temperature along the 36-inch pipe, which decreases and increases across the captured year-long monitoring period. The temperature drop observed at 50m (160 ft) and 150m (490 ft) correspond to the locations at which the 36-inch pipe trench merges from an individual trench (outside of the fault zone on the east and west sides) into a shared trench (shared with the parallel 22-inch pipe inside the fault zone). These temperature fluctuations can be attributed to the cooling effect of the colder water in the 22-inch pipe within the shared trench zone inside the fault zone. Analysis is ongoing to better characterize this thermal interaction.

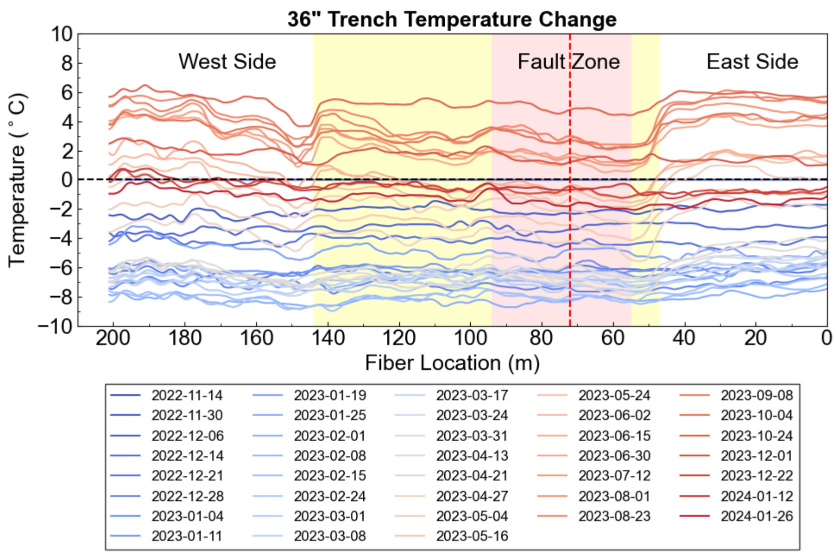


Figure 9. Distributed Trench Temperature along 36-inch Pipeline

Distributed Strain Sensing (DSS) captures fault displacement-induced strain along the pipeline. Figure 10 shows the temperature-compensated distributed strain along the north and south sides of the pipeline cross section. For context, the temperature-compensated strain takes into account and subtracts the thermal strain associated with the measured long-term distributed temperature change along the pipeline. Note, the downstream west end of the DFOS-instrumented alignment is treated as a zero-strain fixed point. Overall, the measured strain trend suggests that pipe exhibits relatively high tensile strain inside the fault zone, and relatively low strain levels outside the fault zone. The measured distributed strain magnitude along both sides of the pipe remains within 100 $\mu\varepsilon$. However, inside the fault zone, measured distributed strain reaches above 150 $\mu\varepsilon$.

These unequal distributed strain trends suggest a combined deformation mechanism resulting from the unique s-curve pipeline geometry at the fault crossing in which the pipeline primarily experiences axial displacement as it is pulled apart in tension in the section parallel to and inside the fault trace, as well as non-zero lateral deflection as the entire alignment crosses the right-lateral strike-slip fault zone. Axial displacement was quantified by integrating average strain between the north and south sides of the pipe. Lateral displacement was quantified by double integrating the difference in strain between the north and south sides of the pipe. Error bounds on the estimated pipeline deformation were determined based on a precision error evaluation which demonstrated a 10 $\mu\varepsilon$ average strain error (taken as the average standard deviation of strain measurements along the pipe over a 4-hour evaluation period) at each measurement location.

This average strain error was included in the integration calculation for both axial displacement and lateral deflection to compute the estimated pipeline deformation. Figures 11 and 12 show the resulting estimated axial displacement and lateral deflection along the pipeline. In this case, estimated pipeline deformations include approximately 4 to 5 mm (0.16 to 0.2 in) of axial displacement along the fault zone and within approximately 1 to 1.5 mm (0.04 to 0.06 in) of lateral deflection across the fault zone. Note, both pipeline deformation estimates exhibit noticeable fluctuations which can be attributed to seasonal water temperature cycles, as well as potentially other environmental factors. Further analysis is ongoing to better characterize these effects. Nonetheless, pipeline deformation behavior is dominated by axial displacement.

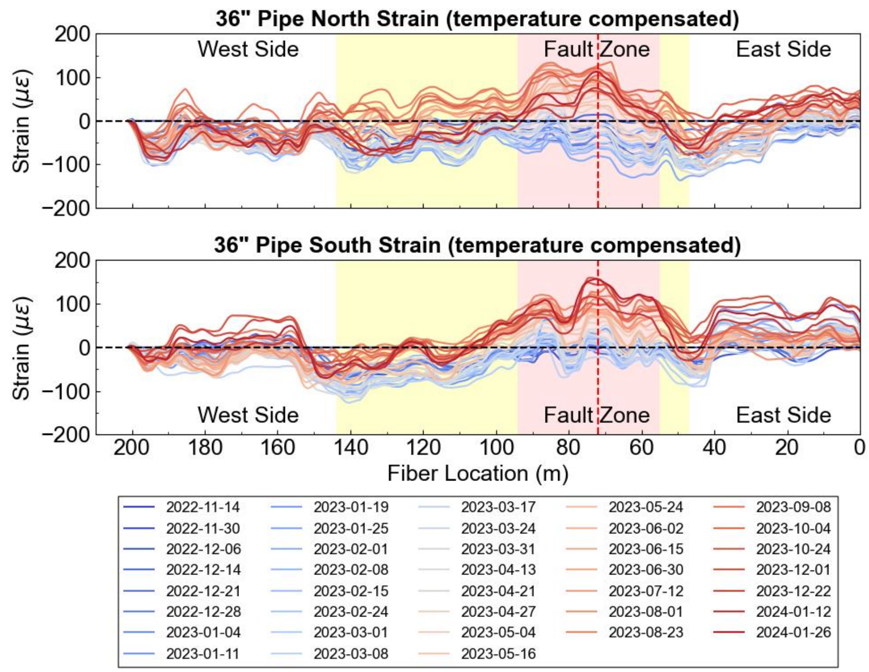


Figure 10. Distributed Strain along North and South sides of 36-inch Pipeline

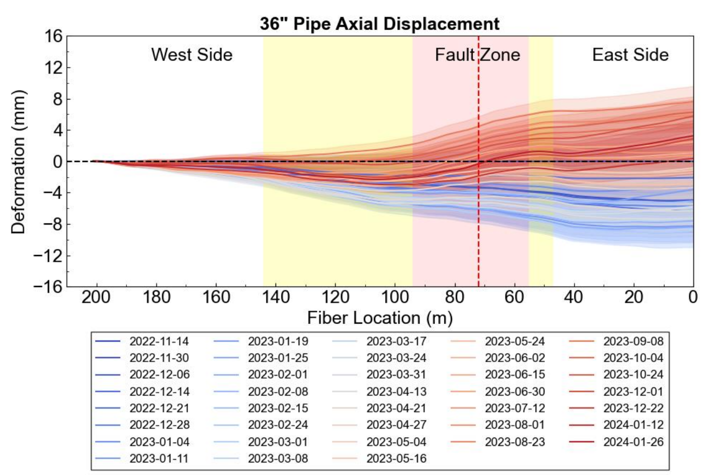


Figure 11. Axial Displacement along 36-inch Pipeline

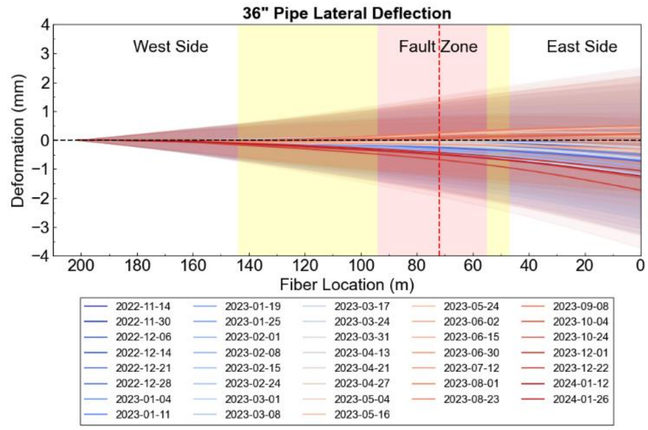


Figure 12. Lateral Deflection along 36-inch Pipeline

Overall, the DFOS system effectively quantifies annual fault displacement-induced distributed pipeline deformation and provides data-driven situational awareness for managing operational processes and predicting life expectancy of lifeline water infrastructure.

NEXT STEPS

UCB will continue to collect and report data on the Claremont Avenue transmission pipelines at least biannually to EBMUD for a monitoring period of at least ten years. Events that may trigger more frequent data collection include observed data trends, signs of distress in the area of the pipelines, change in fault displacement rates, or a seismic event in the area. If or when the pipeline strain measurements show that the pipe is at 50% of its yield point, EBMUD will excavate and expose a 20-foot length of the pipe at the area of concern to inspect it and allow it to reset to relieve stress. The data will also be used to inform future asset management decisions in seismic areas.

It is anticipated that the DFOS system will be improved to more effectively quantify the strain contribution of annual fault displacement, seasonal groundwater and pipe water temperature cycles, daily pipe water pressure cycles, and instantaneous pipe water pressure transients. Additionally, Distributed Acoustic Sensing (DAS) techniques may be applied for subsurface pipeline leakage detection as future opportunities arise. These pipelines are serving as a valuable research and development facility for validating DFOS technologies in field conditions. The Summit PZ South Pipeline Replacement, Phase 1 project was awarded the 2023 Outstanding New Technology Project by the ASCE San Francisco Section.

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