Berkeley CENTER FOR Smart Infrastructure

https://smartinfrastructure.berkeley.edu/

Contract Number: 693JK32050007CAAP

Distributed Strain Sensing for Pipeline Safety Against Fault Moving and Landslide

Kenichi Soga

Director of Berkeley Center for Smart Infrastructure
Distinguished Professor of Civil and Environmental Engineering

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Dr David Xu

- **Peter Hubbard** (PhD., graduated in September 2022) – Performed laboratory and field tests, engaged in the planning of the field installation.

- **Andrew Yeskoo** (PhD., graduated in December 2022) – Engaged in the planning of the field installation.

- **Tianchen Xu** (PhD., expected to graduate in May 2025) – Engaged in the field installation and monthly data acquisition, conducted data analysis, and performed finite element numerical modeling and simulations.

Challenges

- The risk of buried gas pipeline failure due to permanent ground-induced actions due to fault movements and landslides.

- Moving from Reactive actions to Proactive actions to manage the risk of failure.

Vision

- Monitor the actual performance to evaluate the actual risk rather than ‘designed’ based risk assessment.

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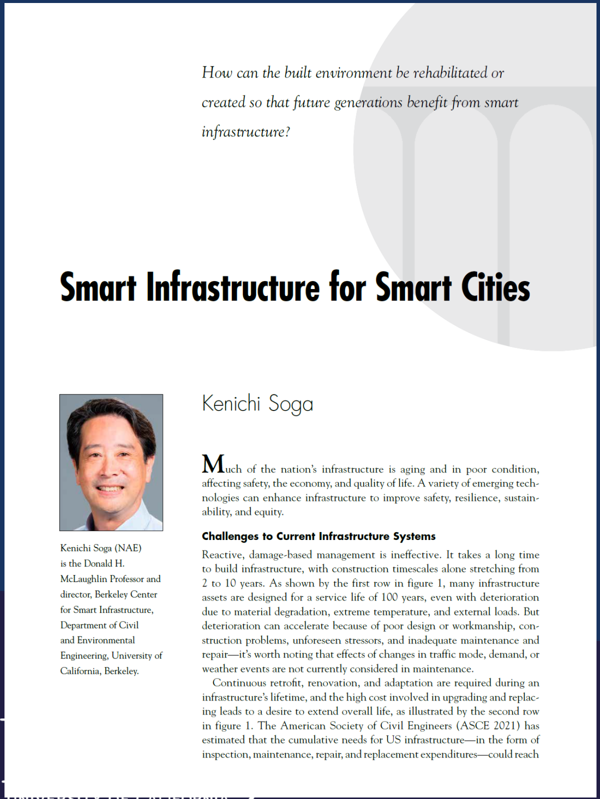
How can the built environment be created so that future generations benefit from smart infrastructure?



How can the built environment be rehabilitated or created so that future generations benefit from smart infrastructure?

Smart Infrastructure for Smart Cities

Kenichi Soga

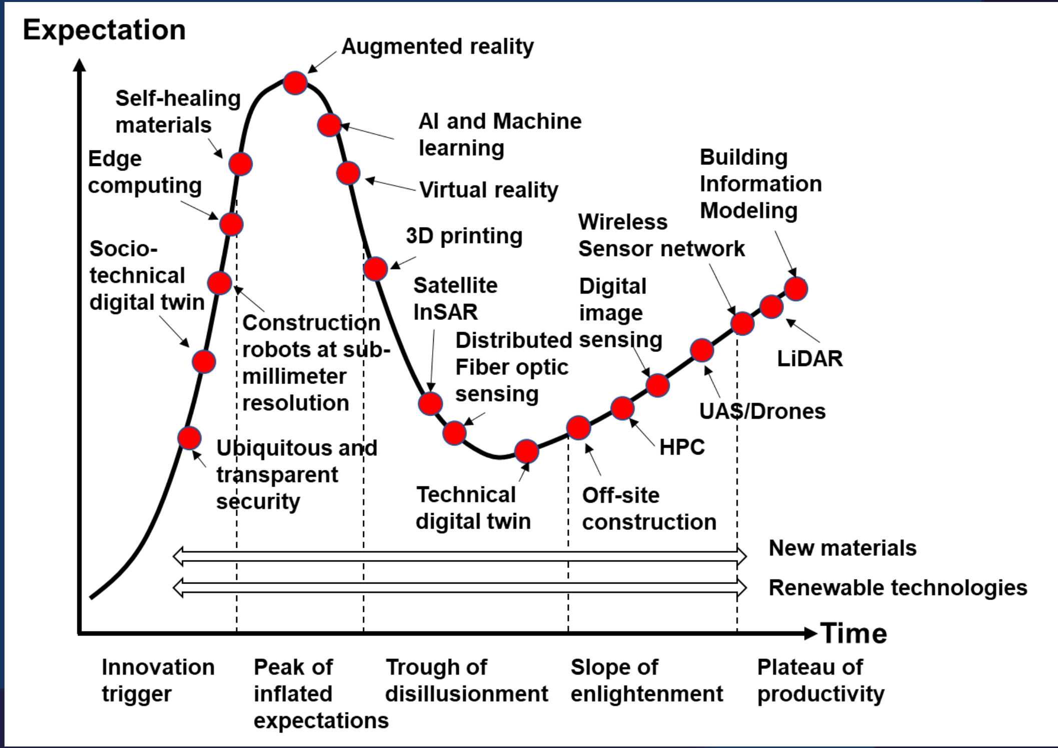
Kenichi Soga (NAE) is the Donald H. McLaughlin Professor and director, Berkeley Center for Smart Infrastructure, Department of Civil and Environmental Engineering, University of California, Berkeley.

Much of the nation's infrastructure is aging and in poor condition, affecting safety, the economy, and quality of life. A variety of emerging technologies can enhance infrastructure to improve safety, resilience, sustainability, and equity.

Challenges to Current Infrastructure Systems

Reactive, damage-based management is ineffective. It takes a long time to build infrastructure, with construction timescales alone stretching from 2 to 10 years. As shown by the first row in figure 1, many infrastructure assets are designed for a service life of 100 years, even with deterioration due to material degradation, extreme temperature, and external loads. But deterioration can accelerate because of poor design or workmanship, construction problems, unforeseen stressors, and inadequate maintenance and repair—it's worth noting that effects of changes in traffic mode, demand, or weather events are not currently considered in maintenance.

Continuous retrofit, renovation, and adaptation are required during an infrastructure's lifetime, and the high cost involved in upgrading and replacing leads to a desire to extend overall life, as illustrated by the second row in figure 1. The American Society of Civil Engineers (ASCE 2021) has estimated that the cumulative needs for US infrastructure—in the form of inspection, maintenance, repair, and replacement expenditures—could reach



Soga, K. 2023. "Smart Infrastructure for Smart Cities", Spring issue, Bridge, National Academy of Engineering, pp.22-29

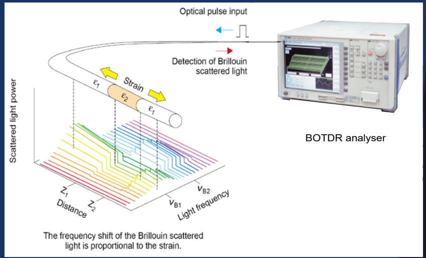
Emerging sensing technologies

Computer Vision, LIDAR and UAV

- Fixed system – 0.1 mm precision
- Not Fixed system – 3-5 mm precision
- 8K&16k cameras, Infrared cameras

InSAR - Satellite

- 10-20 mm precision



Distributed fiber optics - Embedded sensor for life-long monitoring

- Fibre optics – can be less 1 $\mu\varepsilon$ precision (OFDR/DAS)
- Fibre optics – 10 μm precision (for 1 m gauge length) (BOTDA)

WSN – Continuous monitoring at difficult-to-access sites

- WiSen-Leica – tilt, displacement, laser, camera….
- Utterberry – sub millimeter precision
- 8power – vibration energy harvesting based WSN sensors

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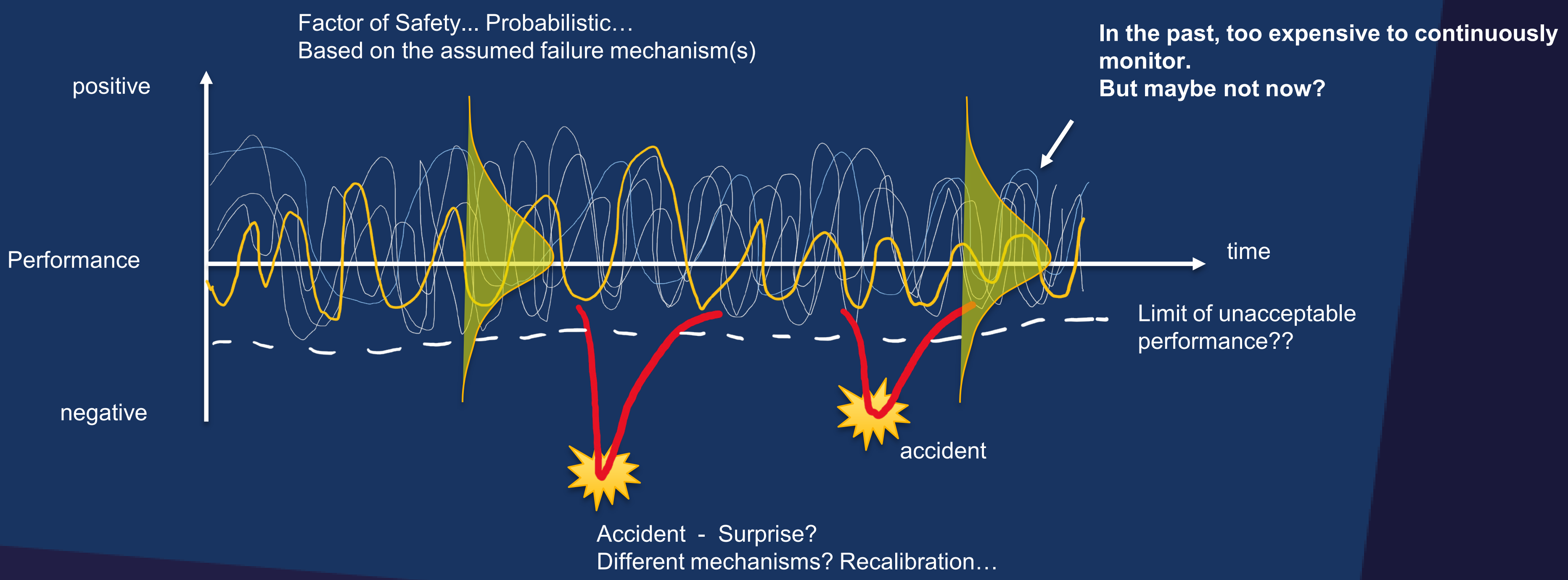
Approach 1 Managing safety by snapshots (set a safety margin)



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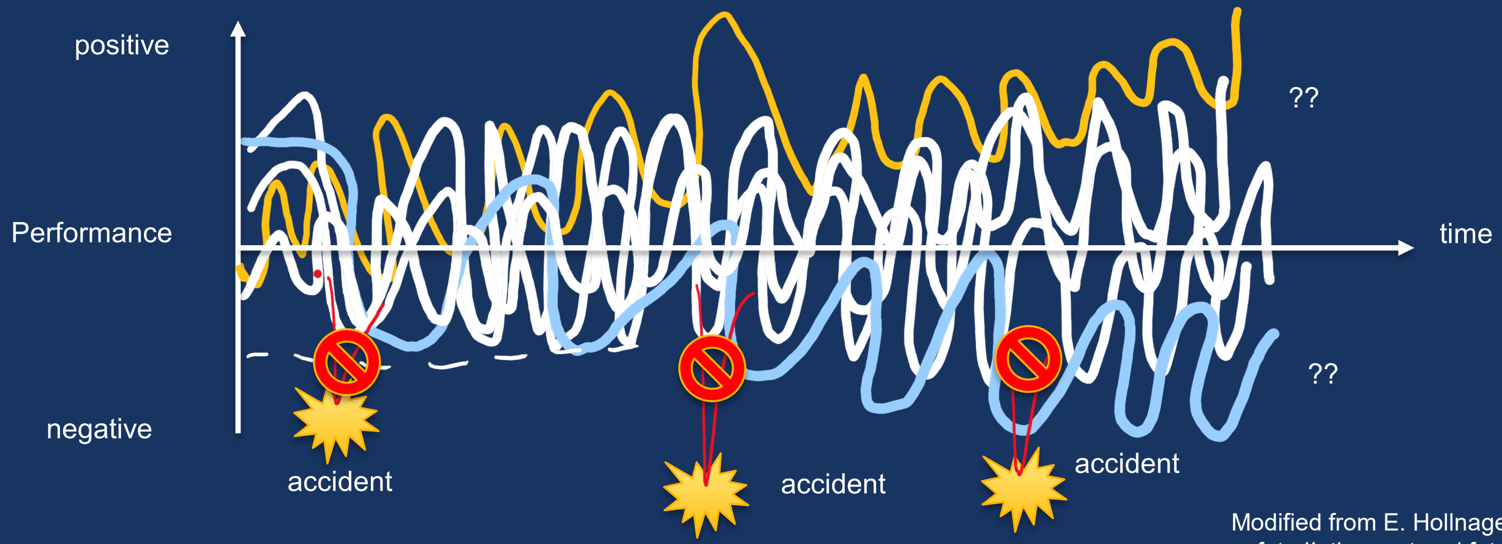
E. Hollnagel (2018) Safety-I and safety-II: the past and future of safety management

Approach 2 Managing safety by everyday work (Real time monitoring)
Monitor – Learn – Anticipate - Respond



Modified from E. Hollnagel (2018) Safety-I and safety-II: the past and future of safety management

If you know the actual performance, you can

- **Learn how to react quickly if a disaster starts to happen.**
- **Cope with future 'unknown' demand – Reduce uncertainty.**
- **Find any potential improvement (i.e. improve design & construction processes, lower resource use, reduce waste,…)**

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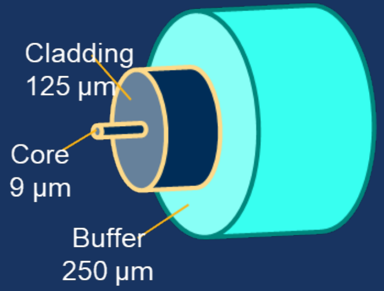
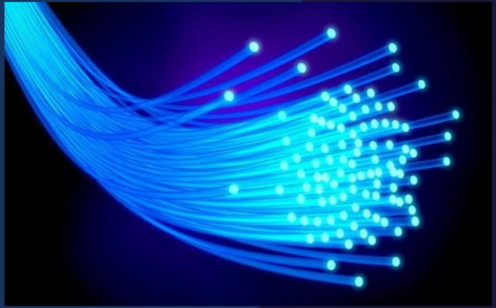
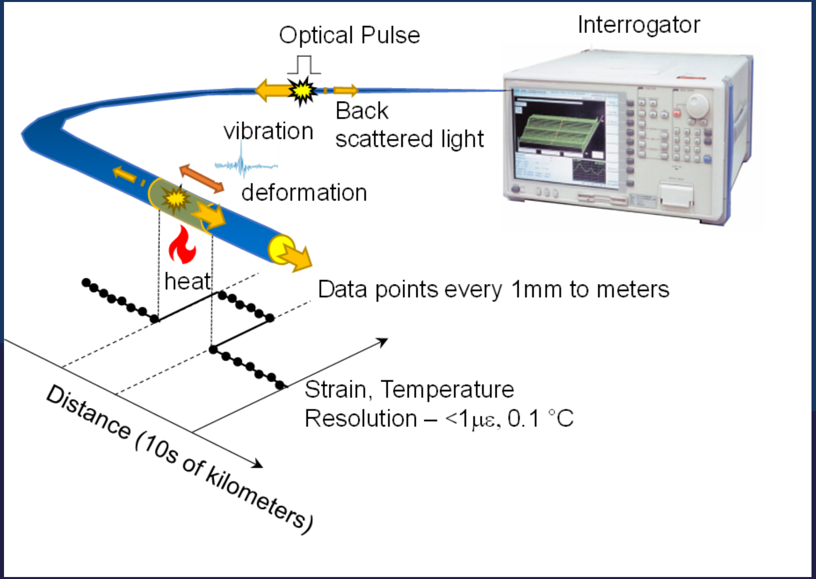
Distributed fiber optic sensing

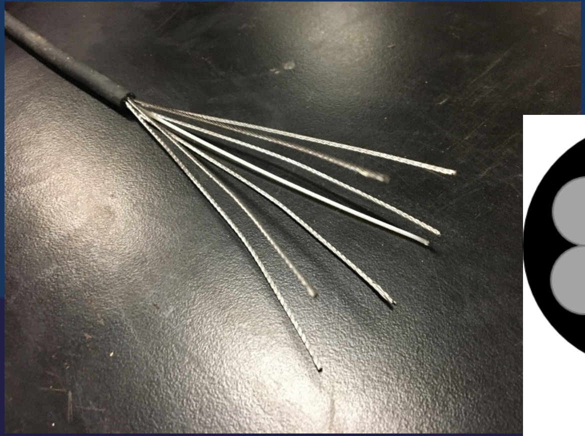
"Continuous Strain/temperature/vibration Profile" along the fibre optic cable

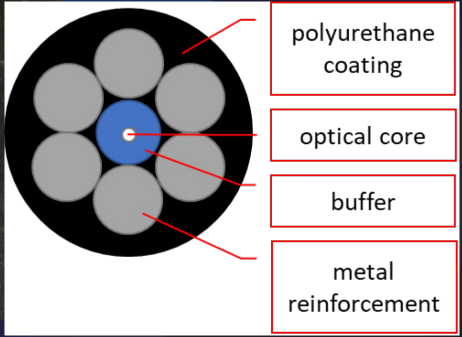
- Distributed Temperature Sensing (DTS)
- Distributed Strain Sensing (DSS)
- Distributed Acoustic/Vibration Sensing (DAS/DVS)



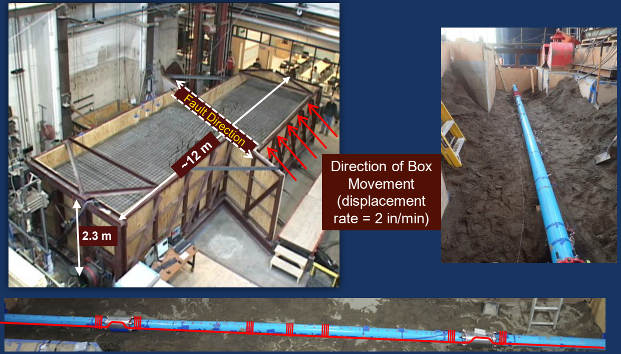






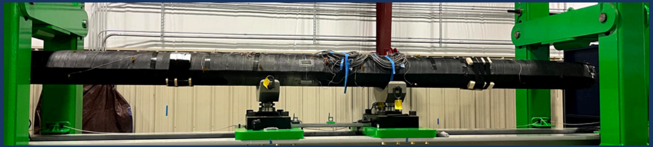


Distributed fiber optic sensing application testing conducted by UC Berkeley

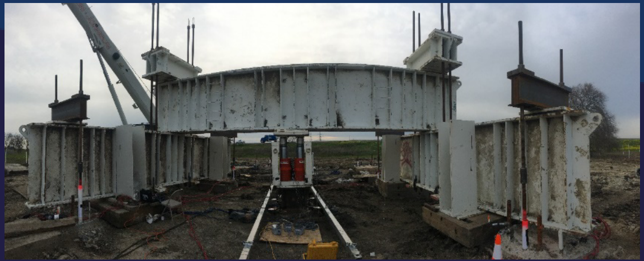


DFOS system testing for monitoring water pipeline subjected to fault movement during an earthquake (with Cornell University)

DFOS instrumented gas pipeline testing



Testing of DFOS system for performance monitoring of bridge foundation piles (with Caltrans)



DFOS monitoring of the deep foundation of a high rise building in San Francisco

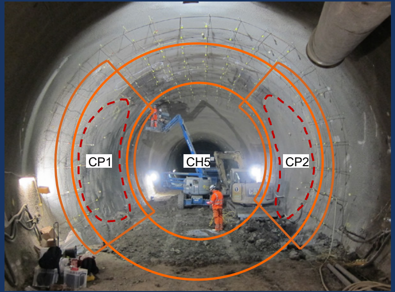
DFOS testing of wellbore casing model for oil and gas application

DFOS installation for concrete pavement (with UC Davis)

Ground Displacements by construction machinery loading

Settlement of Treasure Island Reclaimed land

Crossrail Liverpool street station

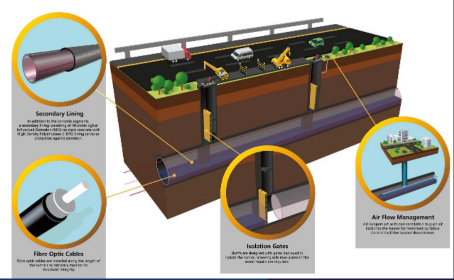


USACE River cutoff walls

Deep slurry walls

Slope monitoring

Singapore's new 51 km long Deep Tunnel Sewerage System

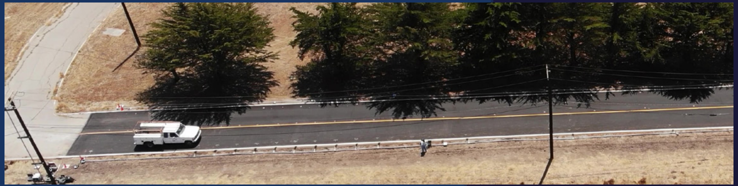


National Grid Tunnel Lining

Caltrans Ground Anchors

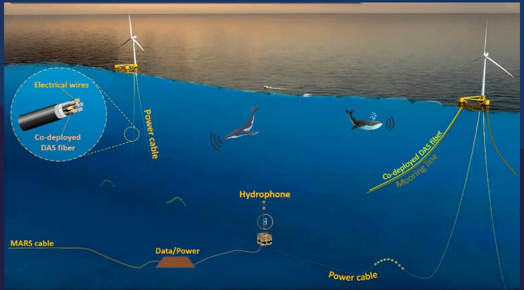
Gas facility monitoring

Smart pavement



EBMUD pipeline fault crossing monitoring

Offshore wind energy



Main Objective

- Examine the feasibility of a Distributed Fiber Optic Strain measurement system for long-term monitoring of buried gas pipelines that are potentially vulnerable to ground deformation across faults and landslides.

Tasks

Task 1: Design

Task 2: Laboratory Test

Task 3: Field Deployment

Task 4: Field Data Analysis

Task 5: Numerical Simulation

Task 6: Commercialization Plan

A total funding from PHMSA - $250,000

PGE’s Cost share is in excess of $62,500 – a portion of a fault-crossing mitigation project that includes about $7M of pipeline re-routing work at a field site in Gilroy, California.

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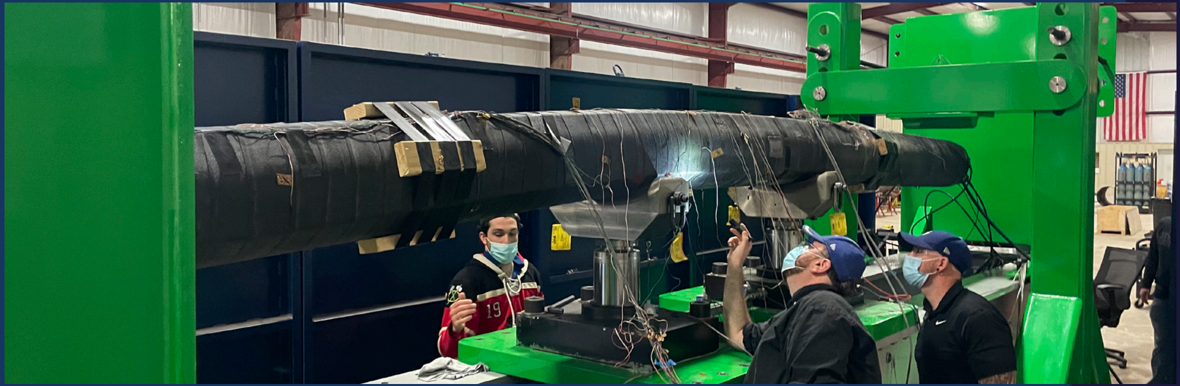
Task 1: Design
Task 2: Laboratory Test

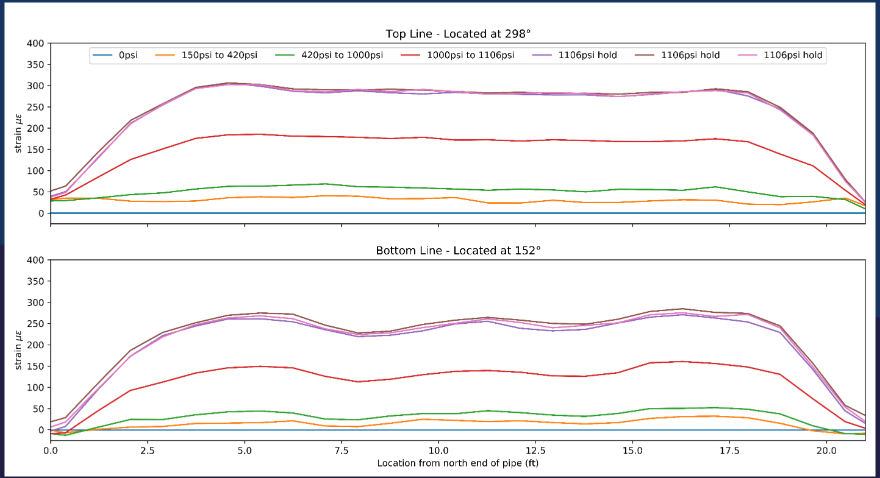
Assess the effectiveness of the fiber optic cable type and attachment method in facilitating adequate strain transfer during pipe deformation.

Deformed pipe after bending with North end showed in near field

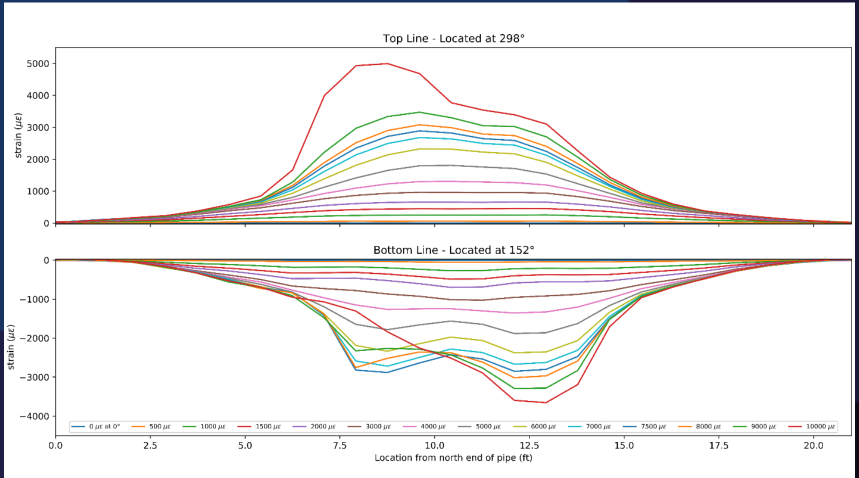


In collaboration with Paulsson, Inc.

Strain profiles measured during pressurization to 1106 psi

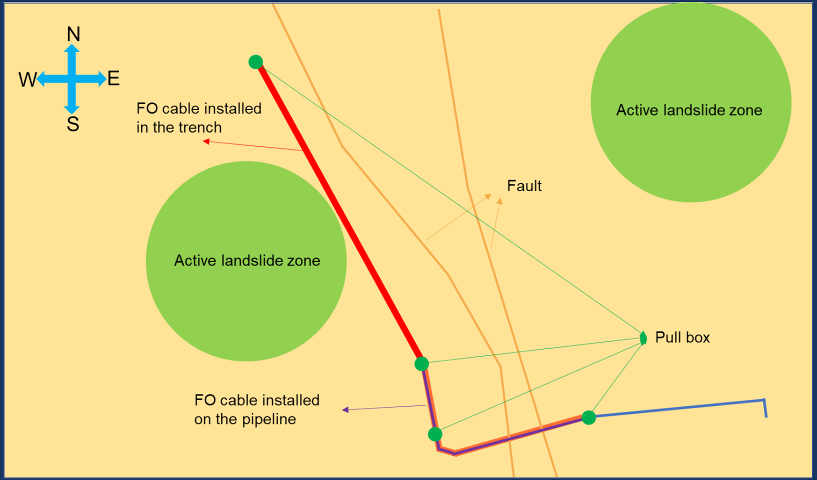


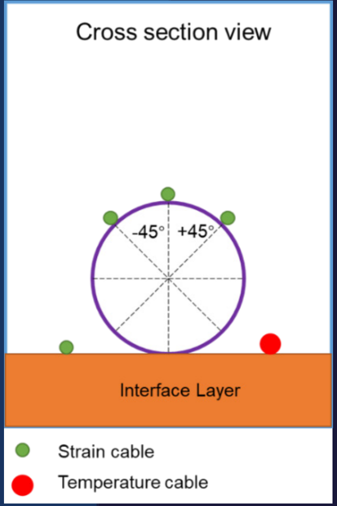
Strain profiles measured during bending



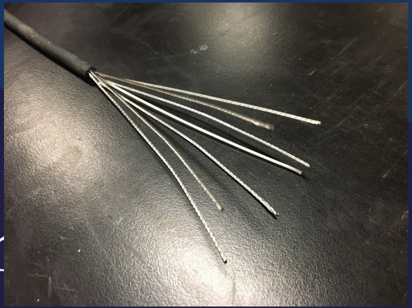
Task 3: Field Deployment

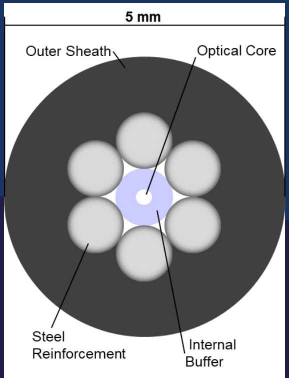
In June 2022, three 400-foot-long fiber optic strain cables were installed on the replaced steel gas pipeline in Gilroy, CA using an attachment method validated by laboratory tests. Additionally, one 1000-foot-long fiber optic strain cable and one 1000-foot-long fiber optic temperature cable were installed in the trench to provide comprehensive information.



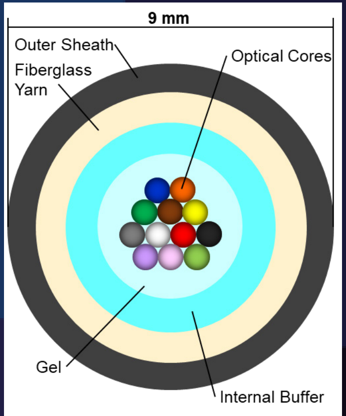


Strain Cable
NanZee NZS-DSS-C02





Temperature Cable
Belden



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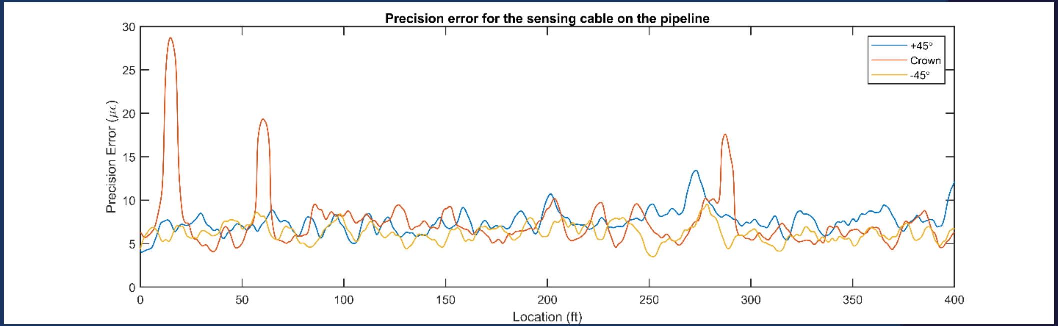
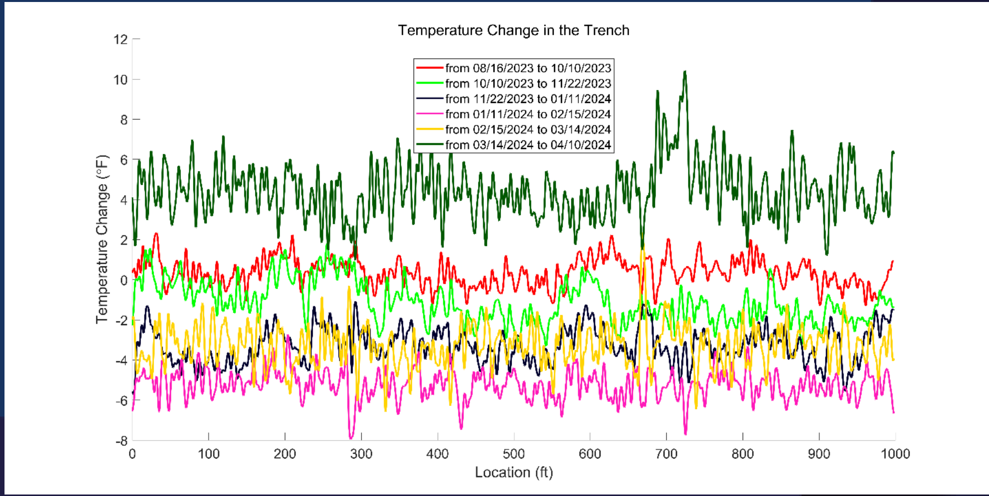
Task 4: Field Data Analysis

Precision Error evaluation



Temperature change between two readings



Follows the metrological data, but the magnitude in the trench is smaller.

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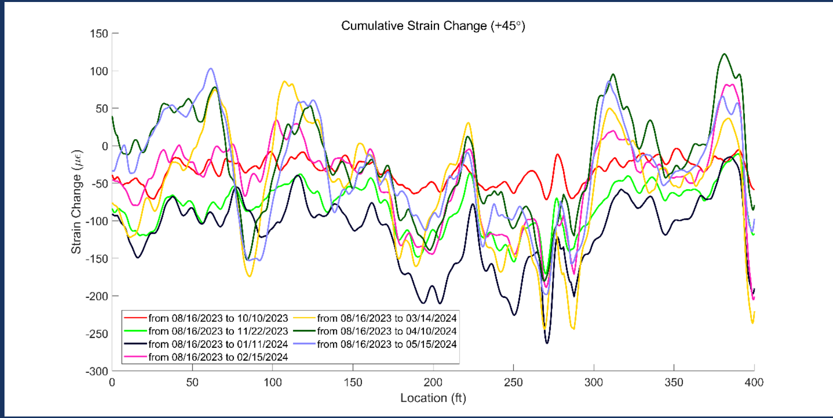
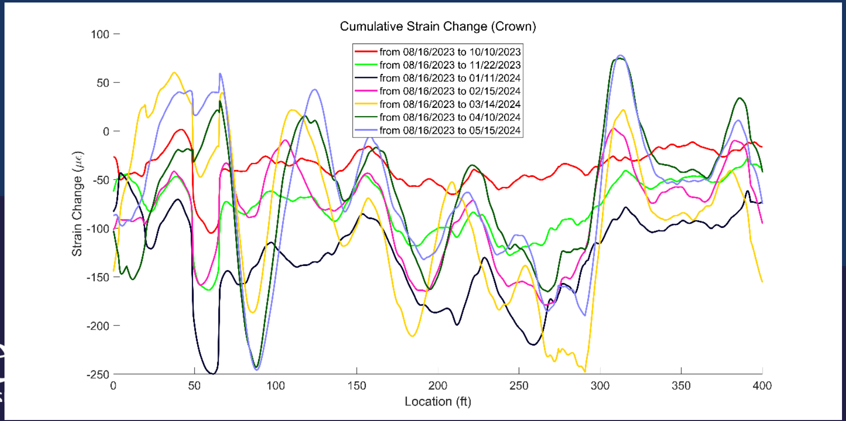
Strain Change with time (from August 2023)

+45° location



Crown location



- No discernible strain resulting from potential geohazards such as fault movement or landslides for the replaced pipeline.
- Correlated with the thermal expansion and contraction of the steel pipeline in response to temperature changes.
- A guideline for long-term strain monitoring of pipeline using DSS has been proposed.
- A new long-term monitoring project funded by the California Energy Commission.

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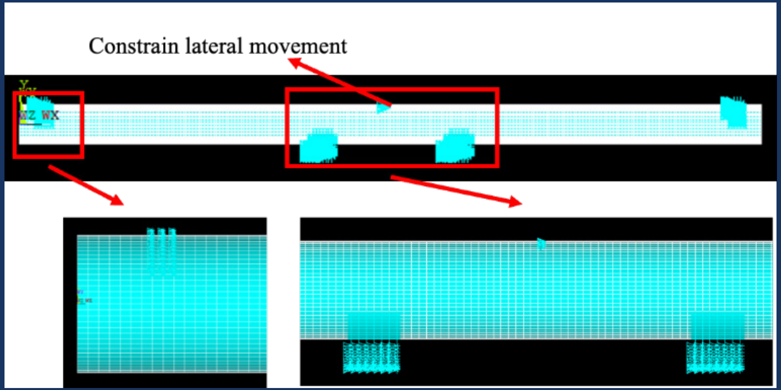
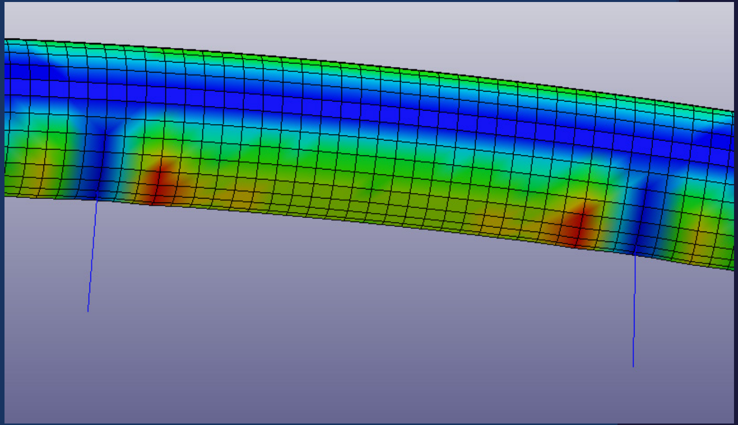
Task 5: Numerical Simulation

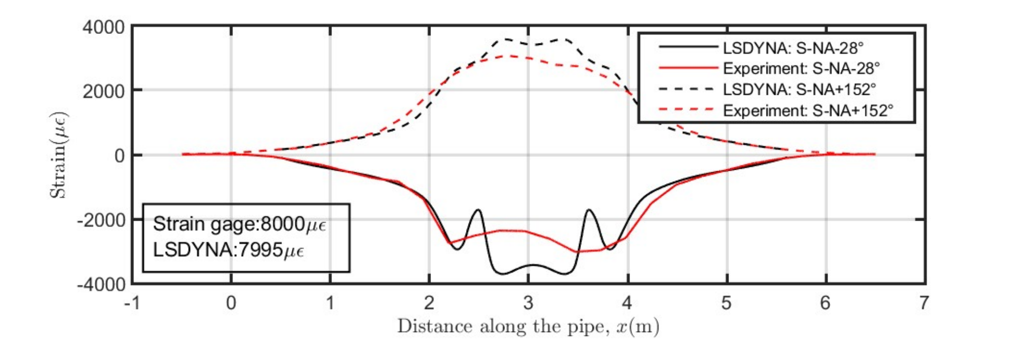
Simulation of the Laboratory Four-Point Bending Test



FEM discretization and boundary conditions



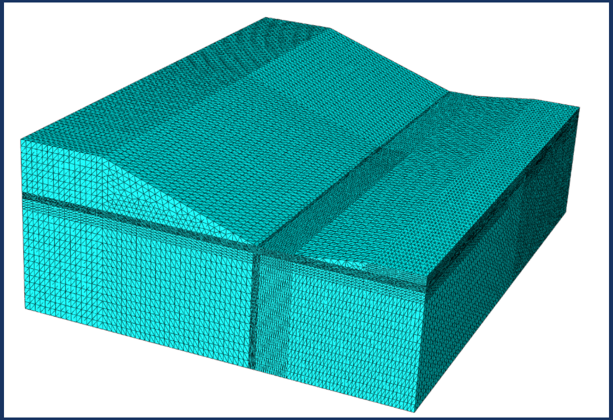
Effective plastic strain distribution around the actuators



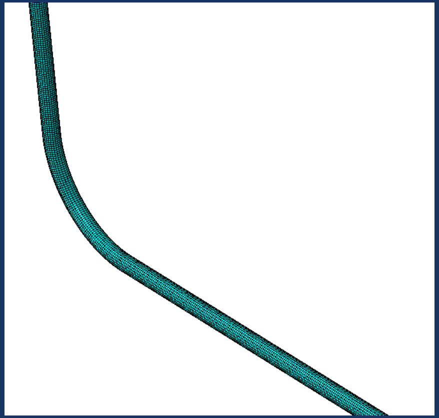
Comparison of the axial strain distribution at the two sensing locations, S-NA-28° and S-NA+152°, from the numerical modeling with the experimental data during Stage 2 for strain in the SG0 sensor equal to 8000 με

Simulation of the Field Test Site

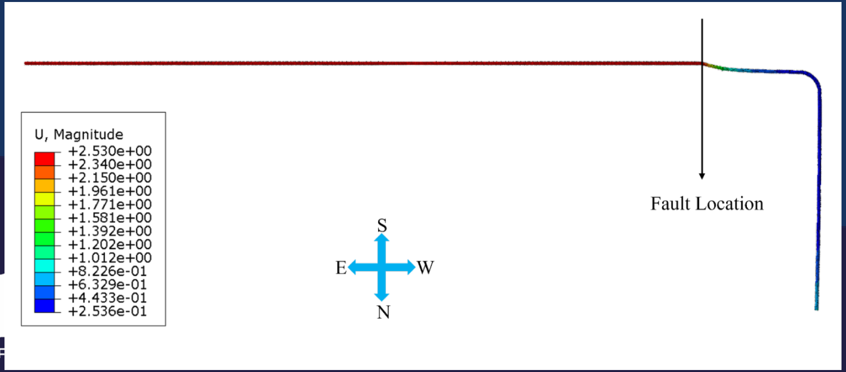
Mesh for the soil model



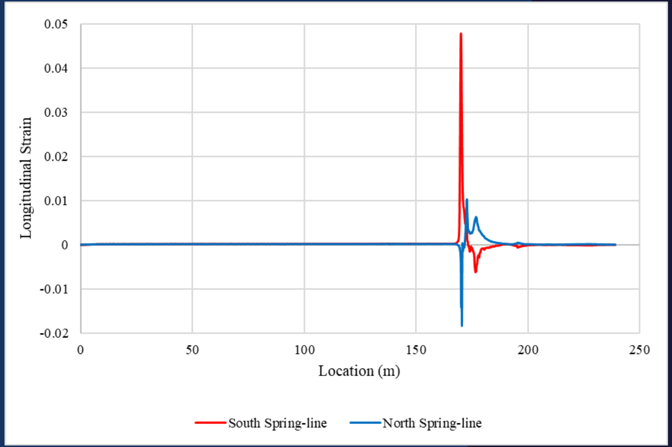
Mesh for the pipeline model



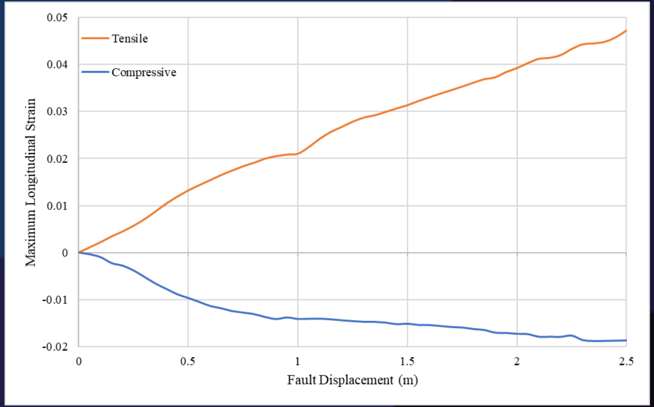
Pipeline deformed shape for the westbound case



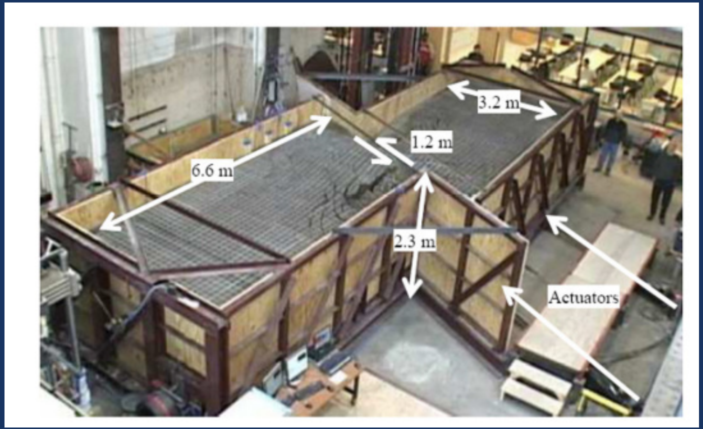
Longitudinal strain distribution of the pipeline for the westbound case

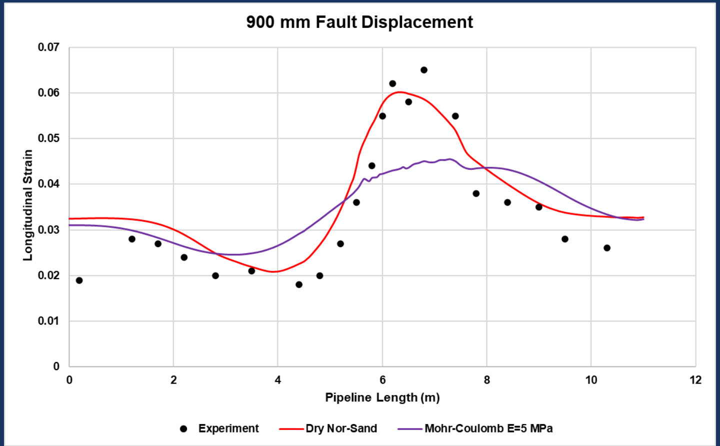


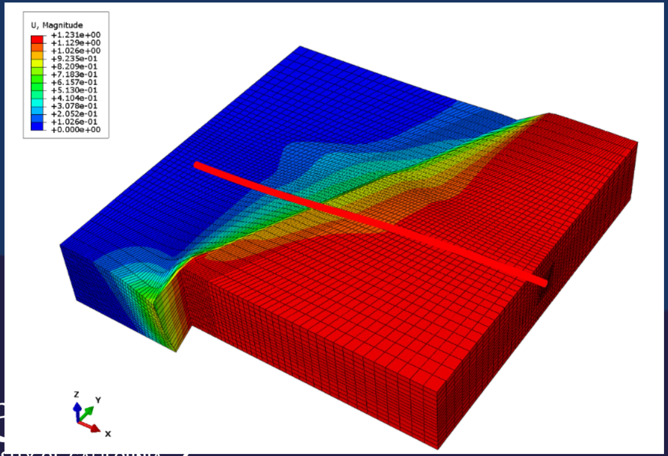
Maximum longitudinal strain with fault displacement for the westbound case



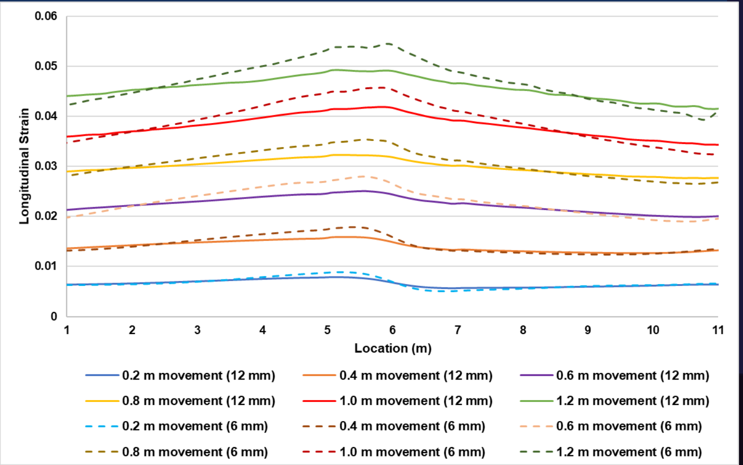
The Role of Distributed Strain Data for Pipeline Assessment







Strain distribution with varying wall thickness



Task 6: Commercialization Plan

- The market demand for DFOS has been assessed by participating in the national I-Crops program funded by the US National Science Foundation. The interviews of 100+ stakeholders show that **more data is not always beneficial without clear usage strategies.**

- There is a need to **develop and deploy DFOS technology in partnership with public and private agencies** to enhance infrastructure management and predict life expectancy.

- The focus should be on **providing low-cost, smart infrastructure solutions that integrate distributed sensing data for better decision-making.**

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Conclusions

- The steel pipe four-point bending experiment demonstrated that the selected fiber optic sensor, combined with the proposed attachment method, ensured excellent deformation coordination with the monitored pipeline.

- Using the tested installation method and fiber optic sensor type, the project successfully installed distributed fiber optic strain sensors on a replaced steel gas pipeline.

- It was possible to monitor thermally-driven strain changes in the pipeline since August 2023. Precision error analysis indicated an error margin of less than 20 $\mu\varepsilon$.

- Utilizing the test data-validated finite element model, both small-scale and large-scale soil-pipeline interaction simulations were conducted. These datasets are important when examining the distributed strain profiles obtained in the field.

- The commercialization study showed that the focus should be on providing low-cost, smart infrastructure solutions that integrate distributed sensing data for better decision-making.

Next Step

- To support commercialization, the team will conduct workshops to engage stakeholders, compare tools, and develop training programs aimed at cultivating a skilled workforce to drive innovation in the construction and infrastructure sector.

- On-going collaborations with other Infrastructure industry partners – see next slides

- In September 2023, the research team received a commercialization project **from the US National Science Foundation to develop a mass-producible, commercial-quality DFOS system for smart infrastructure monitoring.**

- In February 2024, the research team received a project **from the California Energy Commission to demonstrate the use of remote and embedded sensing technologies** to monitor and gain insights into the performance of gas infrastructure assets and manage risk. Data collected will be coupled with an open-source a seismic risk assessment tool in predictive modeling and data analytics. The project will increase gas system safety and reliability by enabling more accurate identification of at-risk infrastructure.

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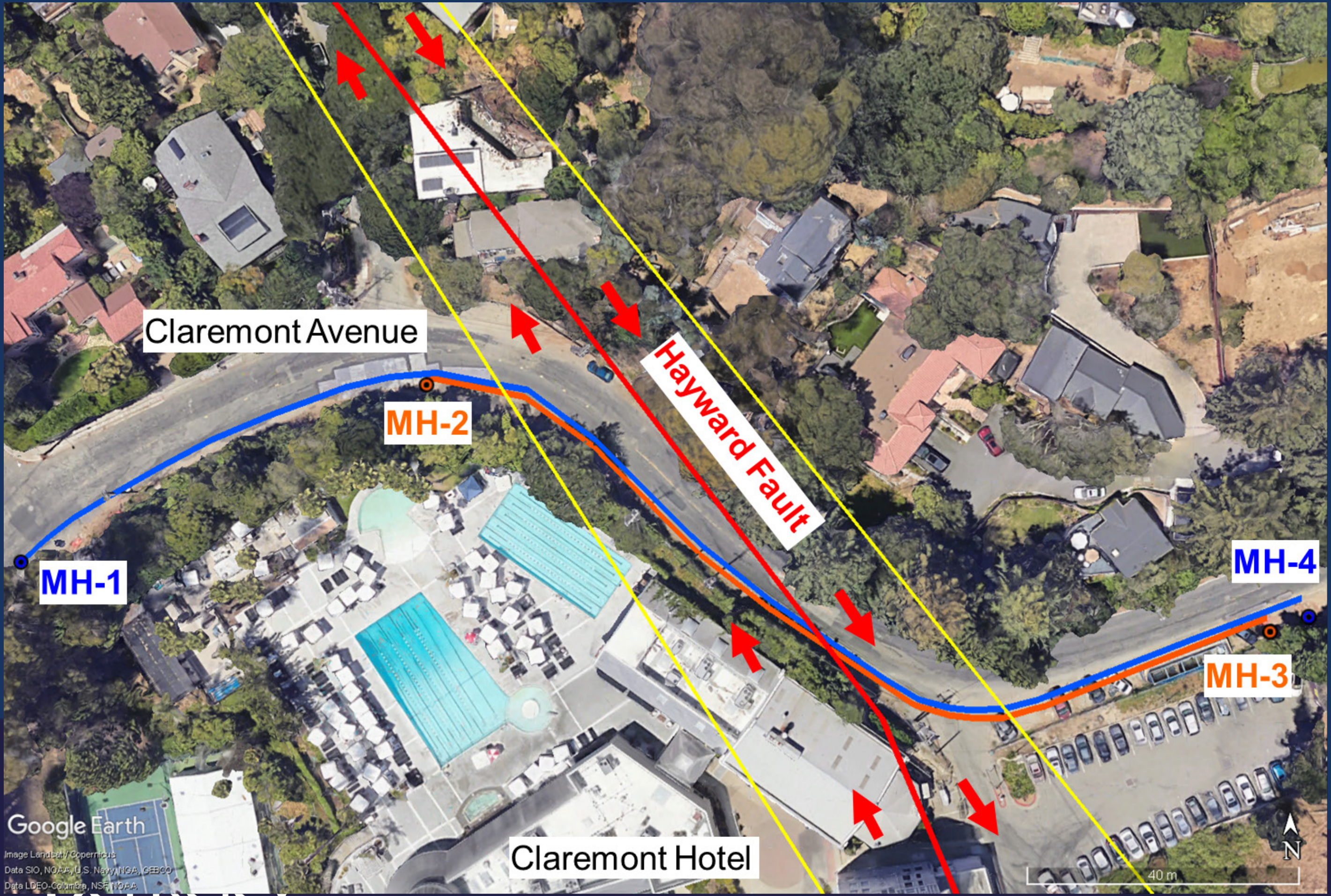
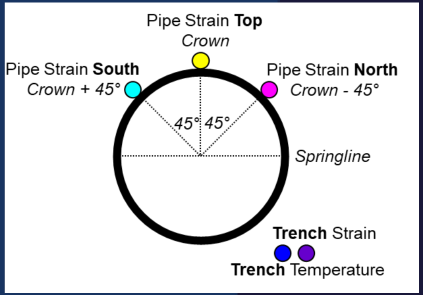
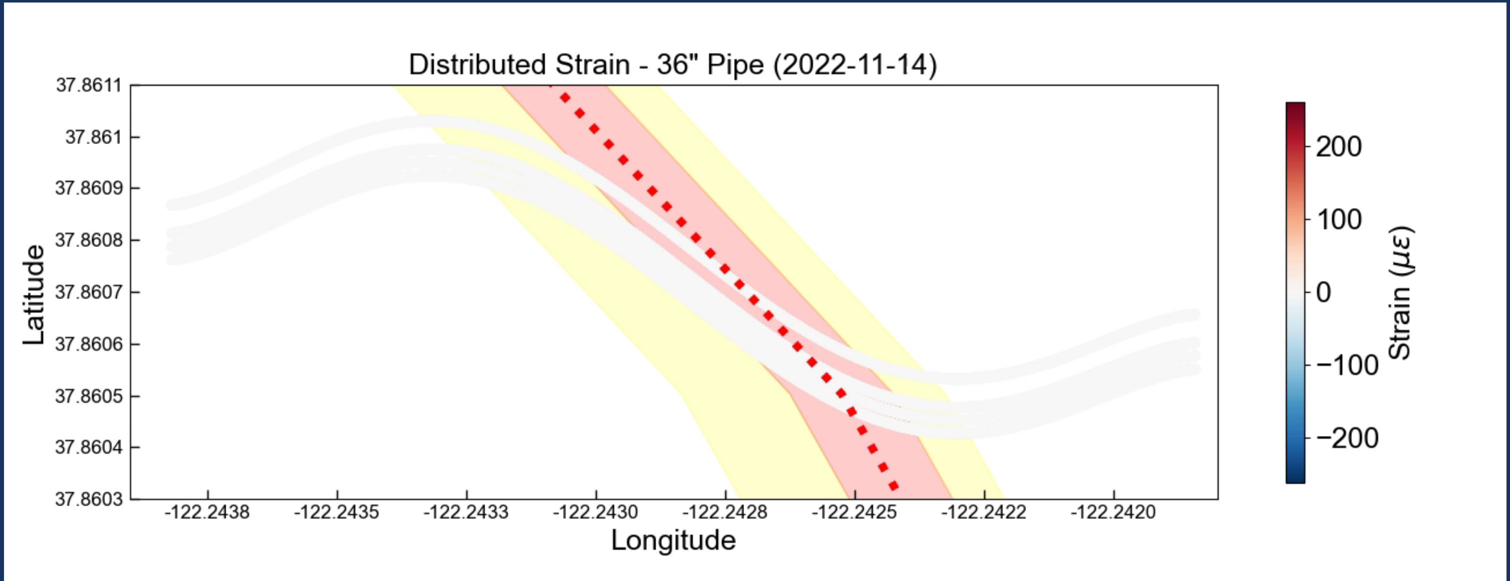


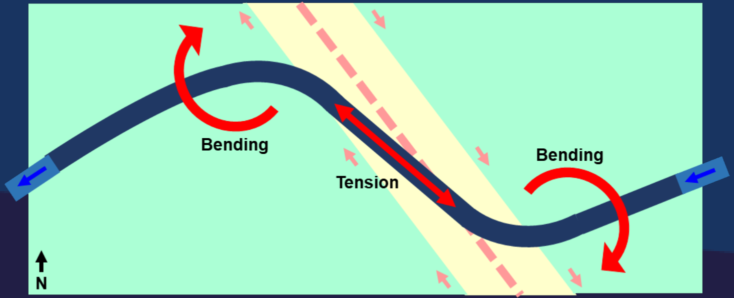
Claremont Avenue
Hayward Fault
MH-1
MH-2
MH-3
MH-4
Claremont Hotel
Google Earth
40 m
N

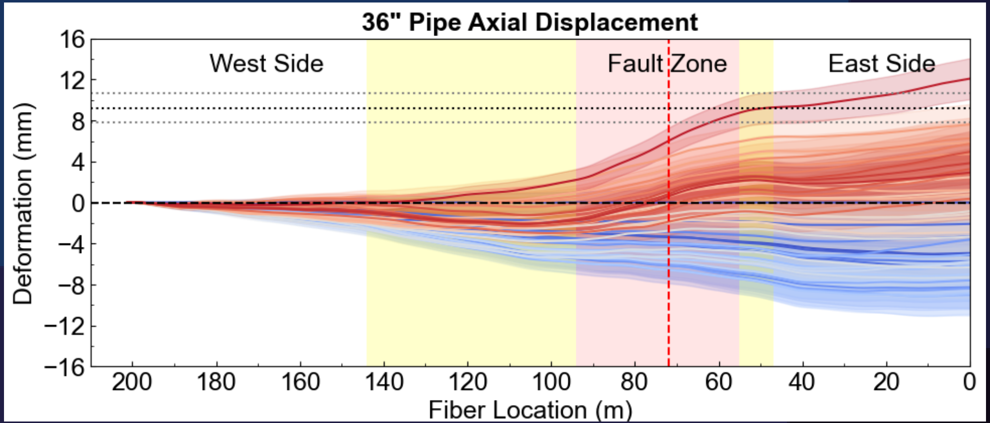


Pipe Strain Top
Crown
Pipe Strain South
Crown + 45°
Pipe Strain North
Crown - 45°
45° 45°
Springline
Trench Strain
Trench Temperature

EBMUD







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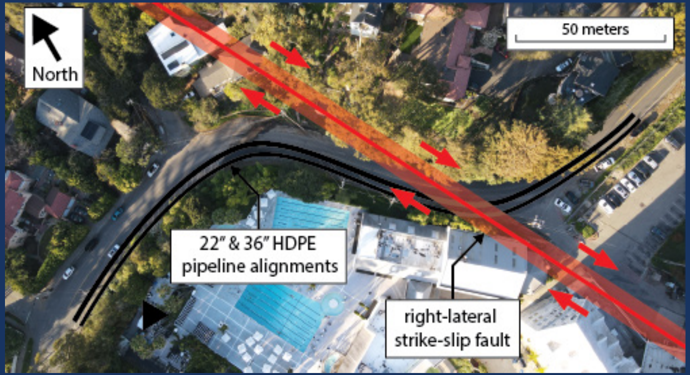
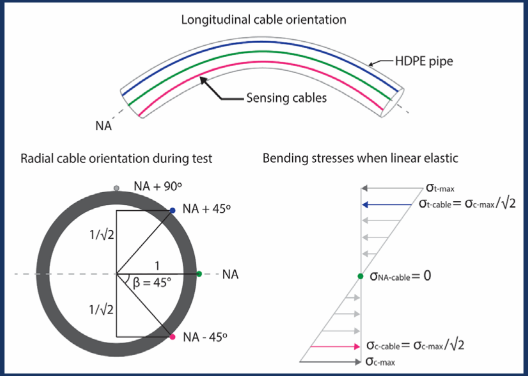
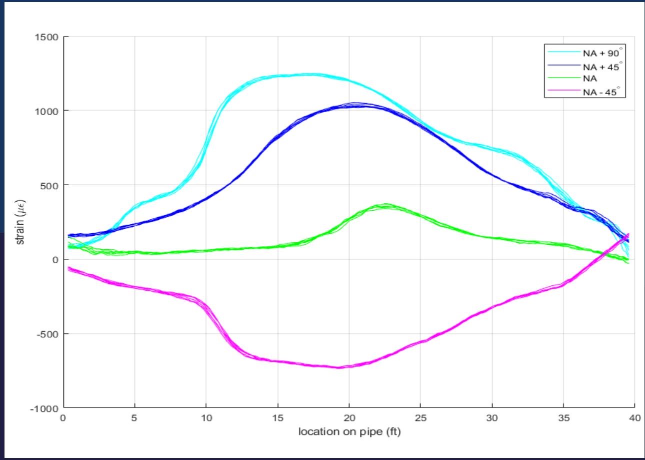
On-site engineering assessment

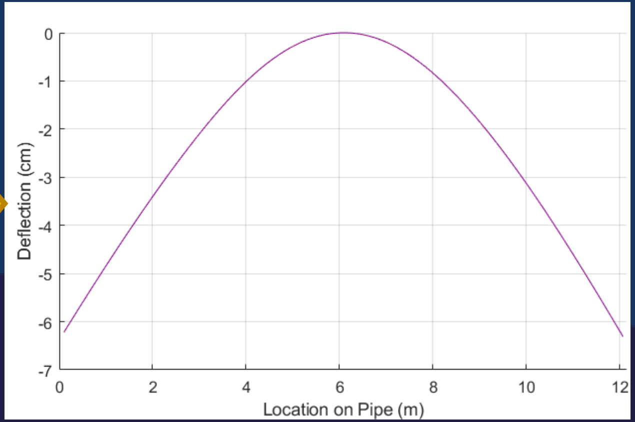




Raw data



Insightful 'shape sensing'



Distributed strain-based assessment

STATE OF CALIFORNIA ENERGY COMMISSION

PG&E

The winner of this year's Pipeline Research Council International (PRCI) photo contest!

Once we bury a pipeline, we are not going to see it for the next 100 years.

Why not embed "intelligence" during construction for future generations?

The installation process of a gas pipeline on which fiber optic sensors have been installed for safety monitoring to measure the strain and temperature all along the pipeline in real time to monitor the pipeline's integrity and safety. Special attachment way, the red tape and black wrap, is used to ensure the fiber optic sensor is installed well. Gilroy, California. 2023

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Thank you.

Acknowledgment - Zhongquan Zhou (ZZ) - General Engineer
Office of Pipeline Safety-Engineering and Research Division

Any questions

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