「埋設インフラのモニタリングの事例」

カリフォルニア大学バークレー校
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UC Berkeley

Berkeley
CENTER FOR
Smart Infrastructure

https://smartinfrastructure.berkeley.edu/

EBMUD
LA DWP
The Metropolitan Water District of Southern California
San Francisco Public Utilities Commission
YUBA WATER AGENCY
PG&E
enel
ERDC
Caltrans
Oregon Department of Transportation
BERKELEY LAB
Bringing Science Solutions to the World
NSF
U.S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration
State of California Energy Commission
Department of Energy United States of America
Berkeley
BAKAR FELLOWS PROGRAM

Emerging sensing technologies

Computer Vision, LIDAR and UAV

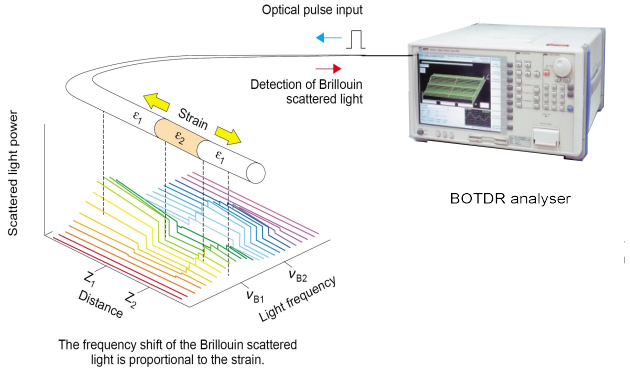
- 固定式システム：0.1mmの精度
- 非固定式システム：3～5mmの精度
- 8Kおよび16Kカメラ、赤外線カメラ

InSAR - Satellite

- 10-20 mmの精度

Distributed fiber optics –長期モニタリングのための埋め込みセンサー

- Fibre optics –1 με 以下の精度 (OFDR/DAS)
- Fibre optics – 10 μm 程度の精度 (for 1 m gauge length) (BOTDA)



Wireless Sensor Network – アクセスが困難な場所での継続的なモニタリング

- 傾き、変位、ひずみ、レーザー、カメラ など

将来の世代がスマートインフラの恩恵を受けられるように、どのようにして建設インフラの分野を再生・創造できるのか？

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

Smart Infrastructure for Smart Cities

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.

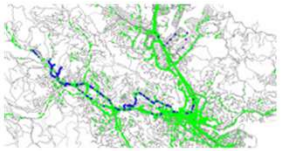
Kenichi Soga

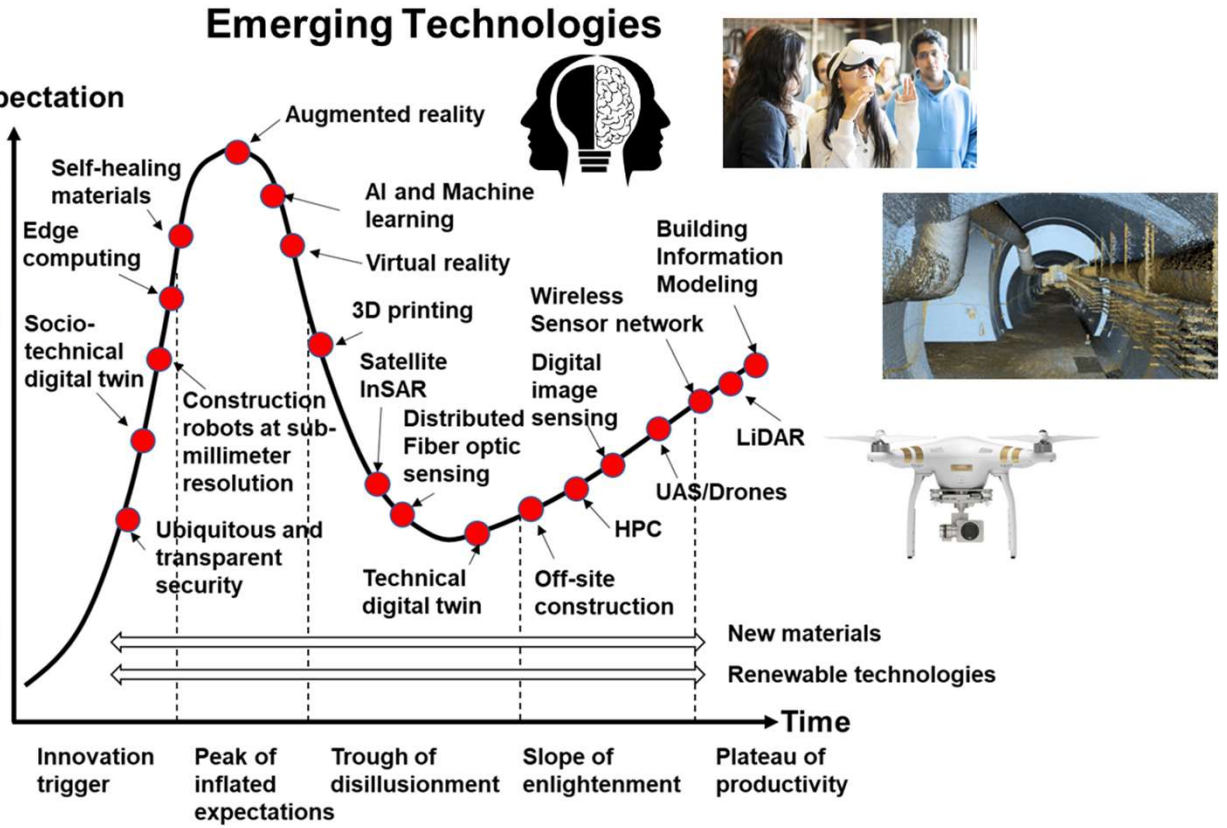
Much of the nation's infrastructure is aging and in poor condition, affecting safety, the economy, and quality of life. A variety of emerging technologies can enhance infrastructure to improve safety, resilience, sustainability, and equity.

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.

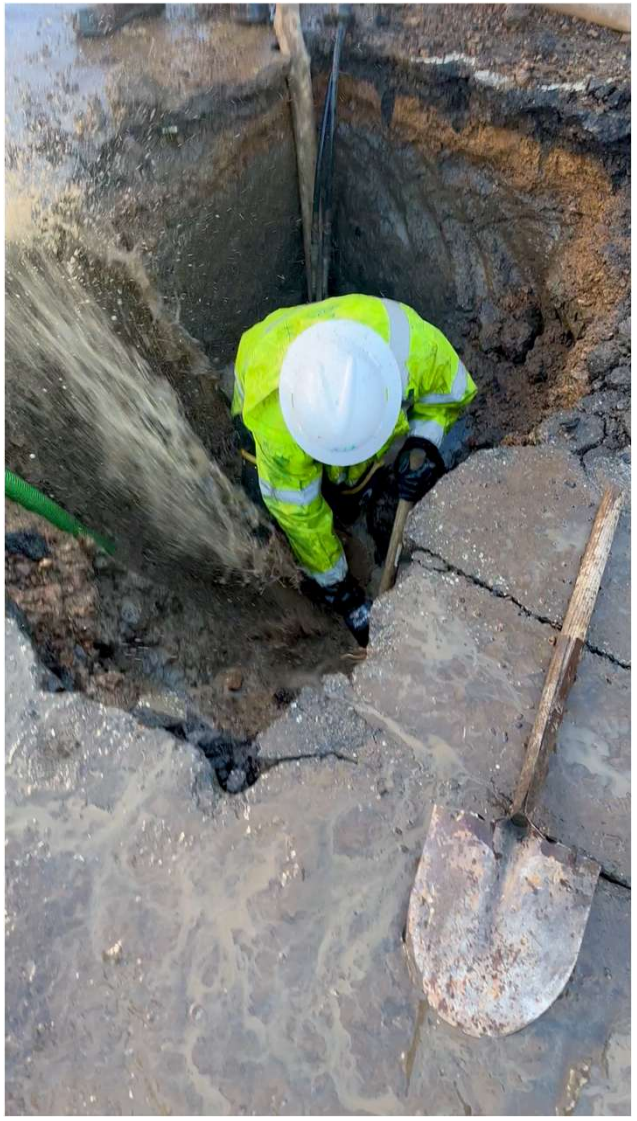
Continuous retrofit, renovation, and adaptation are required during an infrastructure's lifetime, and the high cost involved in upgrading and replacing leads to a desire to extend overall life, as illustrated by the second row in figure 1. The American Society of Civil Engineers (ASCE 2021) has estimated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



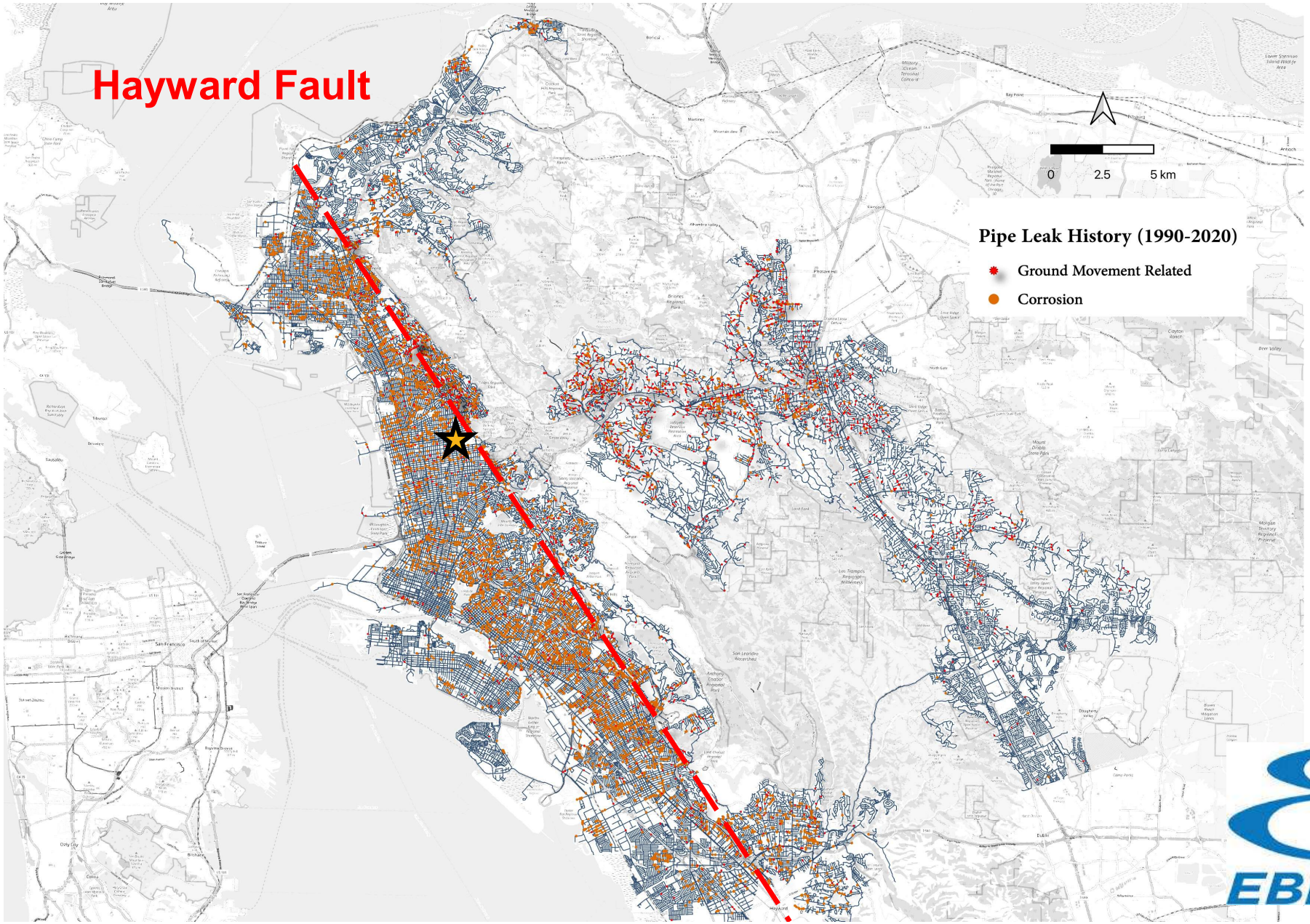


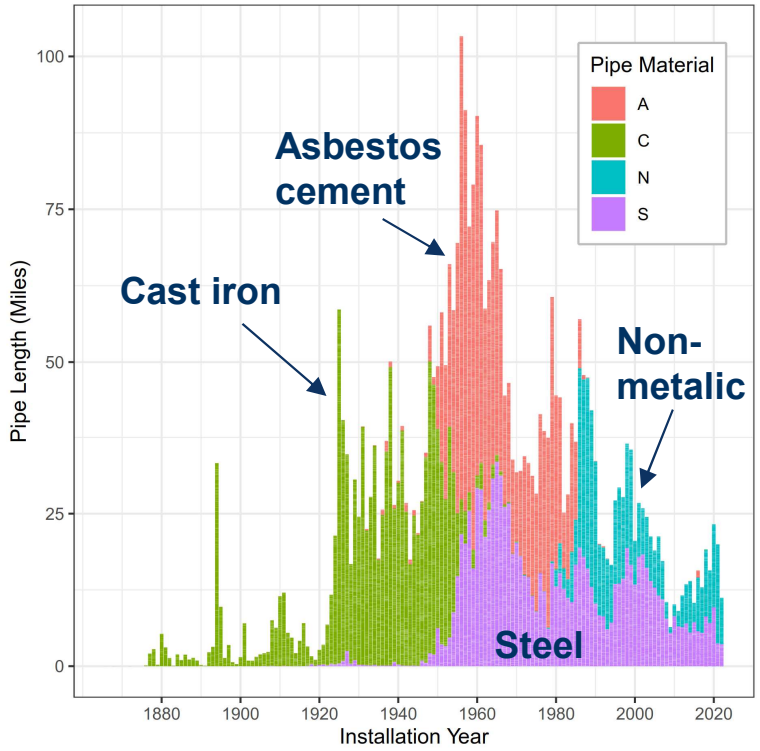
Soga, K. 2023. "Smart Infrastructure for Smart Cities", Spring issue, Bridge, National Academy of Engineering, pp.22-29

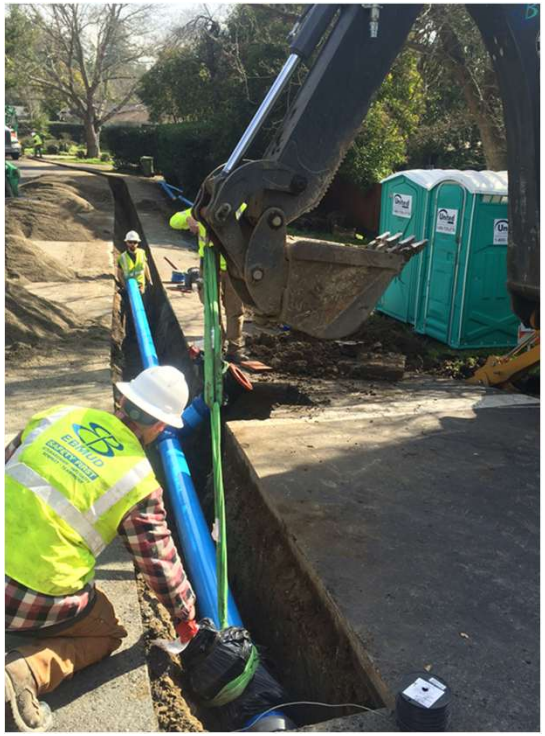
Carlton Chan, EBMUD



David Katzev, EBMUD


Hayward Fault
0
2.5
5 km
Pipe Leak History (1990-2020)
Ground Movement Related
Corrosion





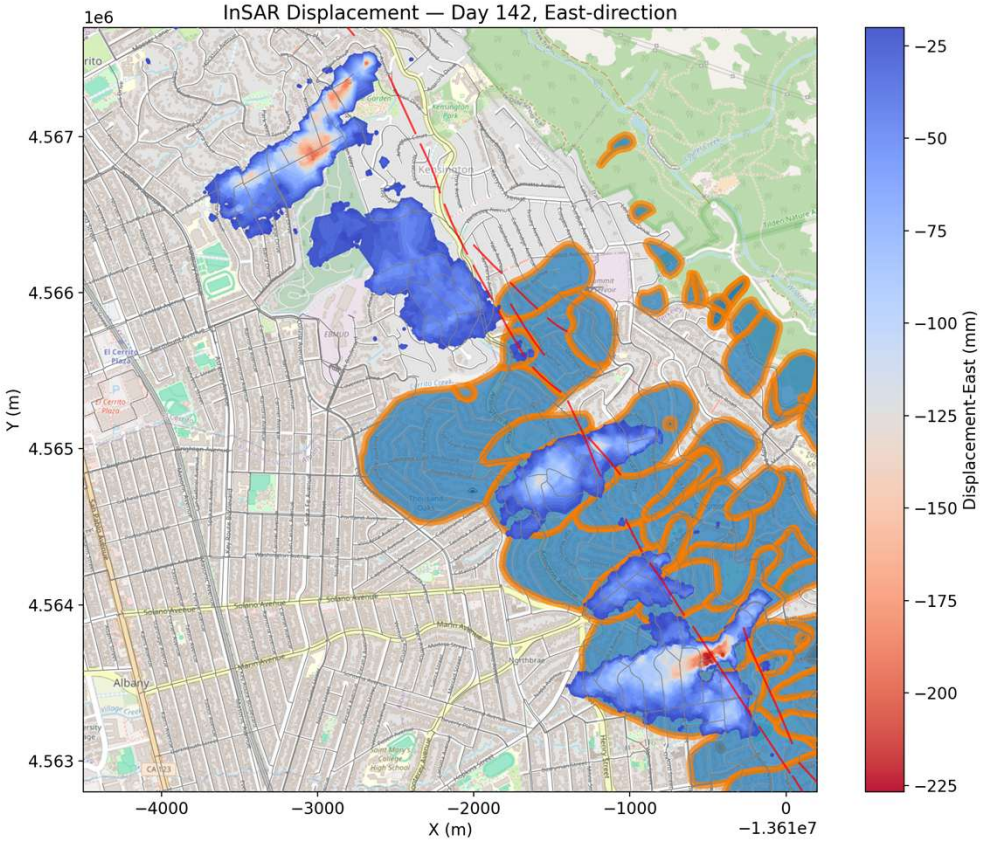
インフラの設計寿命＝100年。すでにこの寿命を超えているものもある。

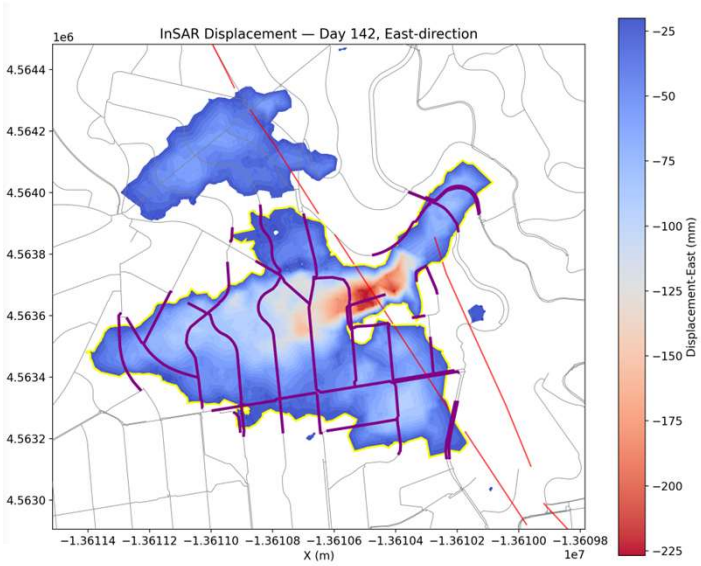
EBMUDは4,200マイルのパイプラインを保有しており、毎年1,000件以上の破損（管の破裂）が発生している。

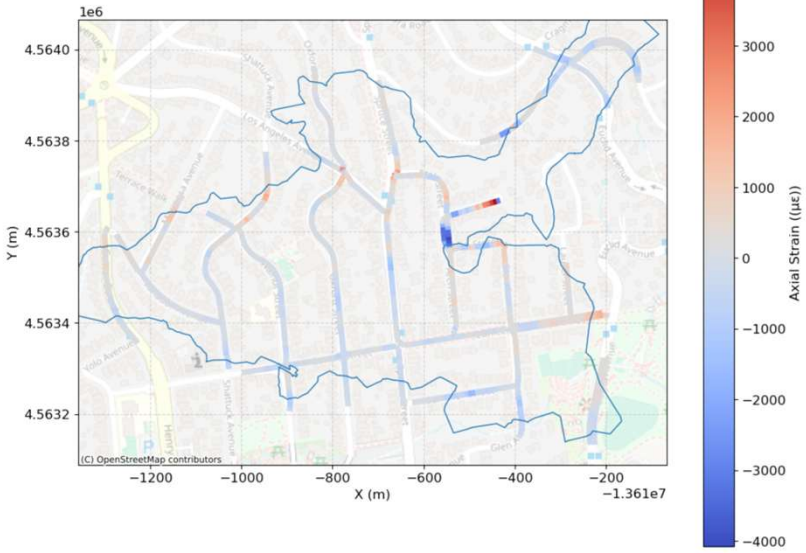
現在は年間25マイルを更新（取り替え）しているが、全てを更新し終えるには150～200年かかる。

どうすれば、もっと効率よく更新できるか？

InSAR

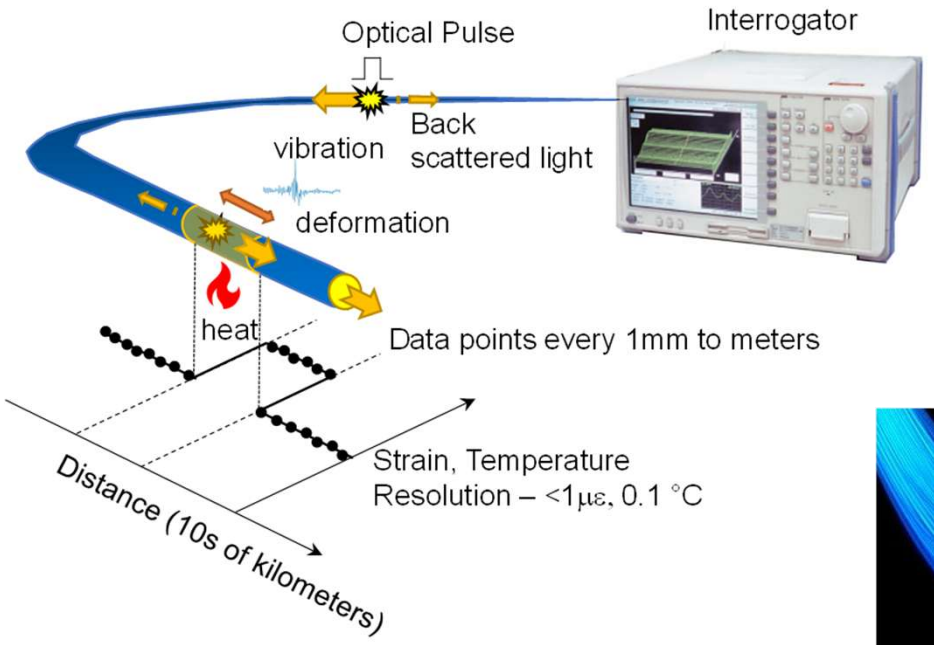

InSAR Displacement — Day 142, East-direction
1e6
4.567
4.566
4.565
4.564
4.563
Y (m)
−4000
−3000
−2000
−1000
0
X (m)
−1.361e7
−25
−50
−75
−100
−125
−150
−175
−200
−225
Displacement-East (mm)

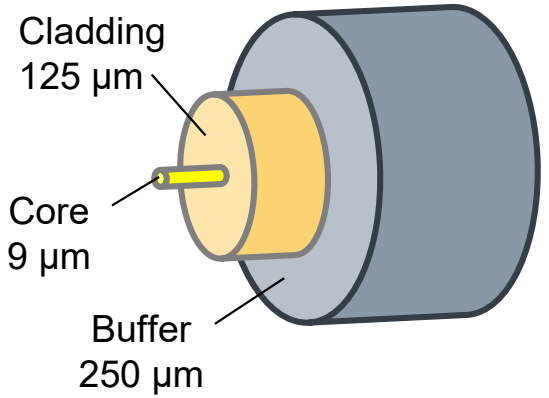

InSAR Displacement — Day 142, East-direction
1e6
4.5644
4.5642
4.5640
4.5638
4.5636
4.5634
4.5632
4.5630
−1.36114
−1.36112
−1.36110
−1.36108
−1.36106
−1.36104
−1.36102
−1.36100
−1.36098
X (m)
1e7
−25
−50
−75
−100
−125
−150
−175
−200
−225
Displacement-East (mm)

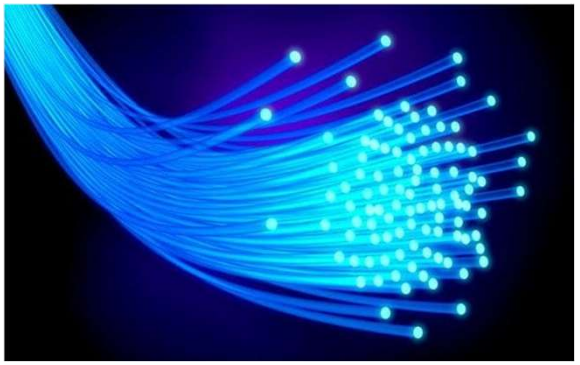

1e6
4.5640
4.5638
4.5636
4.5634
4.5632
Y (m)
−1200
−1000
−800
−600
−400
−200
X (m)
−1.361e7
(C) OpenStreetMap contributors
4000
3000
2000
1000
0
−1000
−2000
−3000
−4000
Axial Strain ((με))

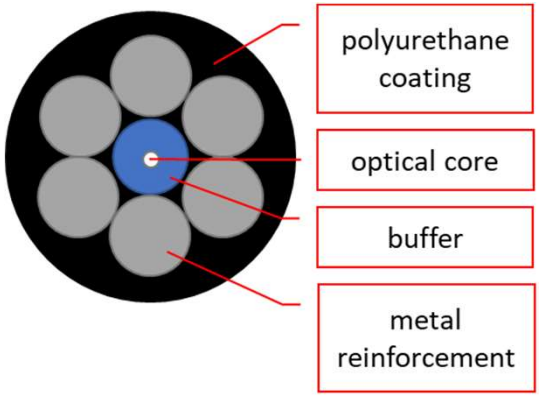
分布型光ファイバセンシング

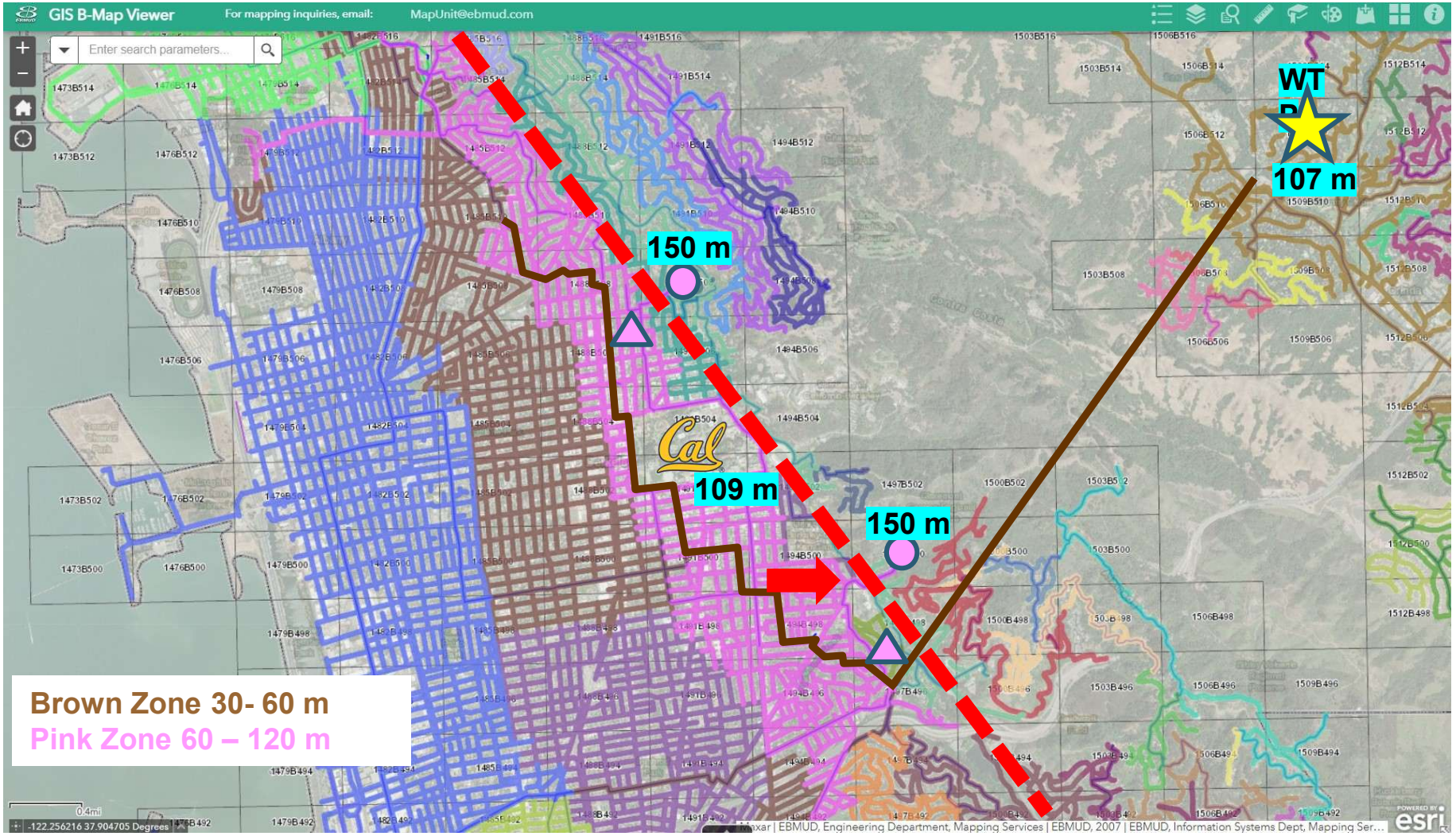
光ファイバーケーブルに沿って「連続的なひずみ／温度／振動のデータ」を得ることができる





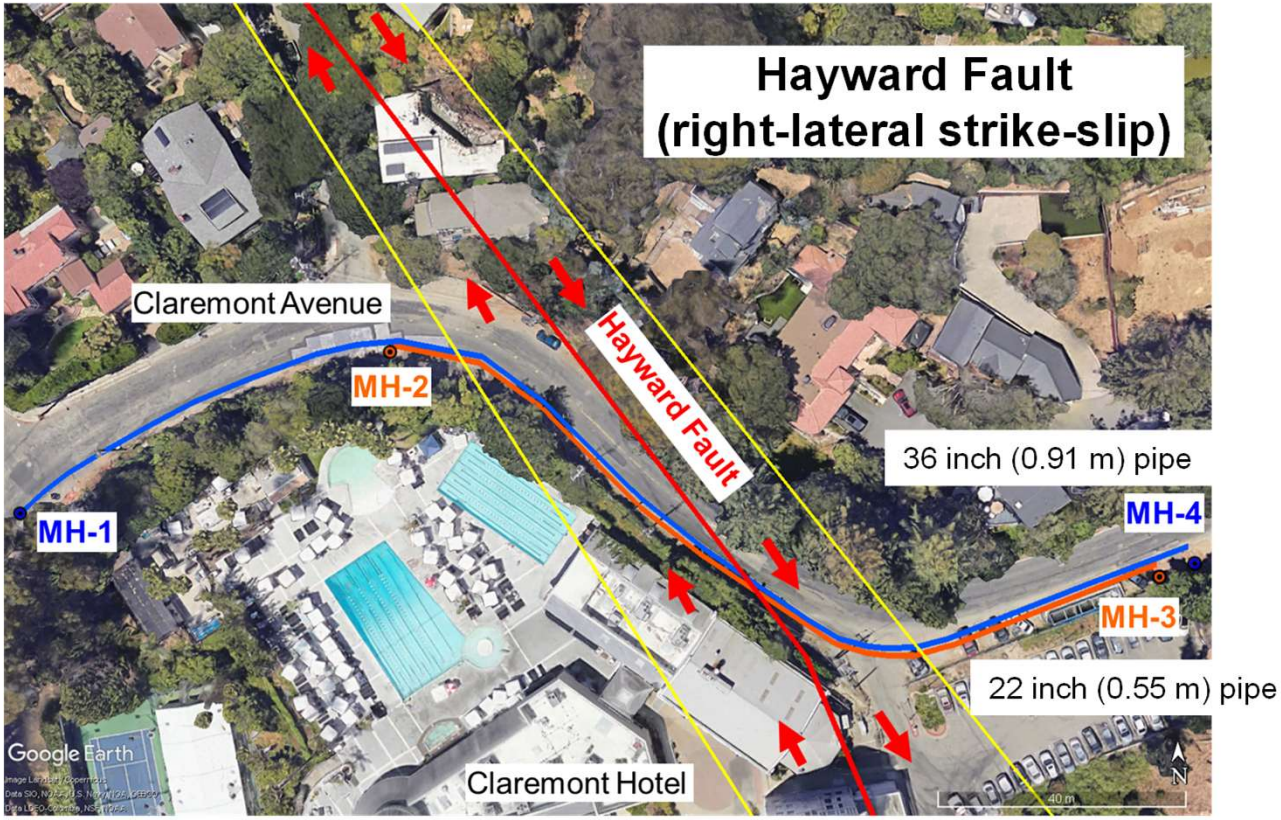


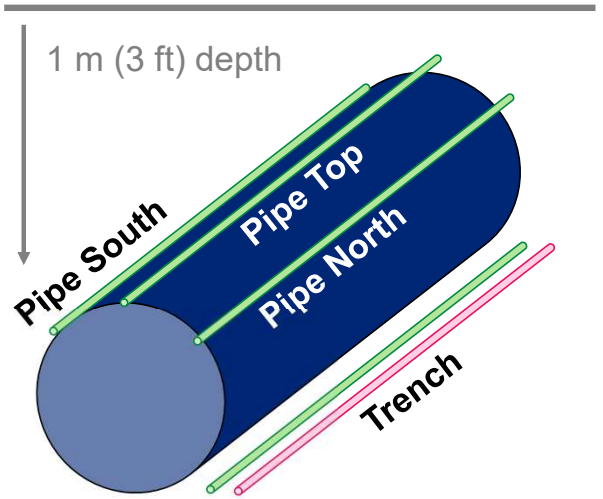



GIS B-Map Viewer
For mapping inquiries, email:
MapUnit@ebmud.com
Enter search parameters...
WT
107 m
150 m
109 m
150 m
Brown Zone 30- 60 m
Pink Zone 60 – 120 m
0.4mi
-122.256216 37.904705 Degrees
esri

バークレーとオークランドに水を供給している重要な基幹パイプライン

ヘイワード断層の横断部は高リスク（年間変位 5 mm）



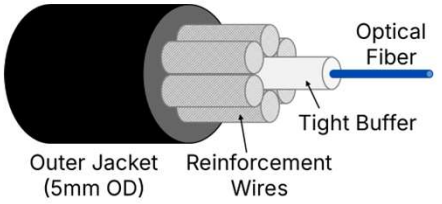


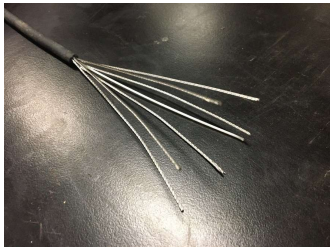
FO cables

Strain Sensing (tight-buffered)

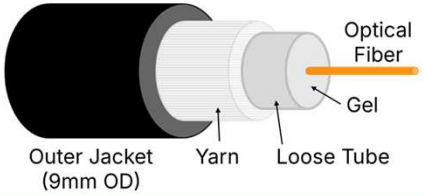
Temperature Sensing (loose-tube

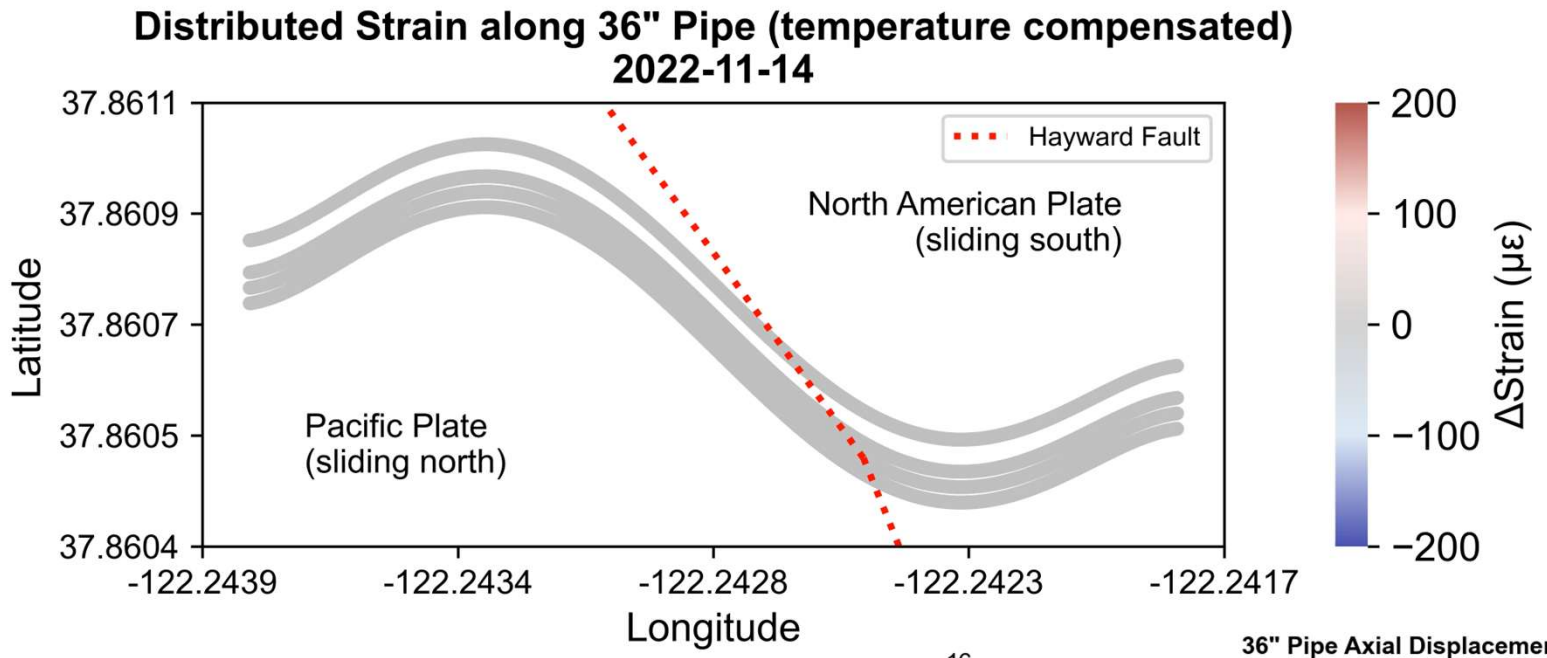
Strain cable

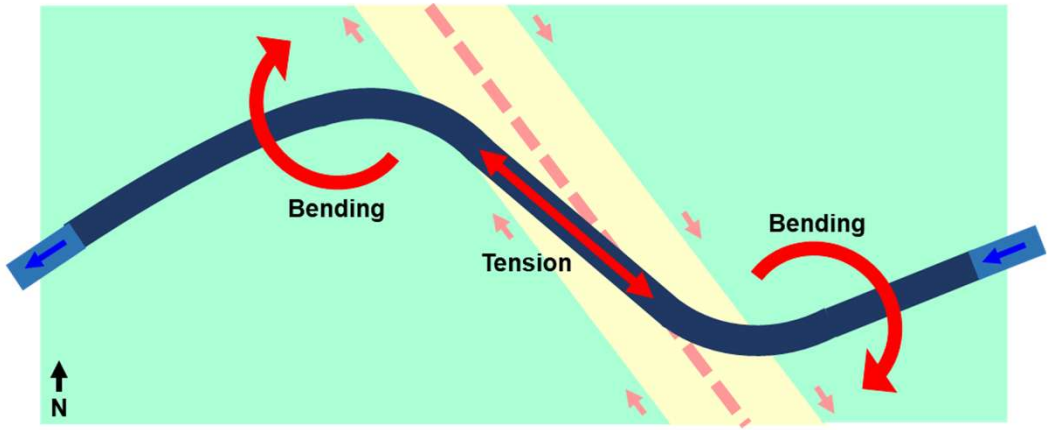


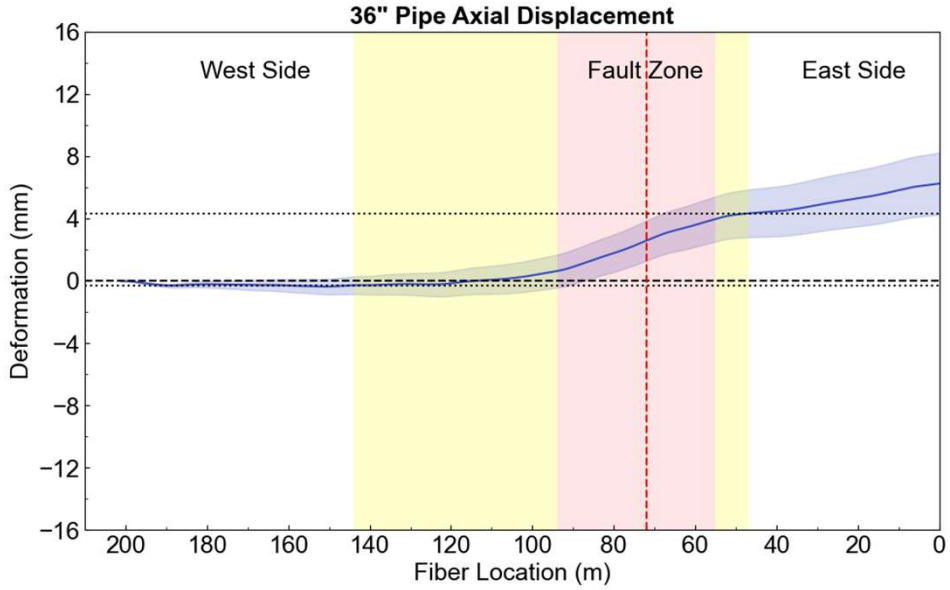


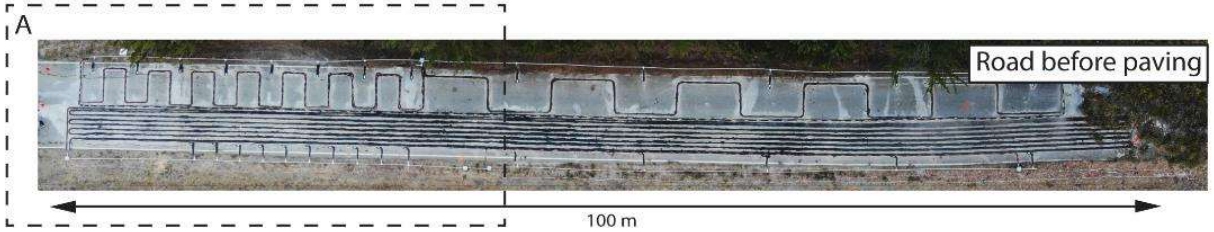
Temperature cable

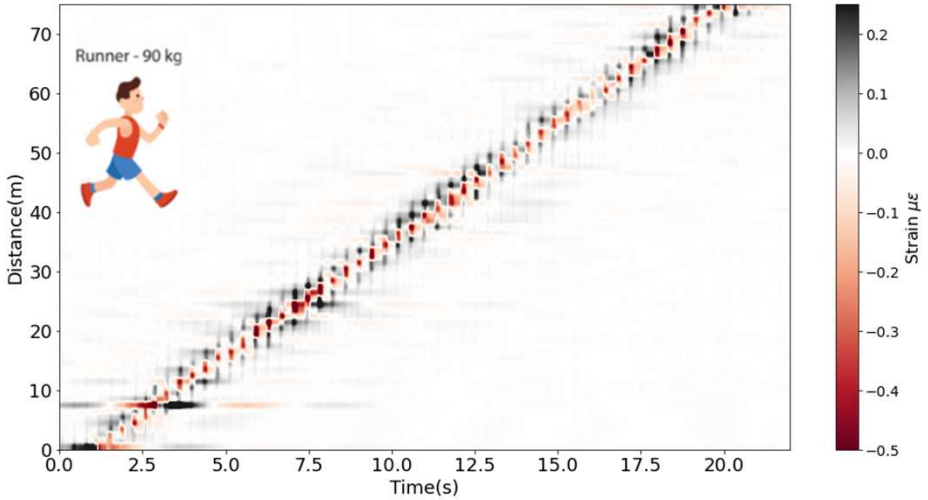


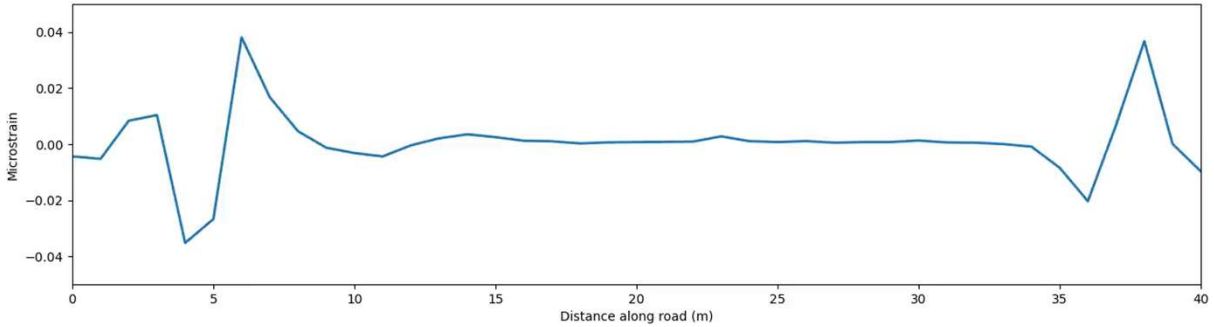

Distributed Strain along 36" Pipe (temperature compensated)
2022-11-14
37.8611
37.8609
37.8607
37.8605
37.8604
Latitude
-122.2439
-122.2434
-122.2428
-122.2423
-122.2417
Longitude
Hayward Fault
North American Plate
(sliding south)
Pacific Plate
(sliding north)
200
100
0
−100
−200
ΔStrain (με)

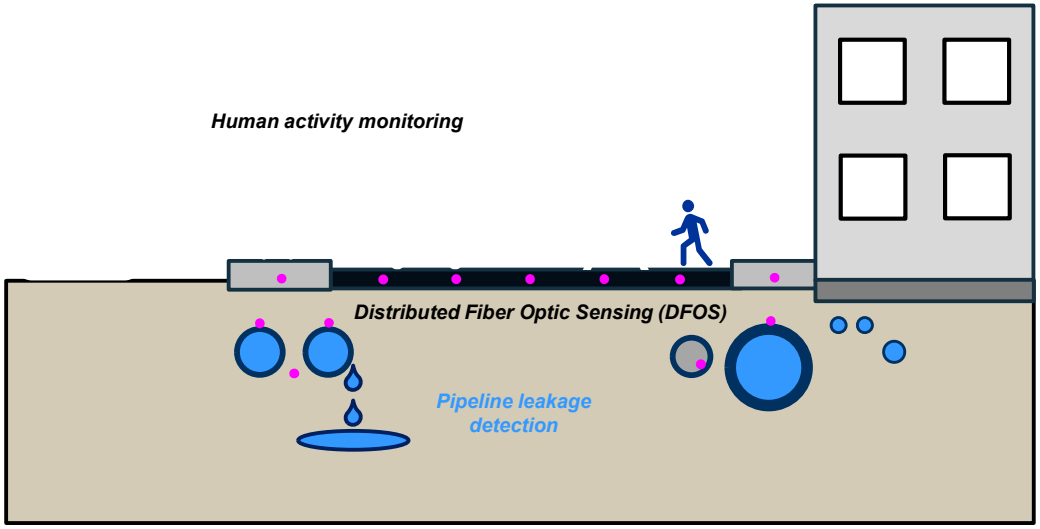

Bending
Tension
Bending
N

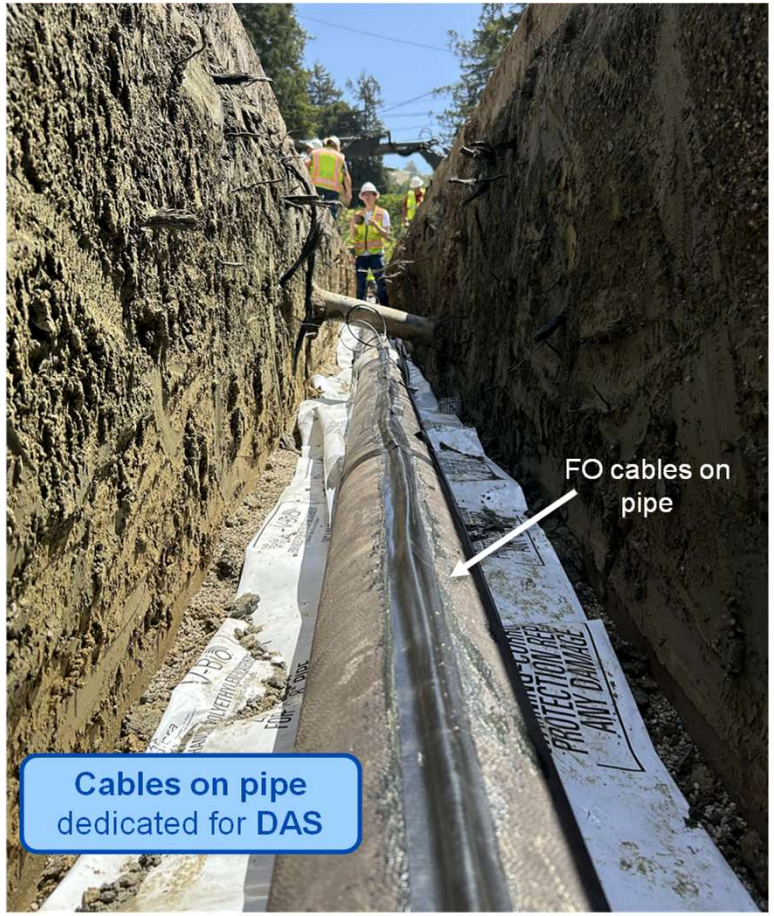

36" Pipe Axial Displacement
West Side
Fault Zone
East Side
16
12
8
4
0
−4
−8
−12
−16
Deformation (mm)
200
180
160
140
120
100
80
60
40
20
0
Fiber Location (m)


A
Road before paving
100 m


Runner - 90 kg
Distance(m)
Time(s)
Strain με


Microstrain
Distance along road (m)

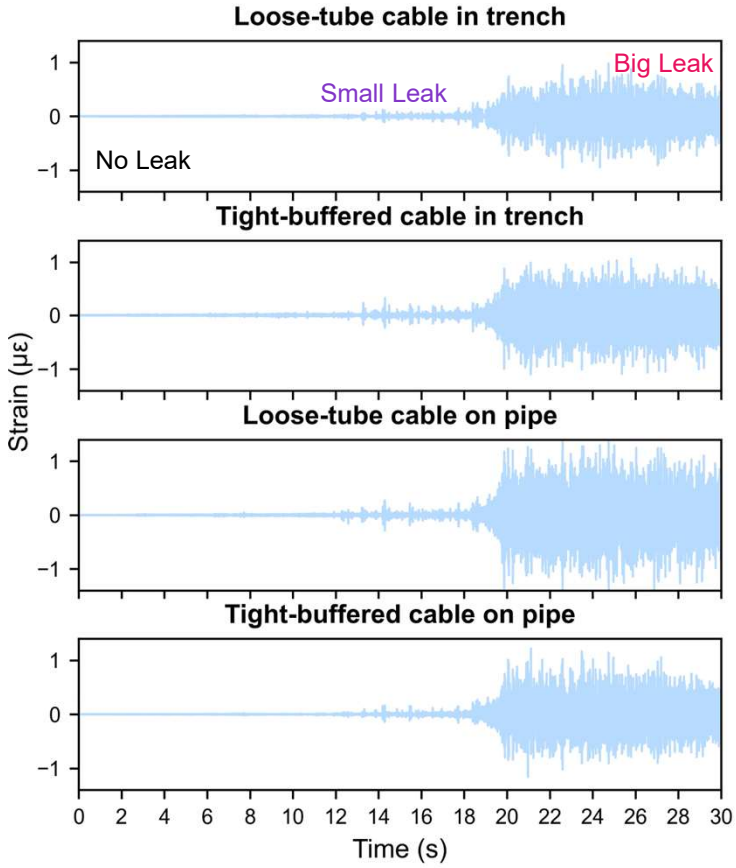


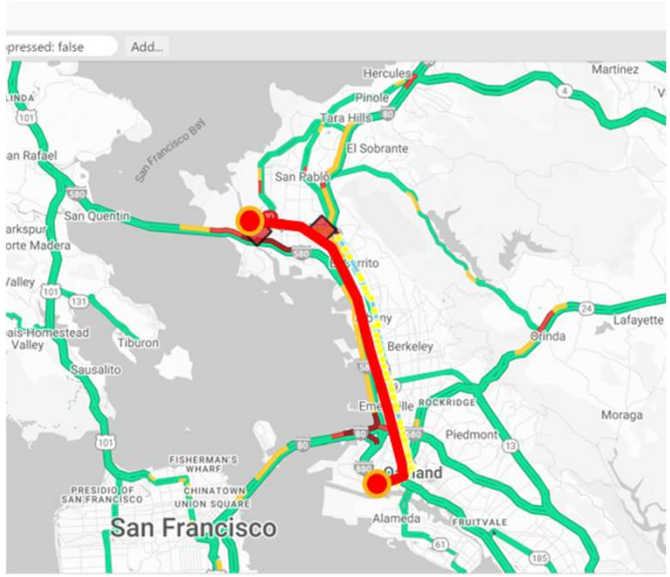


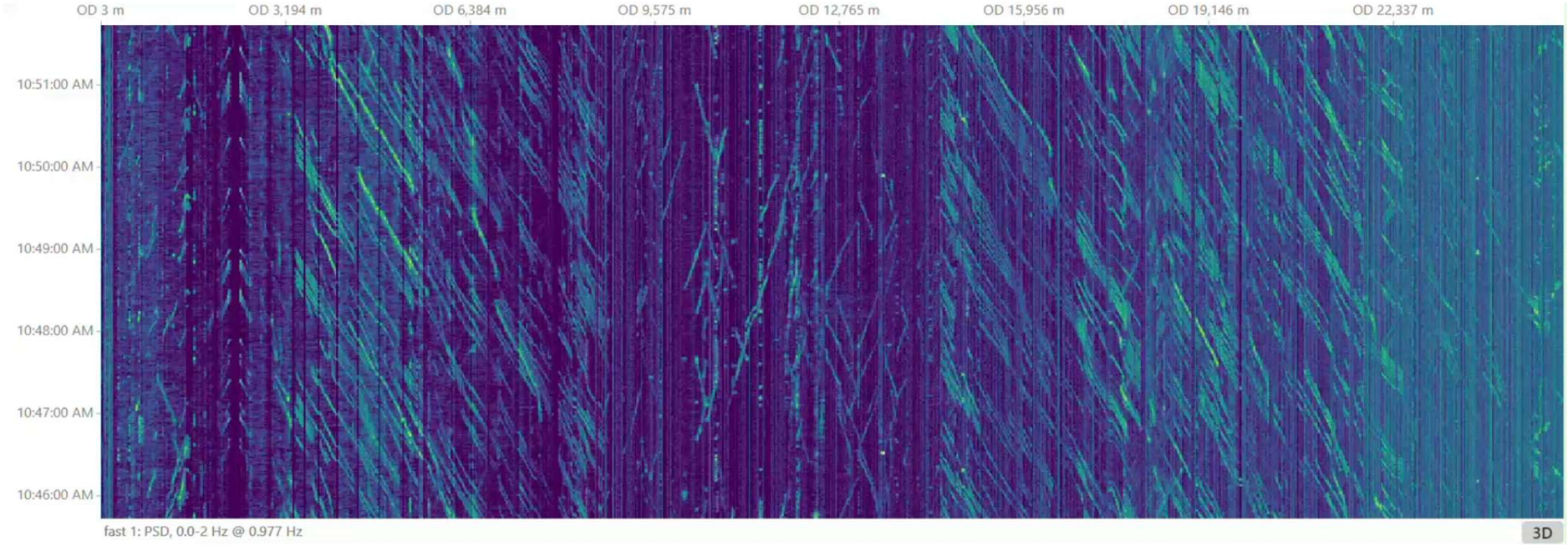
FO cables on pipe

DAS strain timeseries converted to audio

FO cables in trench

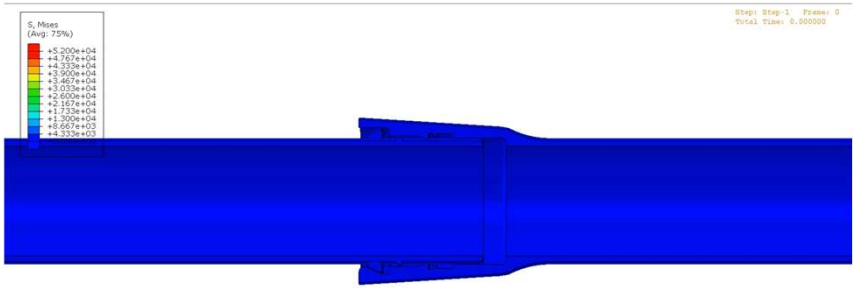


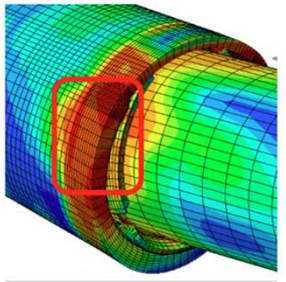

Hercules
Martinez
Pinole
Tara Hills
El Sobrante
San Rafael
San Francisco Bay
San Pablo
San Quentin
Berkeley
Tiburon
Sausalito
Lafayette
Orinda
Moraga
Piedmont
ROCKRIDGE
FISHERMAN'S WHARF
PRESIDIO OF SAN FRANCISCO
CHINATOWN
UNION SQUARE
Alameda
FRUITVALE
San Francisco

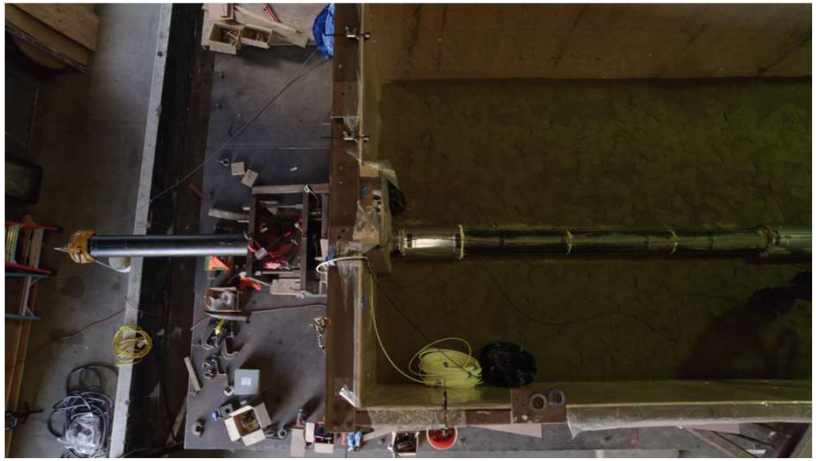

OD 3 m
OD 3,194 m
OD 6,384 m
OD 9,575 m
OD 12,765 m
OD 15,956 m
OD 19,146 m
OD 22,337 m
10:51:00 AM
10:50:00 AM
10:49:00 AM
10:48:00 AM
10:47:00 AM
10:46:00 AM
fast 1: PSD, 0.0-2 Hz @ 0.977 Hz
3D

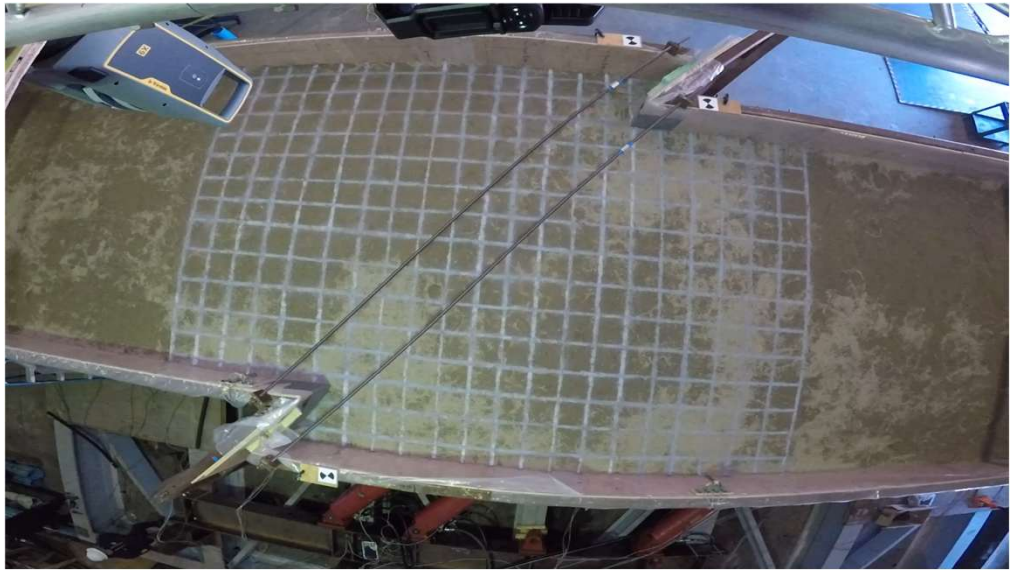
FIBERSENSE®

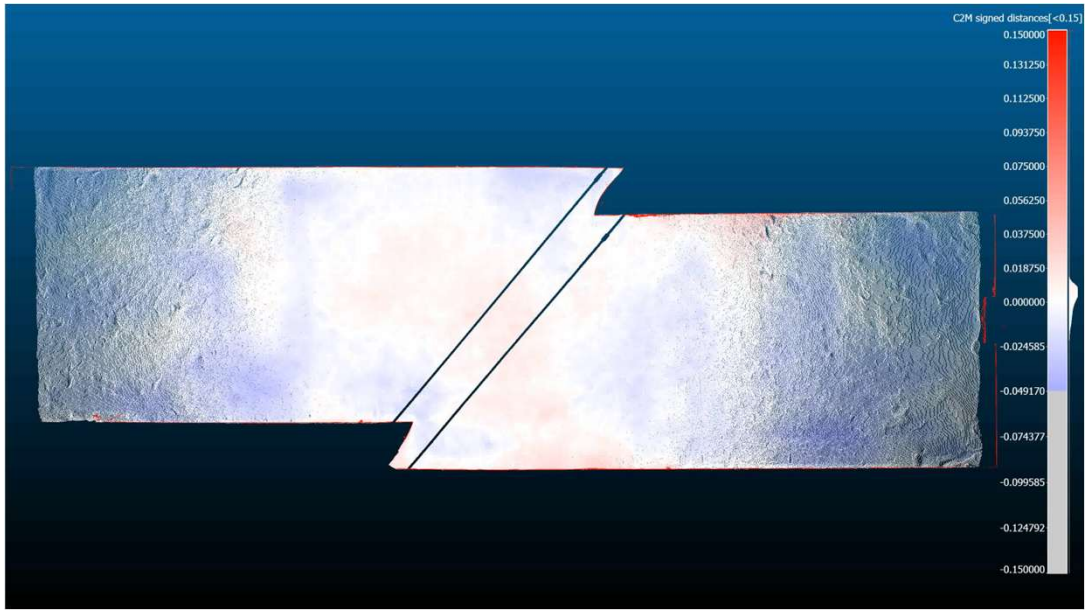
Pipeline Testing










C2M signed distances[<0.15]
0.150000
0.131250
0.112500
0.093750
0.075000
0.056250
0.037500
0.018750
0.000000
-0.024585
-0.049170
-0.074377
-0.099585
-0.124792
-0.150000

Leak sound path influenced by leak orientation

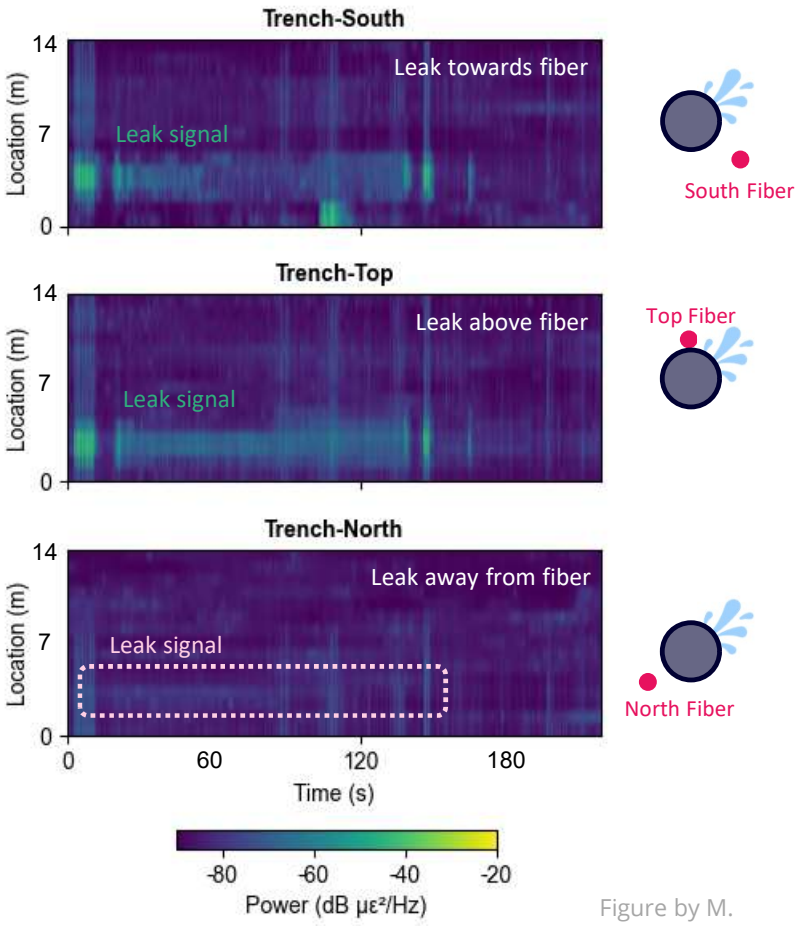
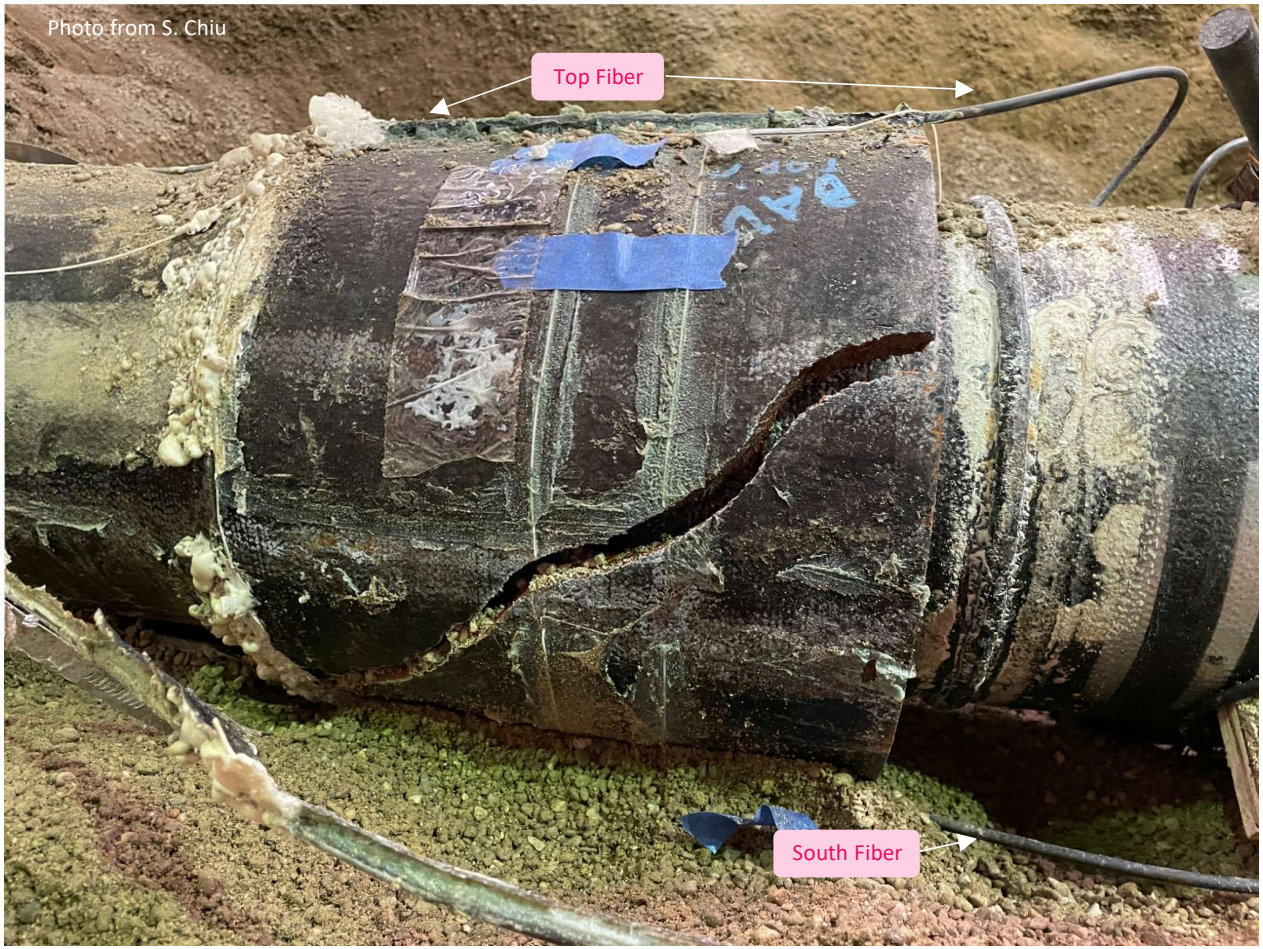
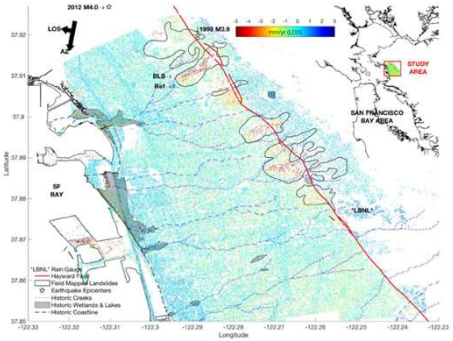


Figure by M. Jasiak



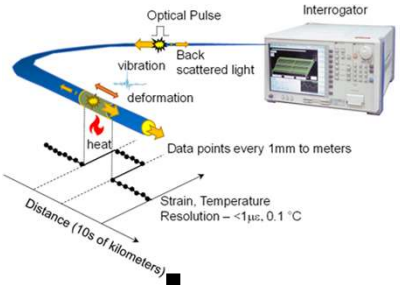
FUNDING PROVIDED BY THE CALIFORNIA ENERGY COMMISSION

InSAR/LiDAR

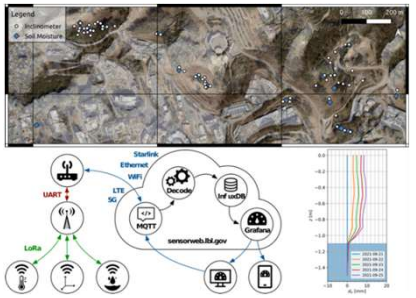


UAV optical and Infrared

Distributed fiber optic sensor



Wireless sensor network



OpenSRA II

Distributed strain information

Initial stage

Field and lab data

Estimated Ground parameters

Estimated structural parameters

Open SRA Model

Action parameters

Ground Movements

Updating stage(s)

Monitored structure

Monitored ground actions

Updated 'system' Ground and Structural parameters

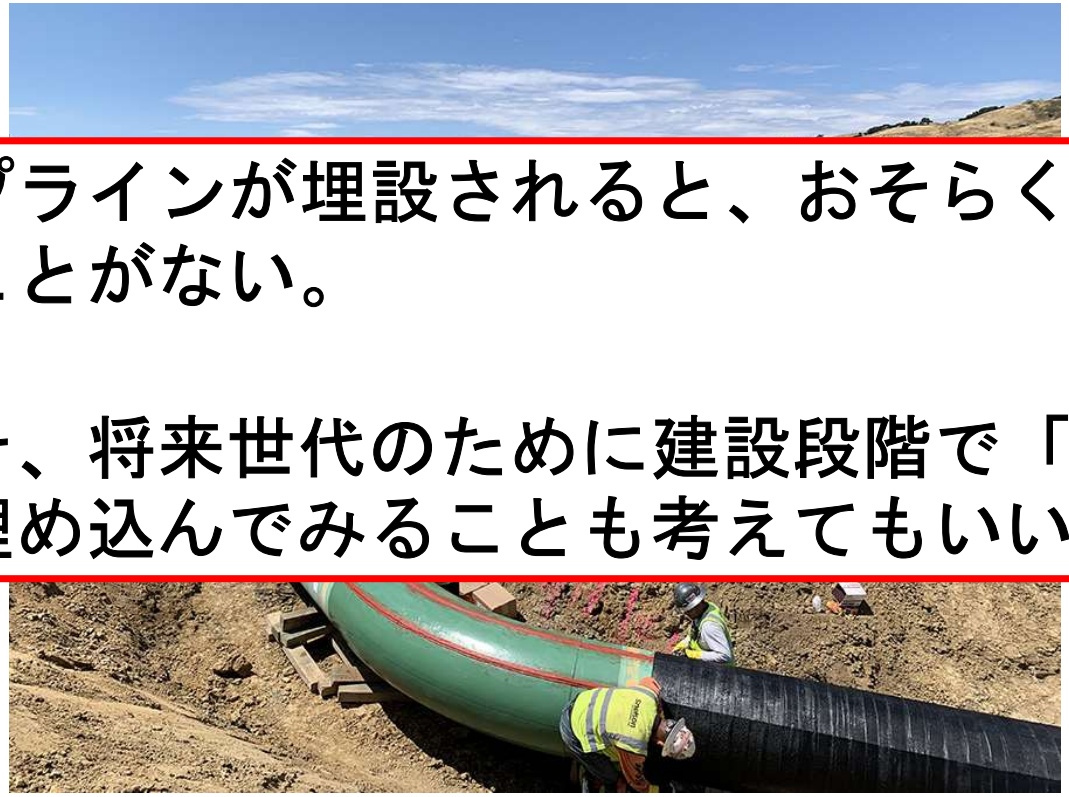
Most Probable Parameters Determining Methods

Updated Model

Assessment stage(s)

Improved model outputs for future performance

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

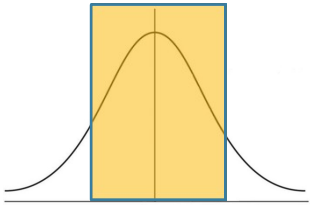


一度パイプラインが埋設されると、おそらく次の100年間は目にすることがない。

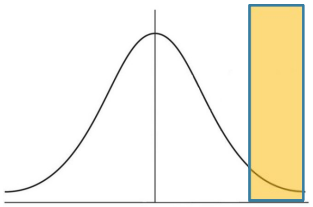
だからこそ、将来世代のために建設段階で「インテリジェンス」を埋め込んでみることも考えてもいいかもしれない。

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

Data + AI/ML + Computation = Value



Data + AI/ML + Computation
+ (Learn + Anticipate + Respond) = Value



「健全なエンジニアリング上の判断」を
「正しい選択と意思決定」につなげる。

“Identify pipes that will break before they have broken”

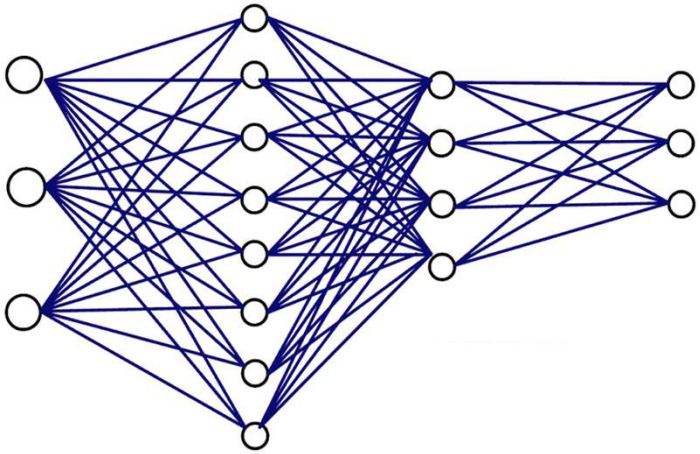
- **Simplified coefficient Models**

$$Score = b_1x_1 + b_2x_2 + b_3x_3 \ldots b_kx_k$$

Covariates (e.g., age, materials…)

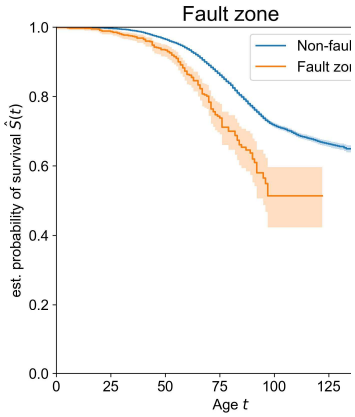
- **Machine Learning Models**

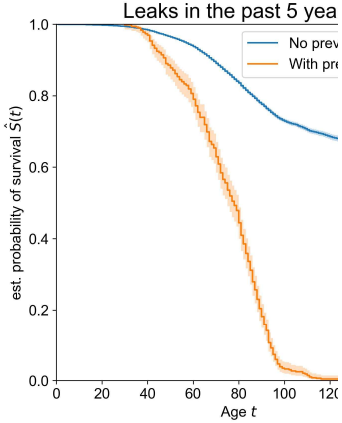
Input Parameters
- Material
- Age
- Diameter
- Soil
- Traffic
- Fault
- Landslide
- Liquefaction
- ….

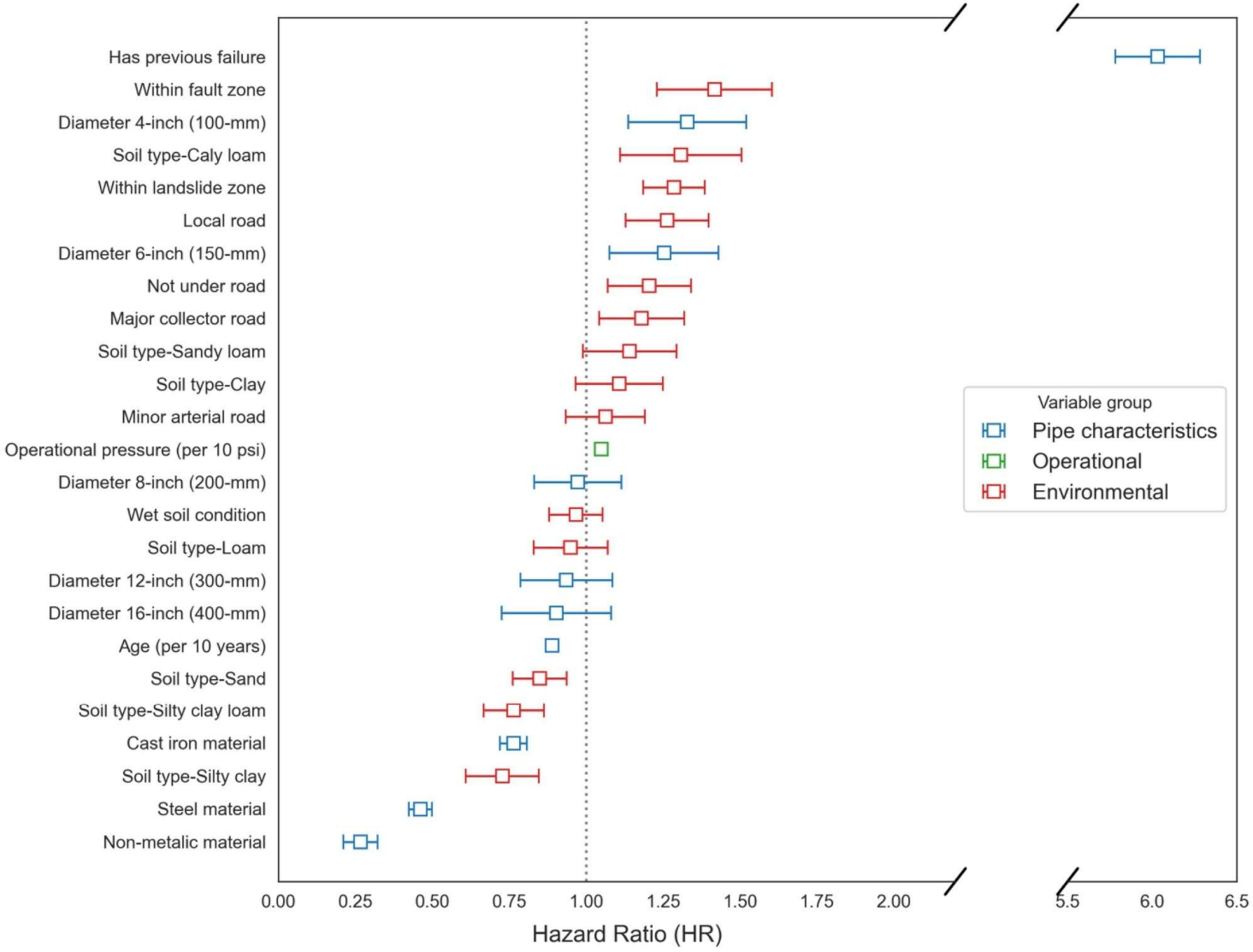


Output Results
- Pipe condition
- **Remaining useful life**

- **Emerging techniques**
- **Data-driven, but…**
- **How do we interpret/ understand/ validate the prediction results?**
- **Unaccountable for wrong predictions?**







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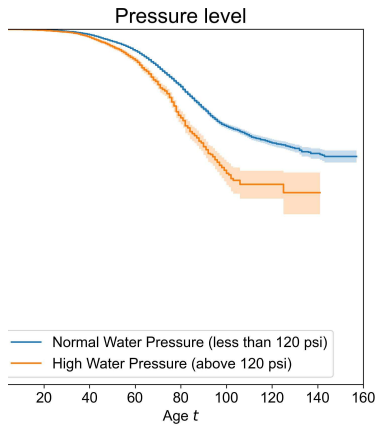
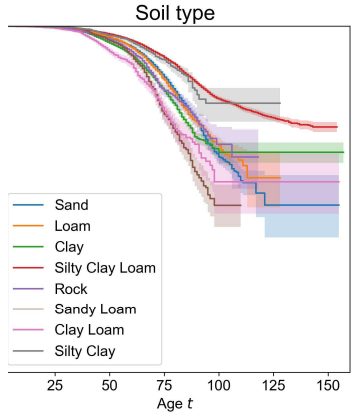
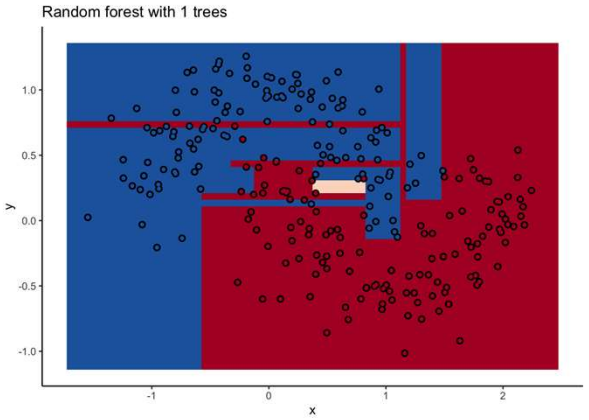


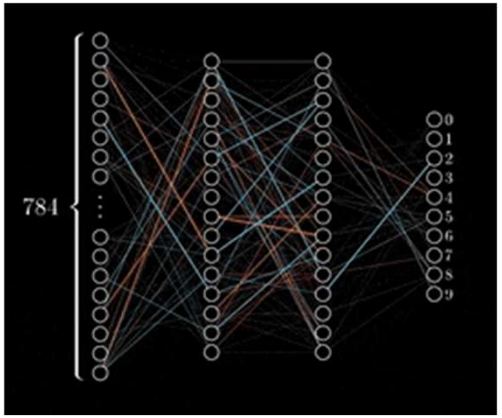


Random Forests

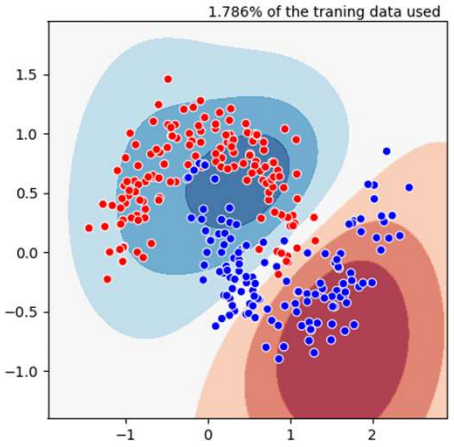


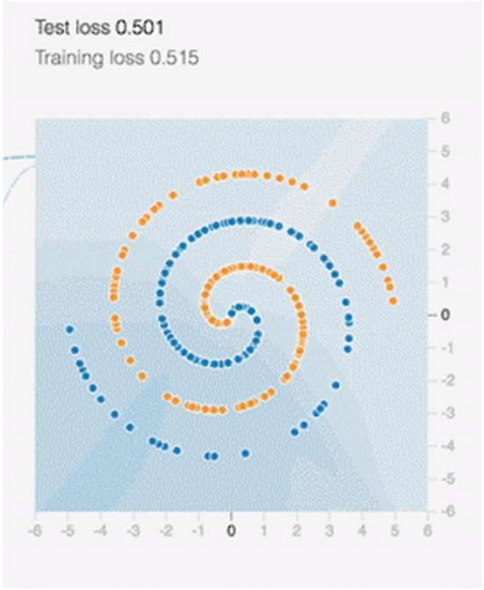
http://www.statistics.cool/post/why-do-random-forests-work/

Neural networks



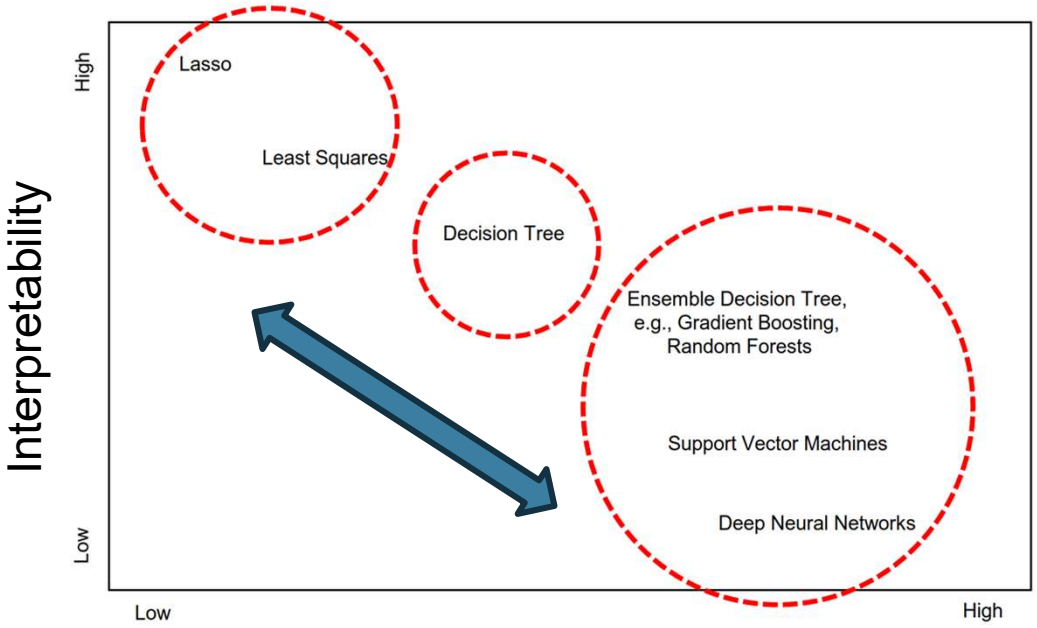
Support Vector Machine





https://towardsdatascience.com/the-simplest-way-of-making-gifs-and-math-videos-with-python-aec41da74c6e

Model flexibility versus Interpretability

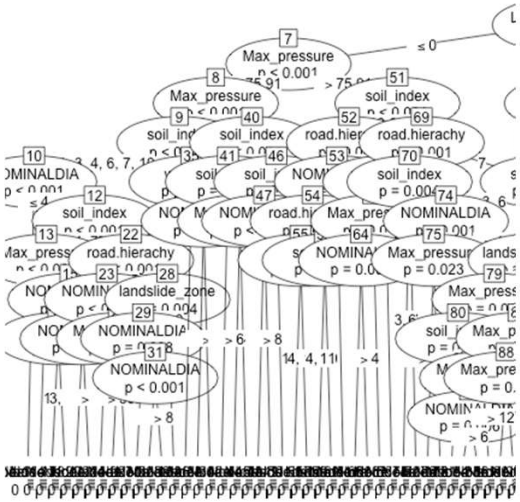


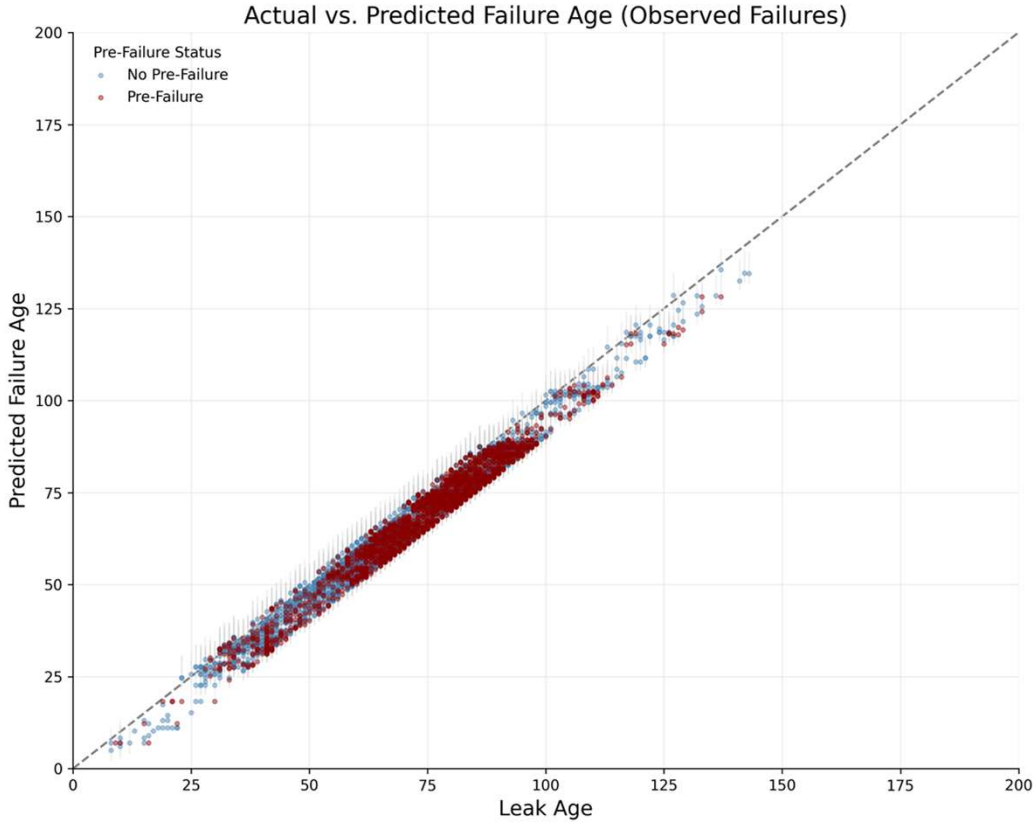
“Personalized survival curve for each pipe”

Left-Truncated and Right-Censored tree based on Conditional Inference Tree (LTRCIT)

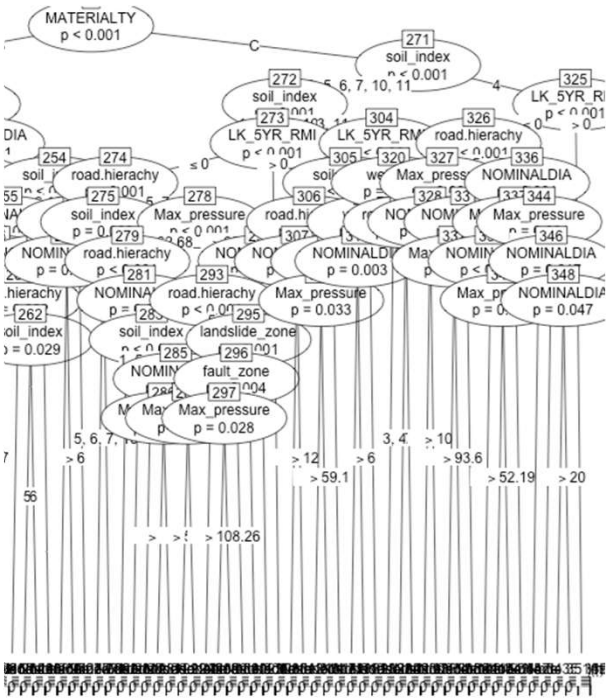
Features (All):

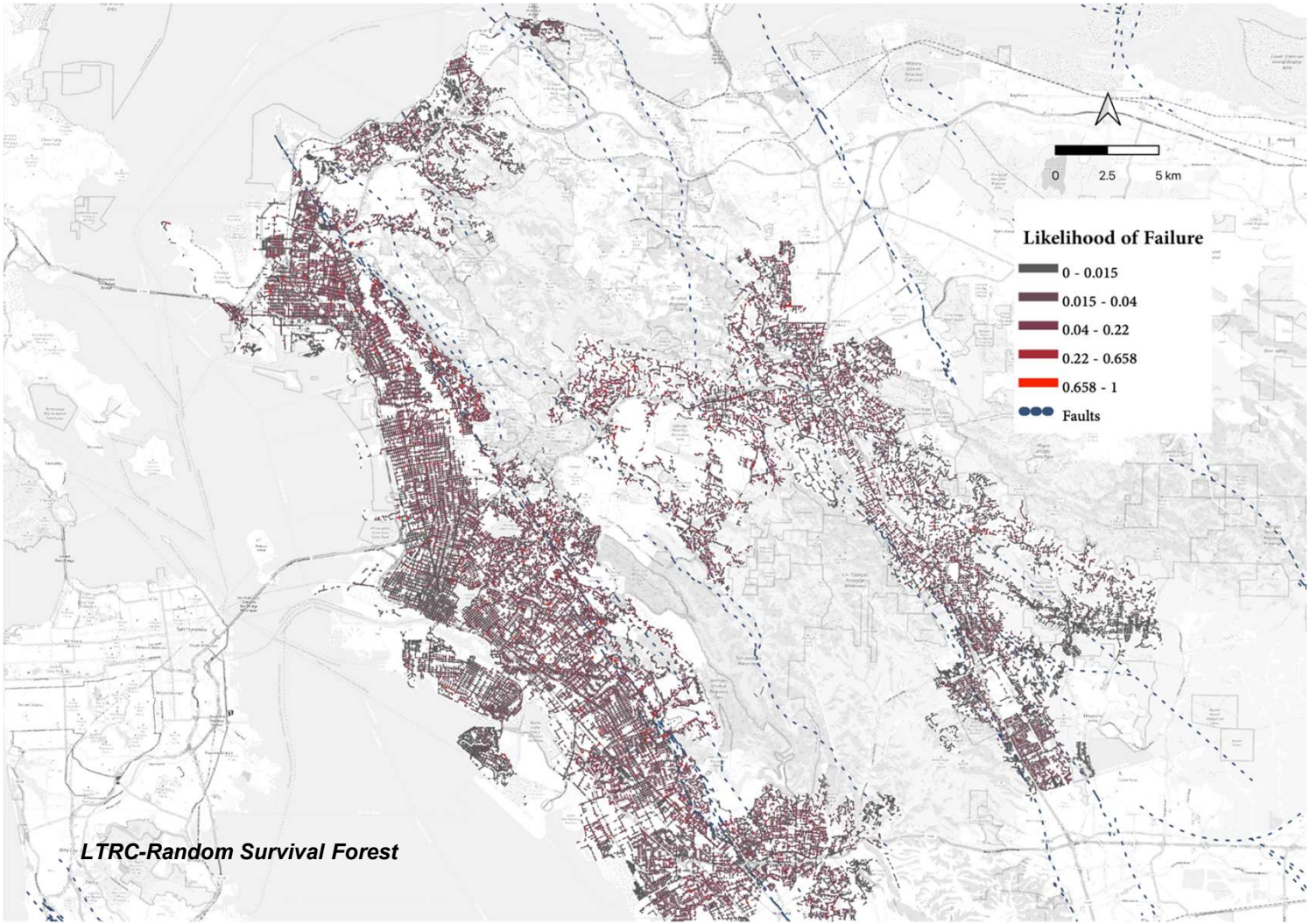
"landslide_zone", "fault_zone", "MAT



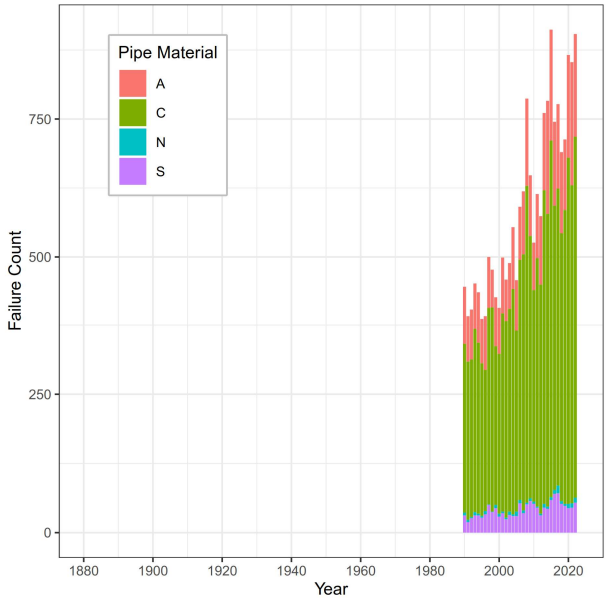


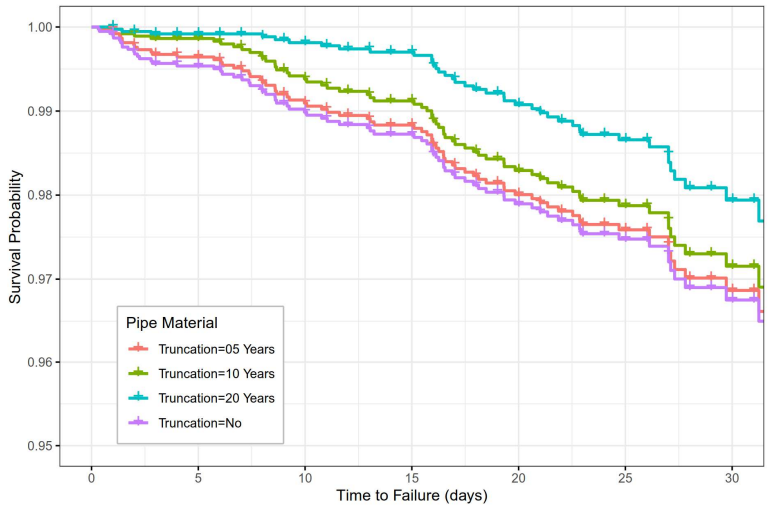
wet_flag", "road.hierachy"




0
2.5
5 km
Likelihood of Failure
0 - 0.015
0.015 - 0.04
0.04 - 0.22
0.22 - 0.658
0.658 - 1
Faults
LTRC-Random Survival Forest

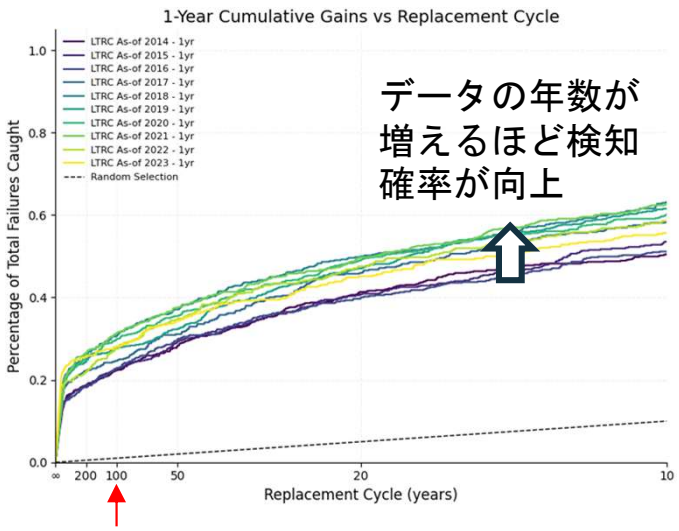
(Left-Truncated and Right-Censored tree based on Conditional Inference Tree





過去のデータを使って次の年の破損を予想

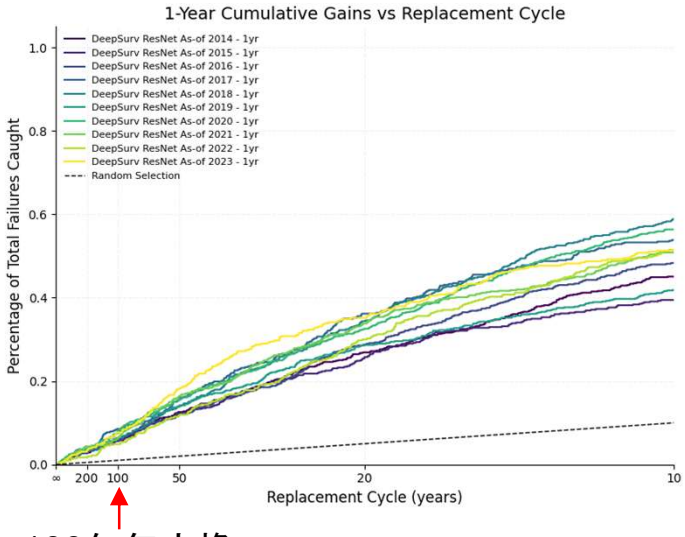
LTRC (Random Forest)



データの年数が増えるほど検知確率が向上

100年毎交換

DeepSurv (Neural Network)



100年毎交換

- **長期に渡るデータの蓄積は重要である。**
- **最新のAIを使っても検知確率はまだ低い。**
- **小さな破損をモニタリングで検知することが必要である。**

System of Systems

“The benefit of infrastructure is diffused…”

“How do we show the value?”

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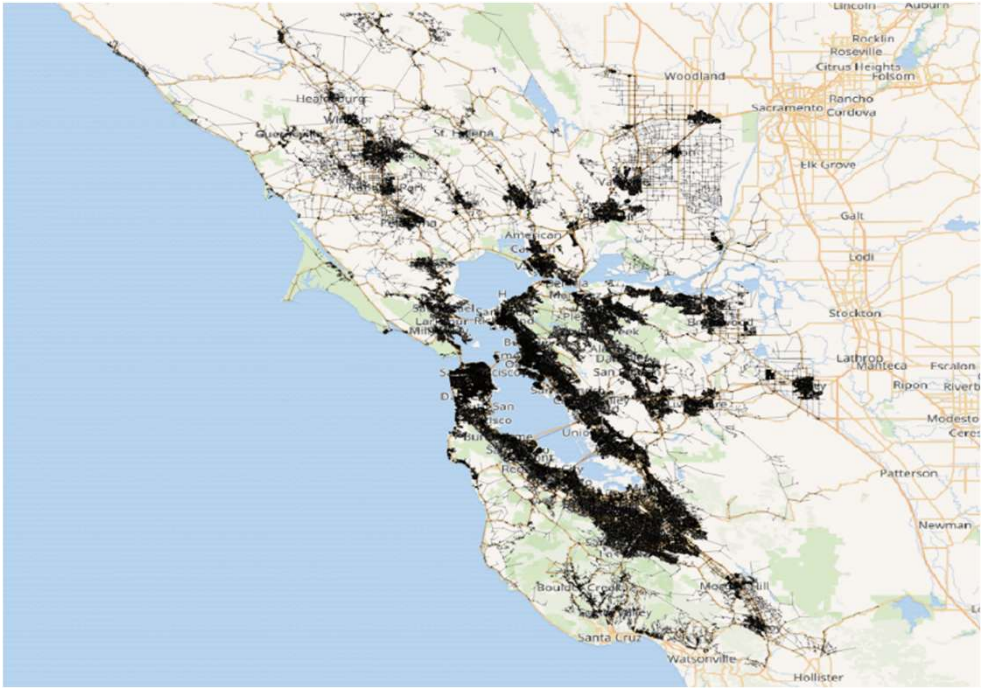
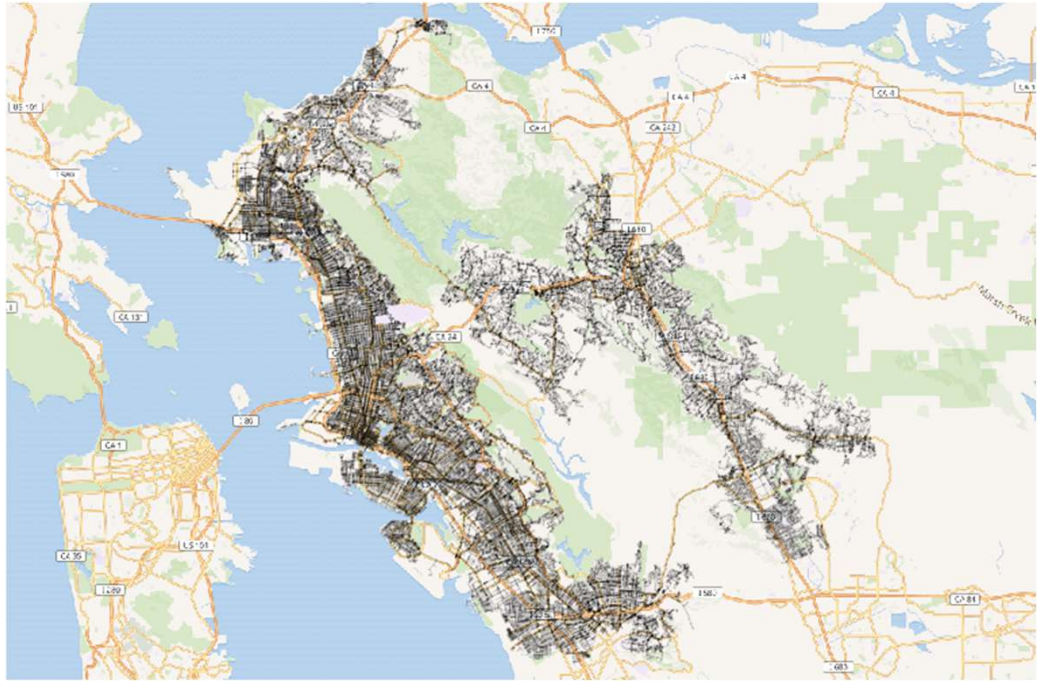
SimCenter NHERI Center for Computational Modeling and Simulation

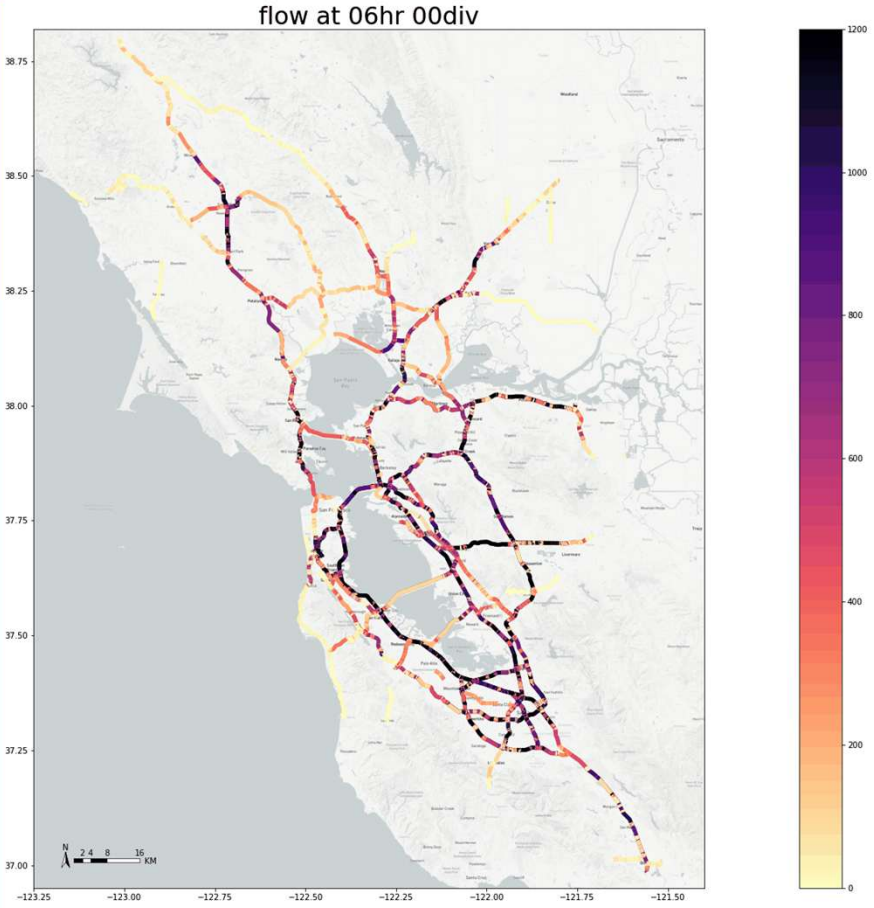
Road Network
250k nodes, 550k edges (OSM)
7 million people
13 people/road segment



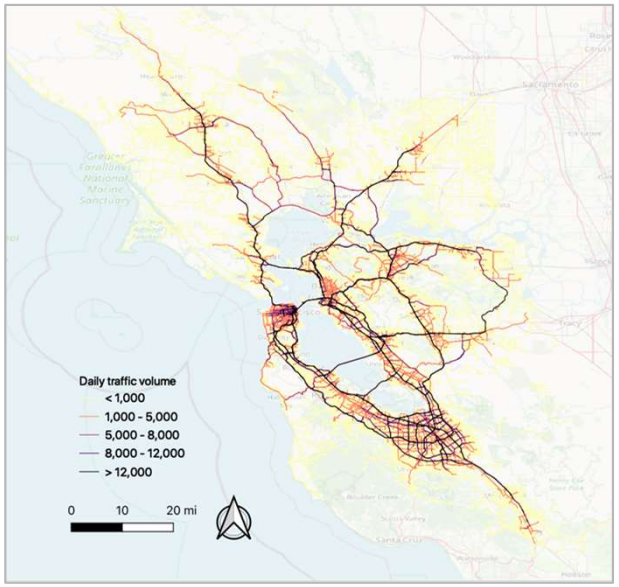
Water Network
100k joints, 100k pipes (EBMUD)
1.4 million customers
14 people/pipe segment



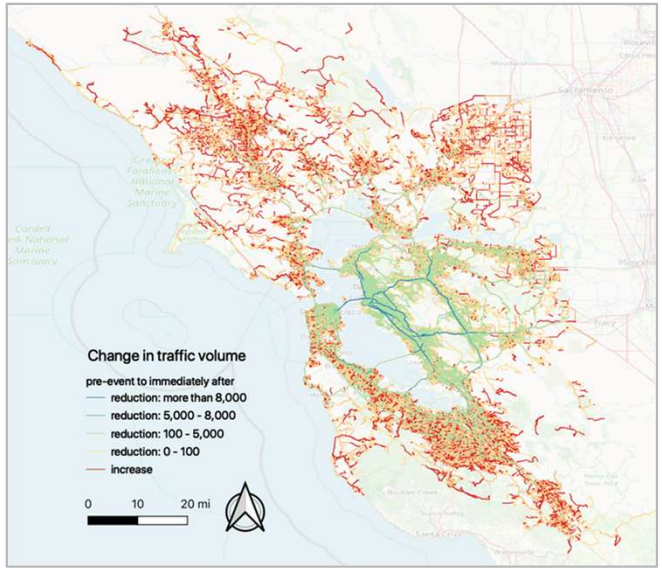
- 9 counties & 7 million people
- Road network: 549,008 links and 224,223 nodes.
- Travel demand: 15 million trips (close to the actual number of daily commute trips).
- Bay Bridge daily traffic: ~260,000



Pre-event traffic volume on Bay Area roads

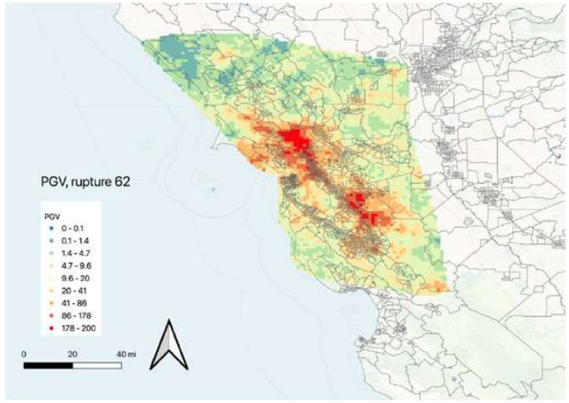


Change in traffic volume Pre-event to immediately after

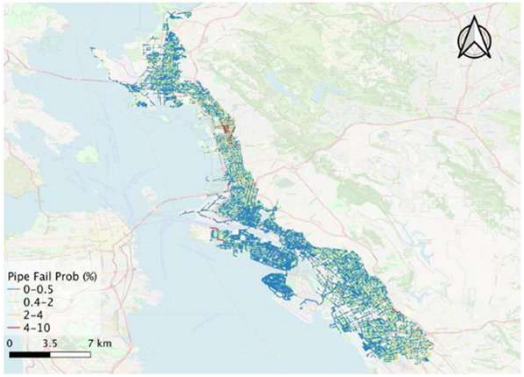


Water pipeline damage after an earthquake
Hayward Fault Earthquake in the East Bay Area
4,200 miles of pipeline

Step 1. EQ scenario + Site characterization

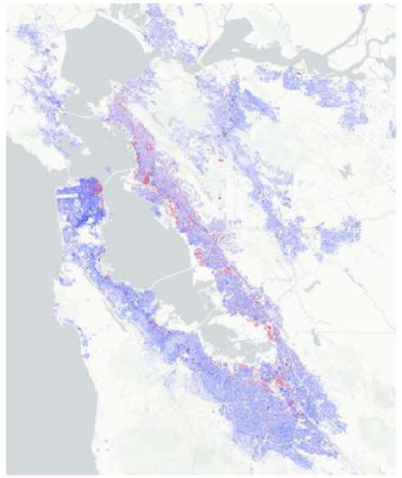


Step 2. Pipe damage

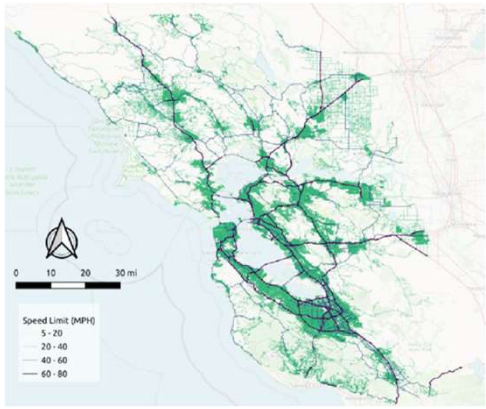


Step 3. Water network

Red tagged building



Traffic disruption

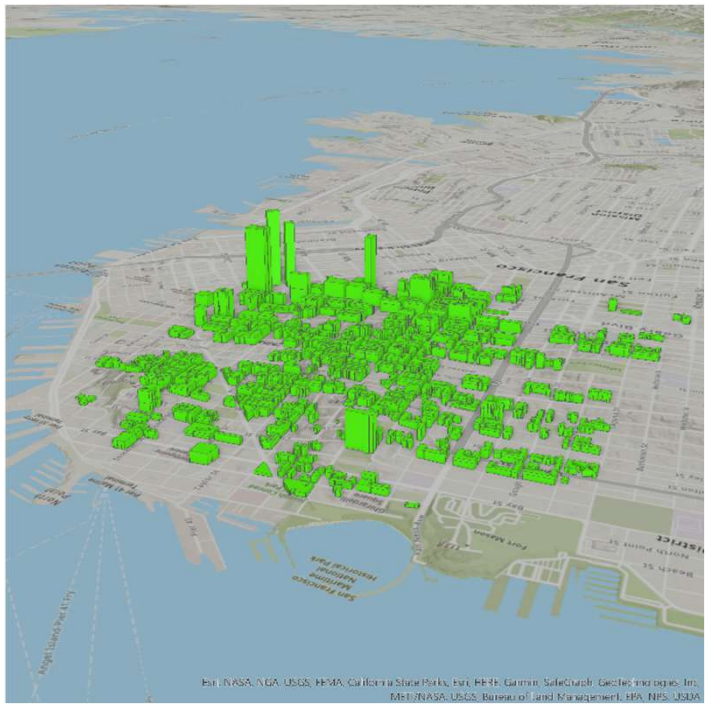


Interdependency

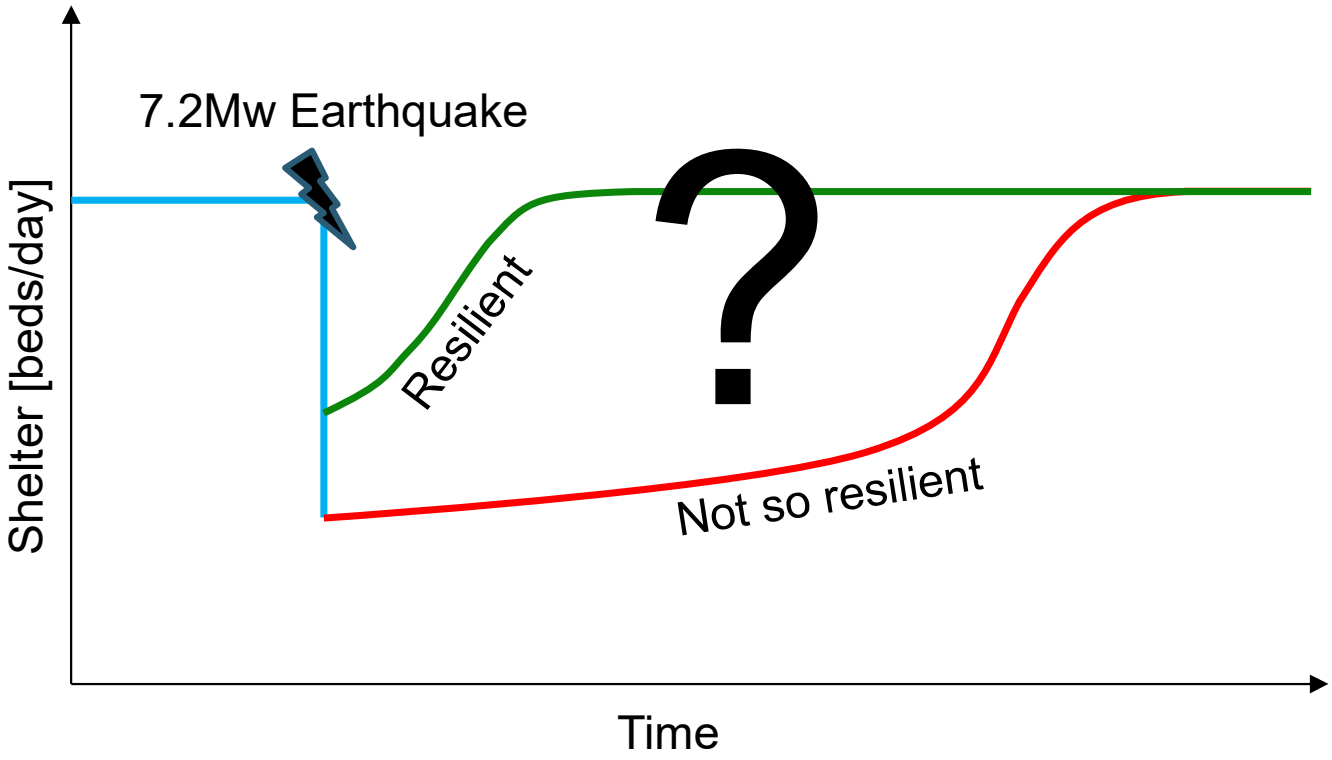
Average water shortage Standard deviation

Recovery, repair (values etc)

Case Study: Housing Resilience of North-East San Francisco

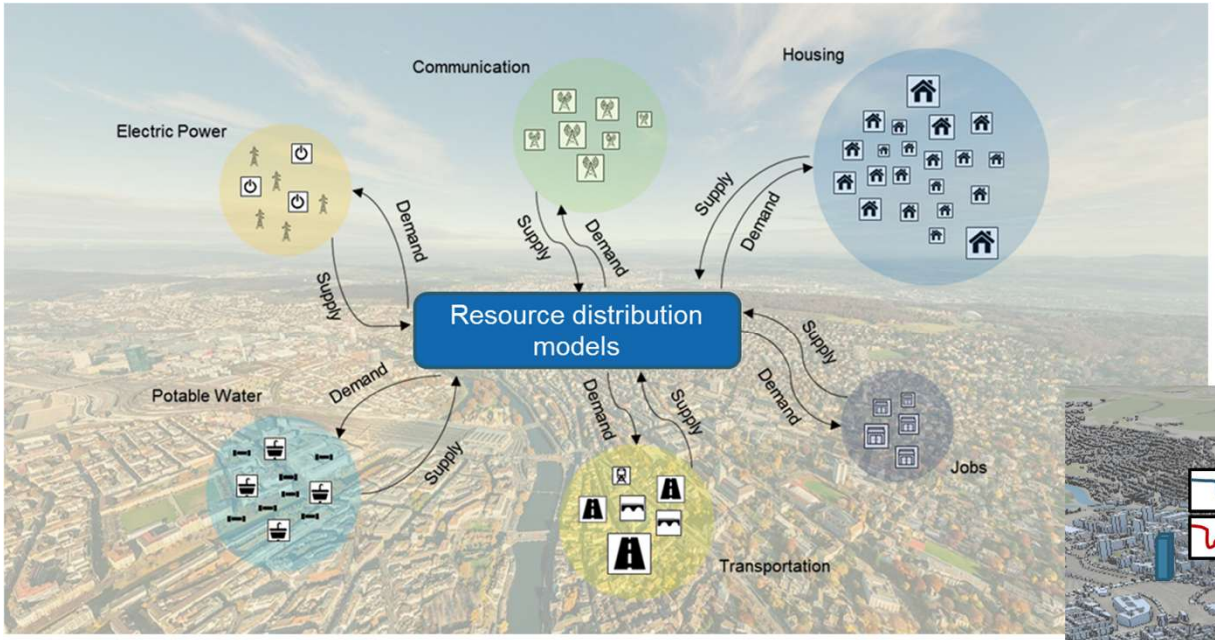


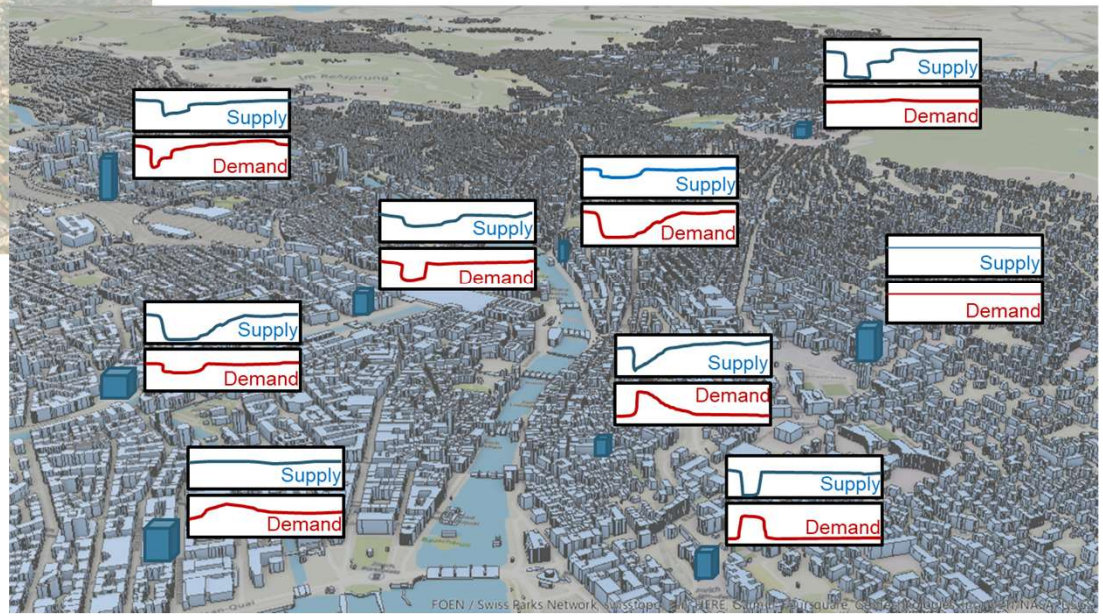
Residential buildings considered in the Case Study.



Blagojević and Stojadinović (2022) *A Demand-Supply Framework for Evaluating the Effect of Resource and Service Constraints on Community Disaster Resilience.* Resilient Cities and Structures.

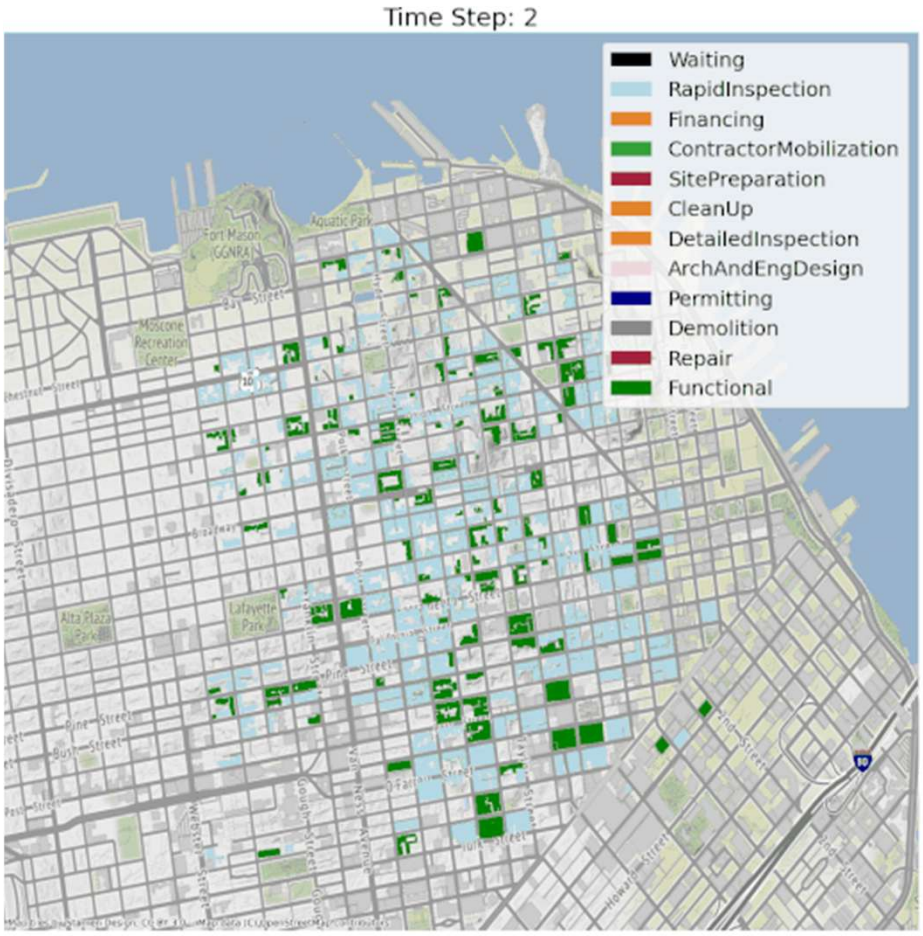
Component interdependencies simulated as a flow of resources and services

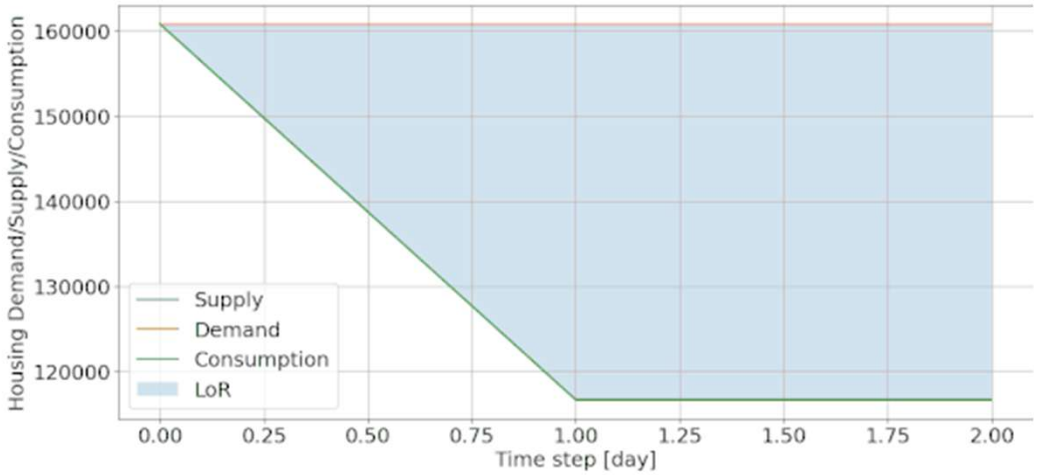


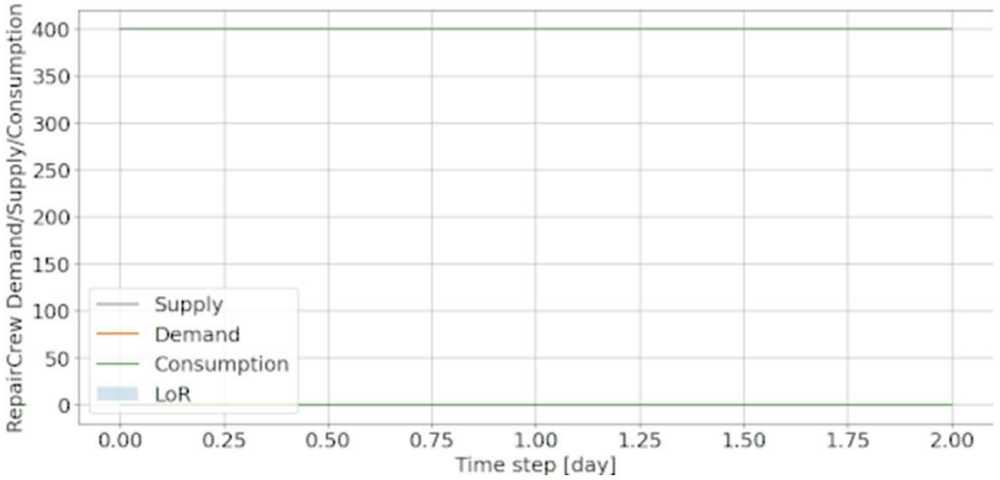


Blagojević, Hefti, Henken, Didier, Stojadinović (2022) *Quantifying Disaster Resilience of a Community with Interdependent Civil Infrastructure Systems.* Structure and Infrastructure Engineering.

Housing recovery of North-East San Francisco







Blagojević and Stojadinović (2022) *A Demand-Supply Framework for Evaluating the Effect of Resource and Service Constraints on Community Disaster Resilience.* Resilient Cities and Structures.

まとめ

- 最近のセンサー技術およびデータ分析のイノベーションは、施工中および維持管理段階におけるインフラの実際の性能を理解するうえで、非常に有望な機会を提供していると考えられる。例えば、分布型光ファイバーは、他のセンサーでは得られない分布ひずみデータを提供できる。

- モニタリングシステムは、施工パッケージの一部として組み込まれるべきである。これにより、長期的かつ積極的な維持管理モニタリングが可能となり、品質管理、保守、災害への強靭性の向上および再利用に貢献できる。

- 次世代の観測工法とは、設計計算とモニタリングの積極的な統合（デジタルツイン）を意味している。つまり、モニタリングデータから学ぶことで、工学的パラメータだけでなく、インフラシステムとしての不確実性を理解することができる。

ご清聴ありがとうございました。

https://www.youtube.com/watch?v=5AxzE7RSGJk

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https://smartinfrastructure.berkeley.edu/

“The Campanile”
UC Berkeley