地盤モニタリングとデジタルトランスフォーメーション

カリフォルニア大学バークレー校
曽我 健一

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Resilient Infrastructure for Sustainability and Equity (RISE)
サステナビリティと公平性を考慮した強靭なインフラ

Berkeley Engineering

Berkeley Center for Smart Infrastructure

PEER

ITS Berkeley Institute of Transportation Studies

CITRIS and the Banatao Institute

Berkeley Water Center

UC Berkeley SWARM LAB 2.0

SimCenter NHERI Center for Computational Modeling and Simulation

TROST

Berkeley GMS Global Metropolitan Studies

iCyPhy

BERKELEY LAB

UNIVERSITY OF CALIFORNIA

Lawrence Berkeley National Laboratory

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

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BAKAR FELLOWS PROGRAM

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What is the Center for Smart Infrastructure?

我々が直面する最も差し迫った課題に対処するために、インフラ所有者、学術機関、産業界、規制当局の間でのパートナーシップ

老朽化するインフラ
- 気候変動
- 水供給と自然資源
- 緊急事態時の地域社会の準備

強靭で持続可能なインフラシステムを実現するための
- 最先端の実験施設と現場試験
- スマートセンサーとロボティクス
- ビッグデータと機械学習
- マルチスケールのコンピュータモデリングとシミュレーション

"Intelligence for life" を備えたインフラシステムを実現するために、革新的なソリューションを提供する。

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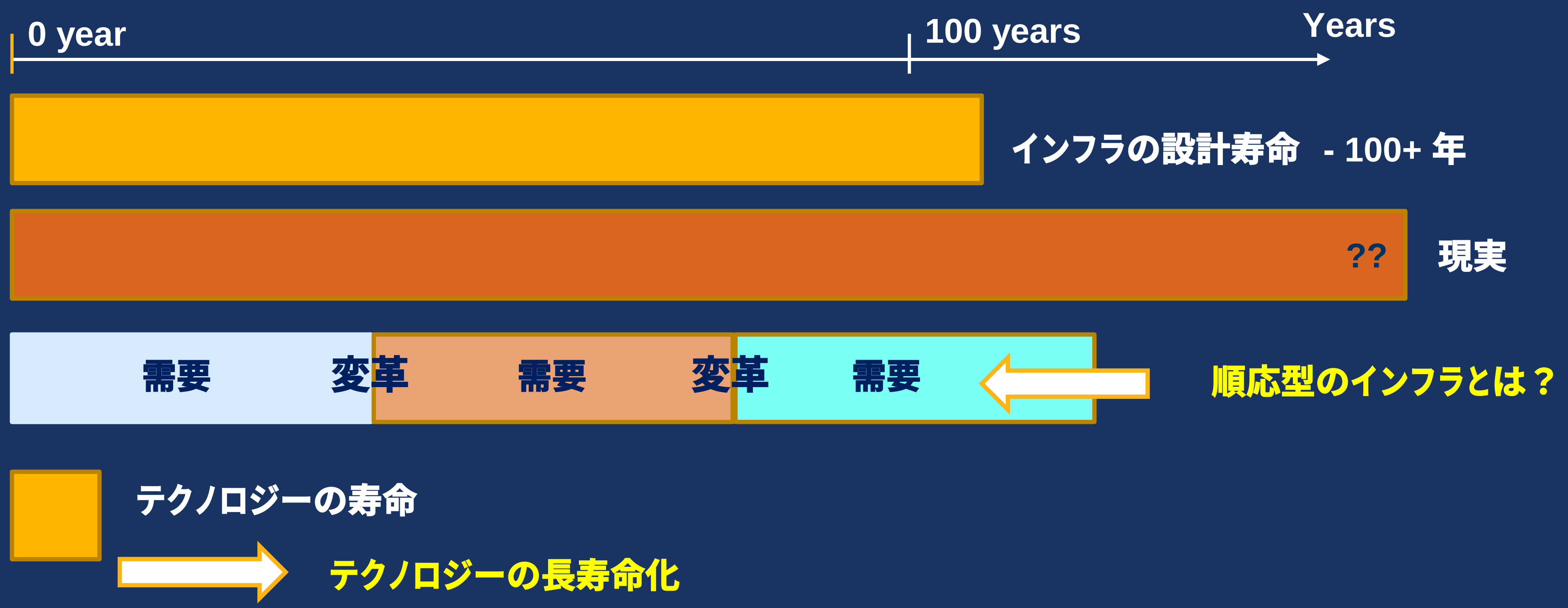

- 都市環境が数十年年単位で変化するため、設計時の予測が現実と異なっている。
- １０年前には深く考えていなかった温暖化による気候の変化に対処するためには、100年設計の概念を再考する必要はないか。
- 順応型のインフラを実現させるには、現時点の状態を把握する必要があり、長い寿命をもつセンシングが求められる。

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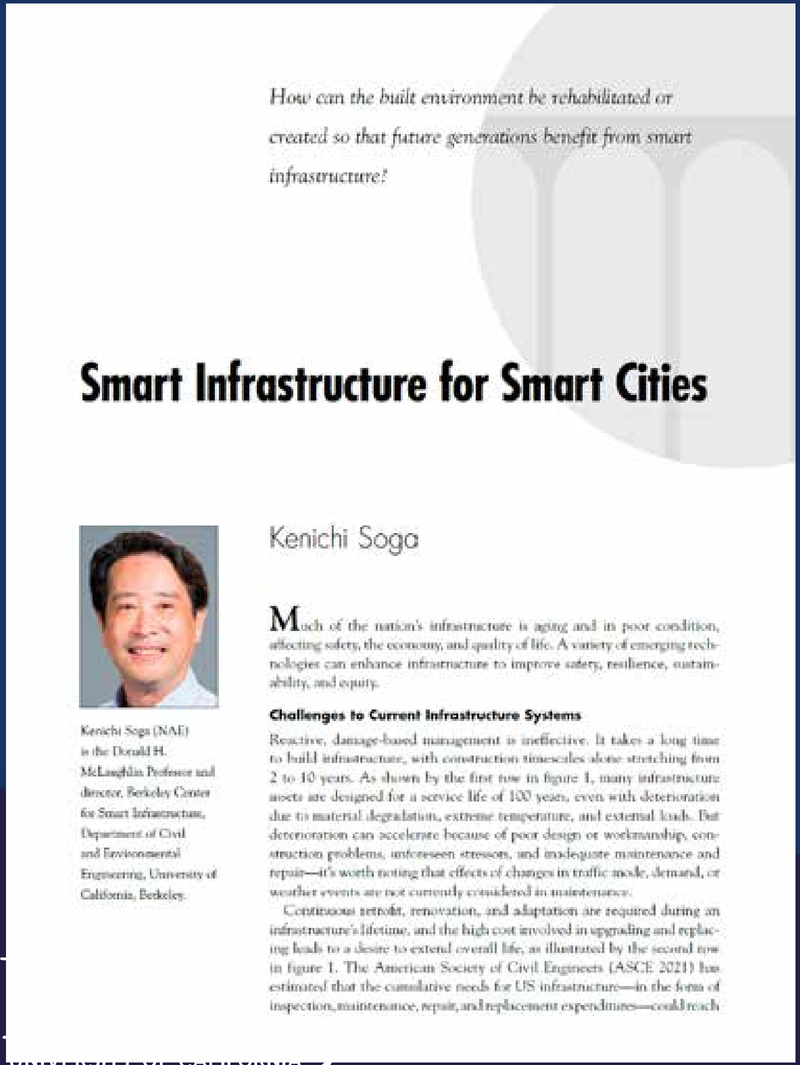
将来の世代が「構築環境」「人工環境」(Built Environment) の恩恵を享受し続けられるようにするためには、どのようにインフラを設計、建設、維持管理すればよいのでしょうか。



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

Smart Infrastructure for Smart Cities

Kenichi Soga

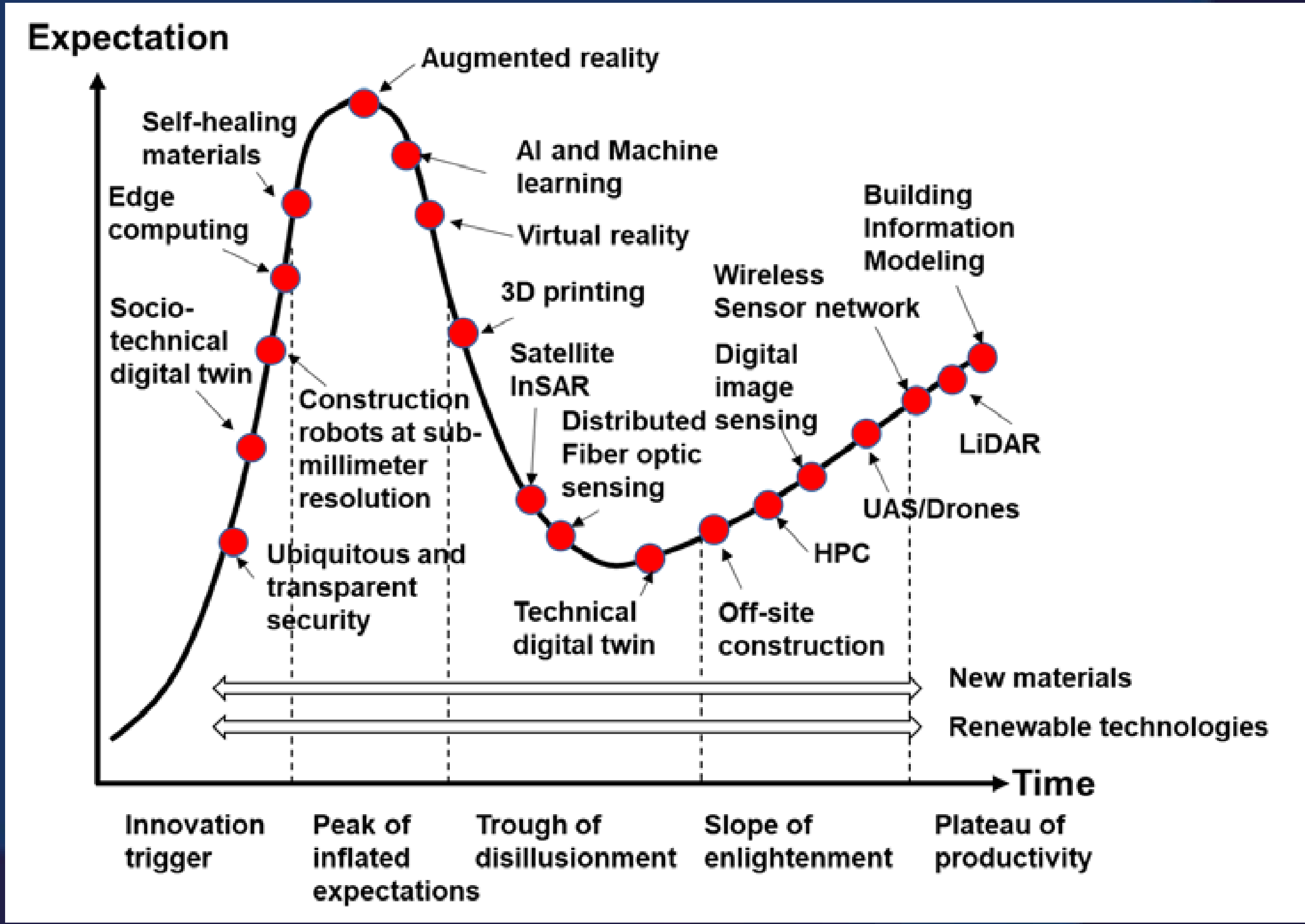
Kenichi Soga (NAE) is the Donald H. McLaughlin Professor and director, Berkeley Center for Smart Infrastructure, Department of Civil and Environmental Engineering, University of California, Berkeley.

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

Examples of Emerging Technologies

ET1 – Distributed sensors and network – Sensors everywhere
ET2 – In-field Autonomy
ET3 – Off-site Autonomy at sub-millimeter resolution
ET4 – From BIM to Socio-technical digital twin
ET5 – High performance computing in the cloud
ET6 – Virtual reality, augmented reality and mixed reality
ET7 – Artificial intelligence and machine learning in extreme events
ET8 – Edge computing
ET9 – Ubiquitous and transparent security
ET10 – New materials – Negative carbon, sensing and adaptive
ET11 – Renewable technologies from micro-scale to mega-scale

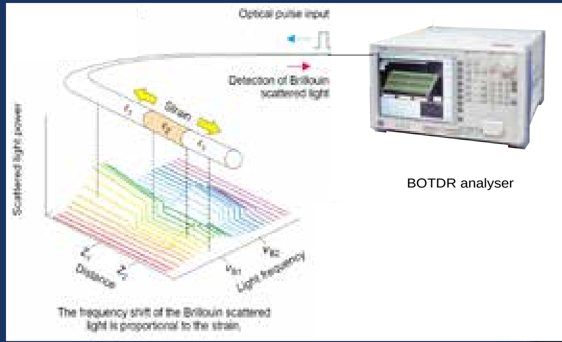
Excitement - Emerging technologies

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 me precision (OFDR/DAS)
- Fibre optics – 10 mm 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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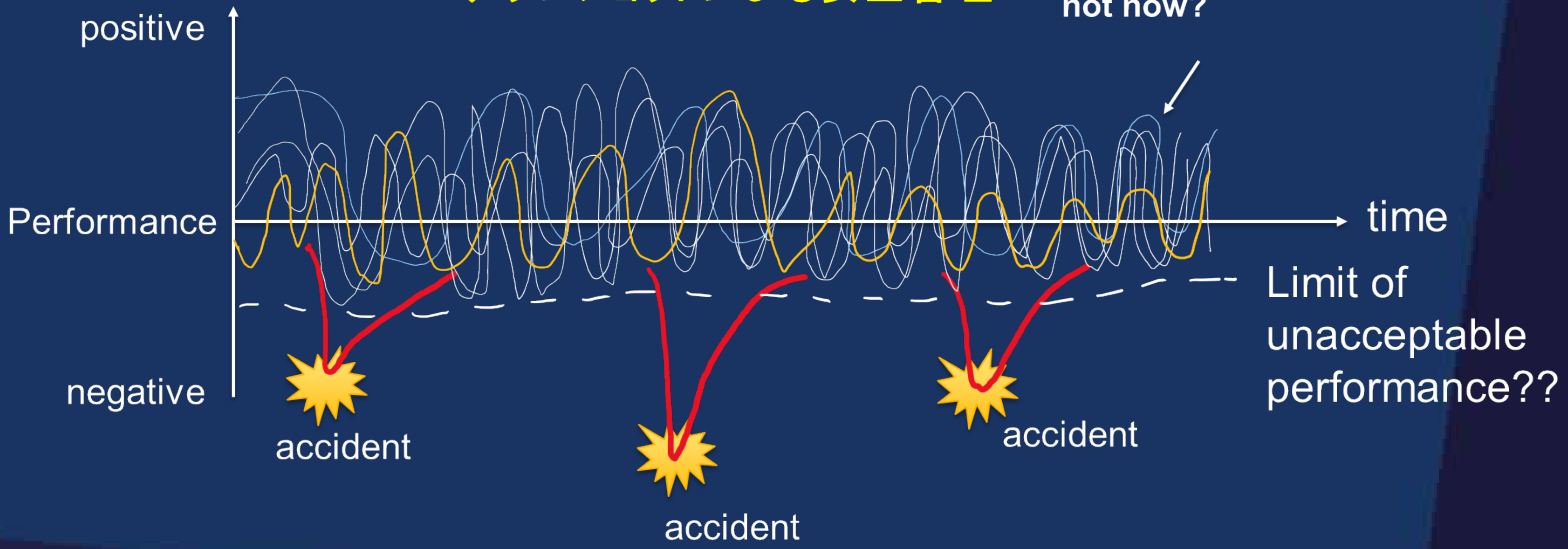
E. Hollnagel (2018) Safety-I and safety-II: the past and future of safety management

アプローチ１
スナップショットによる安全管理

In the past, too expensive to continuously monitor. But maybe not now?



安全率や確率論をもとにした設計。
変形そして破壊メカニズムを仮定する必要がある。

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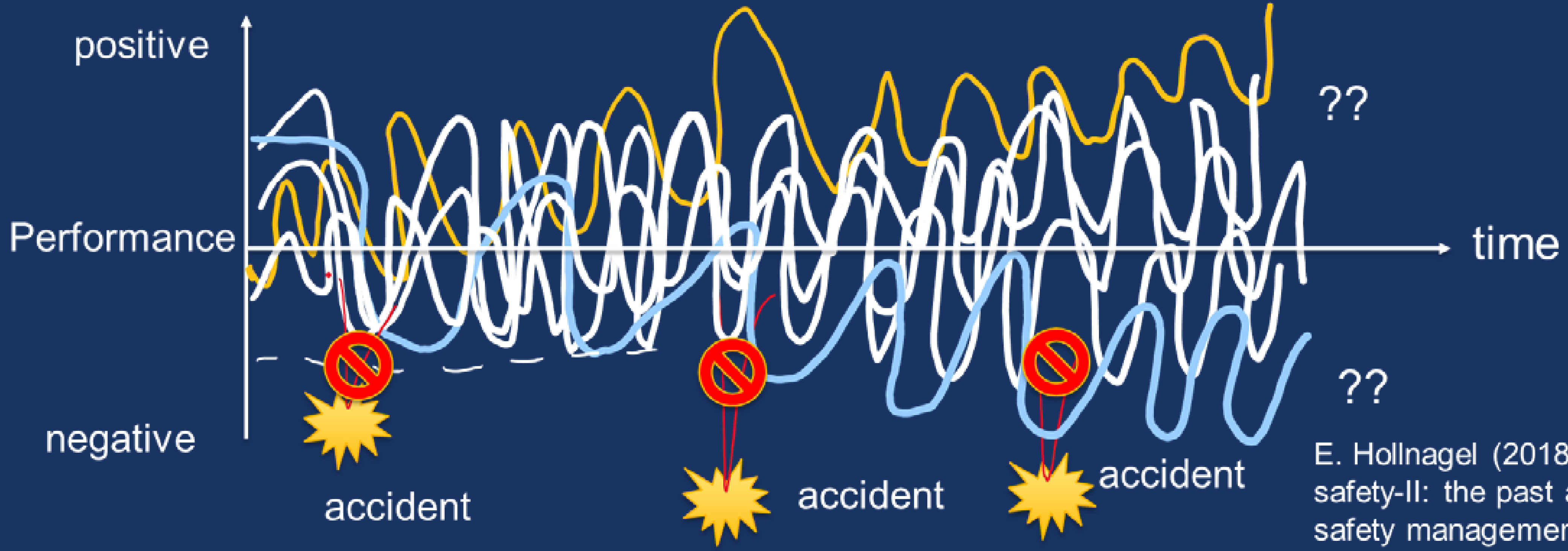
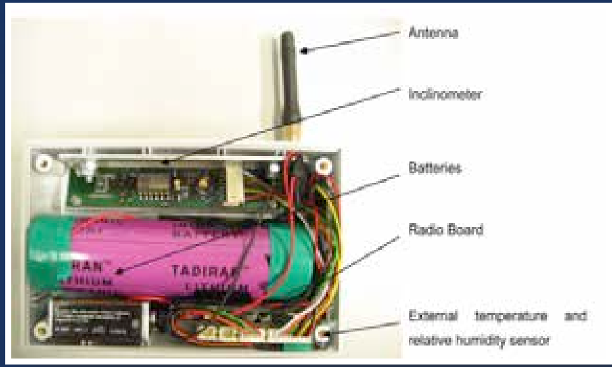
アプローチ２　日常業務による安全管理
モニタリング – 学習 – 予知 – 行動



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

実際の挙動を理解していると、
- 災害が発生した際に迅速に対応する方法が見つけられる。
- 将来の「未知の」需要に対処することができる。
- 潜在的な改善を見つけることができる。つまり、設計、建設プロセスを改善することができる。

WSN Application to Civil Engineering



~2009

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2012

wisen innovation

2015

power

UtterBerry™

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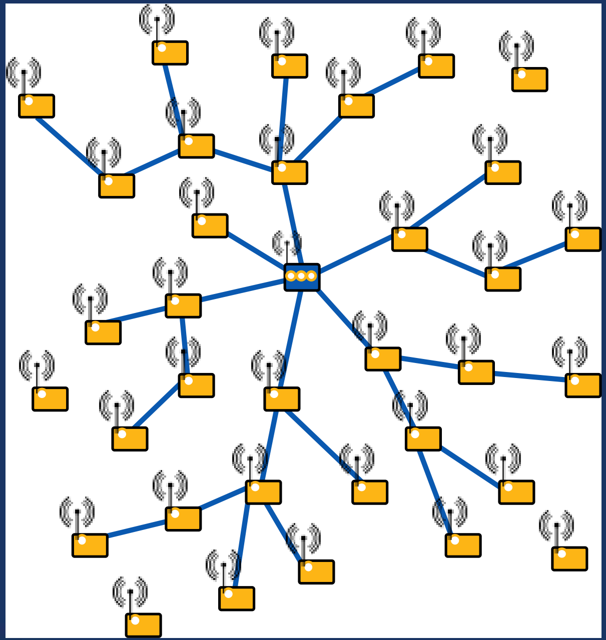

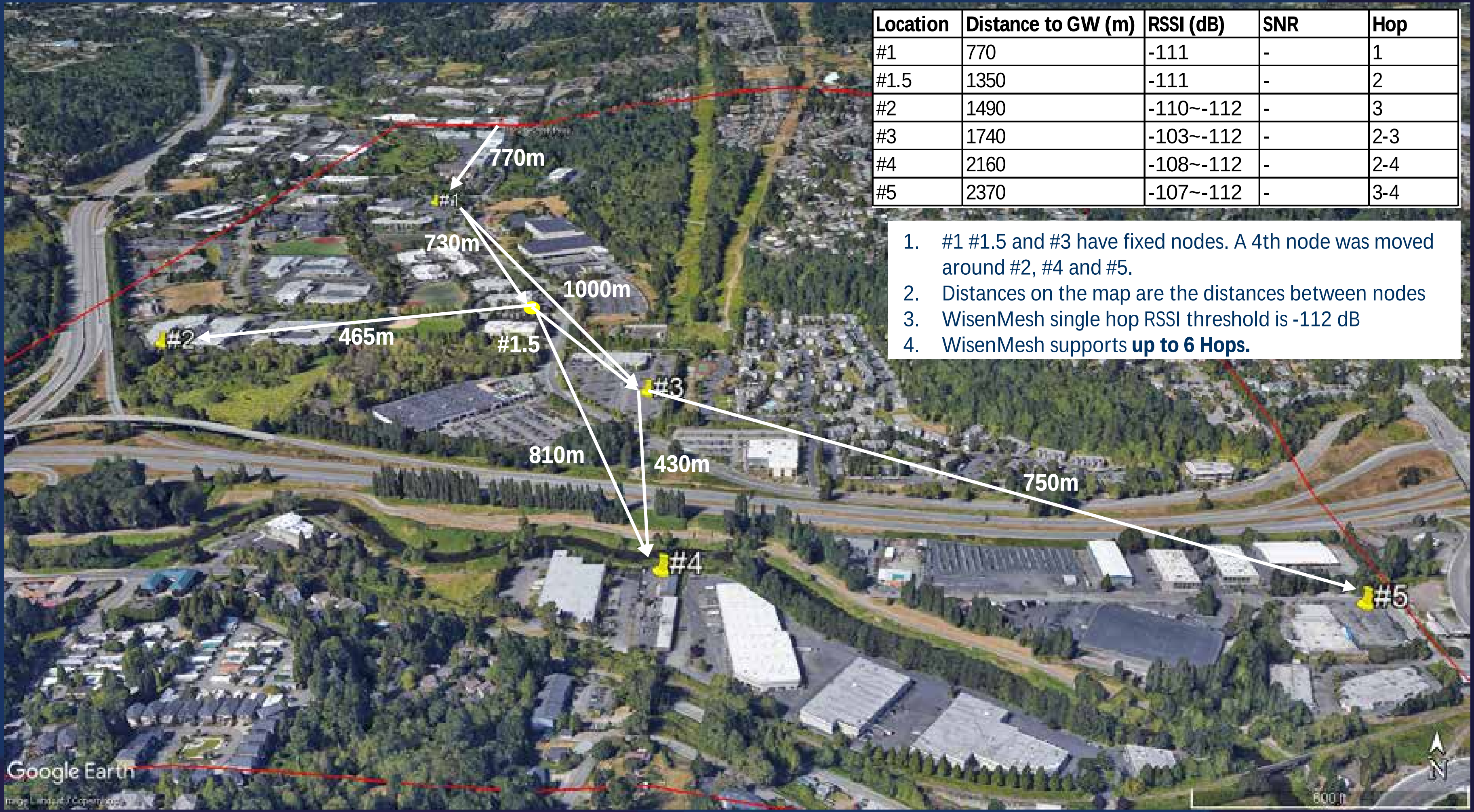

Location	Distance to GW (m)	RSSI (dB)	SNR	Hop
#1	770	-111	-	1
#1.5	1350	-111	-	2
#2	1490	-110~-112	-	3
#3	1740	-103~-112	-	2-3
#4	2160	-108~-112	-	2-4
#5	2370	-107~-112	-	3-4

1. #1 #1.5 and #3 have fixed nodes. A 4th node was moved around #2, #4 and #5.
2. Distances on the map are the distances between nodes
3. WisenMesh single hop RSSI threshold is -112 dB
4. WisenMesh supports **up to 6 Hops.**

Zhangwei Ning, Sixsense

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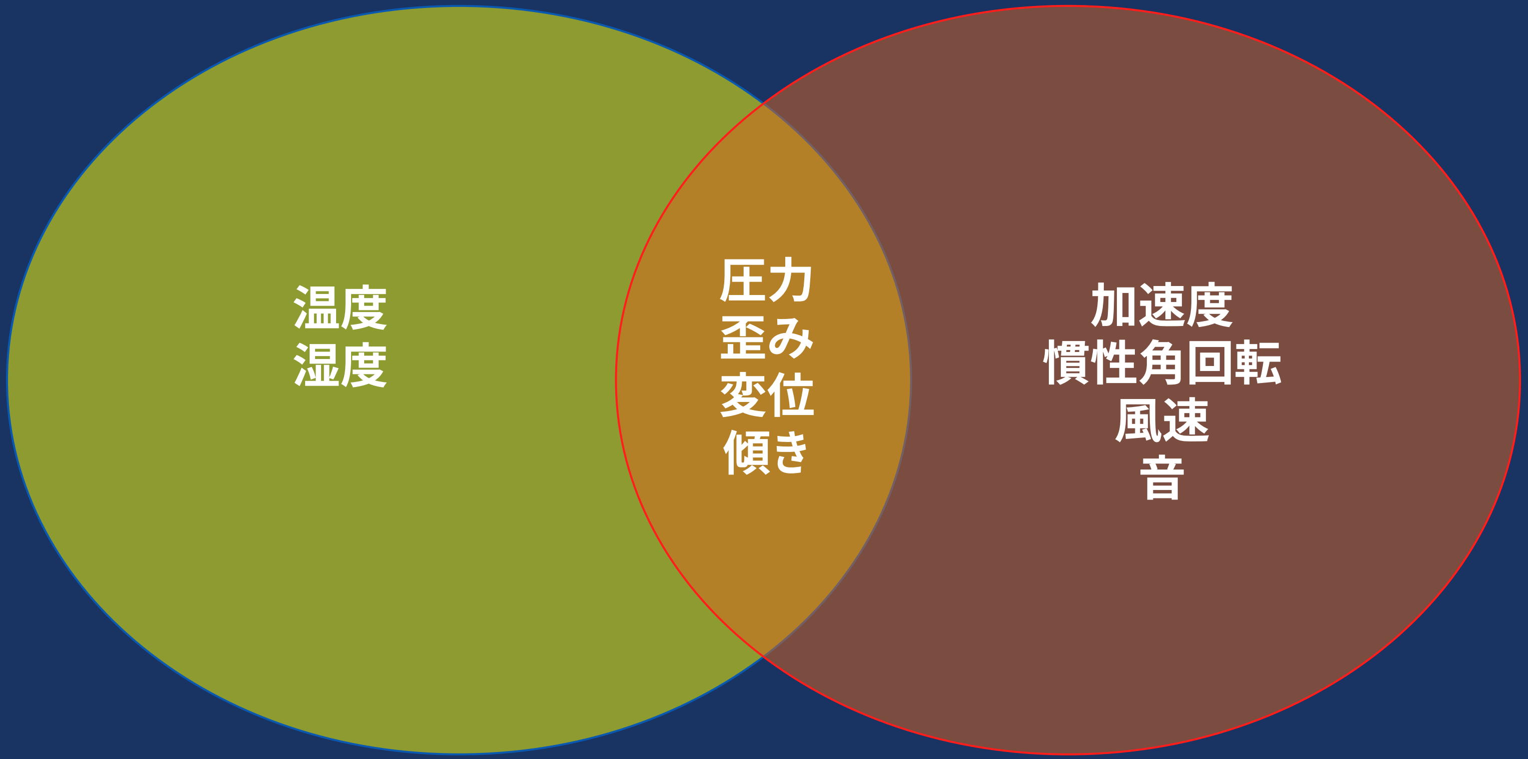
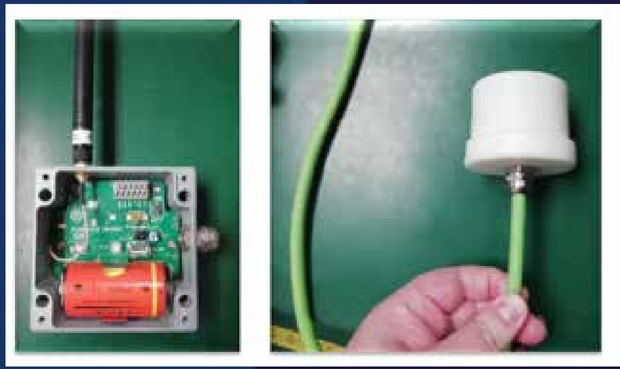
データ　ー　1時間ごと

データ　ー　0.01秒ごと





3000 mAh バッテリー
1 時間単位のモニタリング
メッシュ ネットワーク
理論上は10〜15年程度。

5 秒間の「選択された」録音データの送信には 1 〜 2 分かかります
1 時間間隔の読み取りで バッテリーは40日持つ計算になります。

トリガーモードや自家発電で節電。

power

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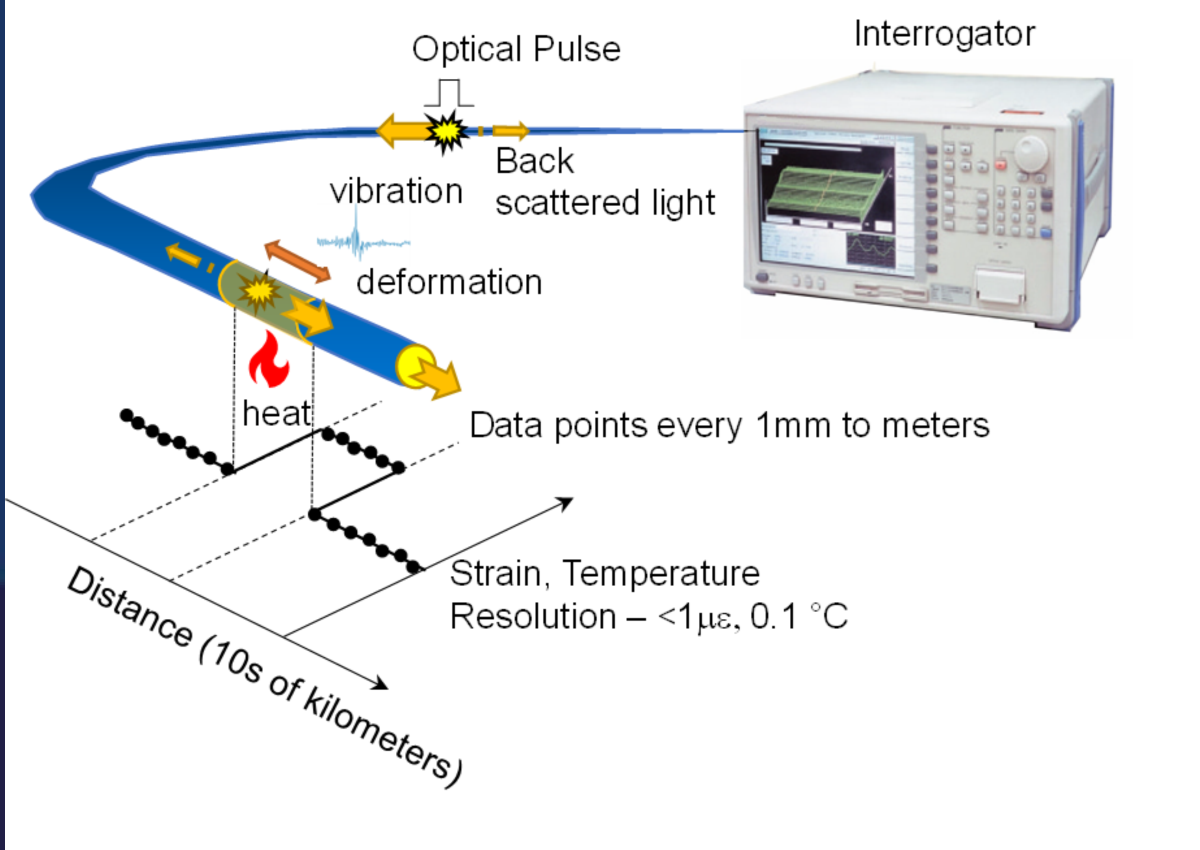
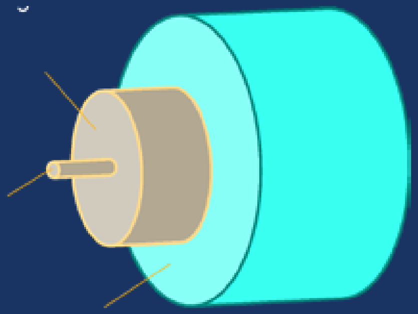
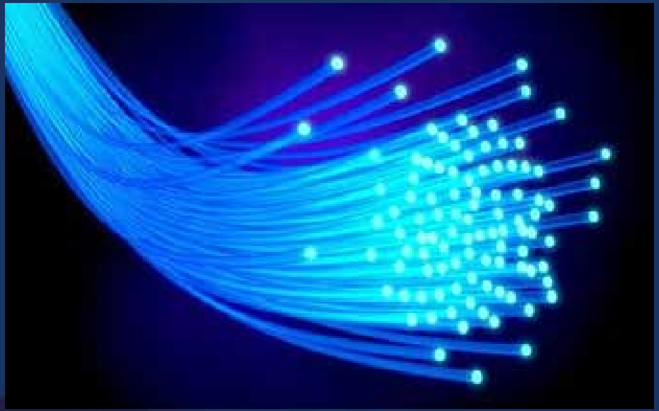
Distributed fiber optic sensing

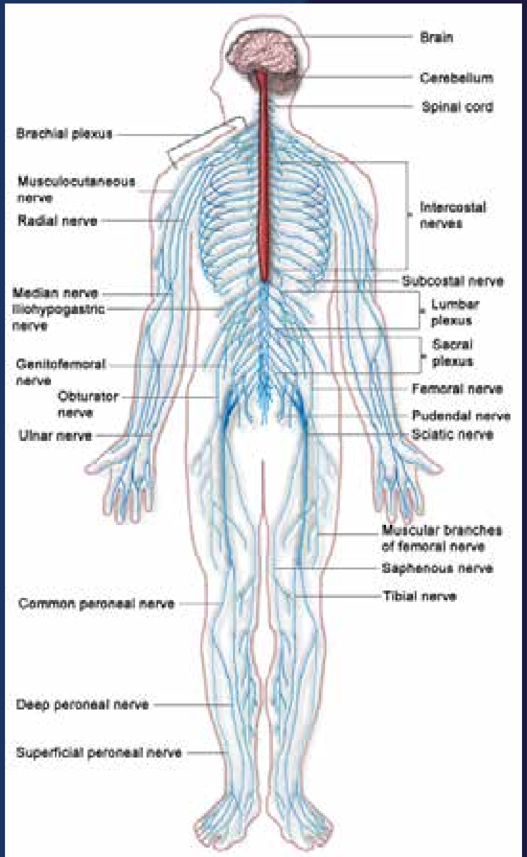
光ファイバーケーブルに沿った「連続的な」歪み/温度/振動の測定技術

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









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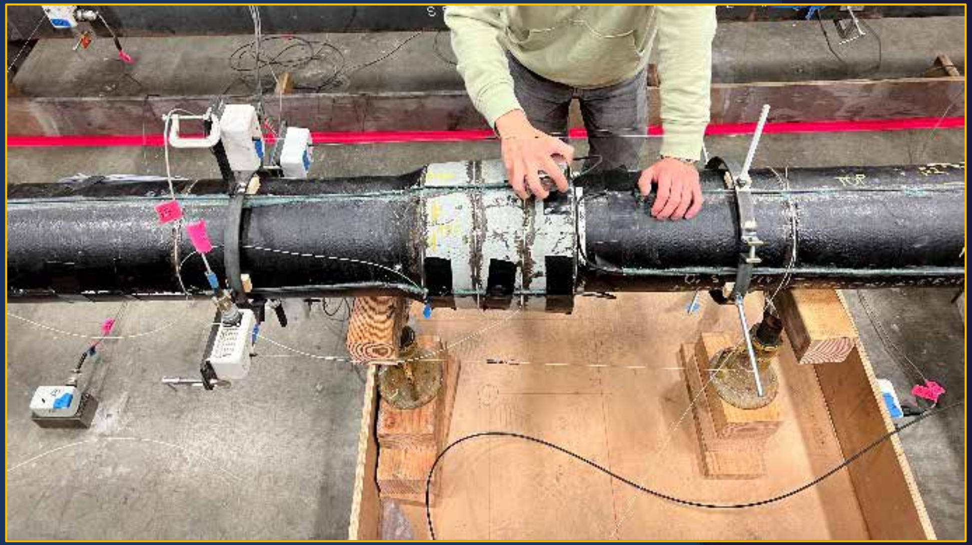
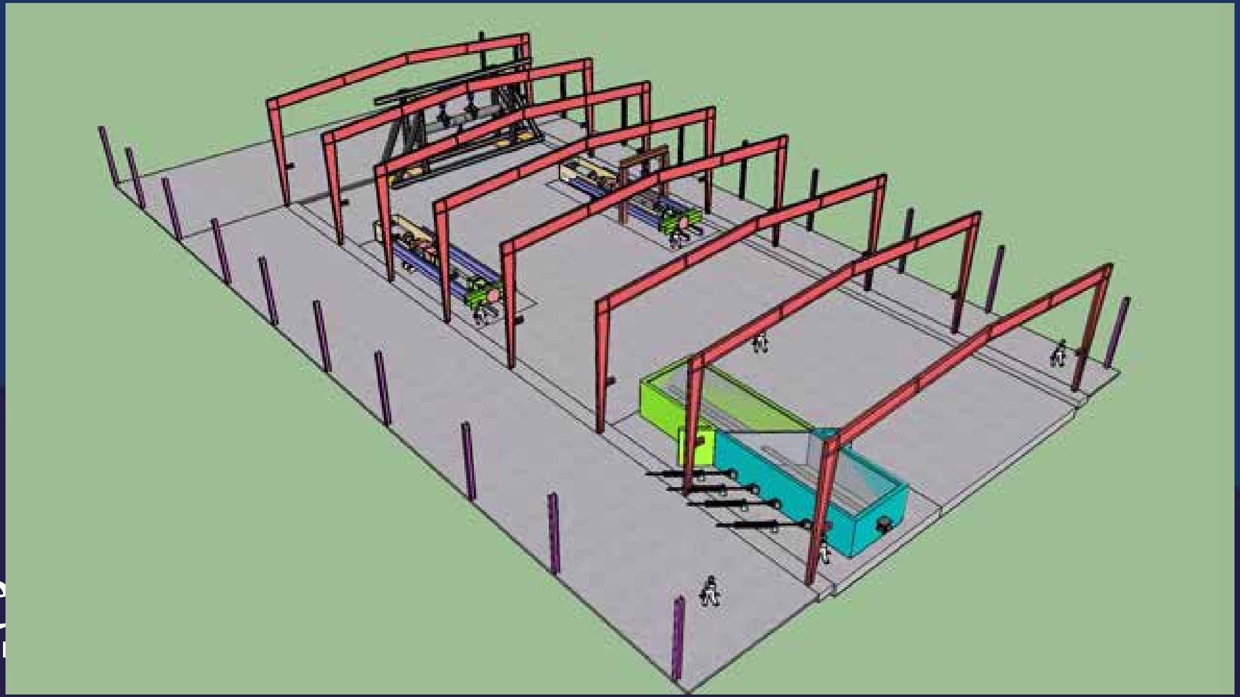
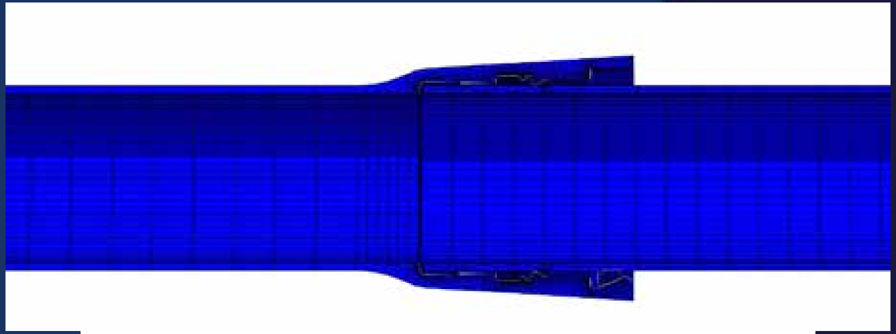
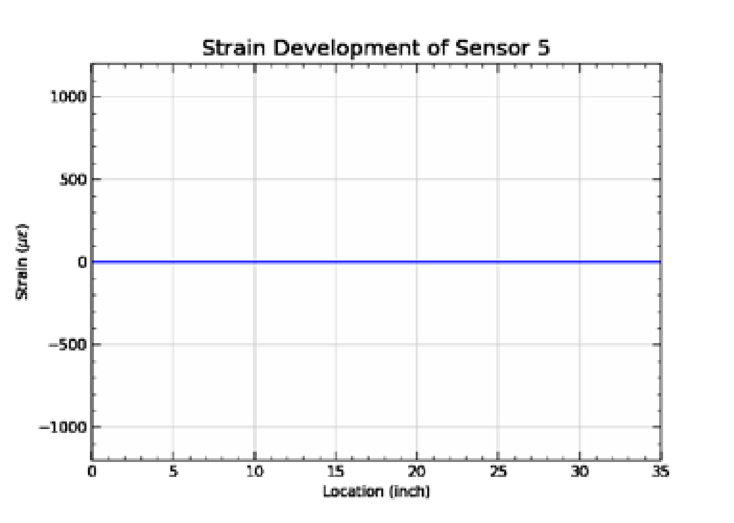
Pipeline Testing









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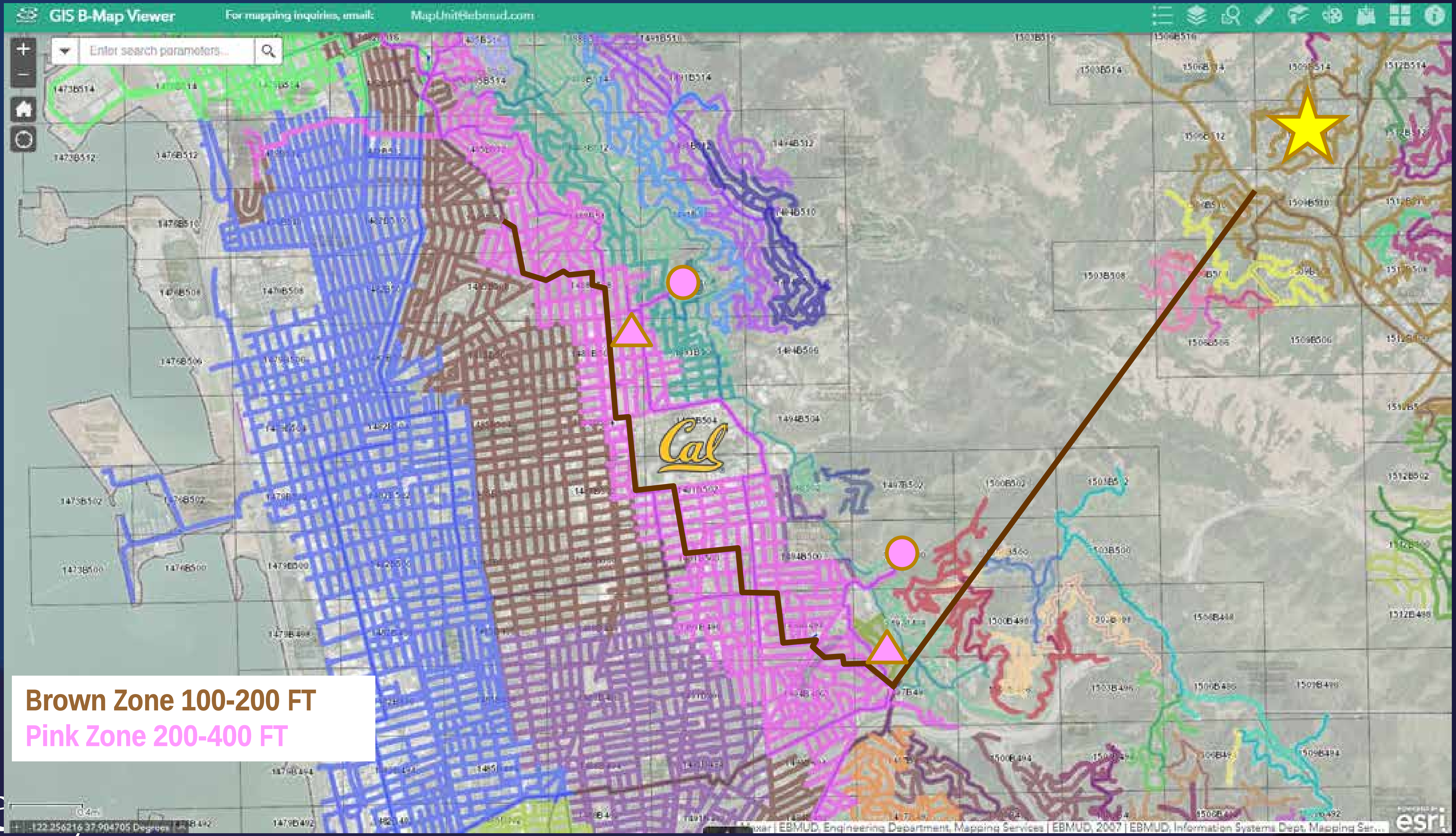
8 inch ERDIP

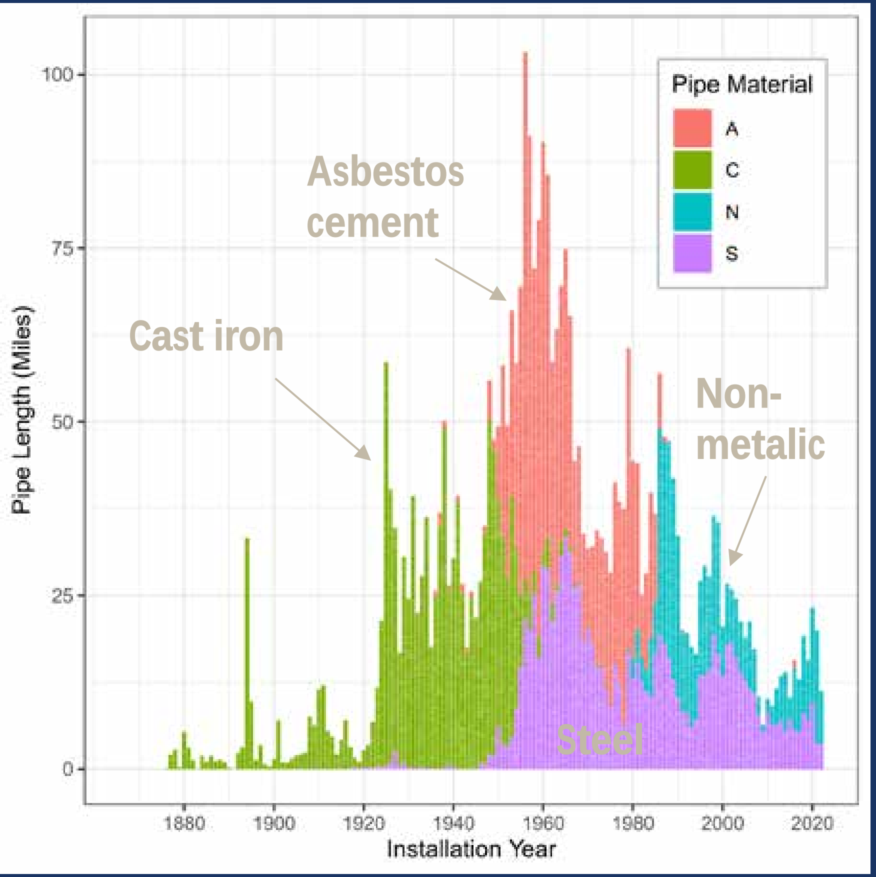

8 inch iPVC


24 inch ERDIP

48 inch DIP

East Bay Municipal Utility District





Design life of infrastructure = 100 years. Some have already surpassed this lifespan..

EBMUD has 4,200 miles of pipelines and experiences over 1,000 breaks each year.

Currently replacing 25 miles/year.. It will take 150-200 years to complete the full replacement.

How can we be more effective?

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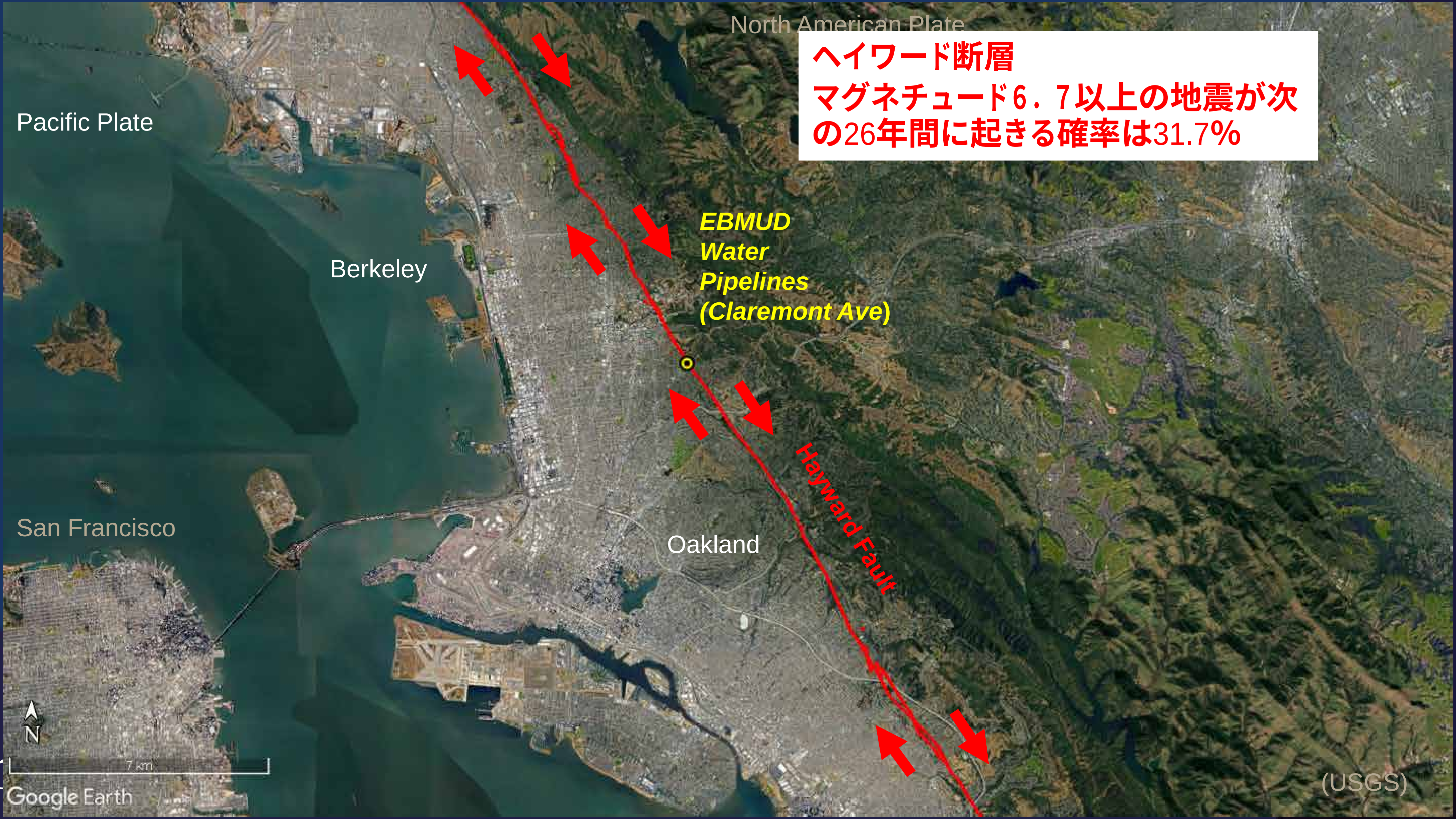
Relevance - *EBMUD*



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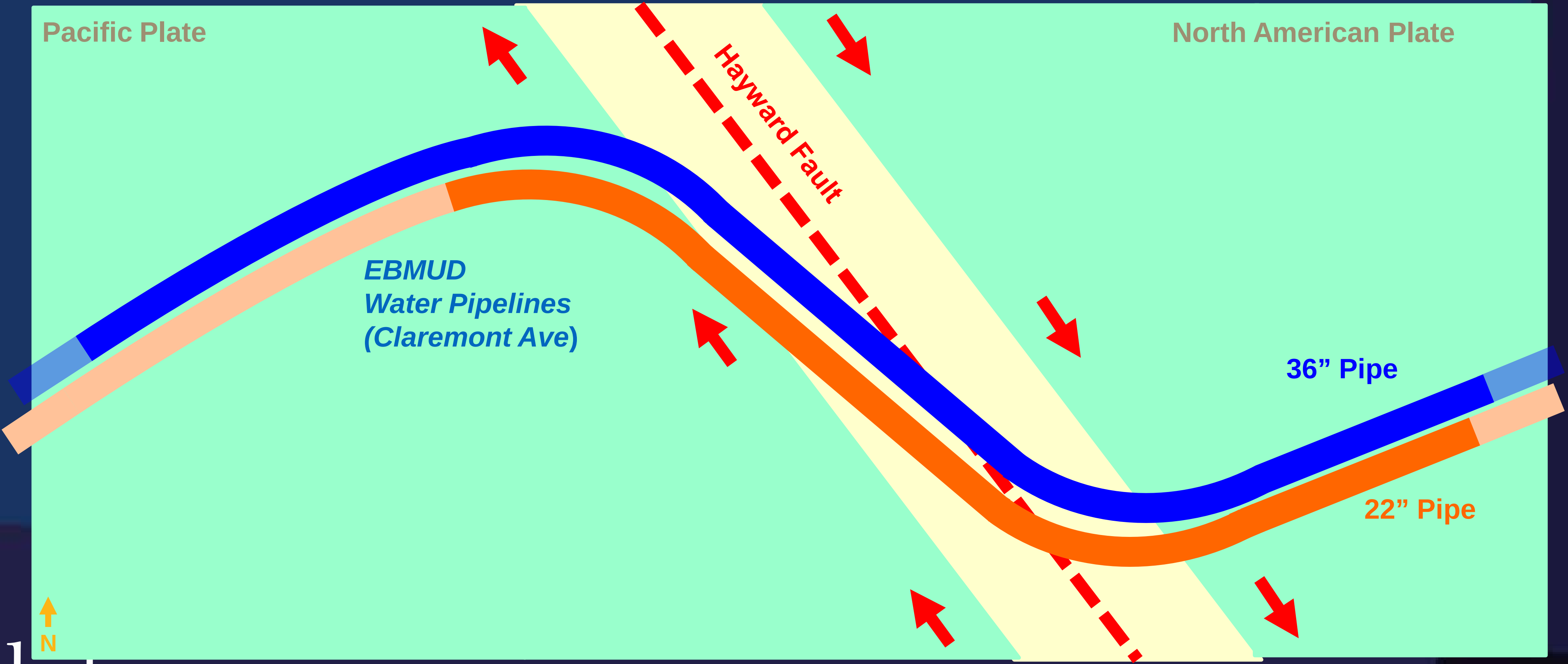
Critical pipelines provide the water for Berkeley and Oakland

High Risk at Hayward Fault crossing (5 mm annual displacement)



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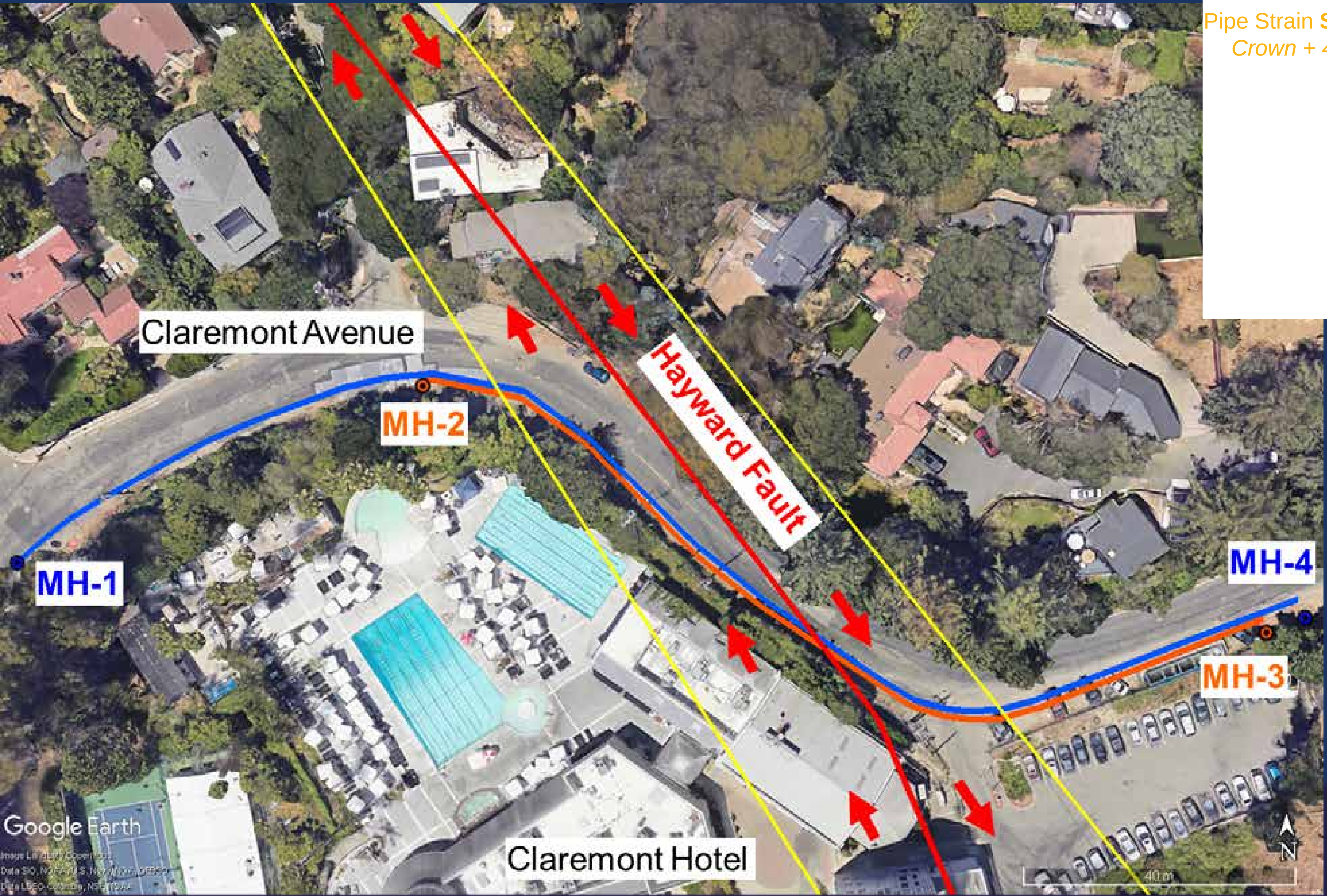
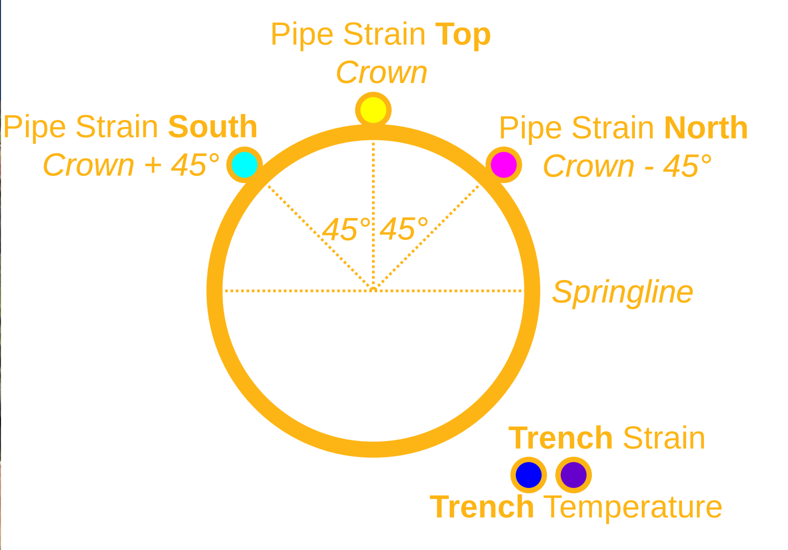
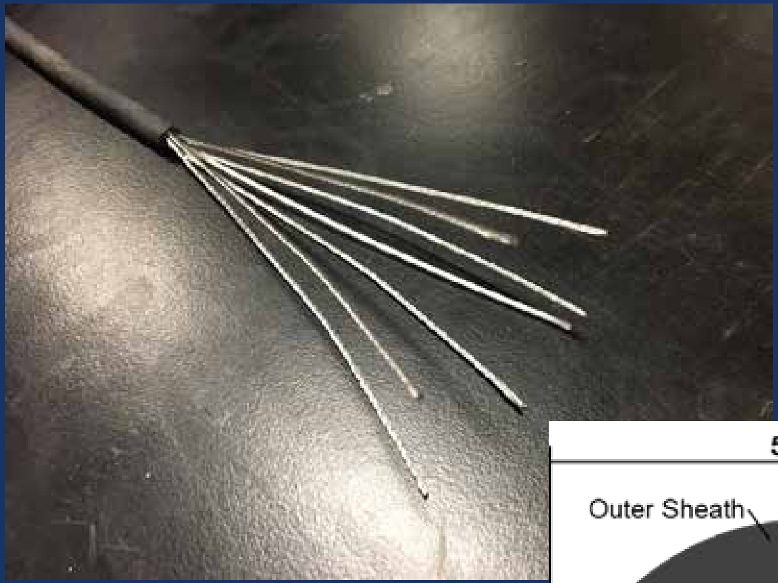


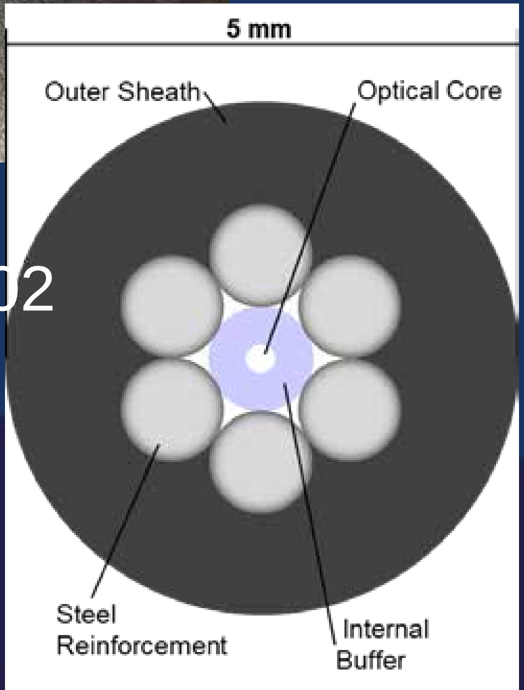
Claremont Avenue
Hayward Fault
MH-1
MH-2
MH-3
MH-4
Claremont Hotel
Google Earth
N
40 m



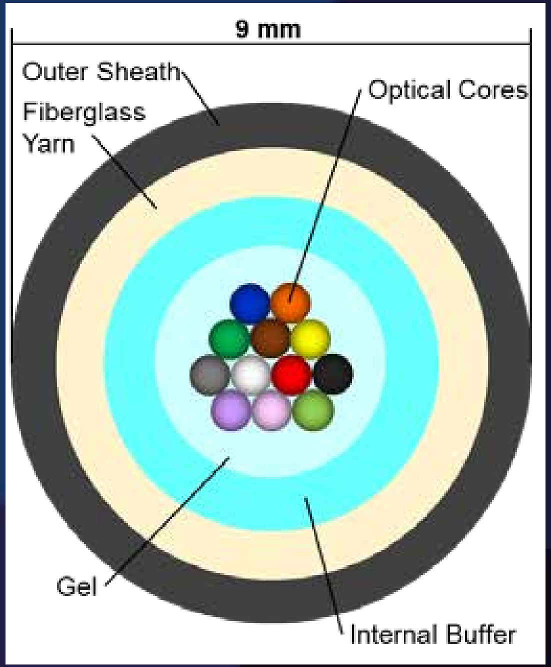
Pipe Strain **Top**
Crown
Pipe Strain **South**
Crown + 45°
Pipe Strain **North**
Crown - 45°
45°
45°
Springline
Trench Strain
Trench Temperature

Strain and Thermal Fiber Optic Cables





NanZee NZS-DSS-C02
Strain Cable



Belden
Temperature Cable

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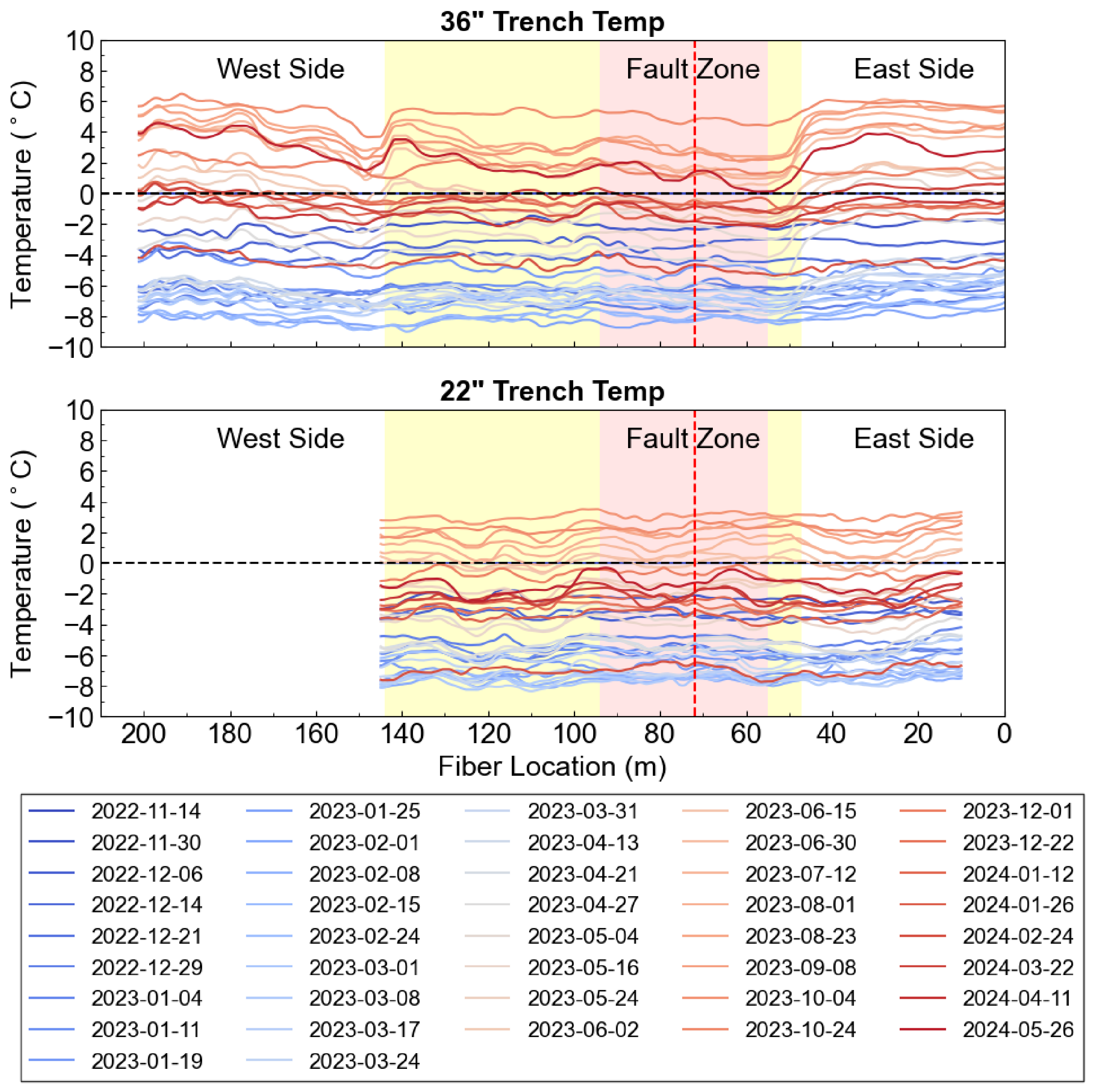
Trench Temperature

- Seasonal temperature cycle
- Temperature drops associated with transition in trench geometry



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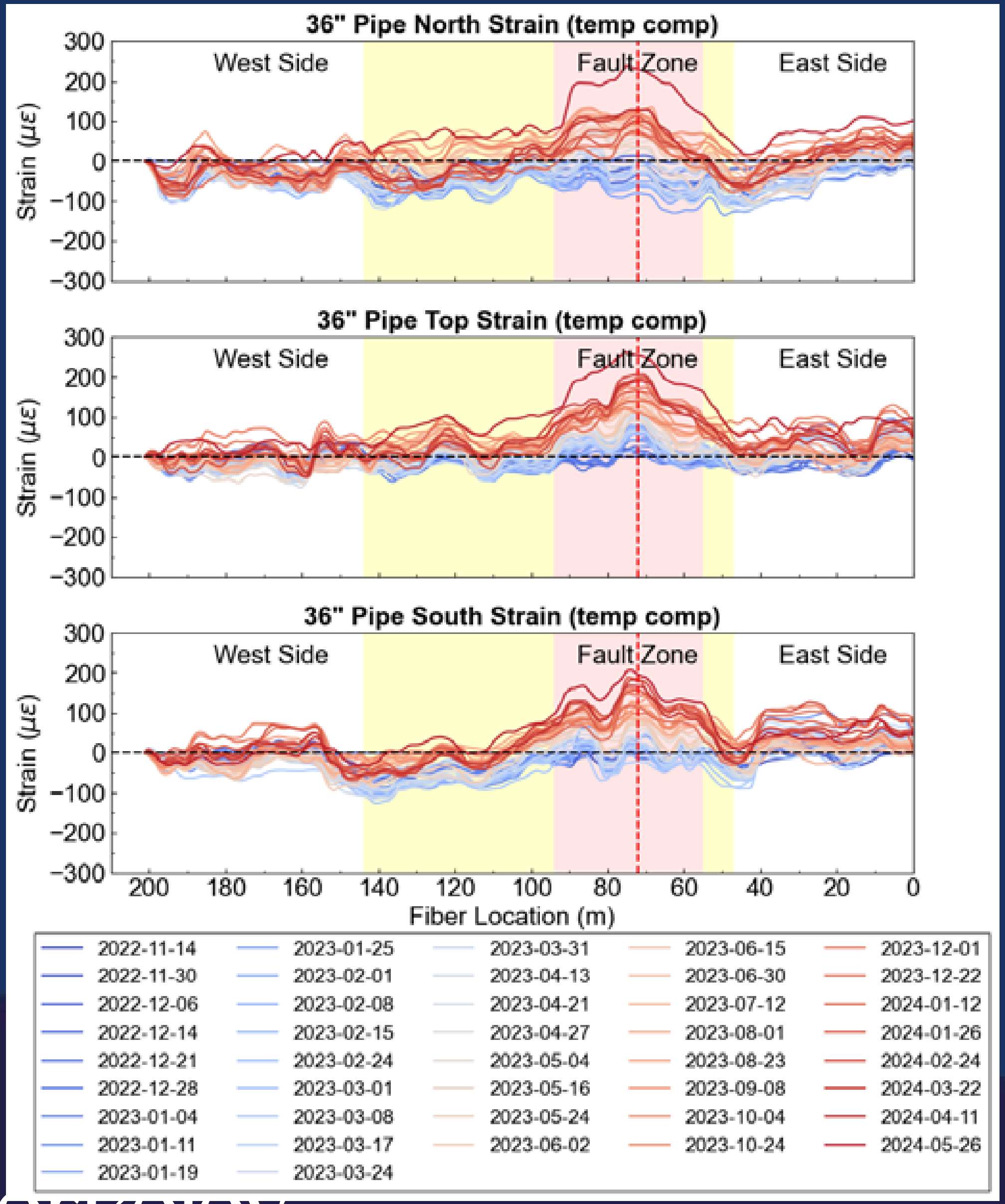

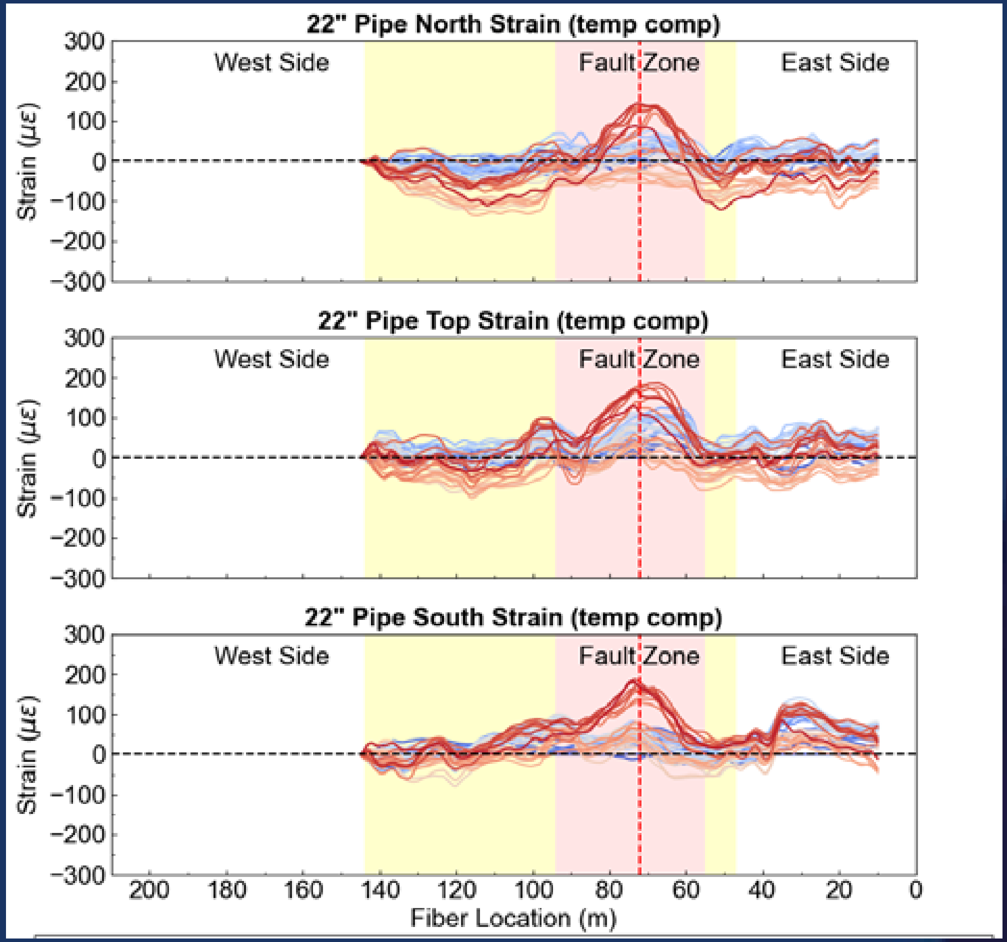

- Increase in tensile strain along pipeline parallel to fault

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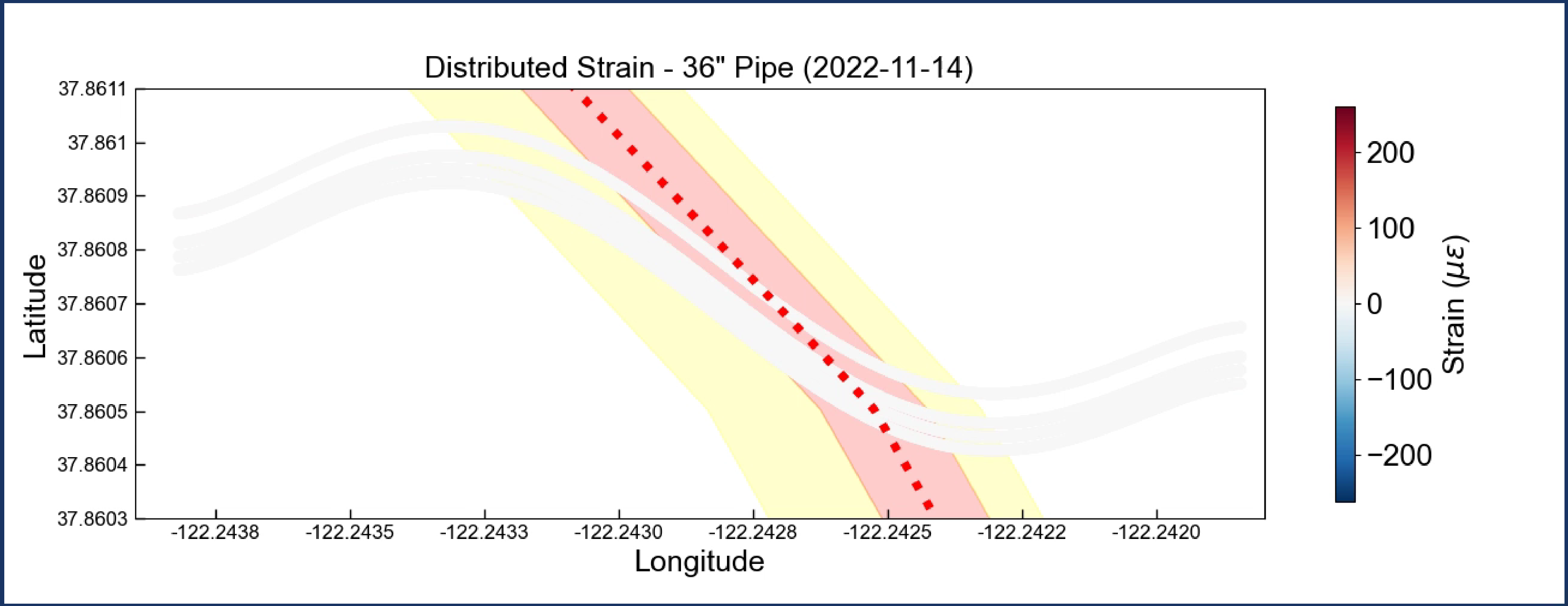

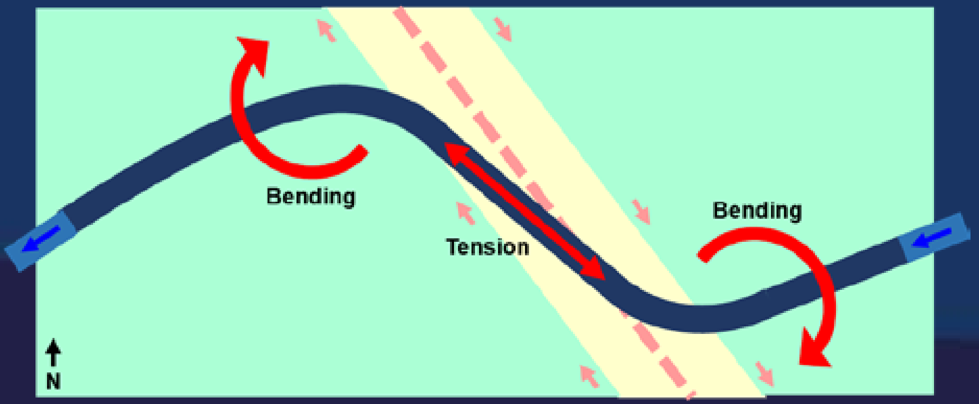

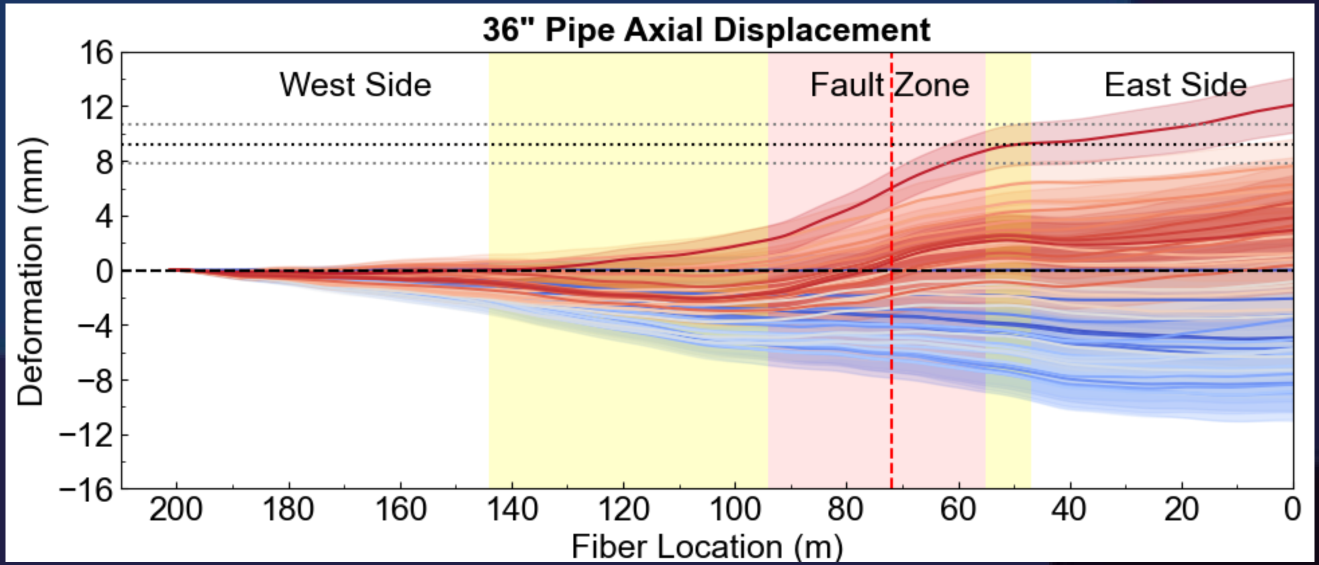

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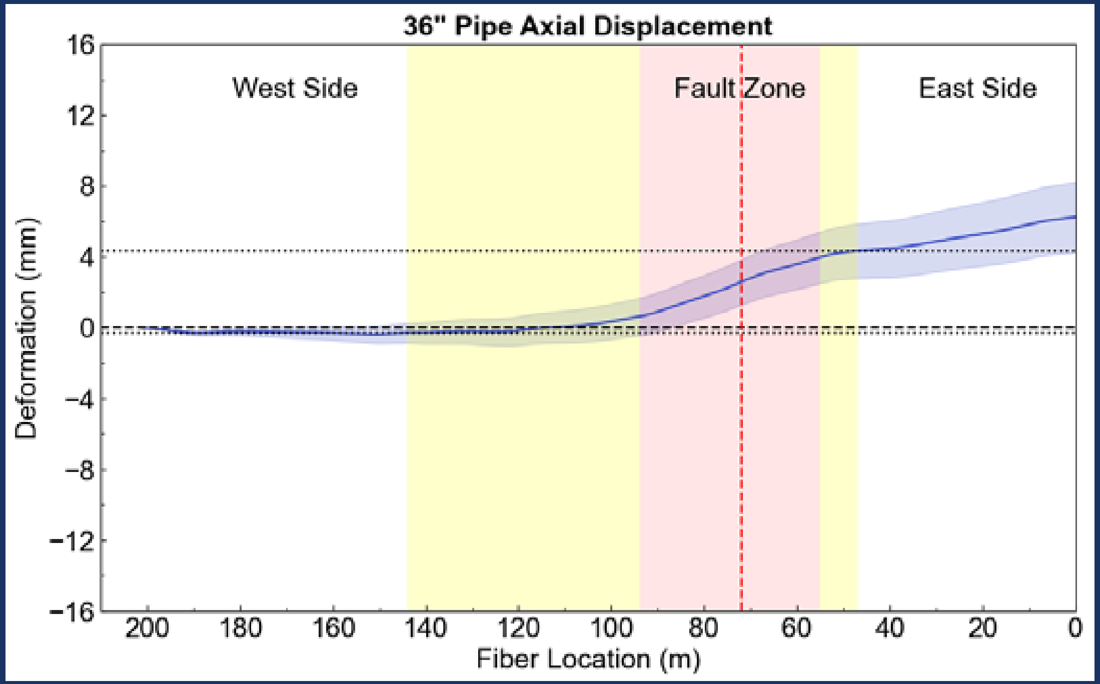
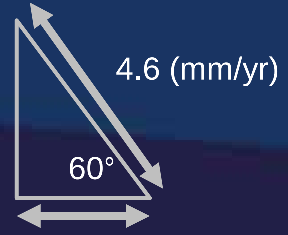
Displacement in the axial direction from DFOS readings

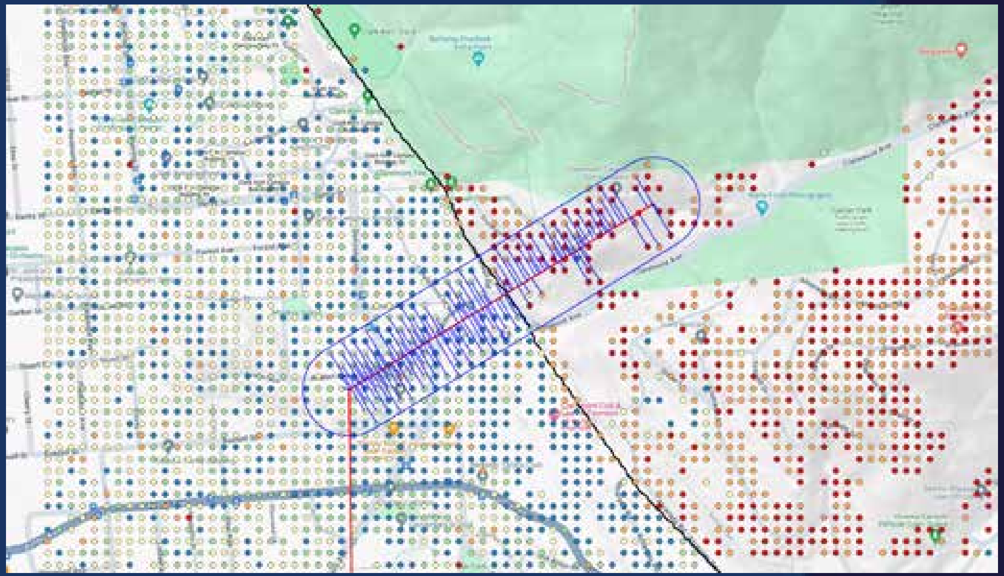


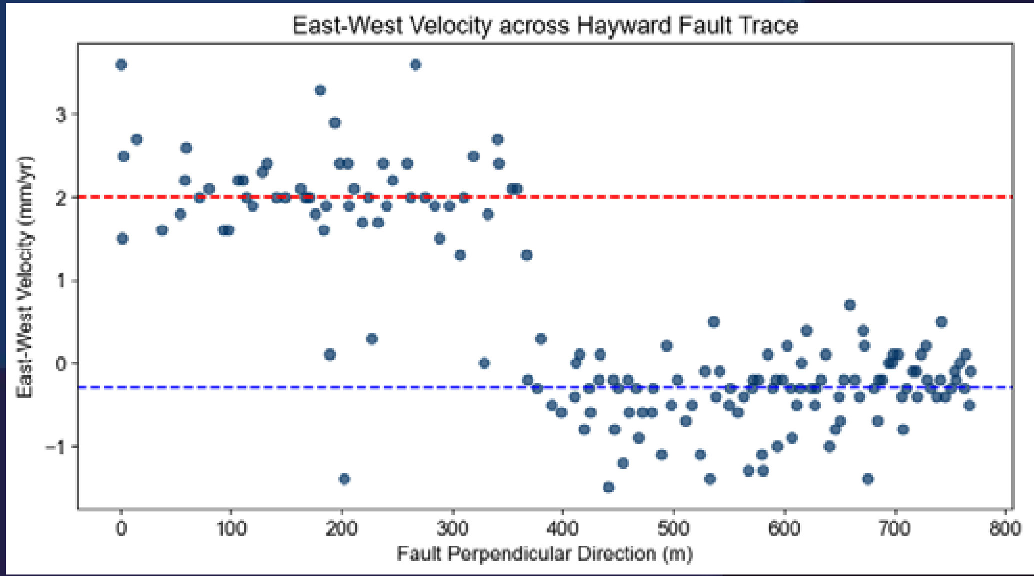
- **Fault Parallel Velocity ~ 4.6 (mm/yr)**



Interferometric Synthetic Aperture Radar (InSAR)

- East-West Velocity across Hayward Fault
- TerreSAR-X satellite descending and ascending observations





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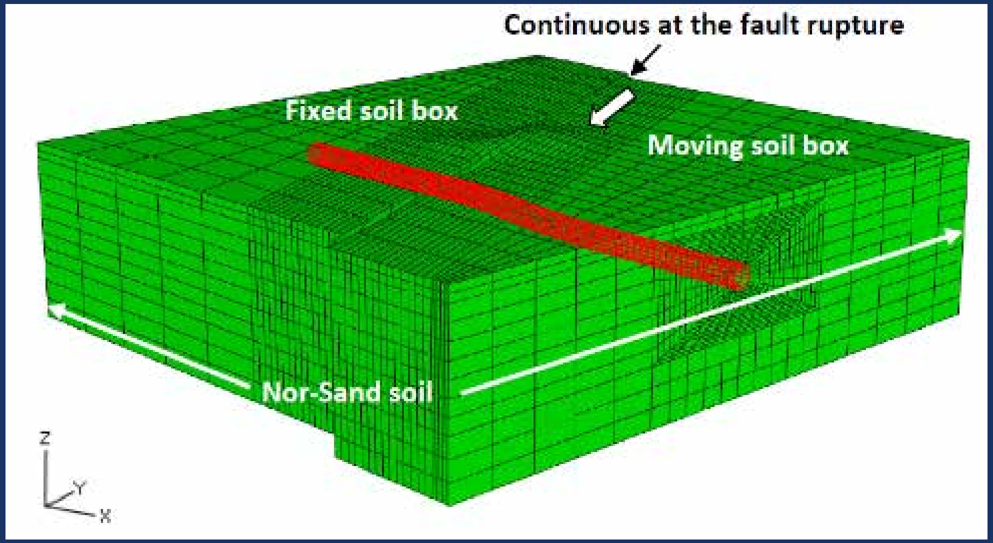
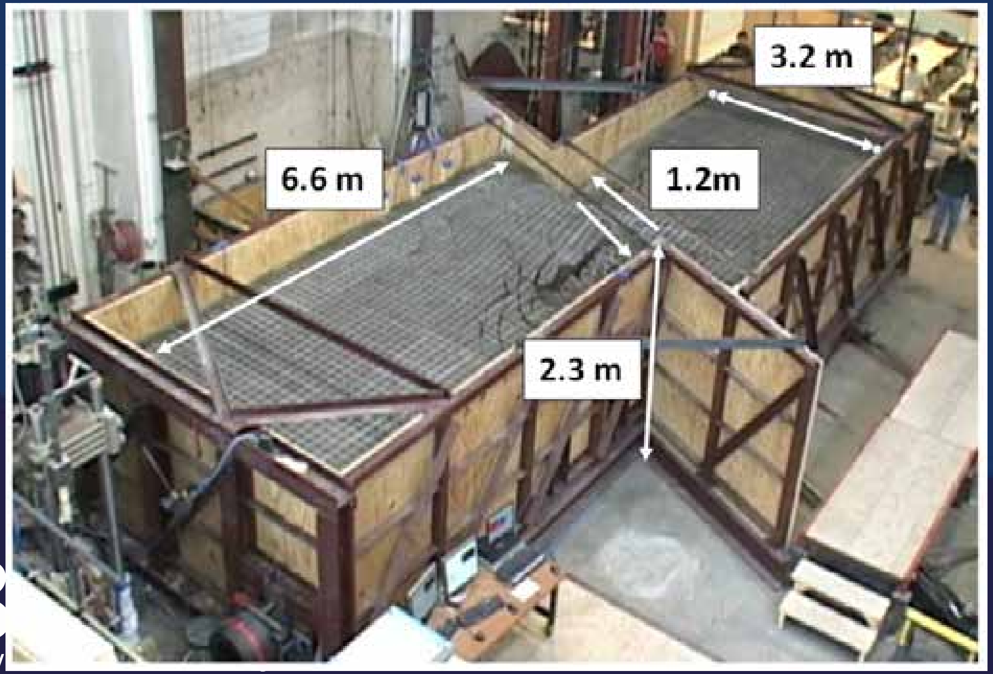
Design… Soil-pipeline interaction

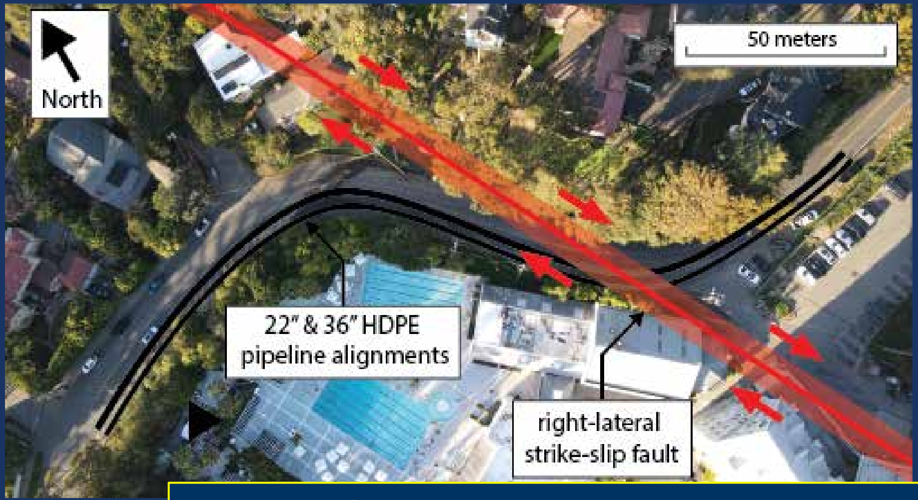


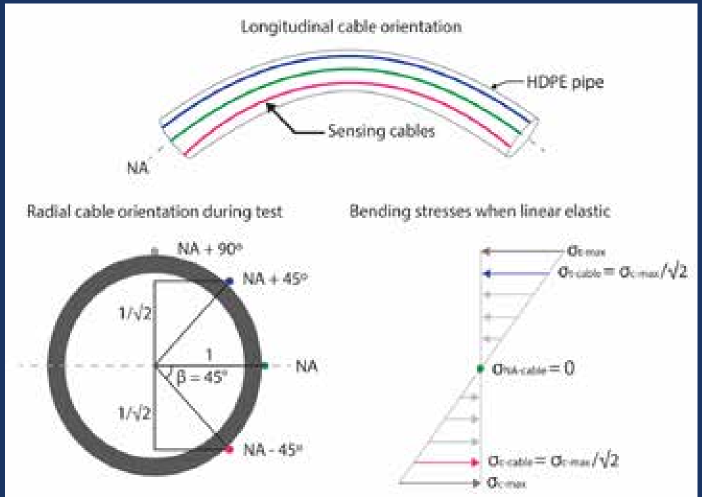


Reality…

An abandoned pipe..
Soil-pipe-pipe

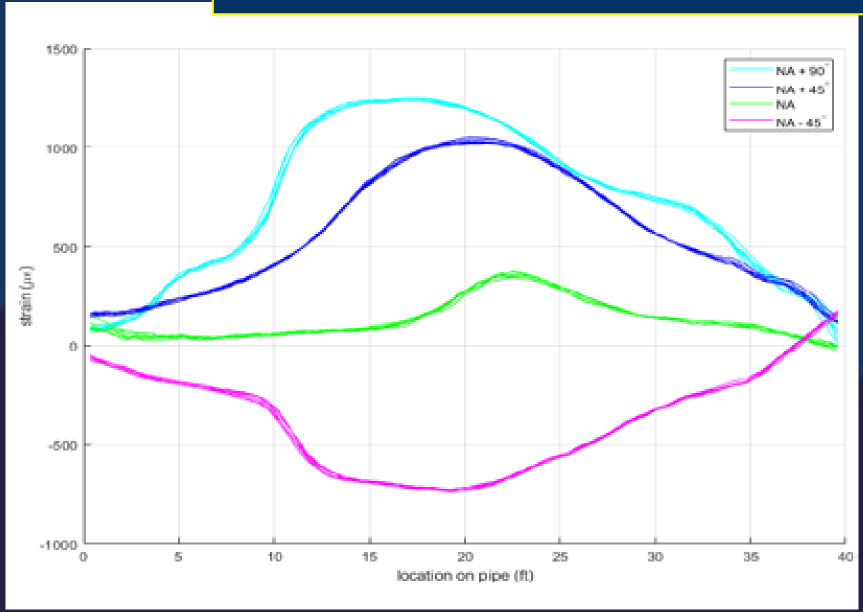
現場データを用いた工学的アセスメント

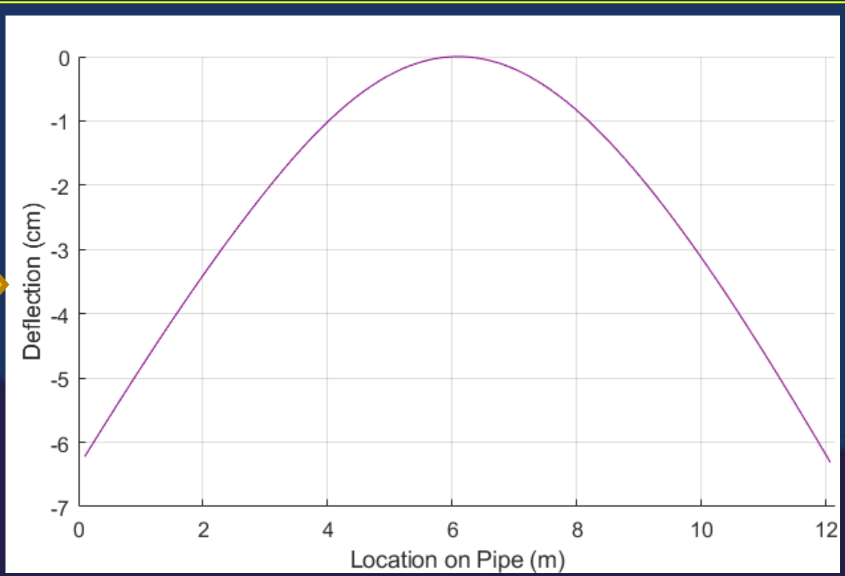




パイプラインを土中に埋めたら、次の 100 年間は見ることができません。
未来の世代のために、建設中に「インテリジェンス」を埋め込む価値とは？

train-based
assessment





Monitoring of PG&E gas pipeline in Gilroy using distributed fiber optic sensing

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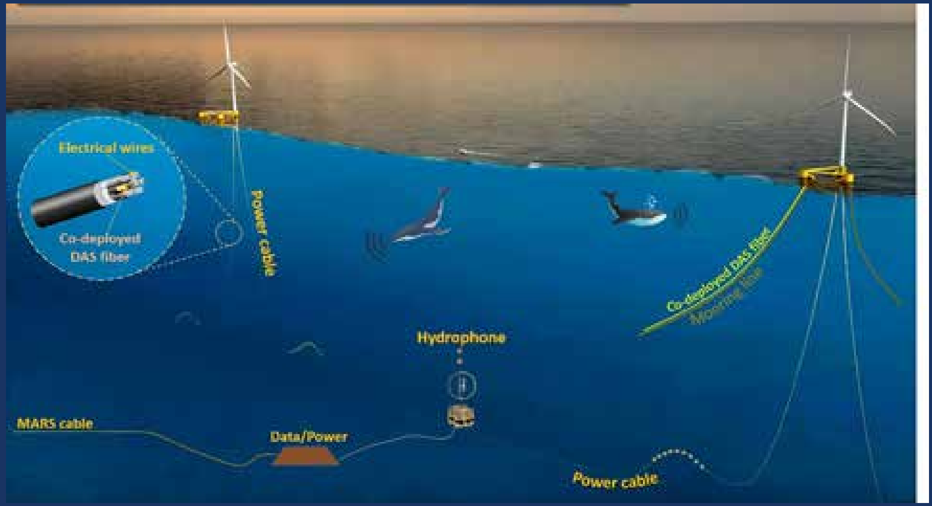
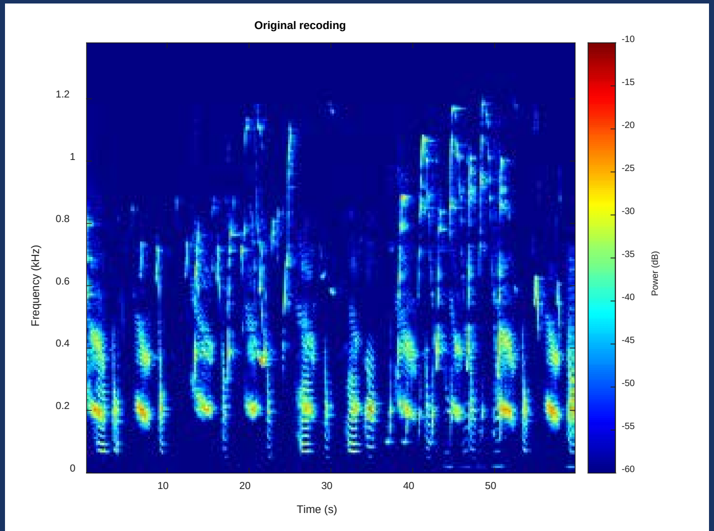
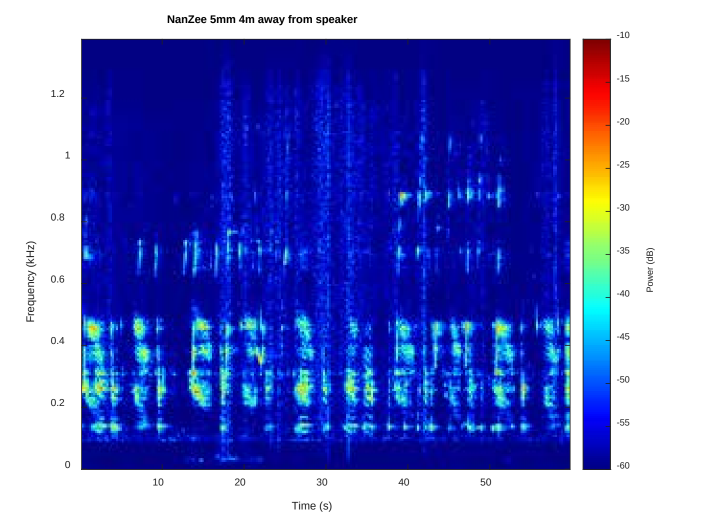
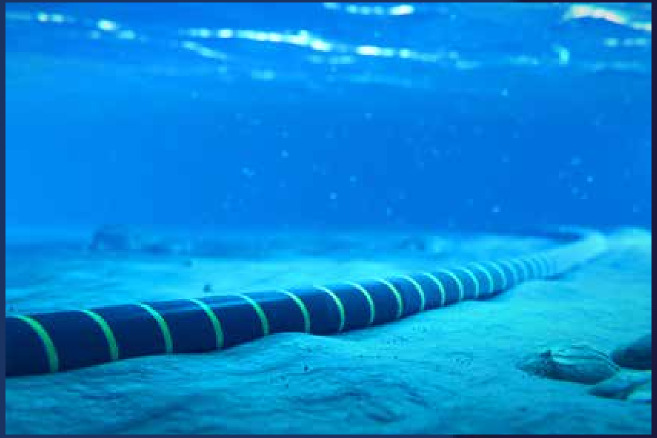
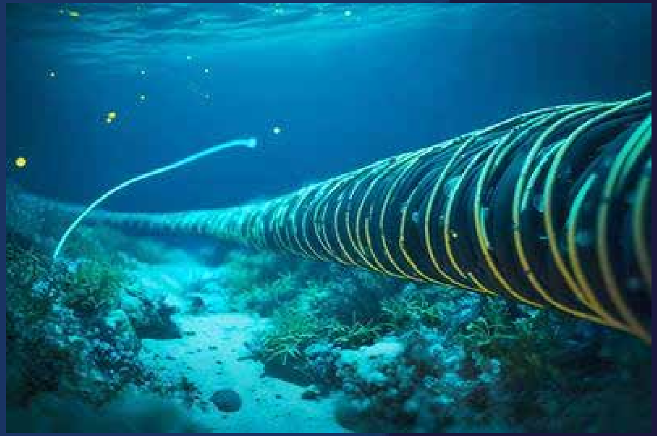
QA/QC of spatial varying data sets

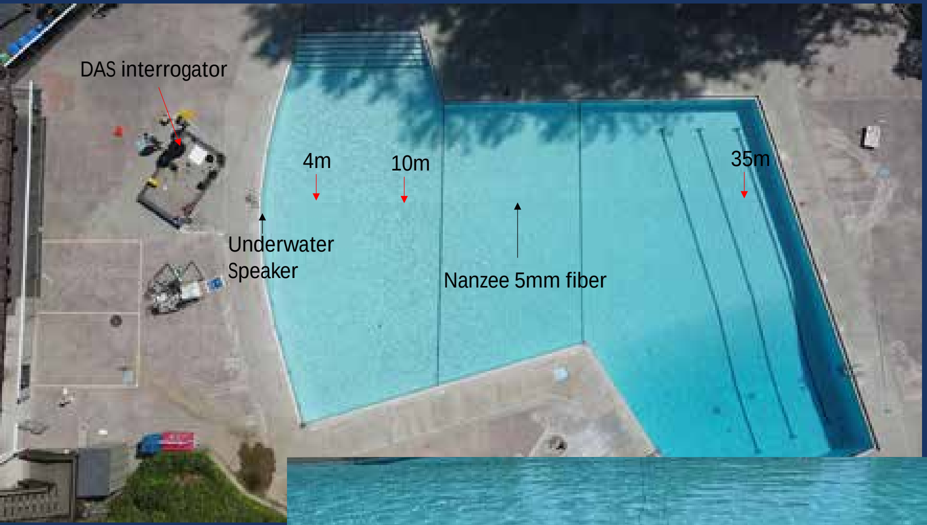


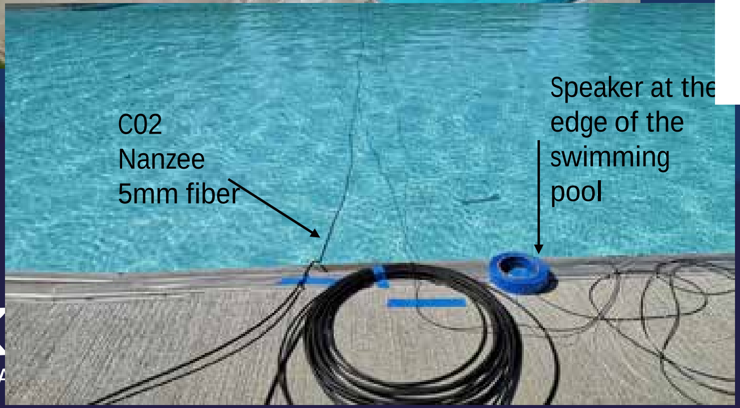


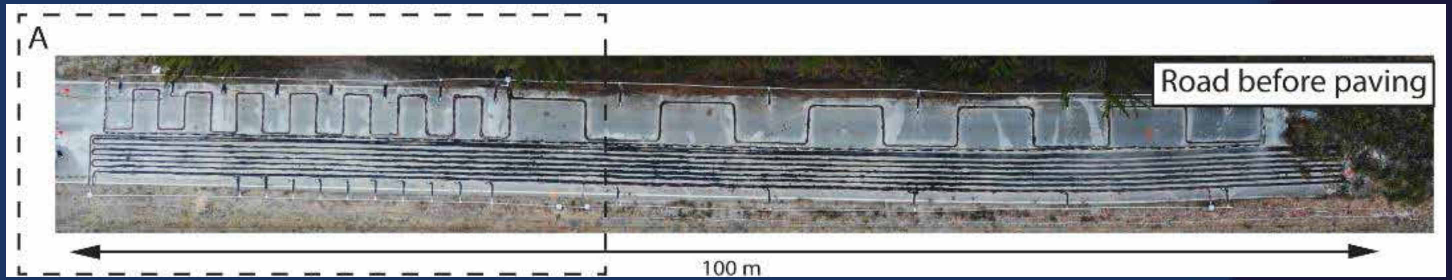




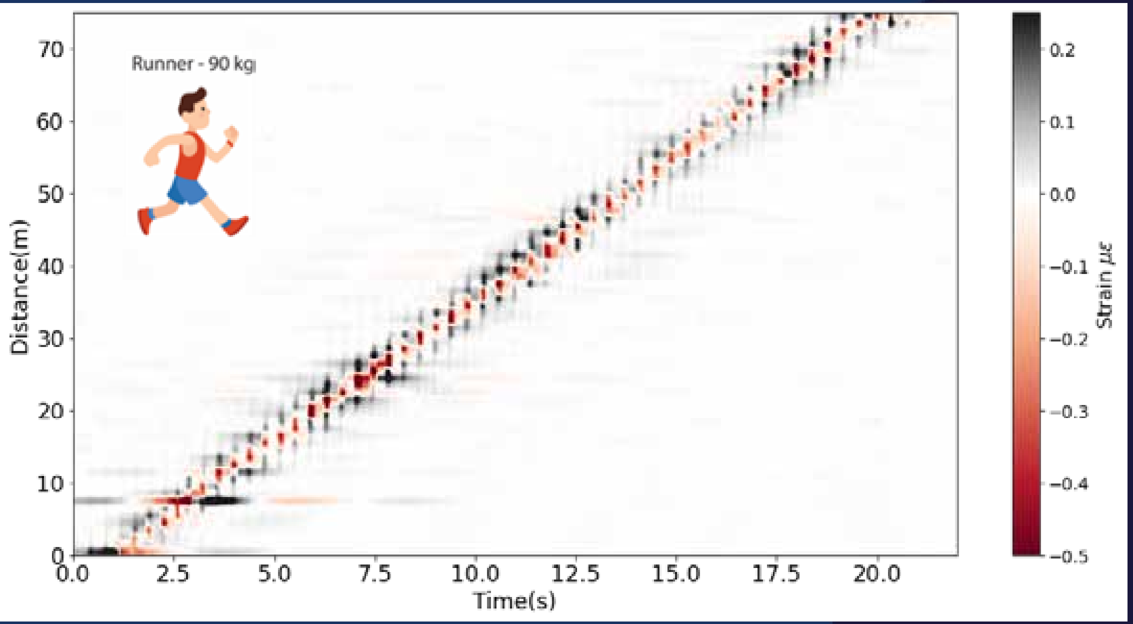




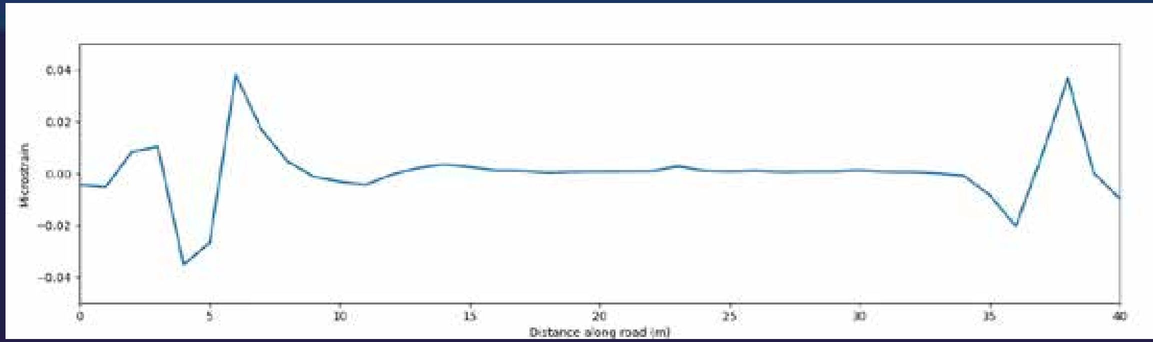




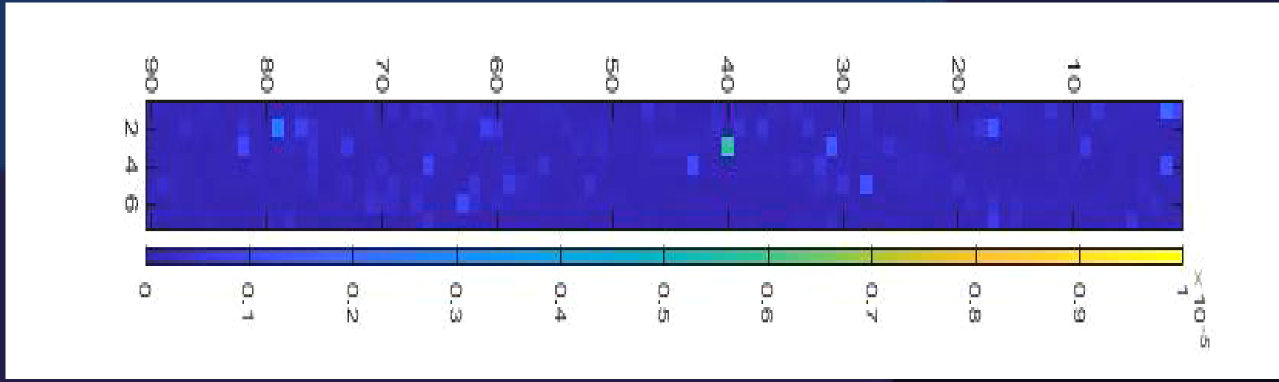
A
Road before paving
100 m

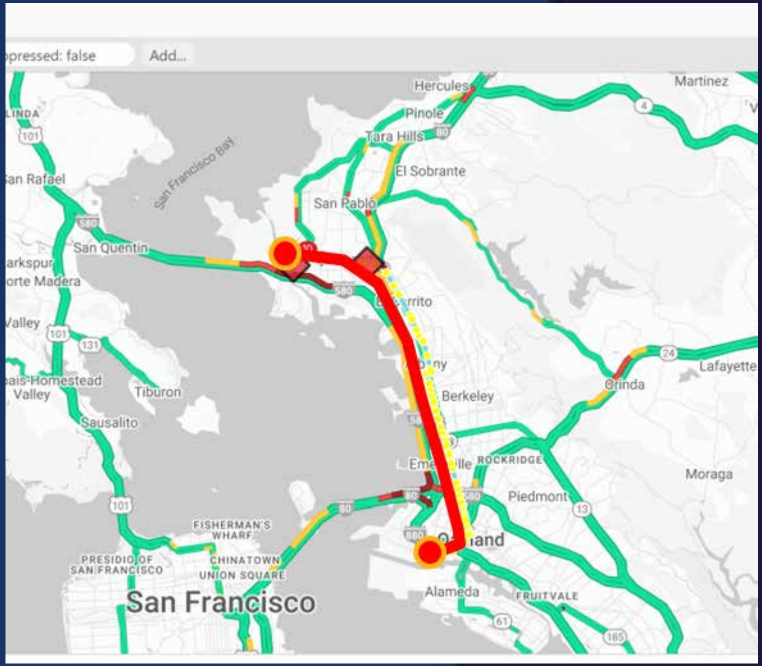


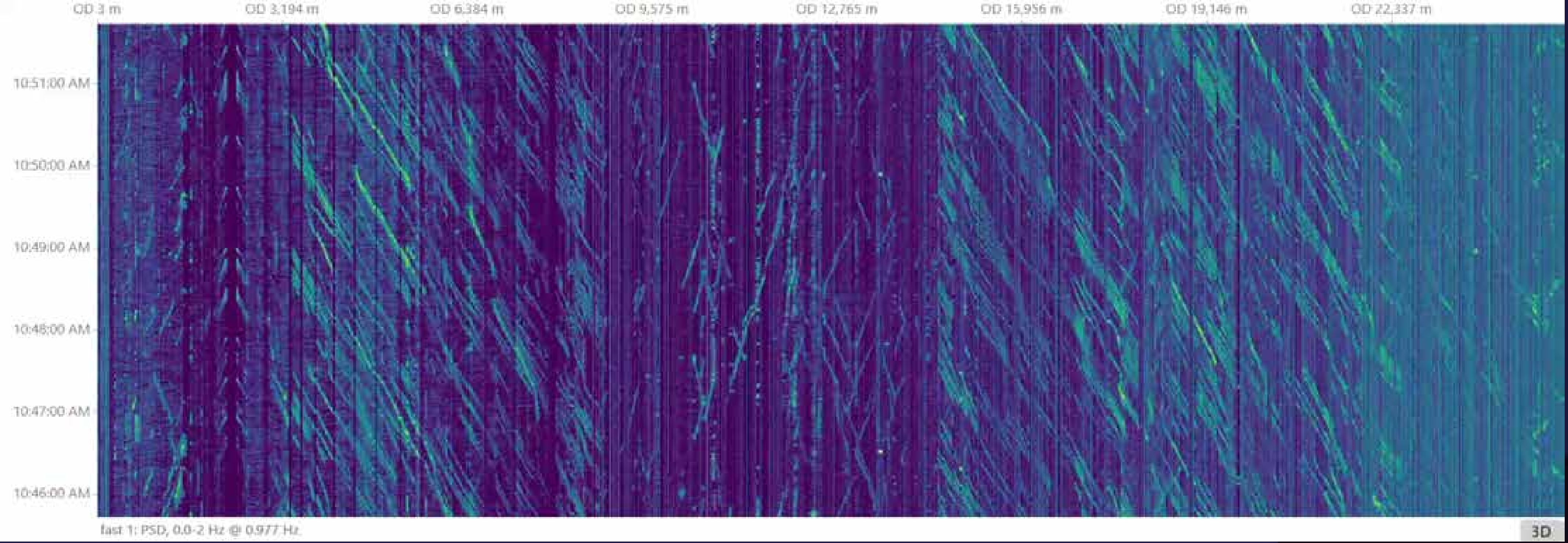
Runner - 90 kg
Distance(m)
Time(s)
Strain με
0 10 20 30 40 50 60 70
0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0
0.2 0.1 0.0 −0.1 −0.2 −0.3 −0.4 −0.5



Microstrain
Distance along road (m)
0.04 0.02 0.00 −0.02 −0.04
0 5 10 15 20 25 30 35 40







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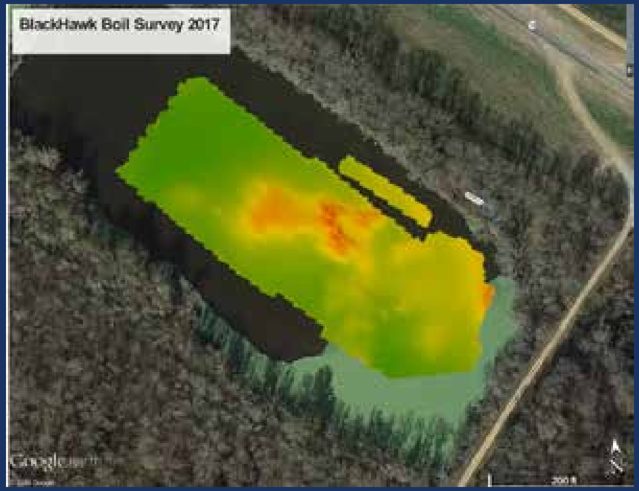
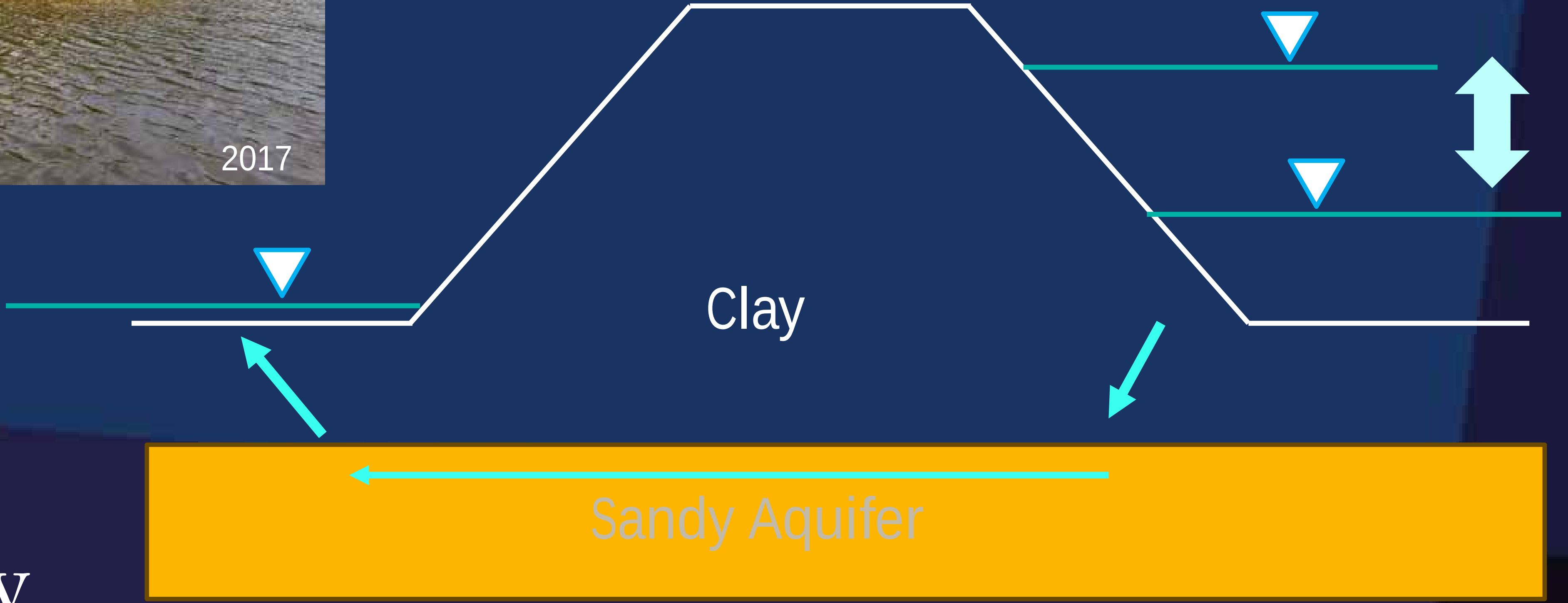
Levee - Black Hawk, Louisiana

- Purpose: Monitor the levee system for seepage, uplift, suffusion.





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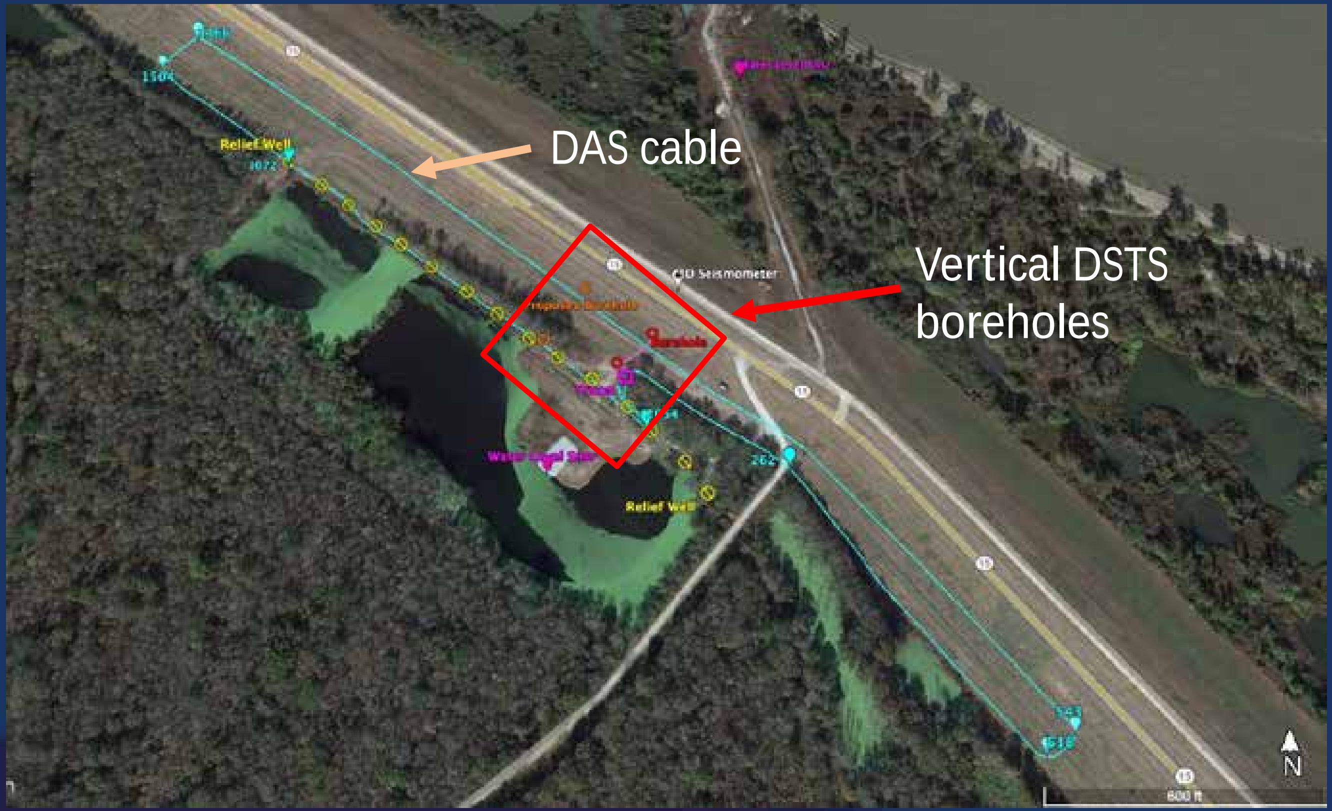
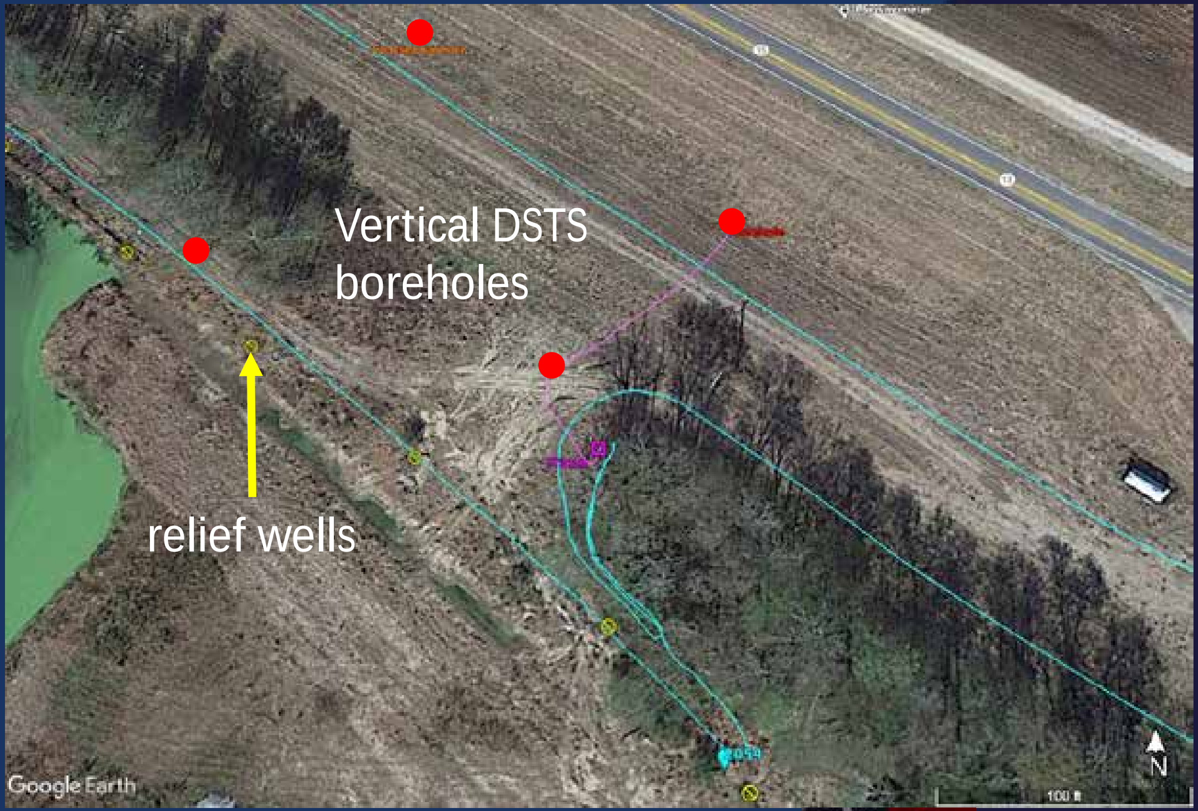
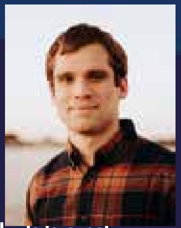
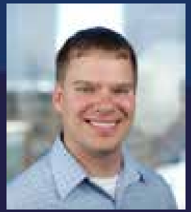
- **Distributed Strain Sensing – Vertical, to detect movement of the clay blanket.**
- **Distributed Temperature sensing – Vertical and horizontal, to detect flow and calibrate strain measurements.**
- **Distributed Acoustic Sensing – Horizontal, to monitor for changes to dynamic properties.**






Peter Hubbard


James Wang


Andrew Yeskoo


John Murphy

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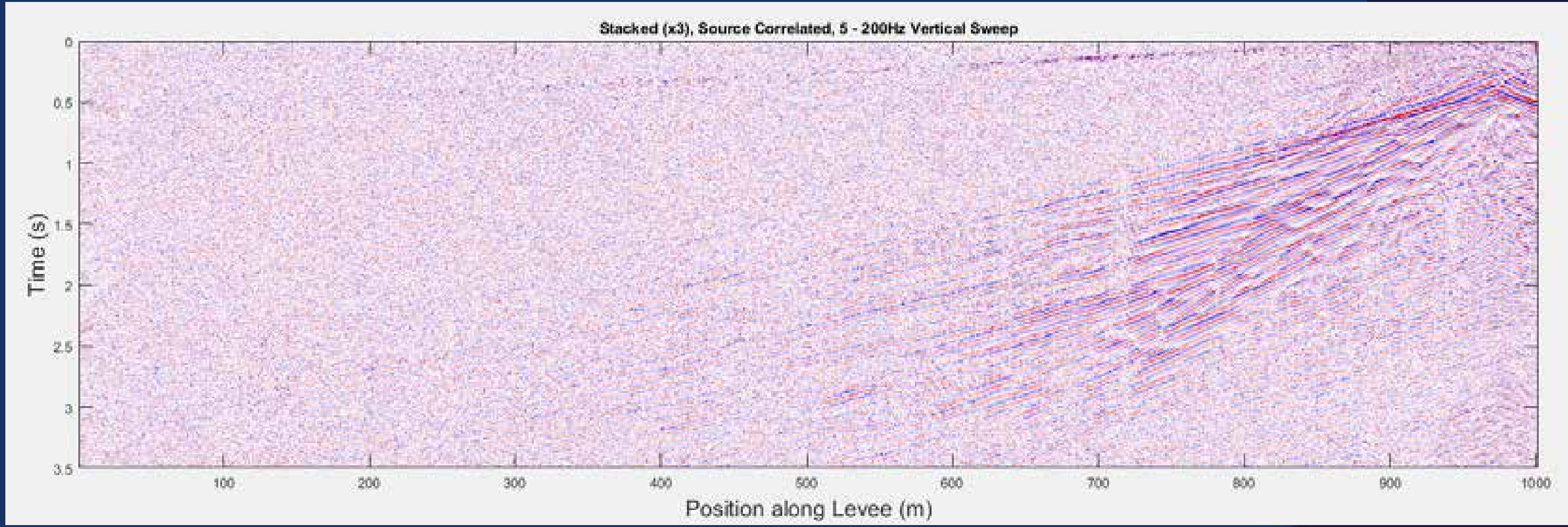
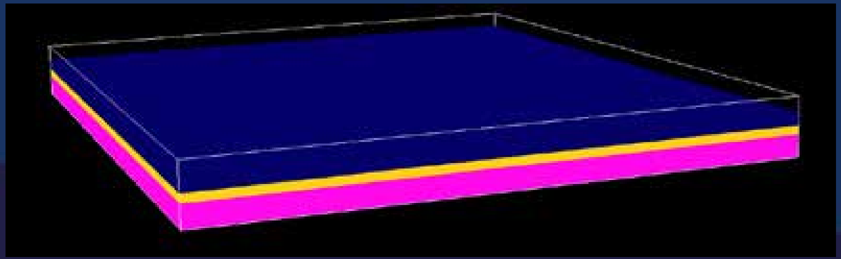
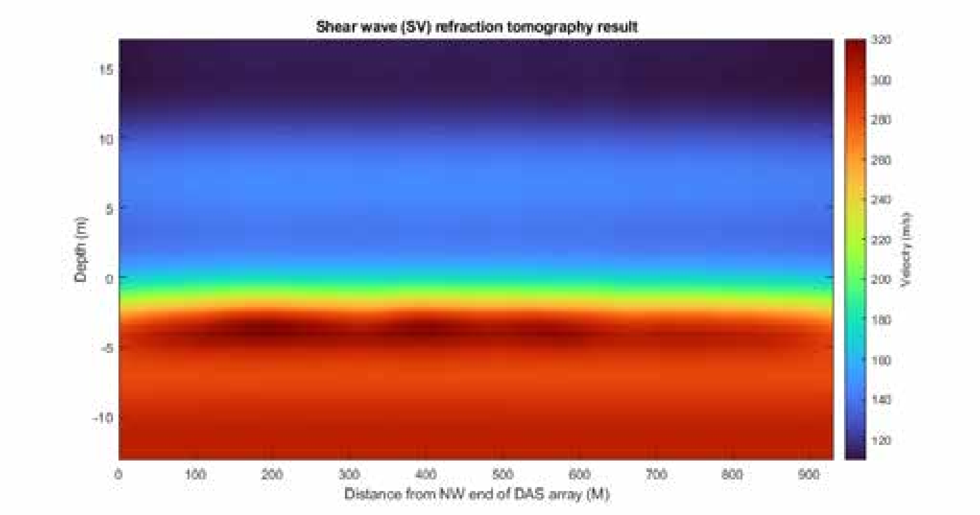
Distributed Acoustic Sensing measurements







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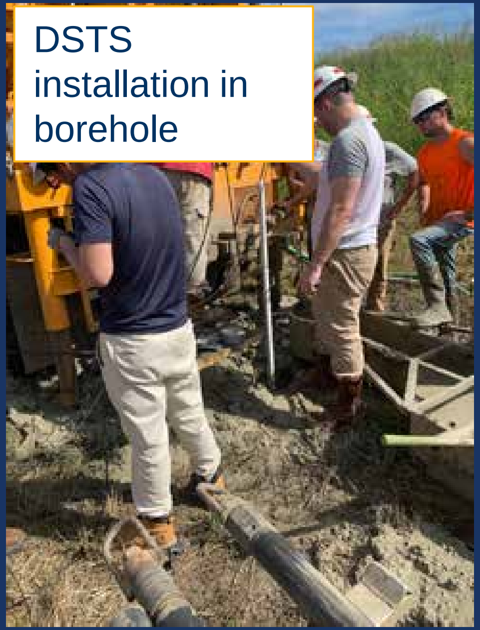
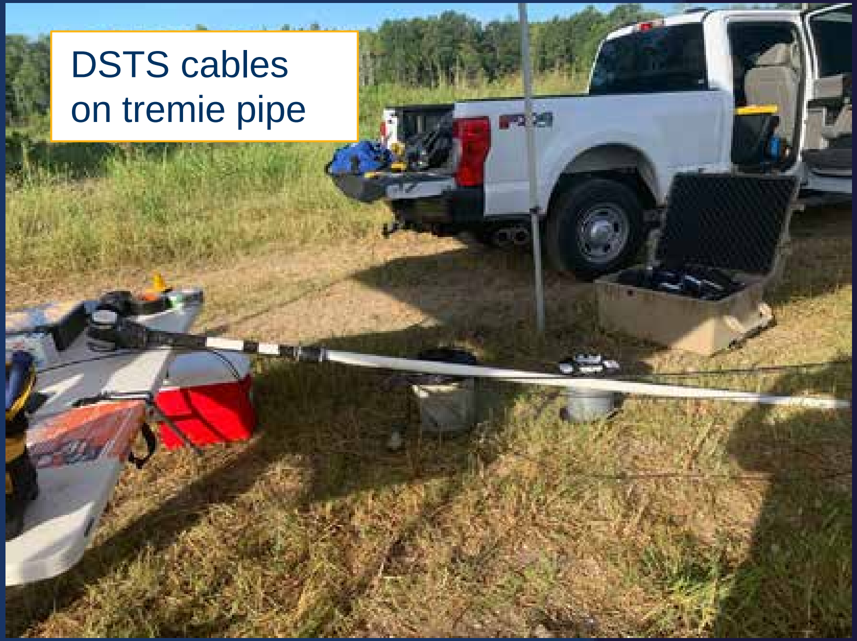
Cable Installation


DSTS installation in borehole


DSTS cables on tremie pipe

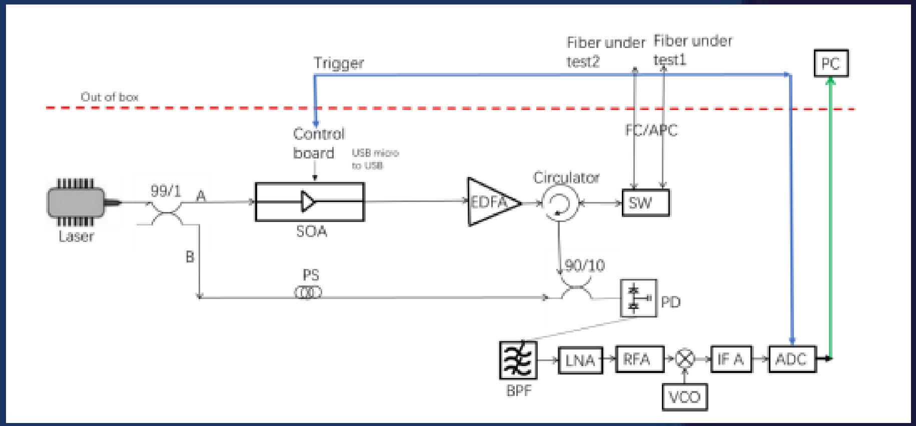

DAS Installation using a cable plow


Pre-tensioning process


Final appearance of DSTS installation

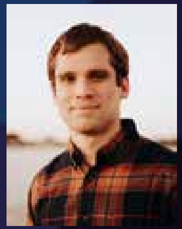
System development

- **Design**
- **Construction**
- **Deployment**
- **Autonomous operation**



DSTS – optoelectronic schematic

Linqing Luo



Peter Hubbard

James Wang

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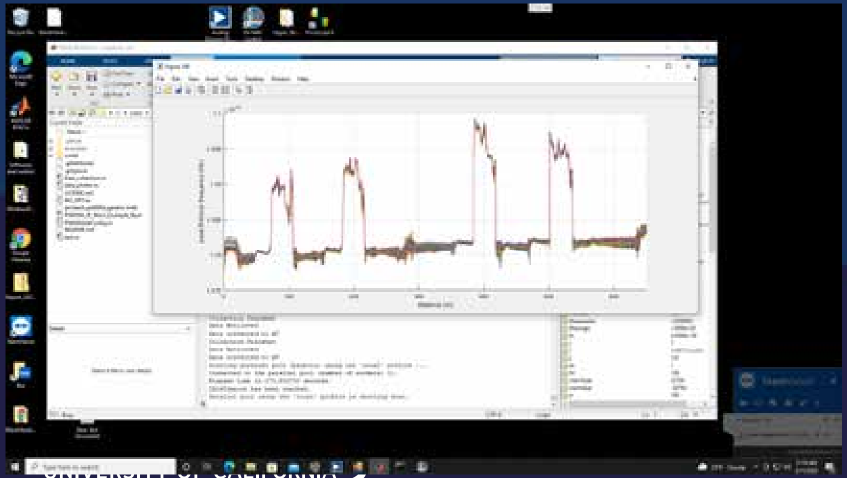
Data Acquisition

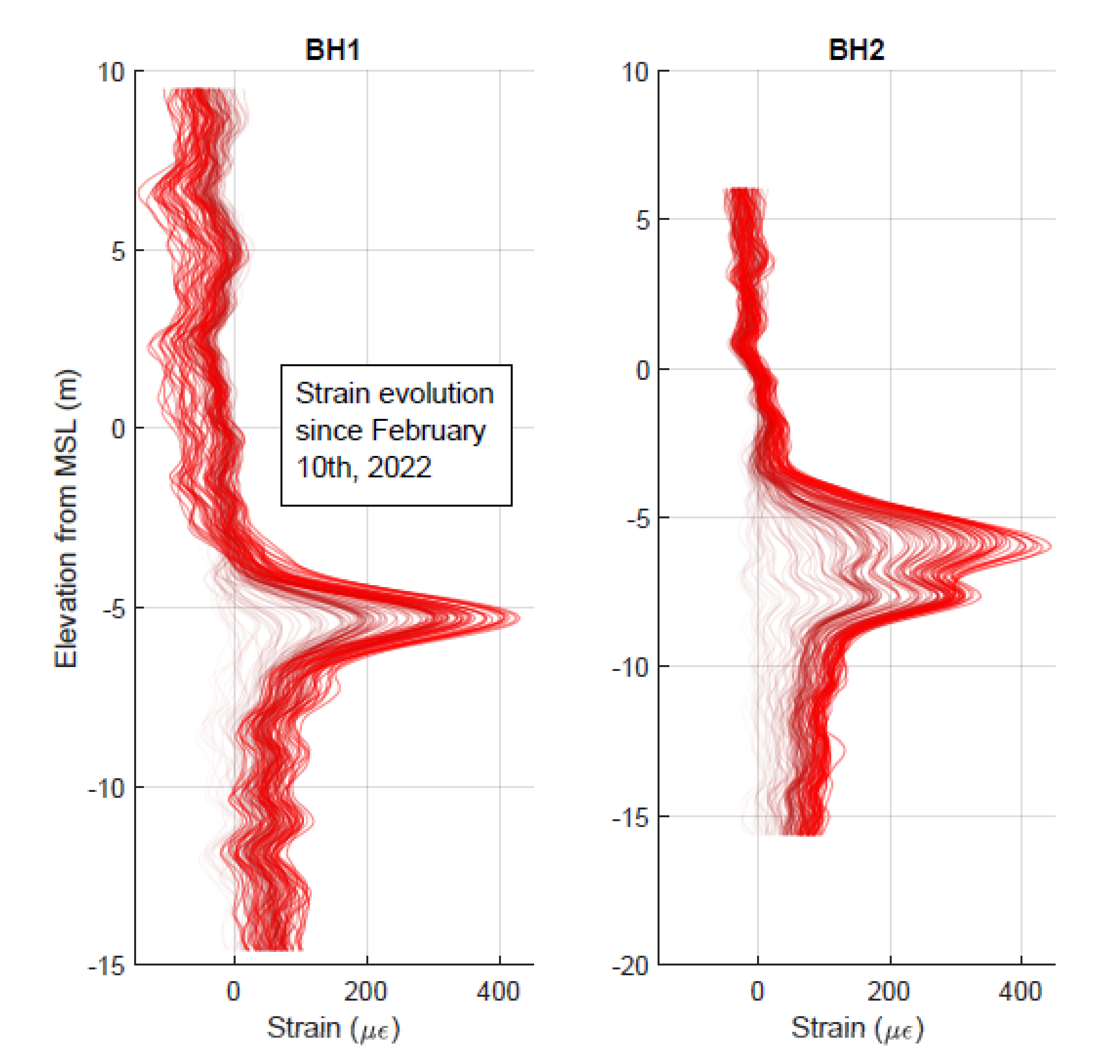
Tricon permanent equipment housing

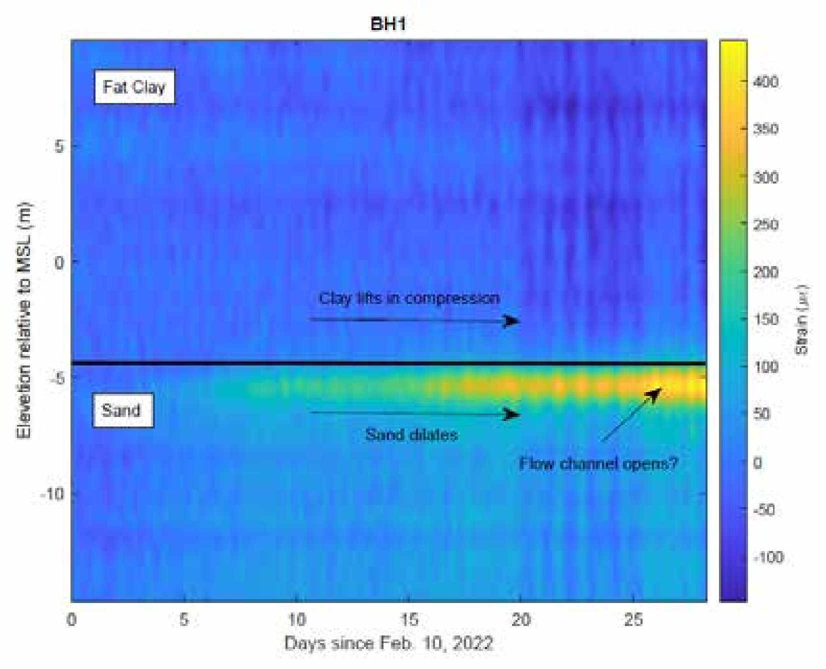
DAS workshop, Oct. 2021

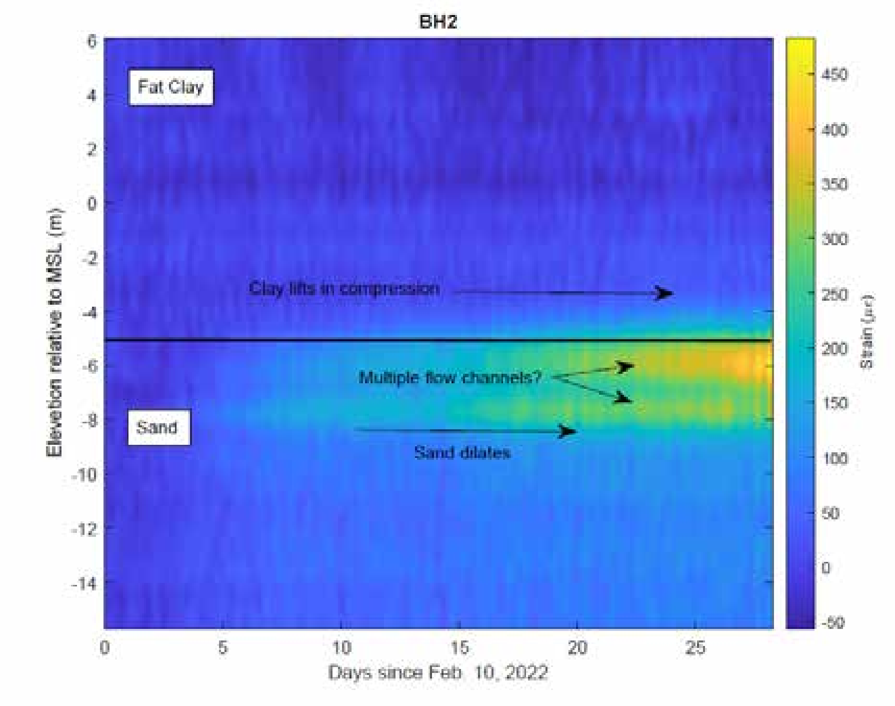
24/7 remote access to real-time DSTS data



Subsurface vertical strain monitoring







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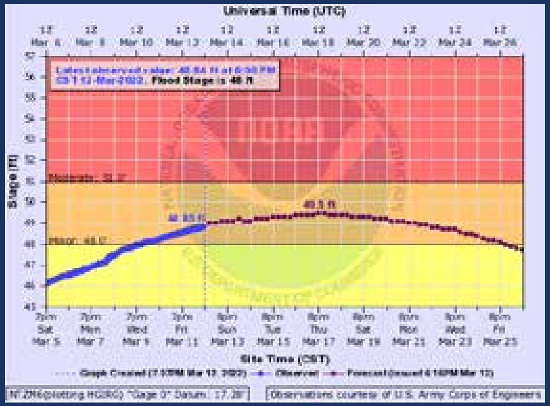
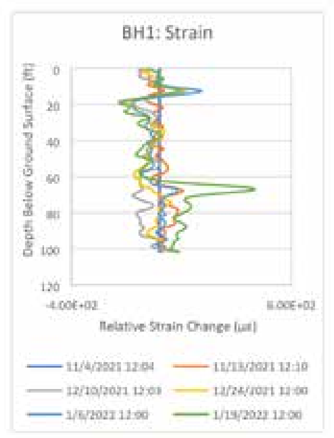
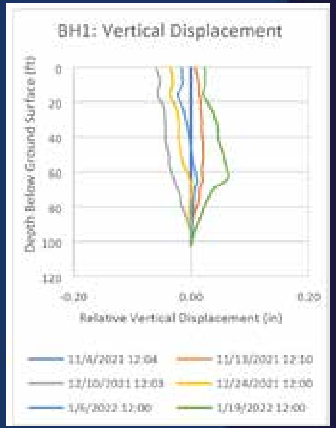
System level performance

River level

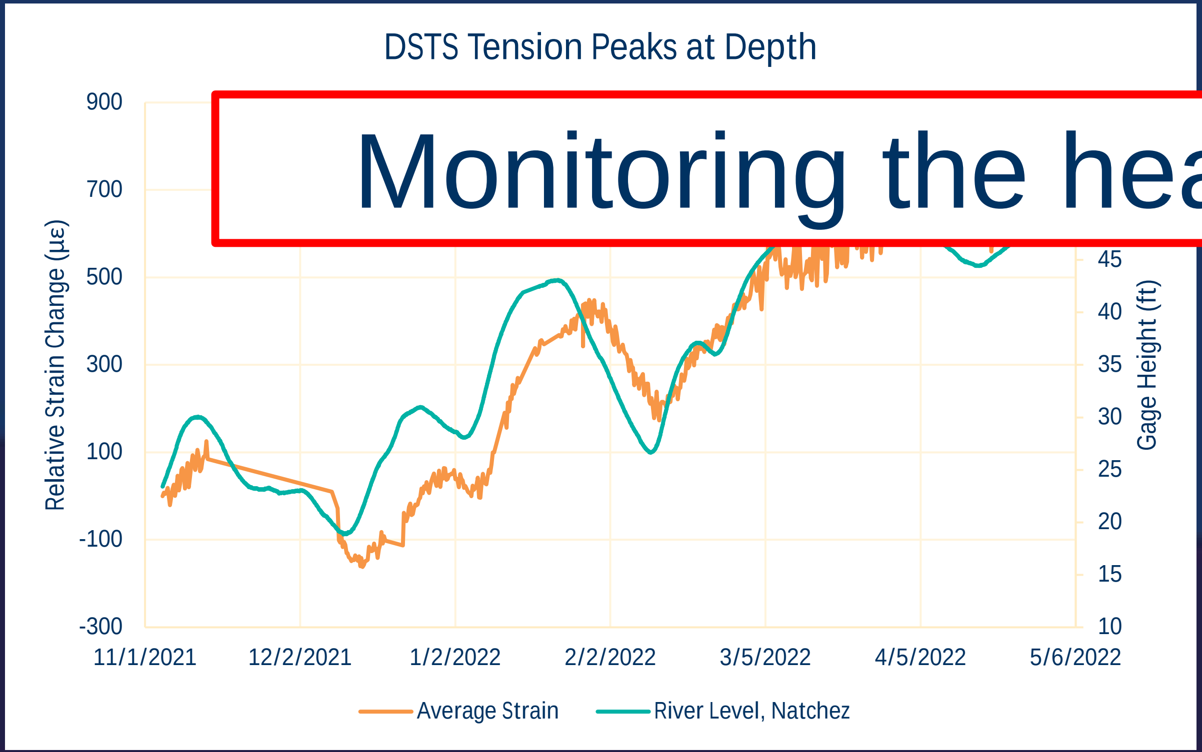




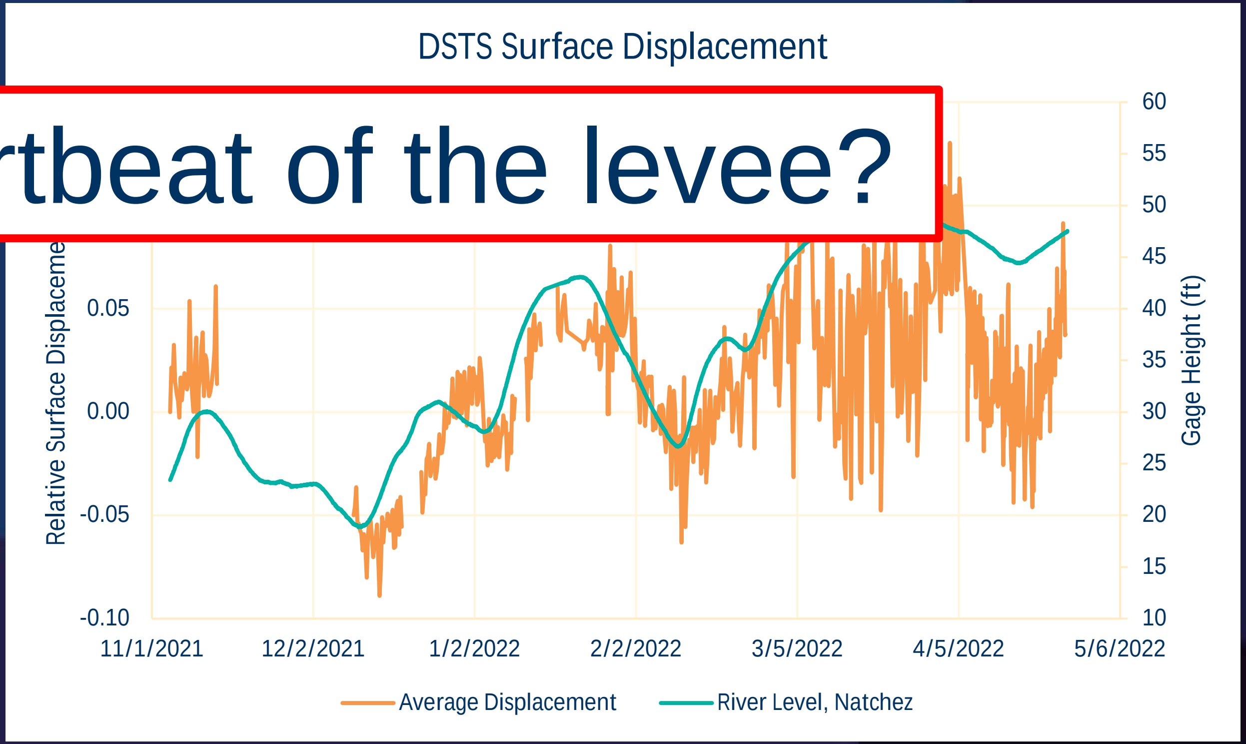
$$u(z) = \int \varepsilon(z)\, dz$$



Maximum strain versus time

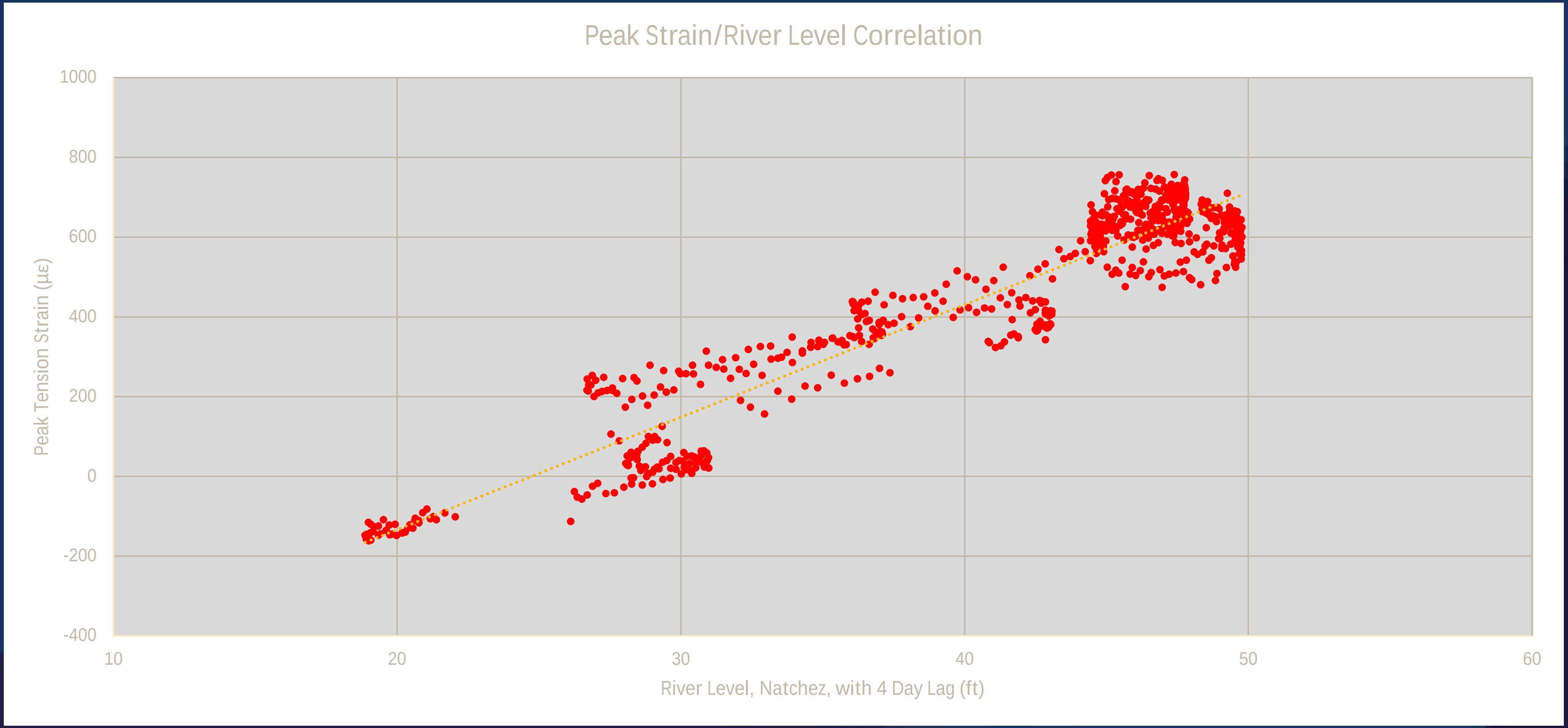


Surface displacement versus time



Monitoring the heartbeat of the levee?

Correlation between peak strain and river level (with 4 day lag)



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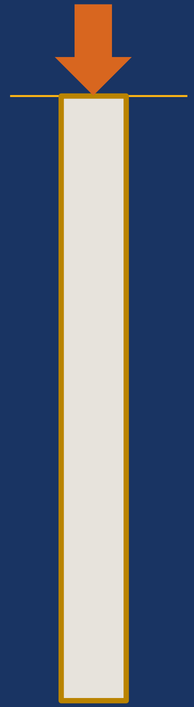
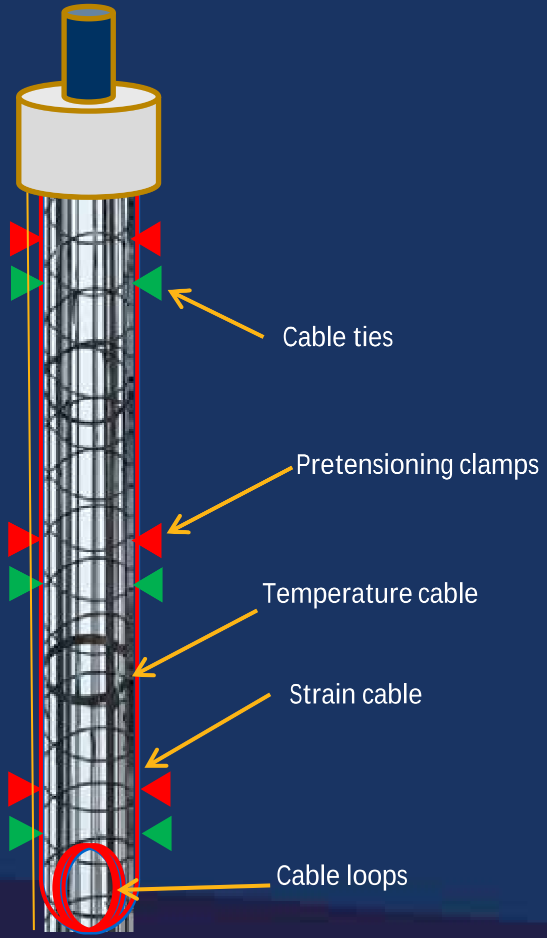
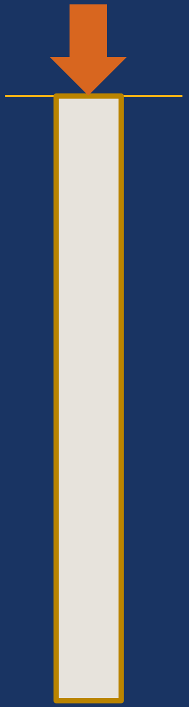
Deep Foundations

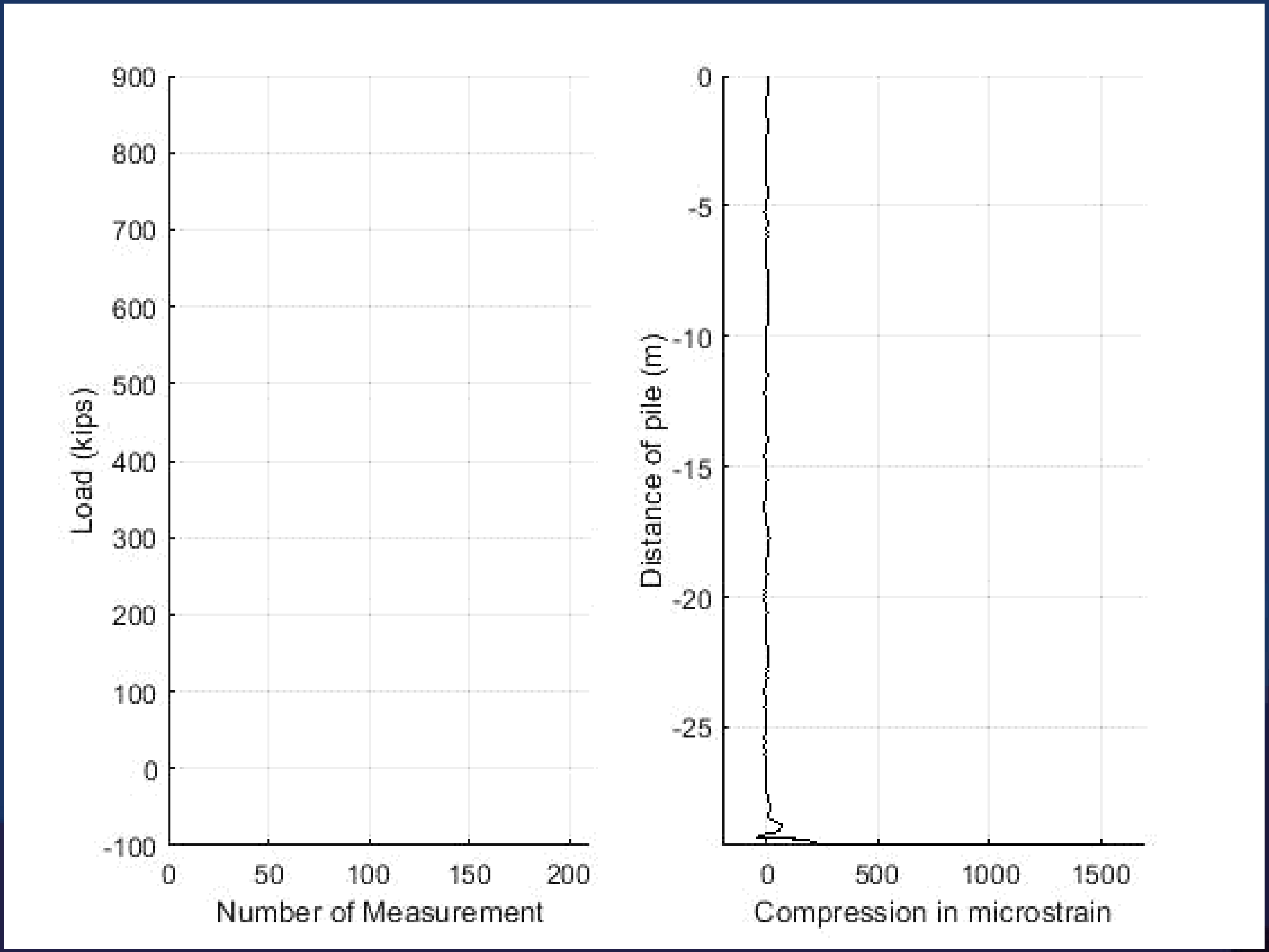
A pile loading test...





A pile loading test...





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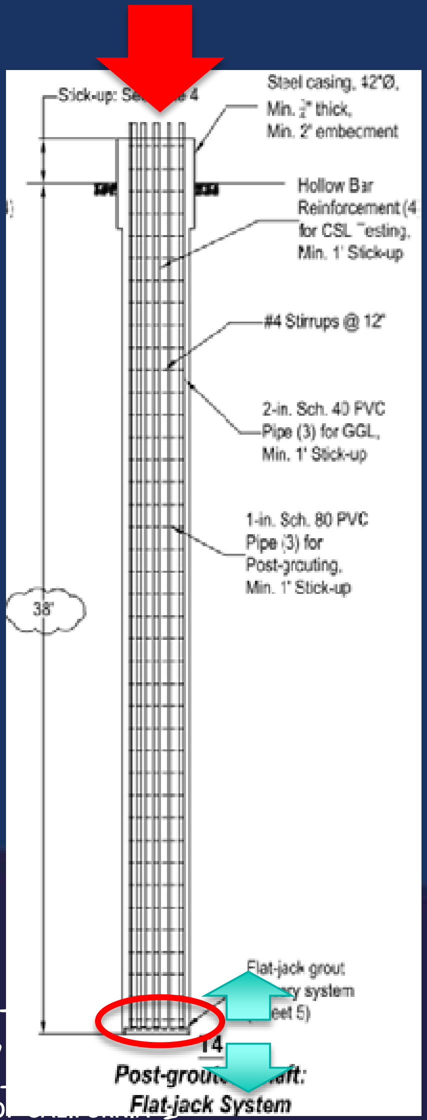
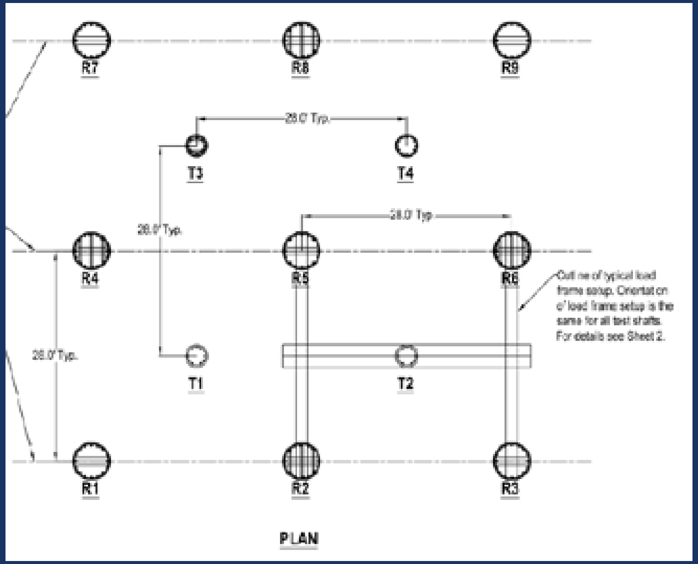
Deployment of Post Grouting Technique to improve Drilled Shaft End-Bearing Resistance





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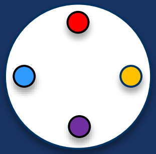
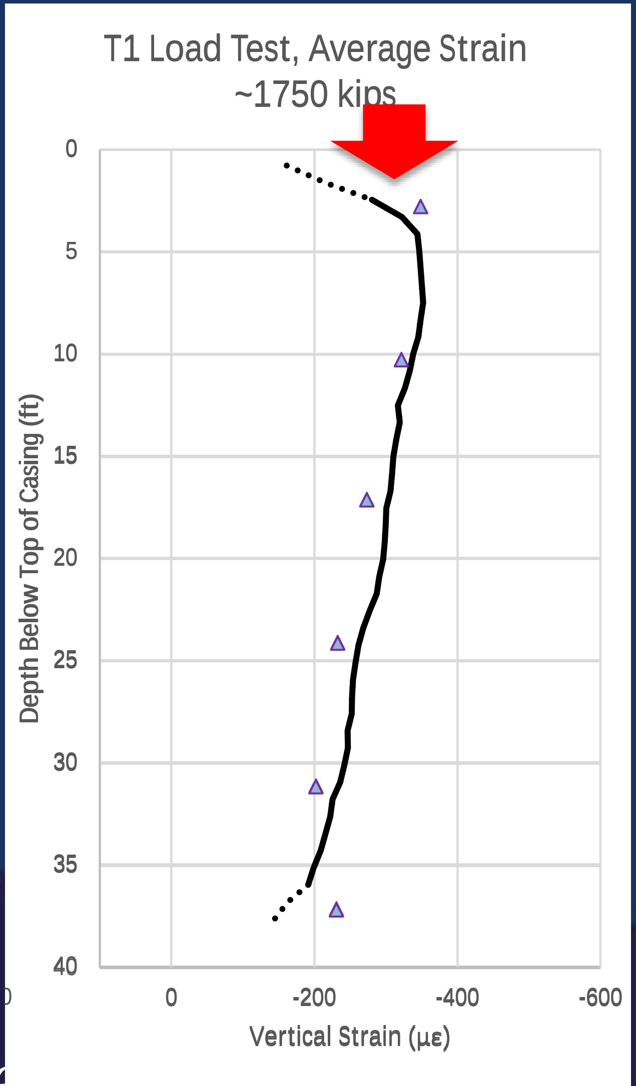
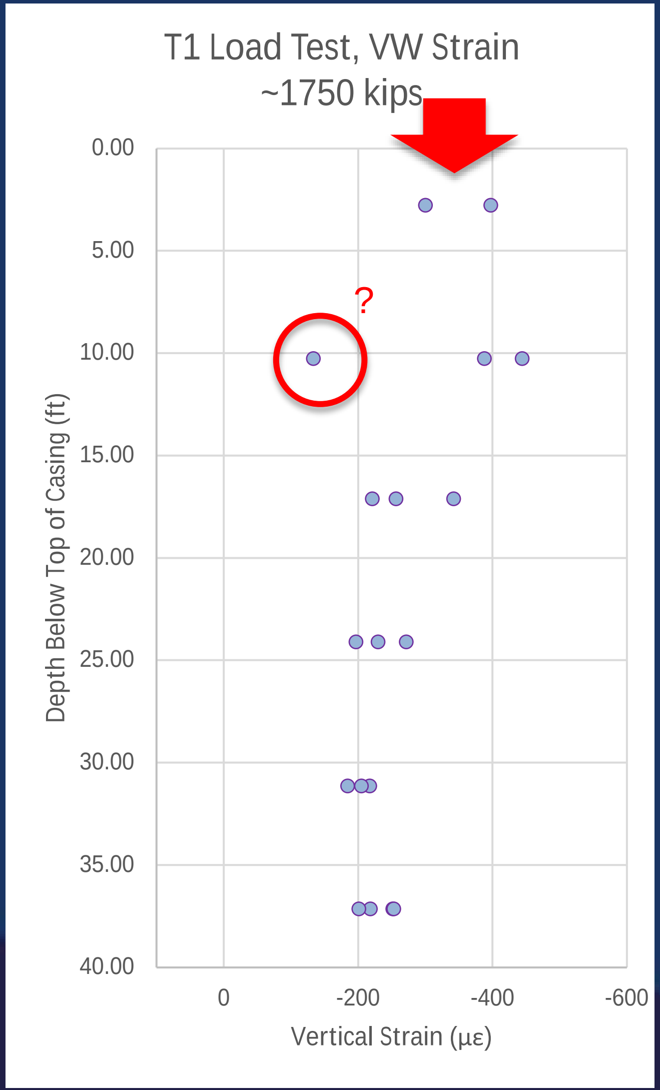
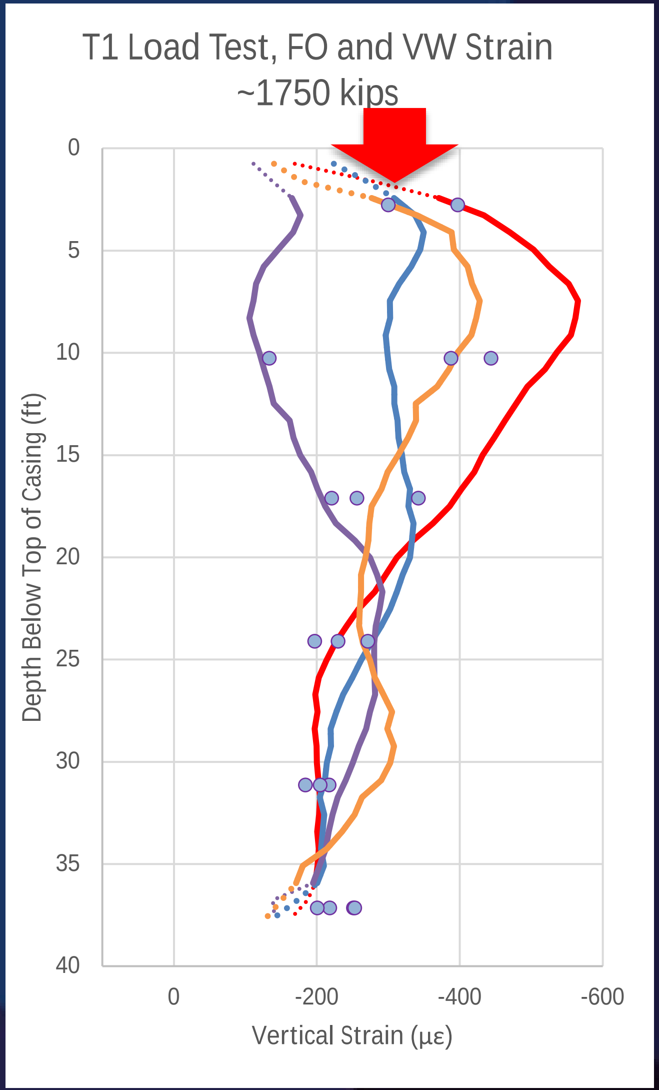
FO Strain vs. VW Strain Gauges Variation









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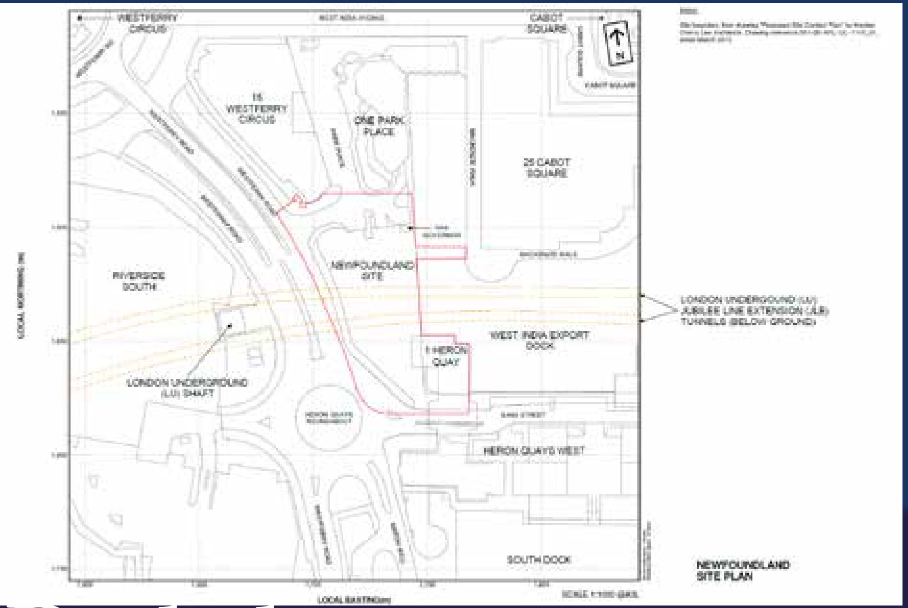
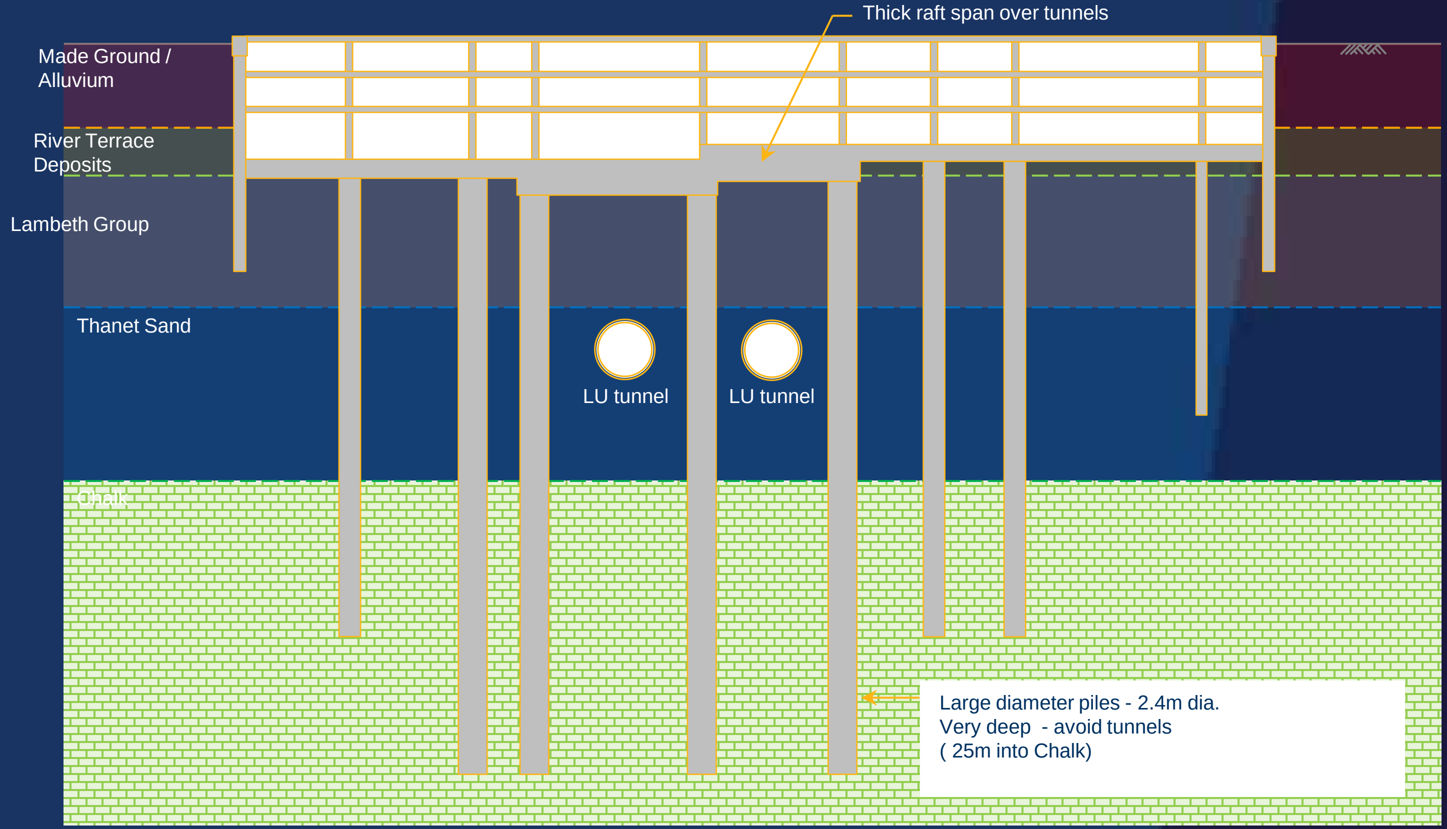
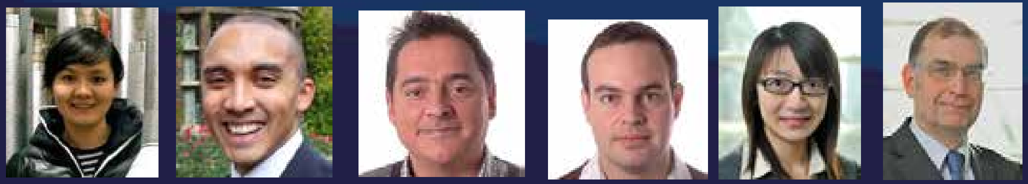
A building construction at the Isle of Dog, London







Echo Ouyang | Musa Chunge | Cedric Kechavarzi | Loizos Pelecanos | Vivien Kwan | Duncan Nicholson

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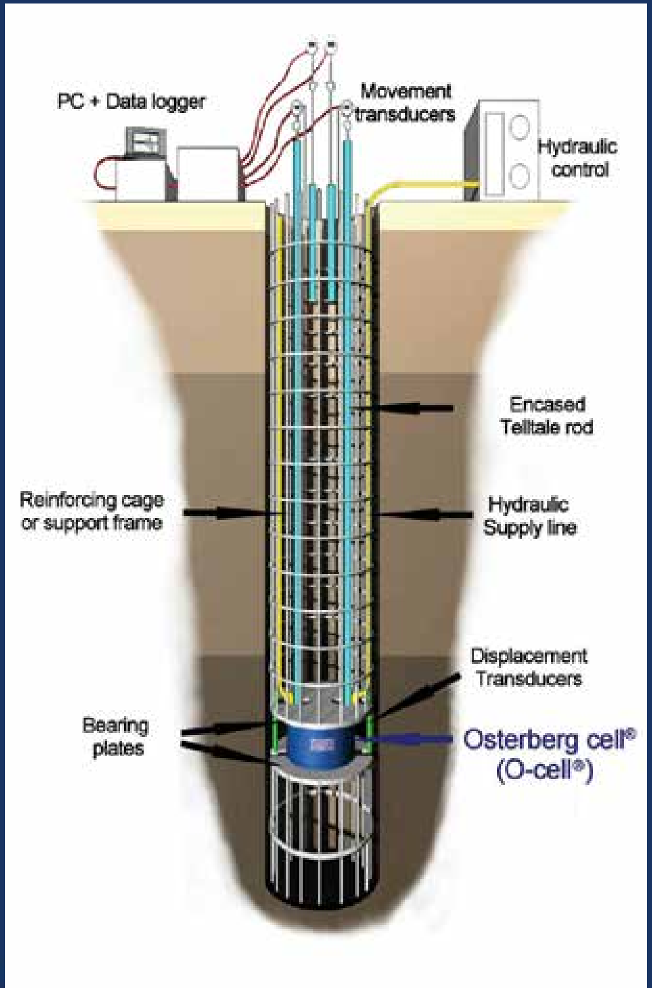
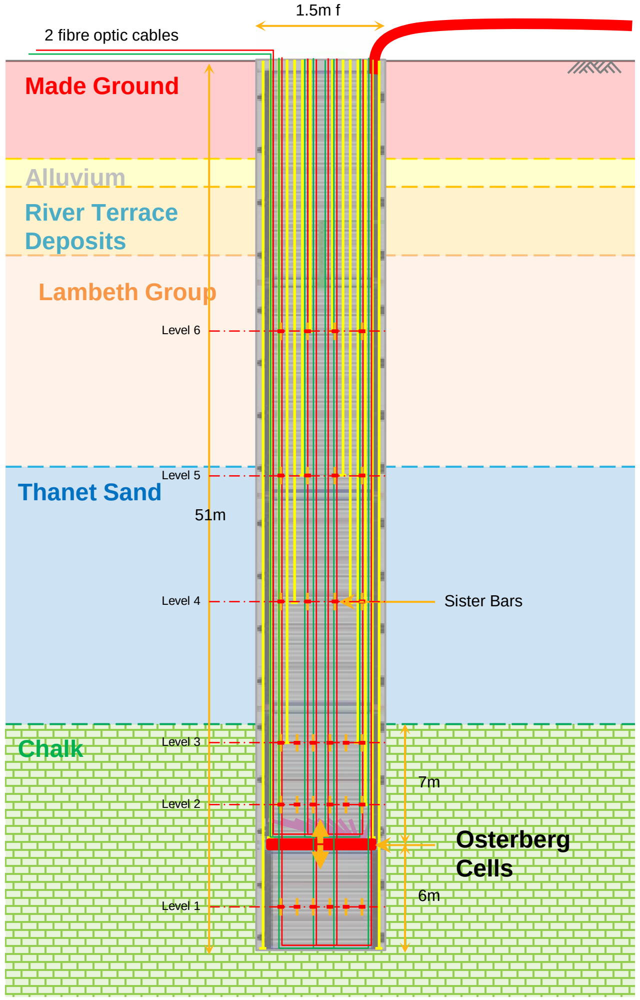
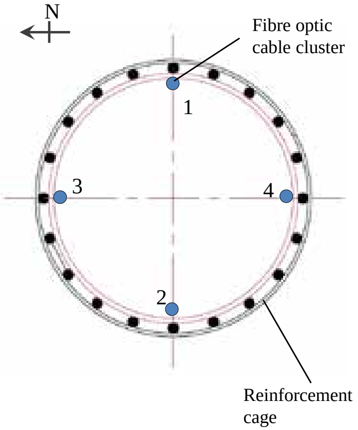
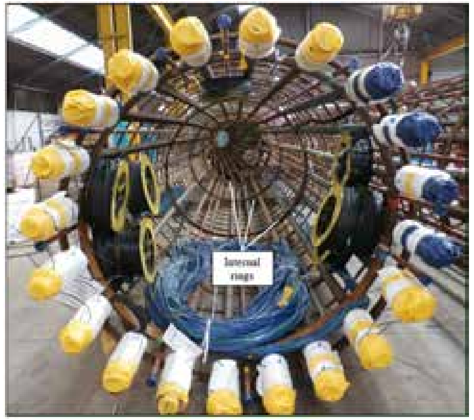
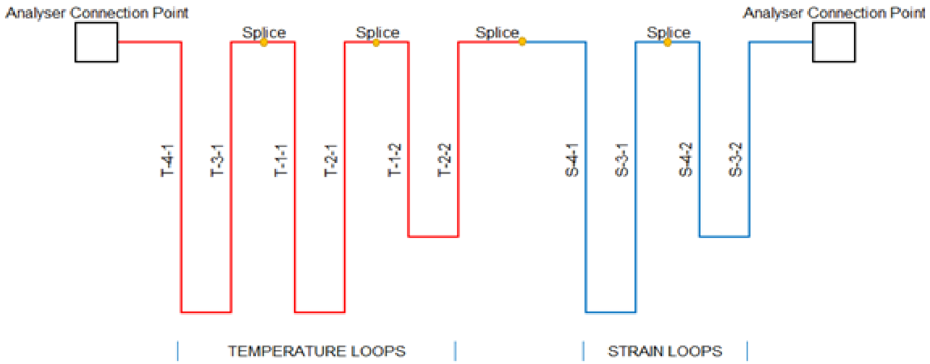
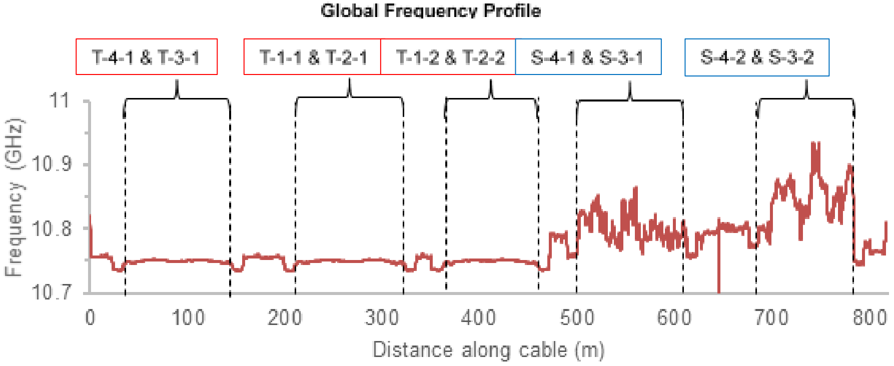






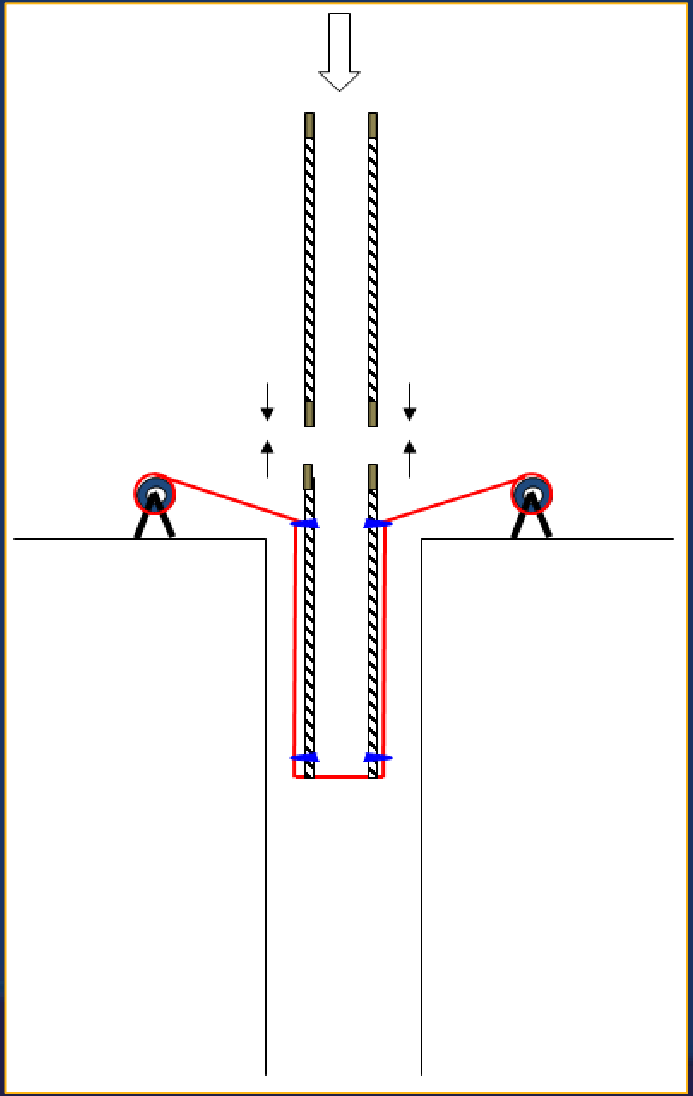




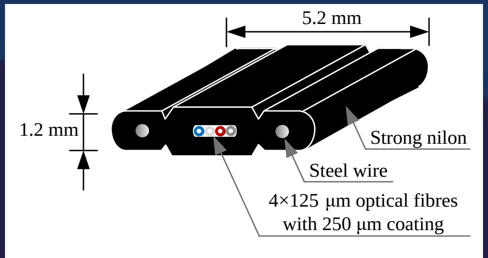


- Diameter = 1.5m
- Length = 51m
- Osterberg-cell
- Load up to 31MN

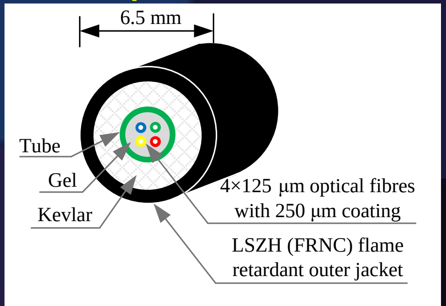
Minimal disturbance to actual construction operations



Strain cable



Temperature cable



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Conventional Strain Gauge System

Distributed FO system

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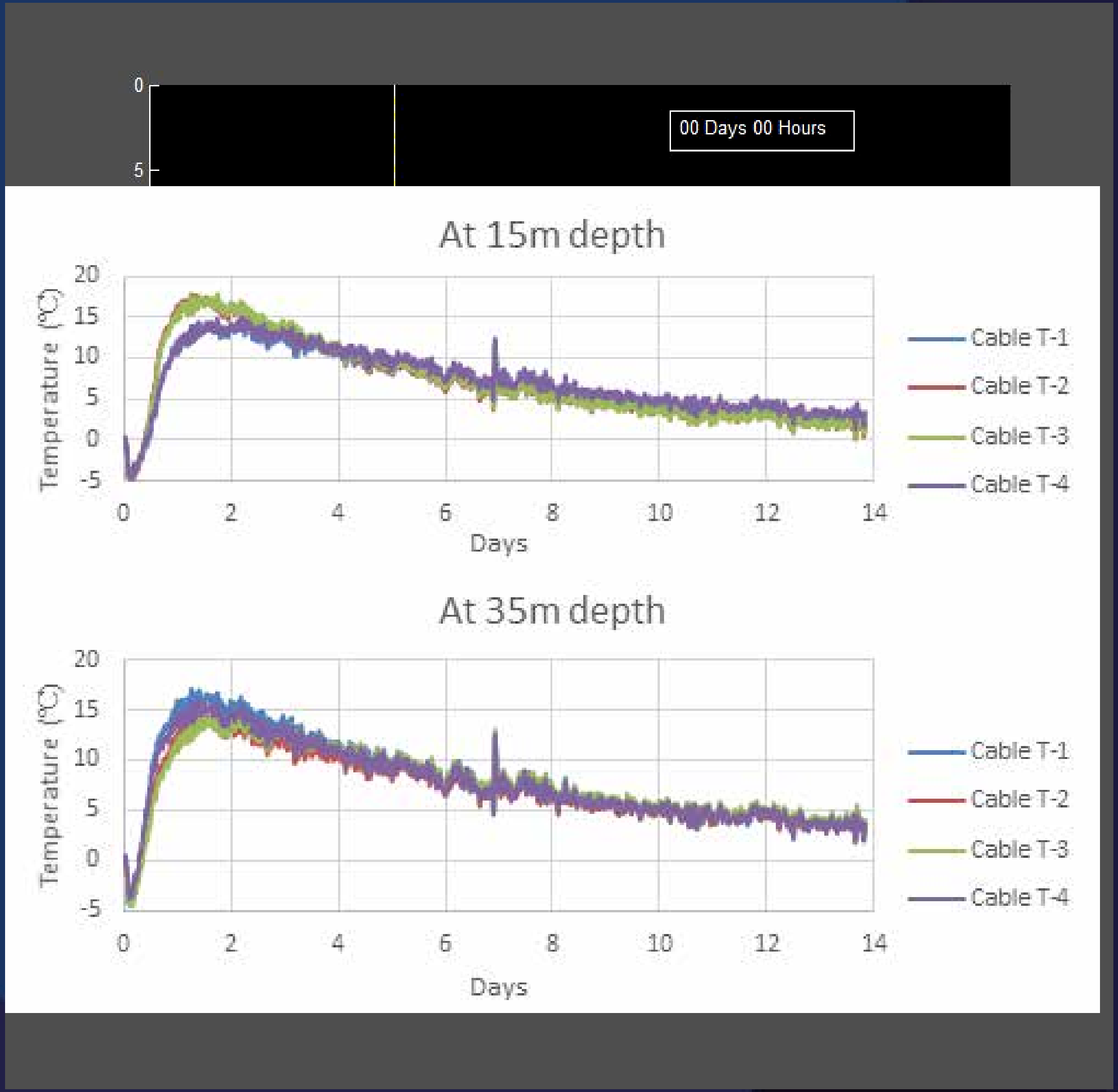
PROBLEMS WITH PILE CONSTRUCTION

- Construction can be challenging
  - alignment
  - concrete quality and placement
  - soil collapse
- Visible inspection not possible
- Repair and rework is very difficult
- Not all anomalies are defects/detrimental

FHWA-NHI-10-0161.



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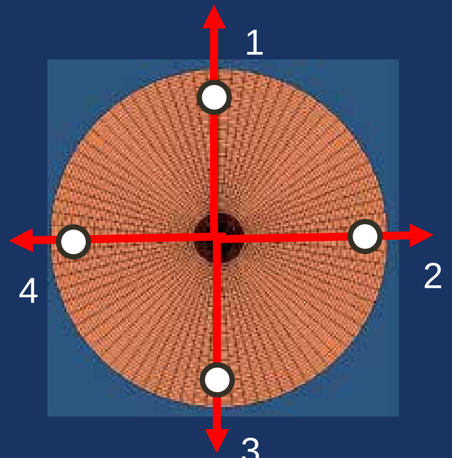
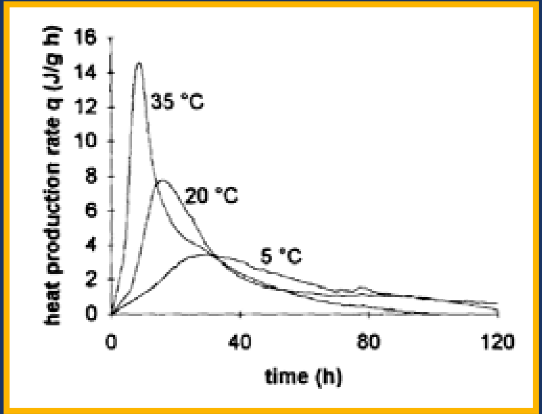
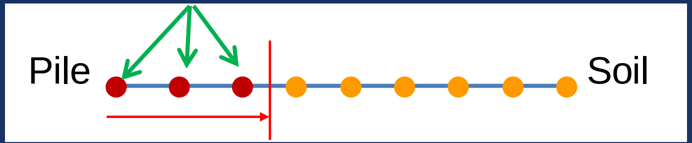
Rui, Y., Kechavarzi, C., O'Leary, F., Barker, C., Nicholson, D. and Soga, K., 2017. Integrity testing of pile cover using distributed fibre optic sensing. *Sensors*, *17*(12), p.2949.

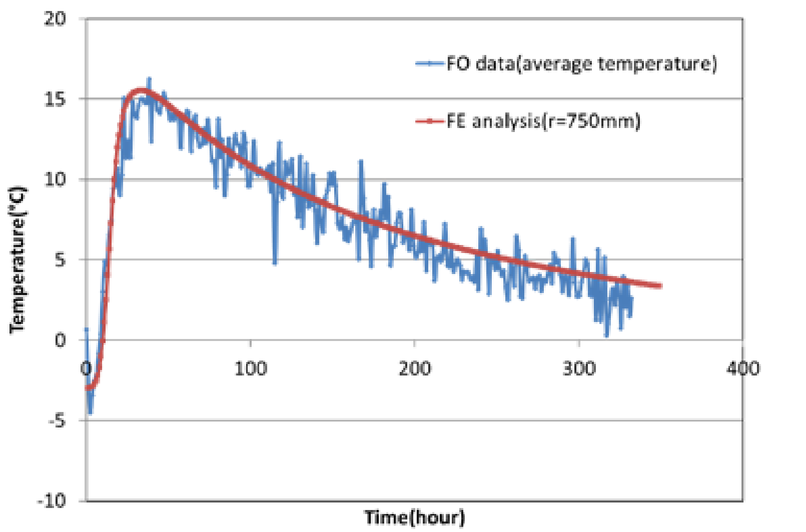


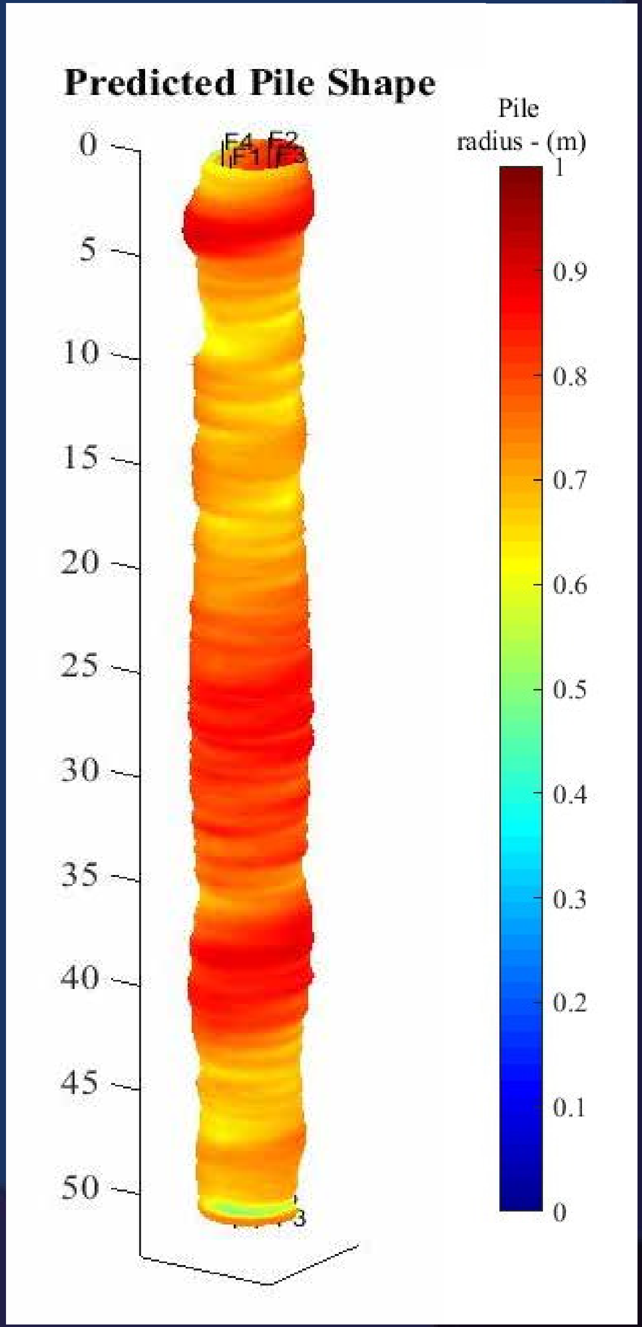


Source of concrete heating

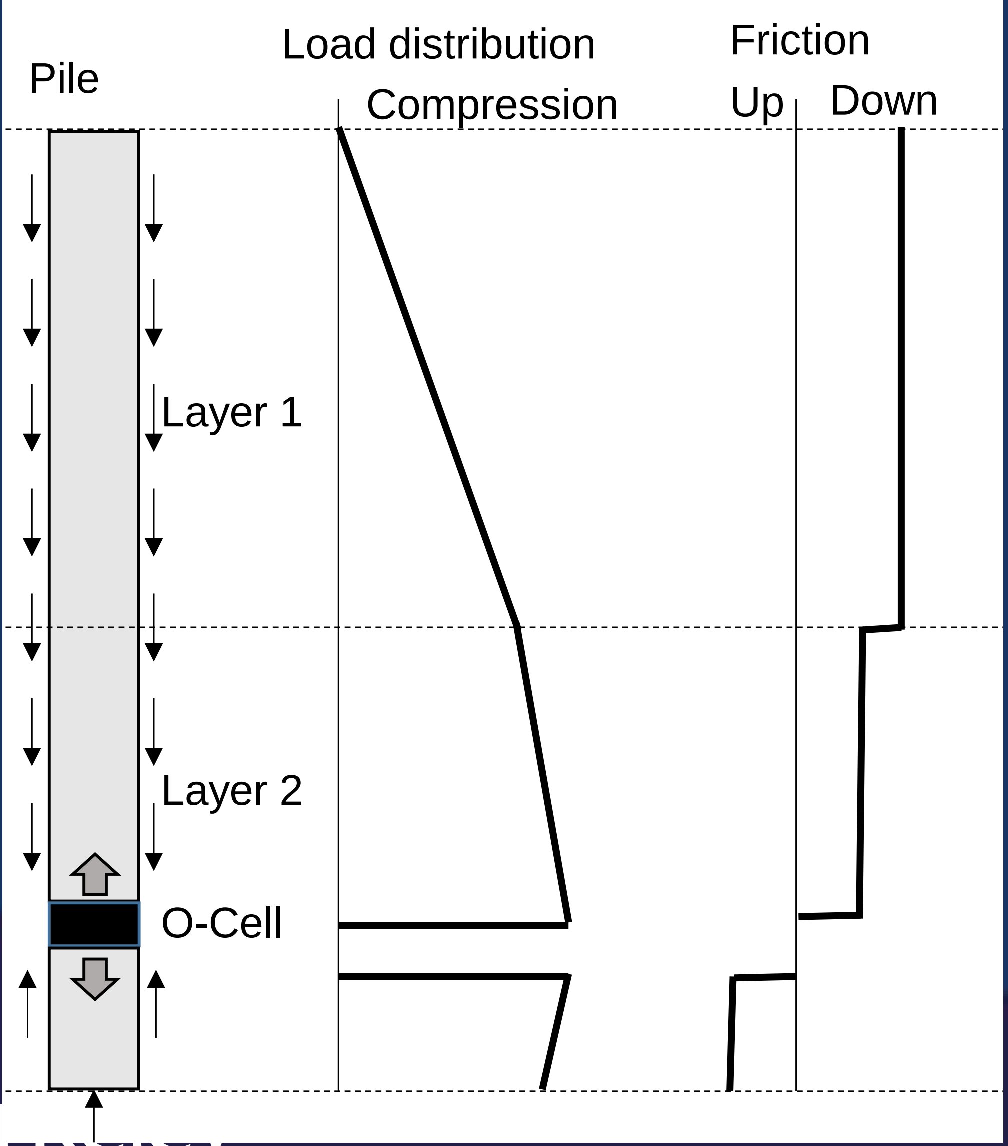


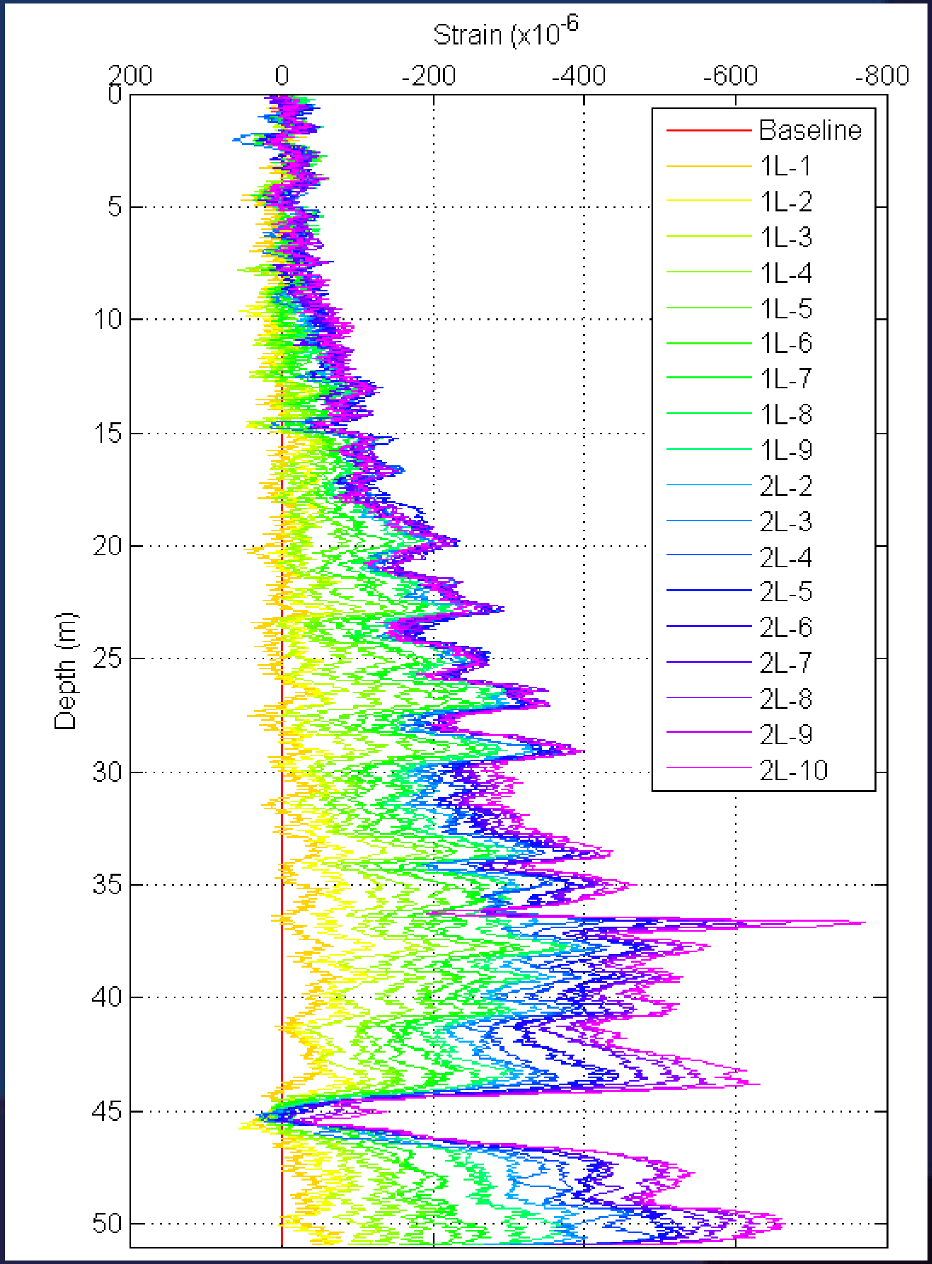
Find the pile radius which match the temperature profile (20 x 4 x 50 = 4000 data sets)

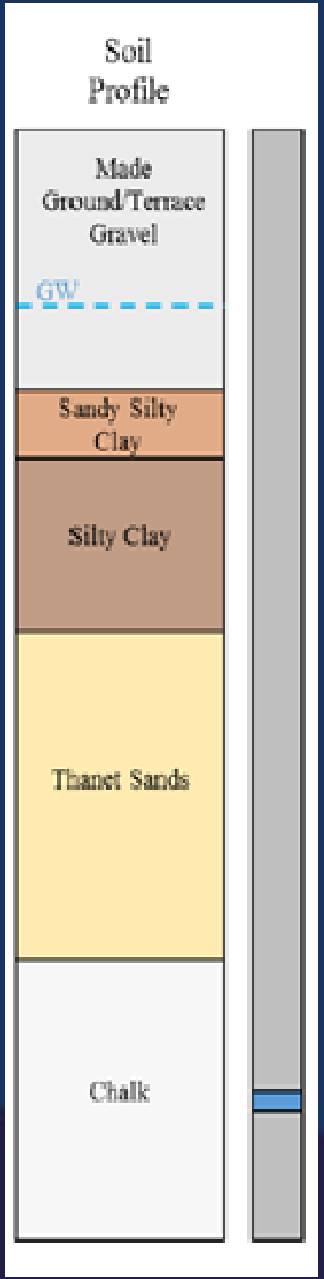


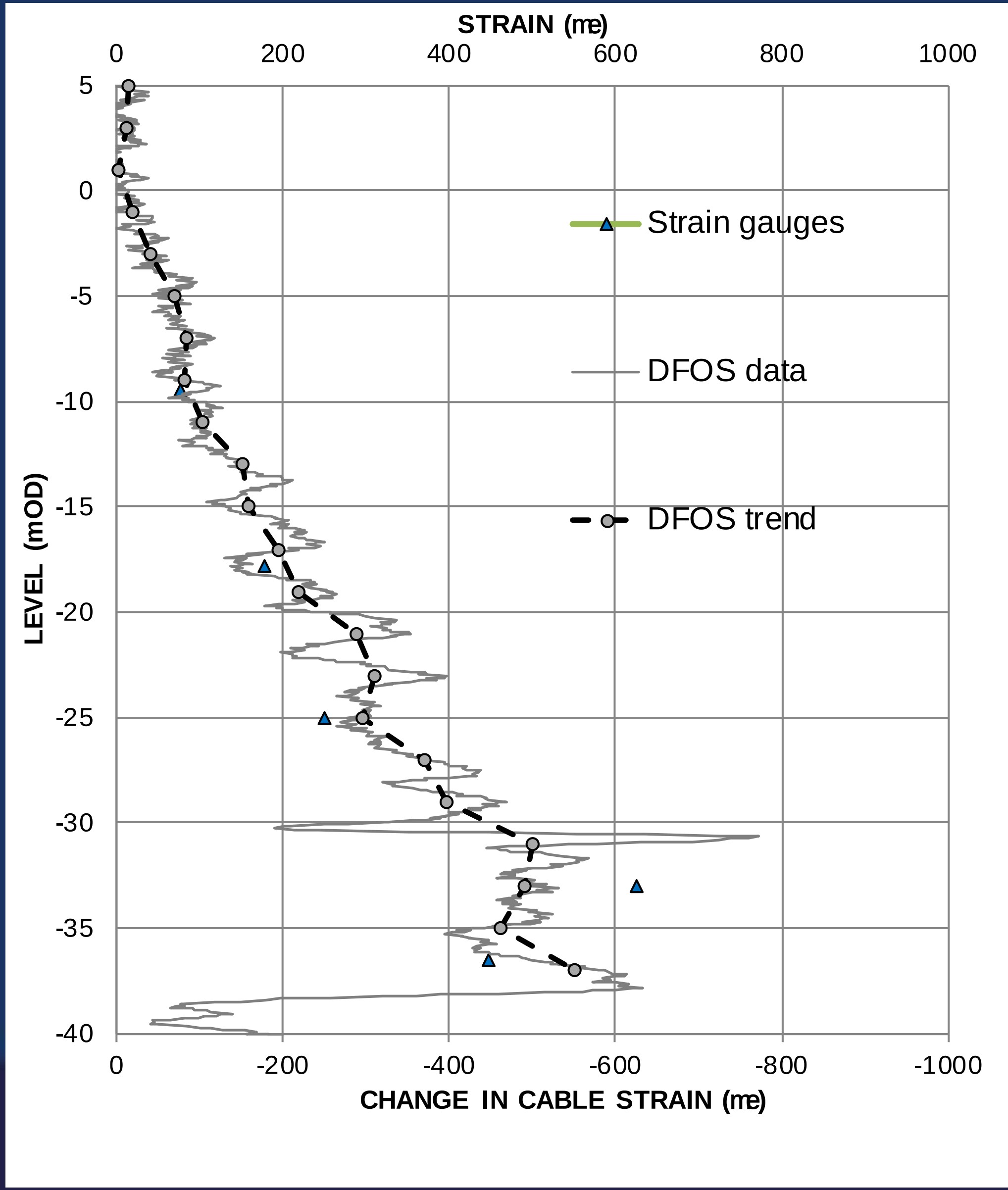


Mechanism of Loadcell testing









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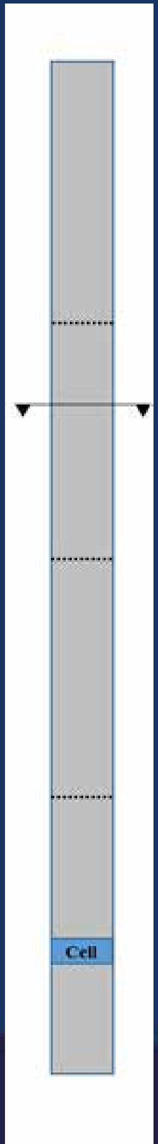
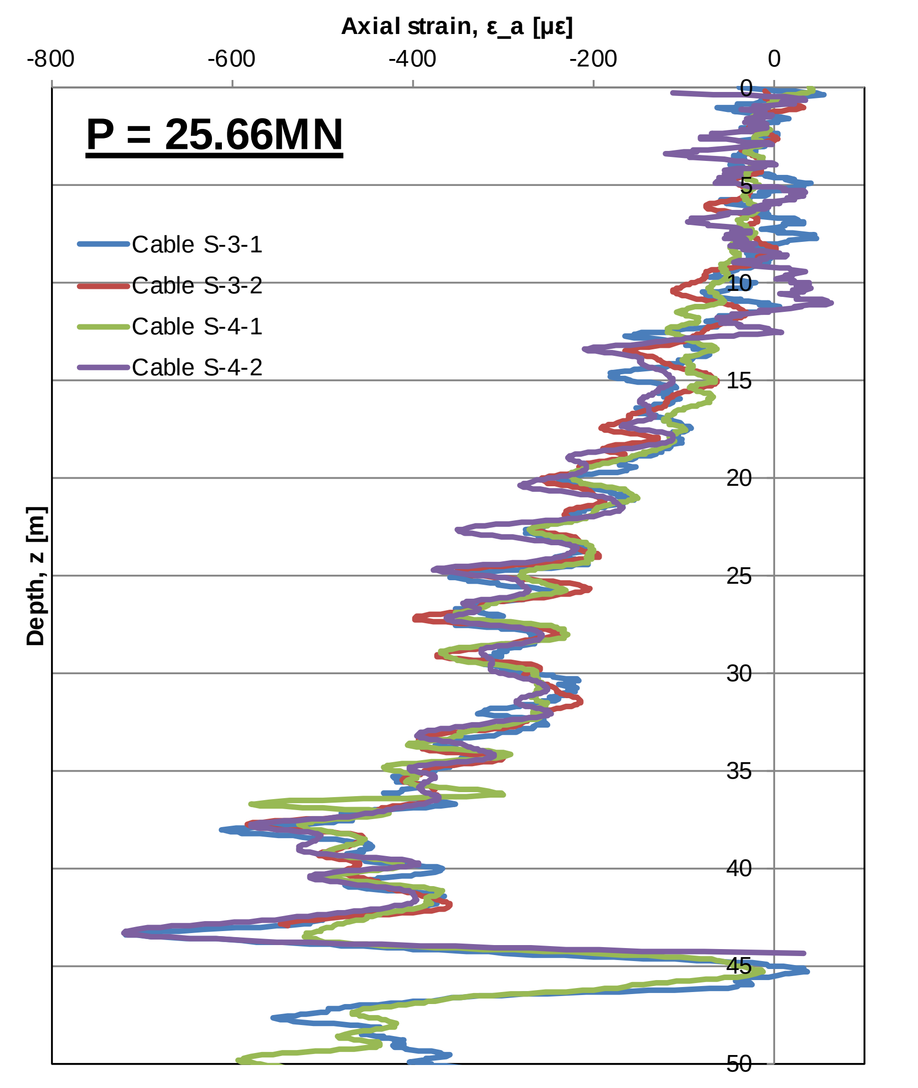
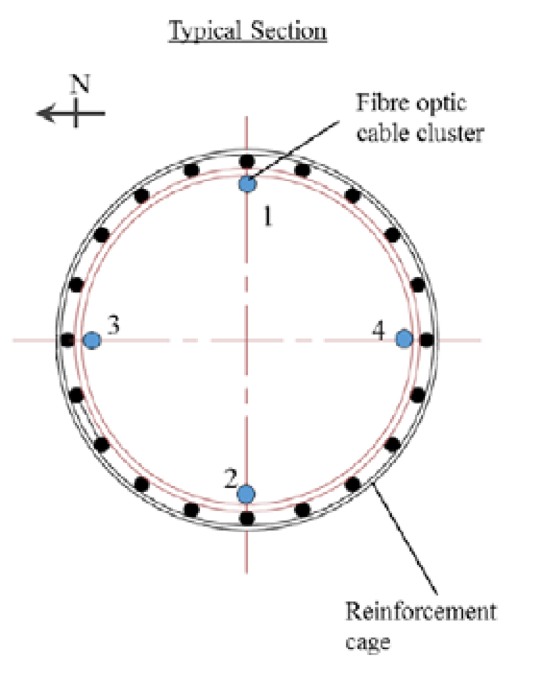
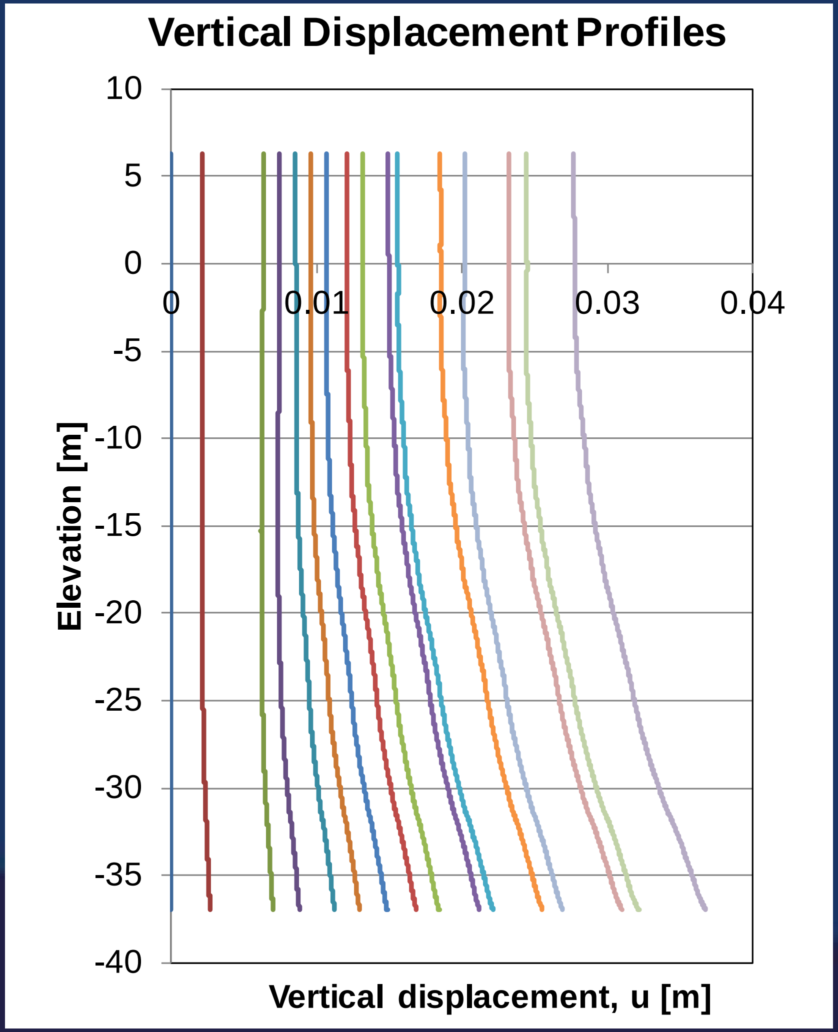
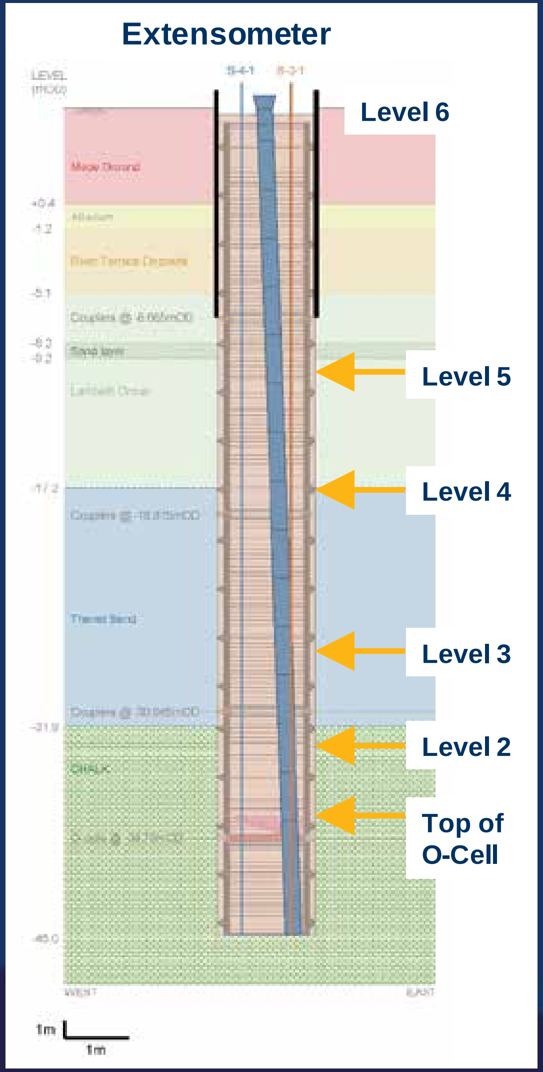

Cell

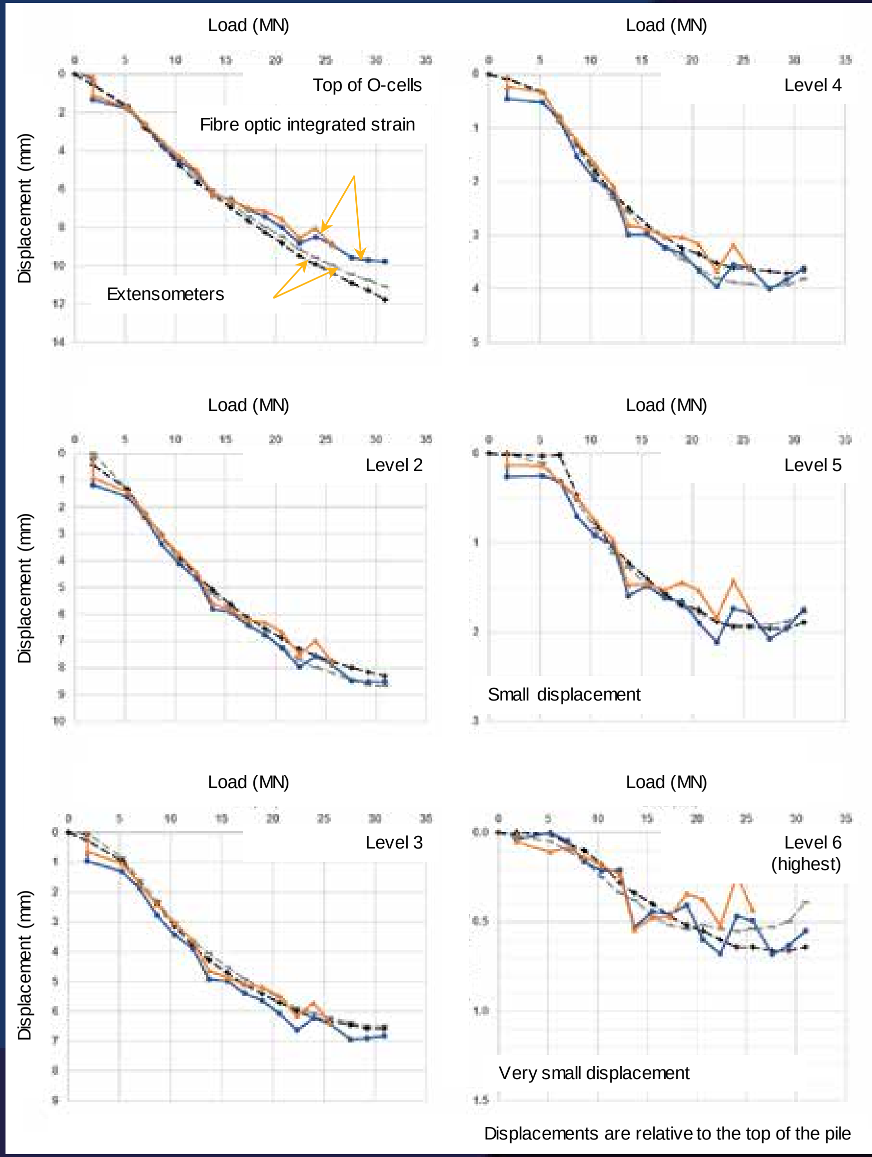

Axial strain, ε_a [με]
-800
-600
-400
-200
0
P = 25.66MN
Cable S-3-1
Cable S-3-2
Cable S-4-1
Cable S-4-2
Depth, z [m]
0
5
10
15
20
25
30
35
40
45
50


Typical Section
N
Fibre optic
cable cluster
1
2
3
4
Reinforcement
cage

$$u(z) = \int \varepsilon(z)\, dz$$







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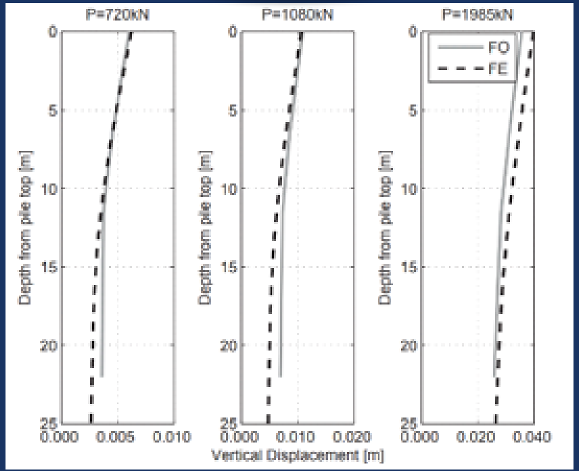
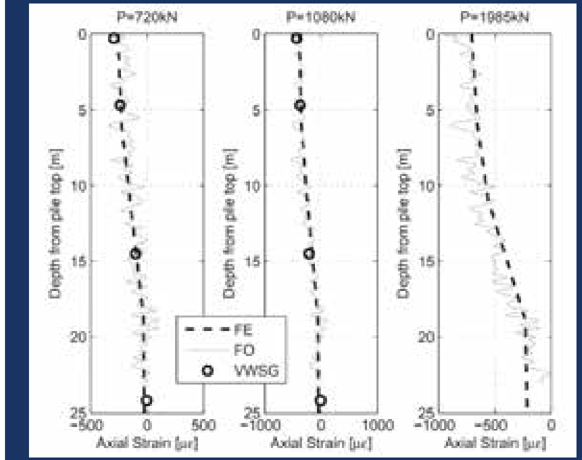
Displacement

$$u(z) = \int \varepsilon(z)\,dz$$



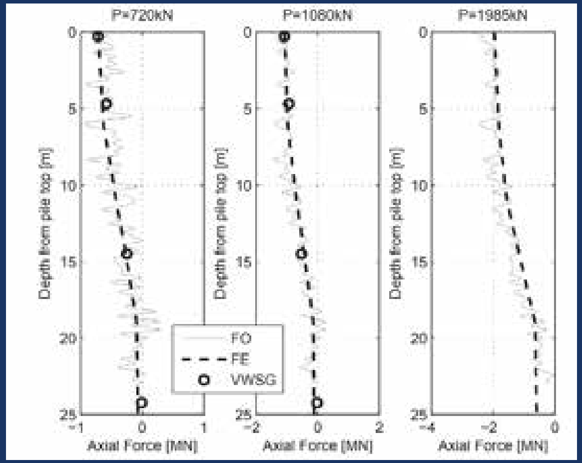
Strain

$$\varepsilon(z)$$



Force

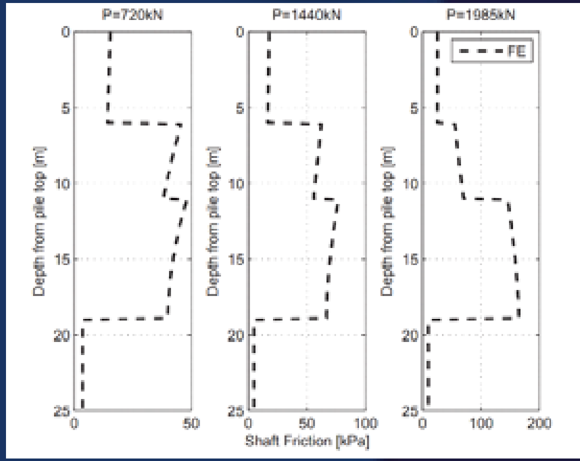
$$F(z) = EA\varepsilon(z)$$



E = pile stiffness
A = cross-sectional area

Shaft Friction

$$t(z) = \left(\frac{dF}{dz}\right)\left(\frac{1}{C}\right)$$



C = circumferential length

- Strain profiles used to obtain force, displacement and shaft friction profiles
- Numerical integration and differentiation are needed for processing – Not reasonable with point sensors

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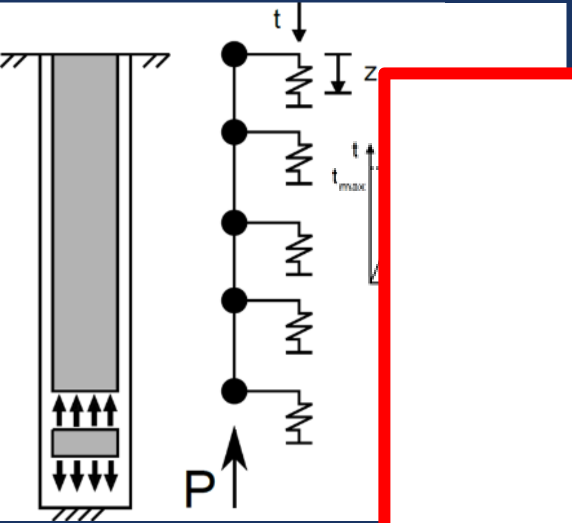
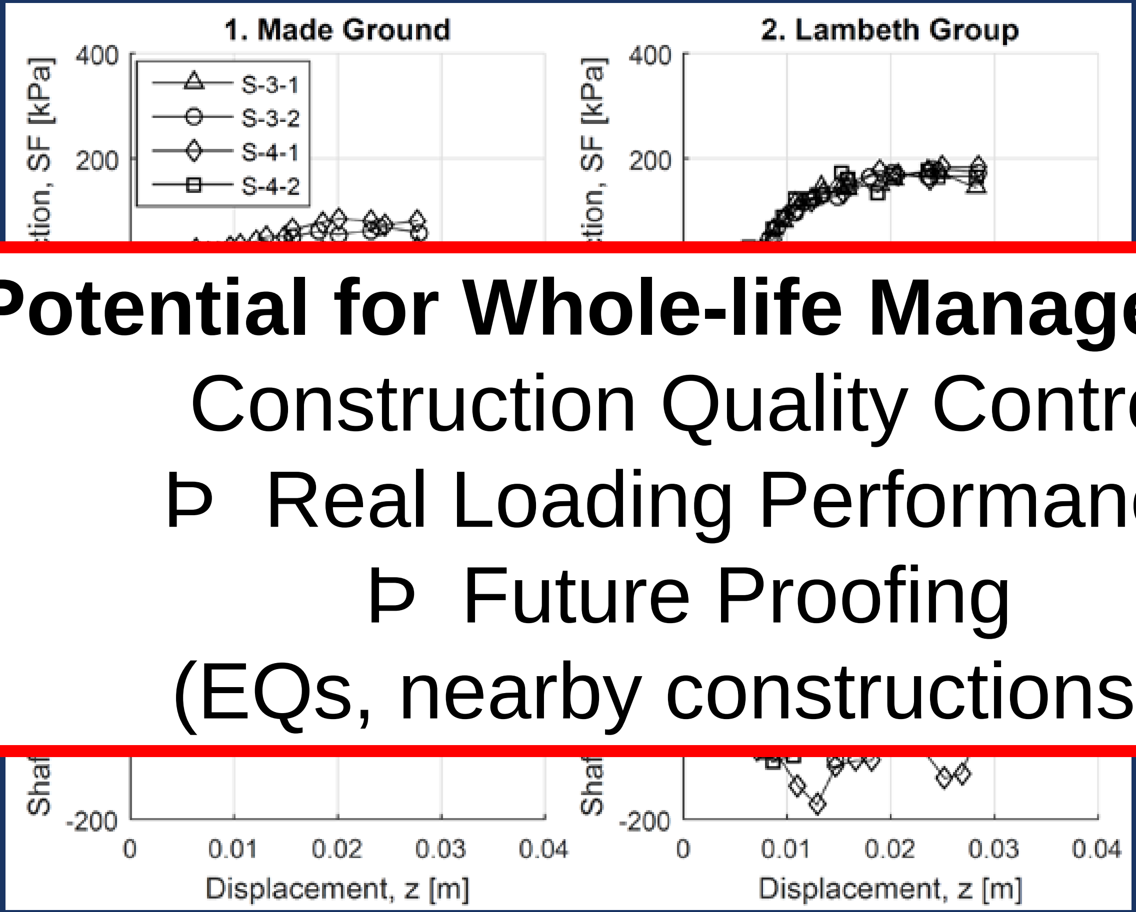
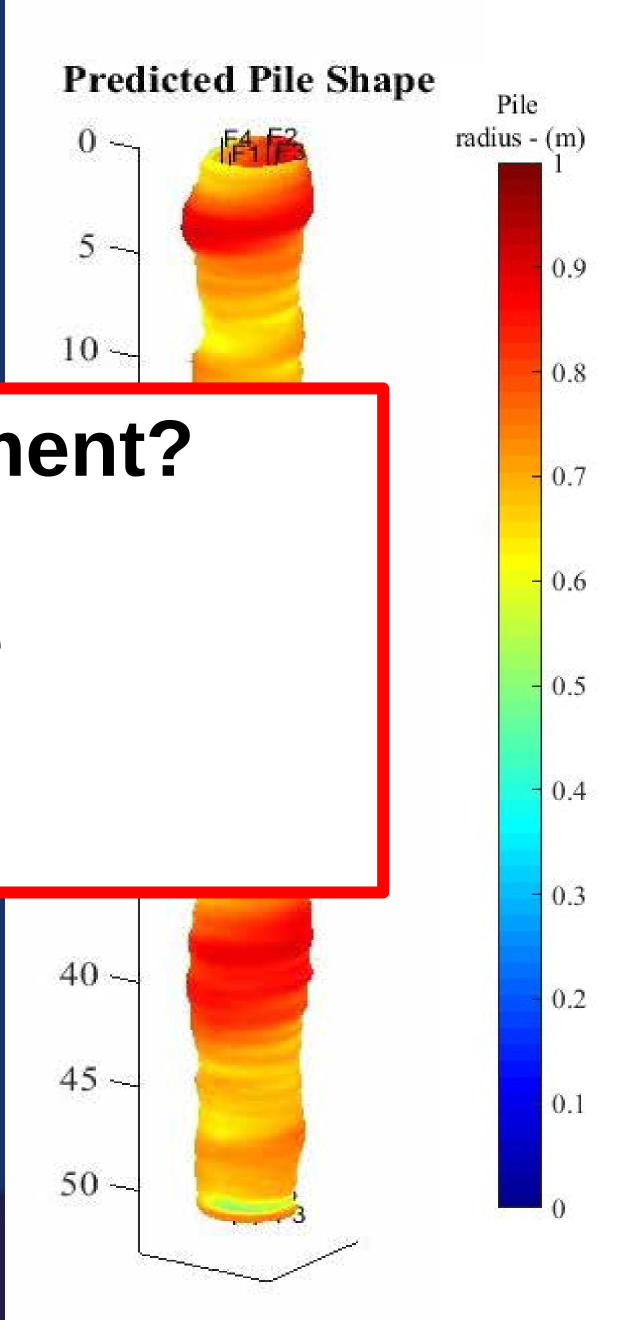
Pelecanos, L., Soga, K., Elshafie, M.Z., de Battista, N., Kechavarzi, C., Gue, C.Y., Ouyang, Y. and Seo, H.J., 2018. Distributed fiber optic sensing of axially loaded bored piles. *Journal of Geotechnical and Geoenvironmental Engineering*, *144*(3), p.04017122.







Potential for Whole-life Management?

Construction Quality Control

Þ Real Loading Performance

Þ Future Proofing

(EQs, nearby constructions..)

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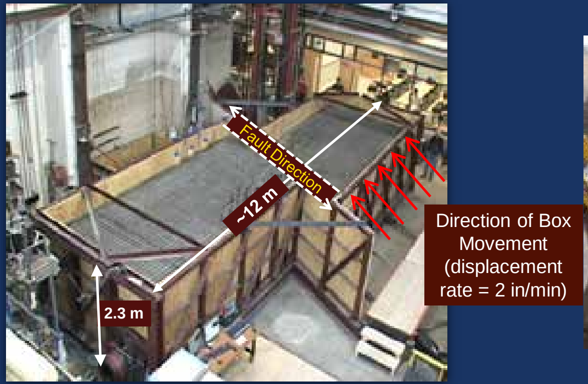
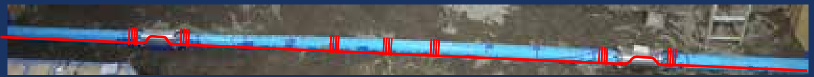
Distributed fiber optic sensing application testing conducted by UC Berkeley





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

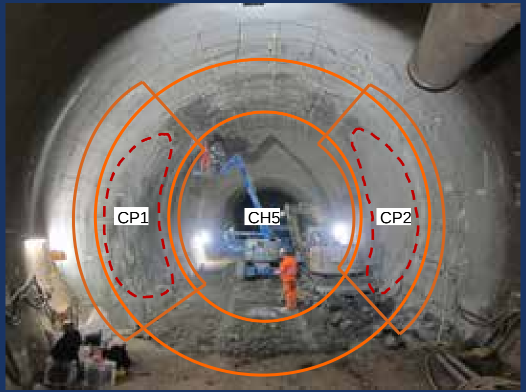
DFOS testing of wellbore casing model for oil and gas application

DFOS installation for concrete pavement (with UC Davis)

Ground Displacements by construction machinery loading

Settlement of Treasure Island Reclaimed land

Crossrail Liverpool street station

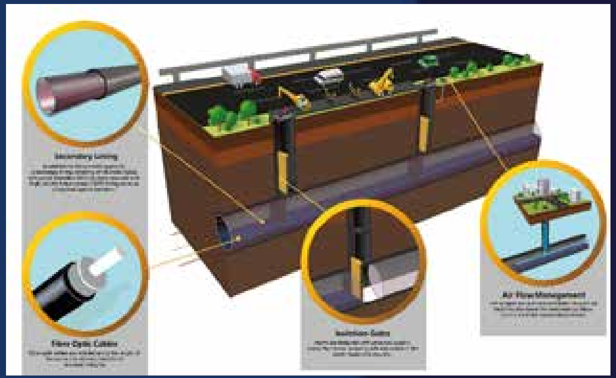


USACE River cutoff walls

Deep slurry walls

Slope monitoring

Singapore's new 51 km long Deep Tunnel Sewerage System

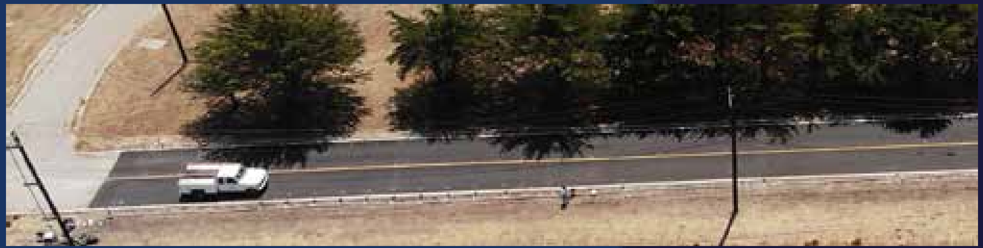


National Grid Tunnel Lining

Caltrans Ground Anchors

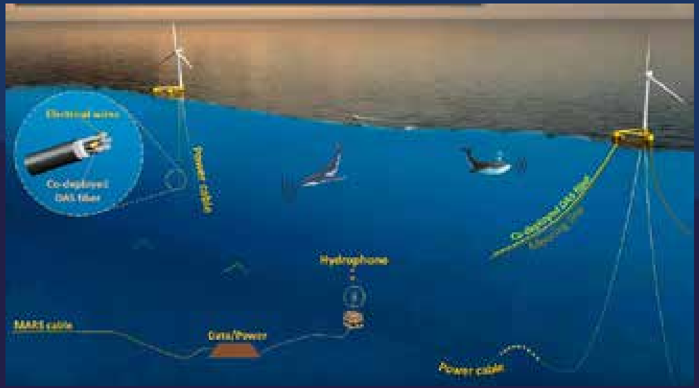
Gas facility monitoring

Smart pavement

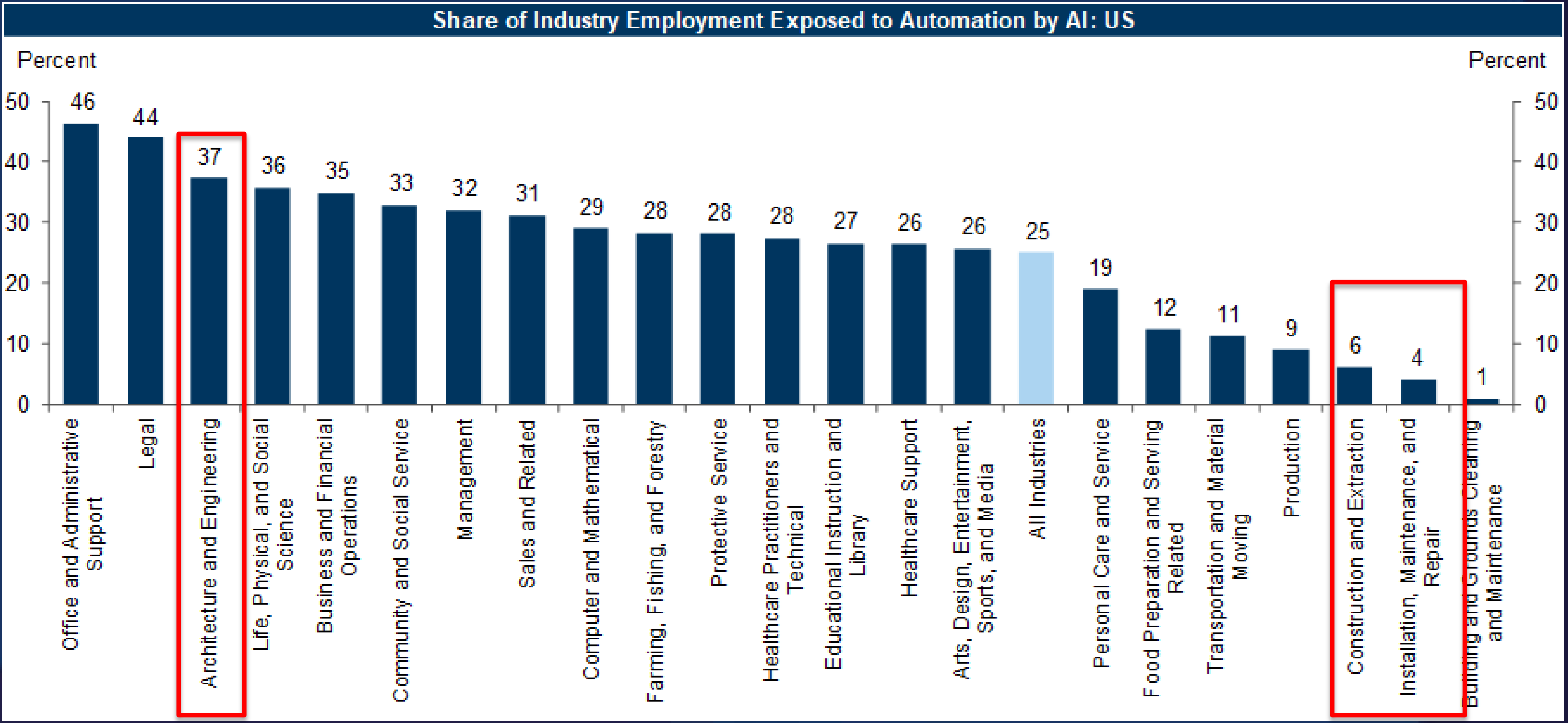


EBMUD pipeline fault crossing monitoring

Offshore wind energy



One-Fourth of Current Work Tasks Could Be Automated by AI in the US and Europe



2023 Goldman Sachs Global Investment Research

https://www.gspublishing.com/content/research/en/reports/2023/03/27/d64e052b-0f6e-45d7-967b-d7be35fabd16.html#

Toward Self-driving Tunnel Boring Machine

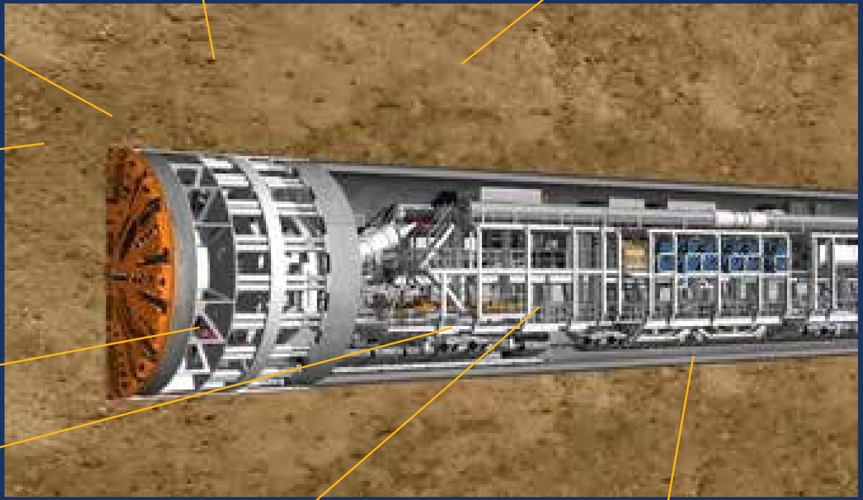
(1) Interpret the geologic conditions
(2) Manage excavation performance
(3) Control the trajectory
(4) Limit the induced ground movements

(1) Excavation & advance
e.g., thrust force, cutter rotation speed, cutter torque, etc.

(2) Steering:
e.g., JSD, articulation, copy cutter, etc.

(6) Tail grouting:
e.g., grout volume, flow, pressure.

(3) Ground conditioning:
e.g., foam volume & injection pressure, polymer volume & injection pressure, etc.

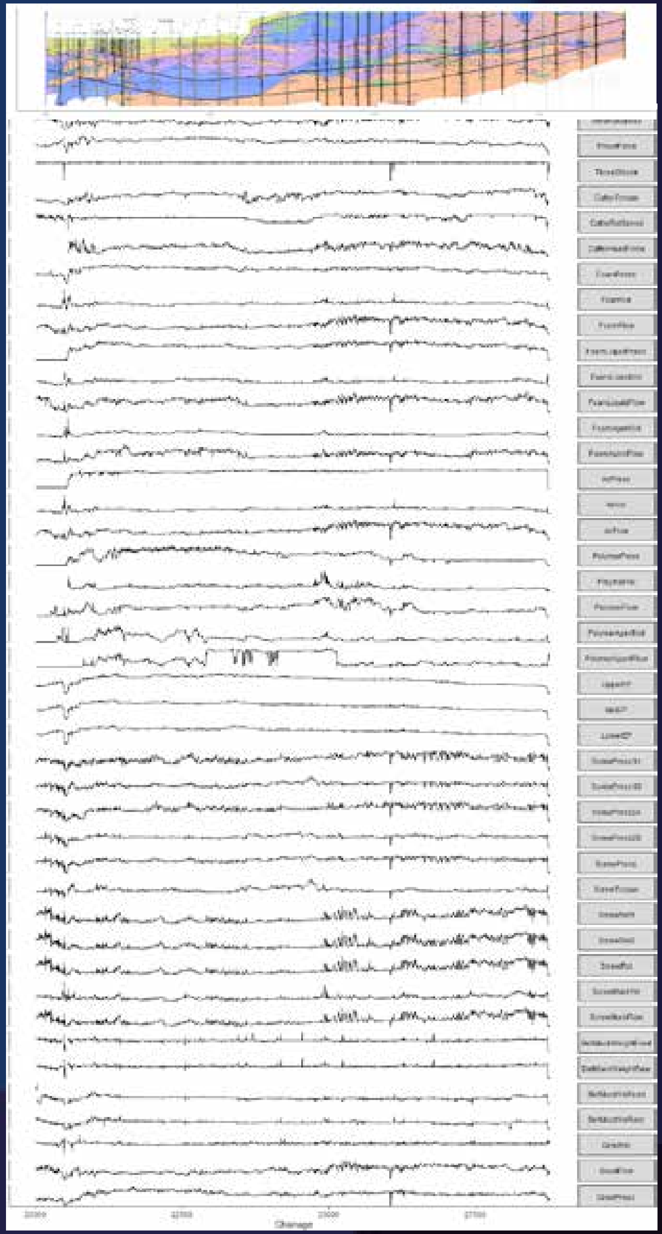


(4) Earth pressure balance:
e.g., chamber pressure, screw rotation, torque, pressure, etc.

(7) Segment lining erection
(not considered)

(5) Conveyor belt muck:
e.g., muck volume, weight, etc.

(8) Mechanical, electrical features, & others
e.g., oil volume & pressure, pipe temperature, electricity voltage, amp., etc. (not considered)



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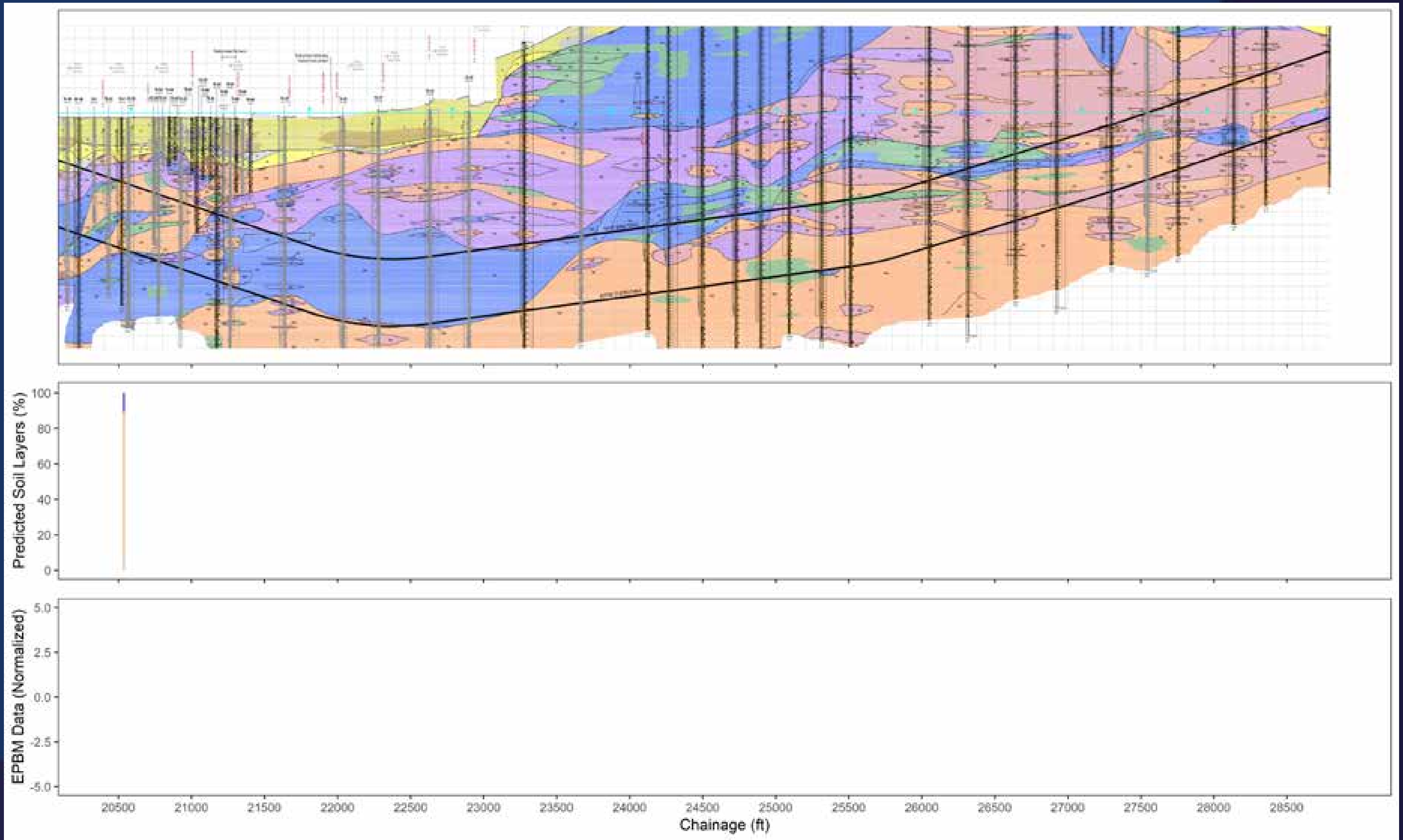
Seattle

SR 99 tunnel

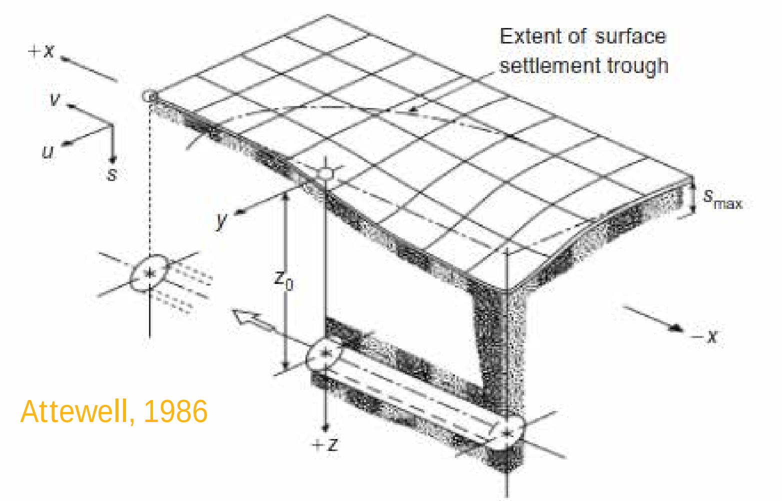
Double shield EPBM 17 m dia.

~ 6000 features

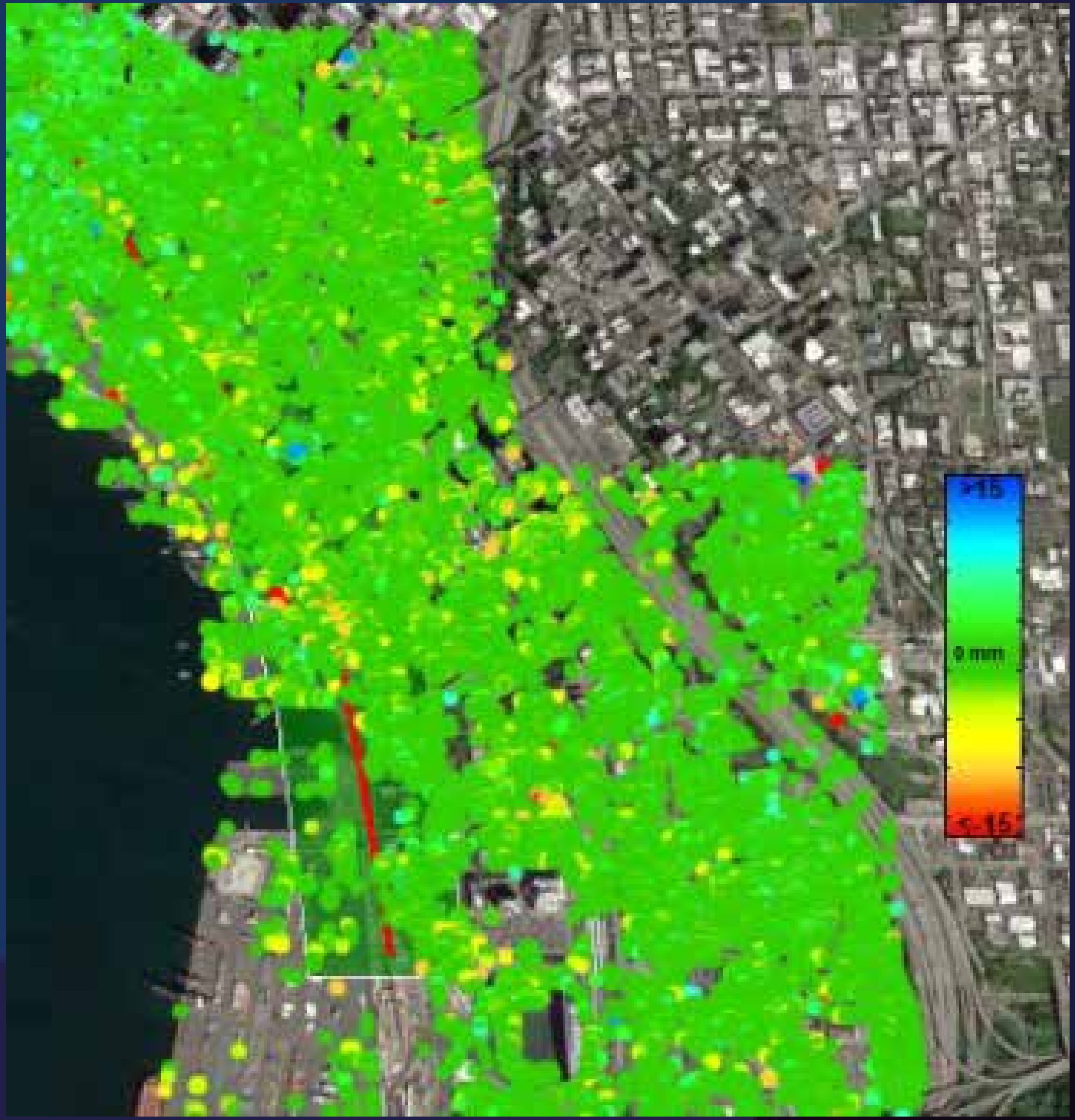
Real time supervised geologic interpretation



Building owner's interest
Building settlement - Connecting to ground monitoring data



Attewell, 1986



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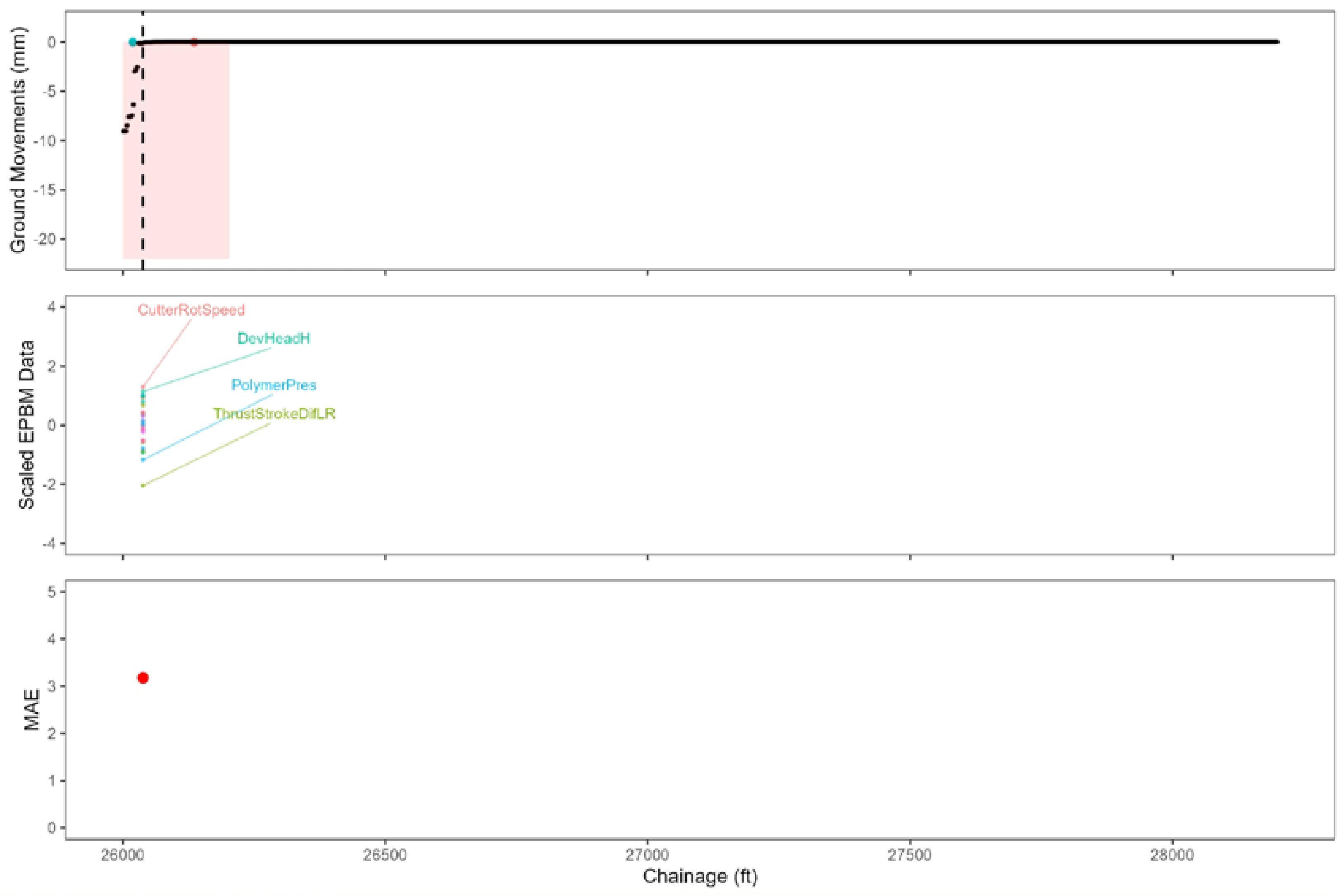
Real time ground movement estimation based on TBM operation data

Ground movements at 10 ft above the TBM

Generated EPBM data during tunneling



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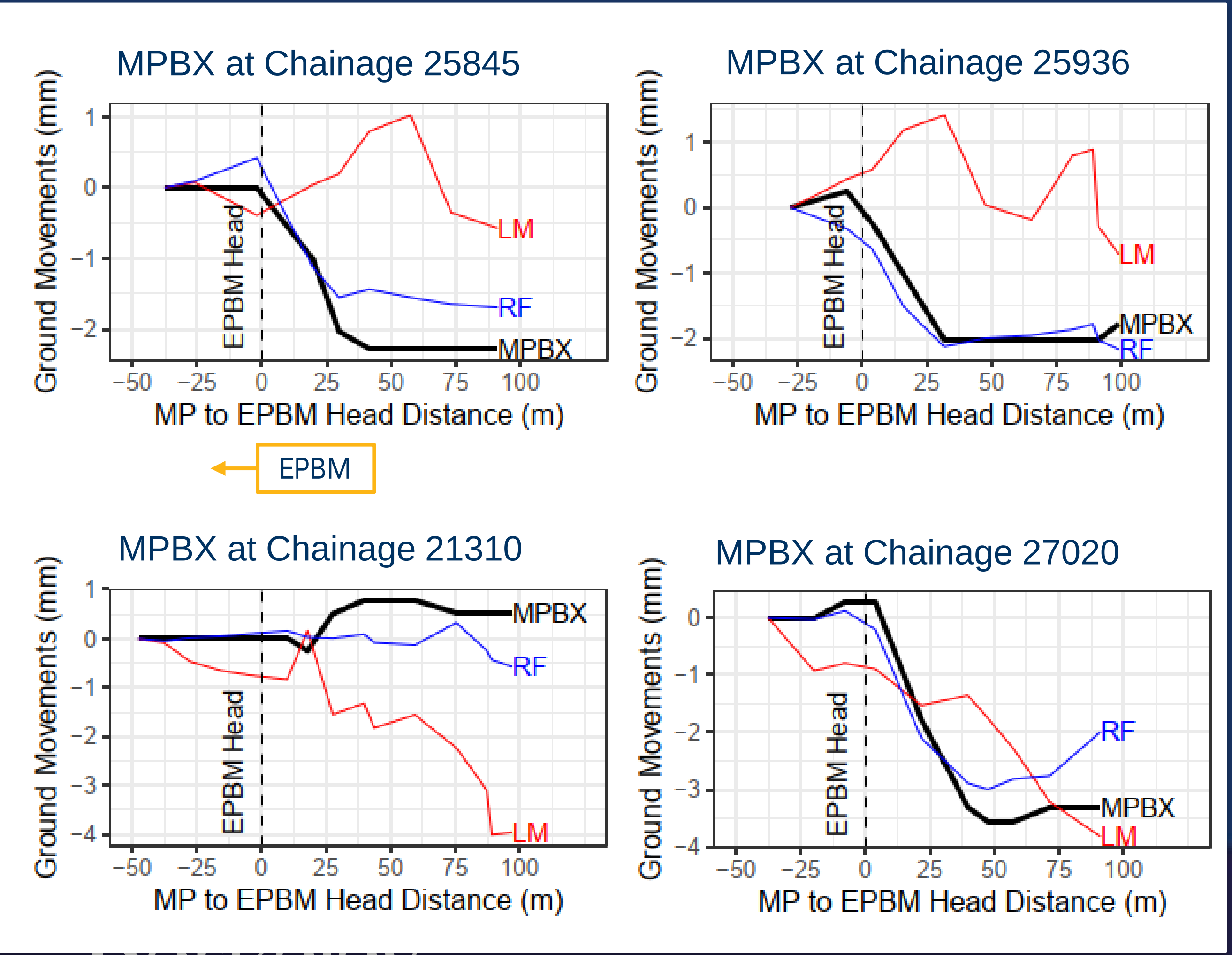
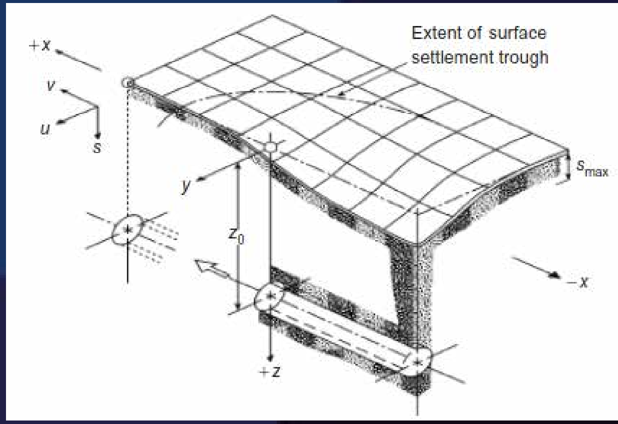
Comparison to the actual measurements: MPBX testing data set



- Machine learning (RF) can convert EPBM data to settlement
  - Linear model cannot capture
  - Interactions among the data were not linear
- And heaving
  - Linear model cannot capture
  - Simplified model (gaussian) cannot capture
- Preliminary model à a lot of room to improve



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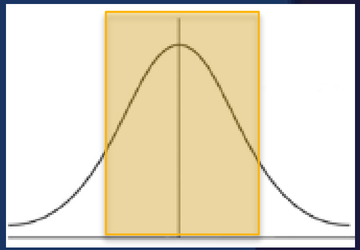
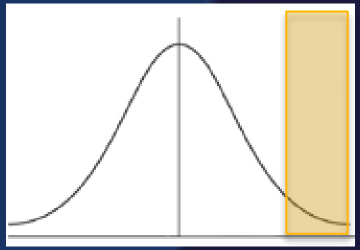
Tunnel Operator's interest
Detecting the anomalies in machine operation

Data + ML + Computation = Value



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



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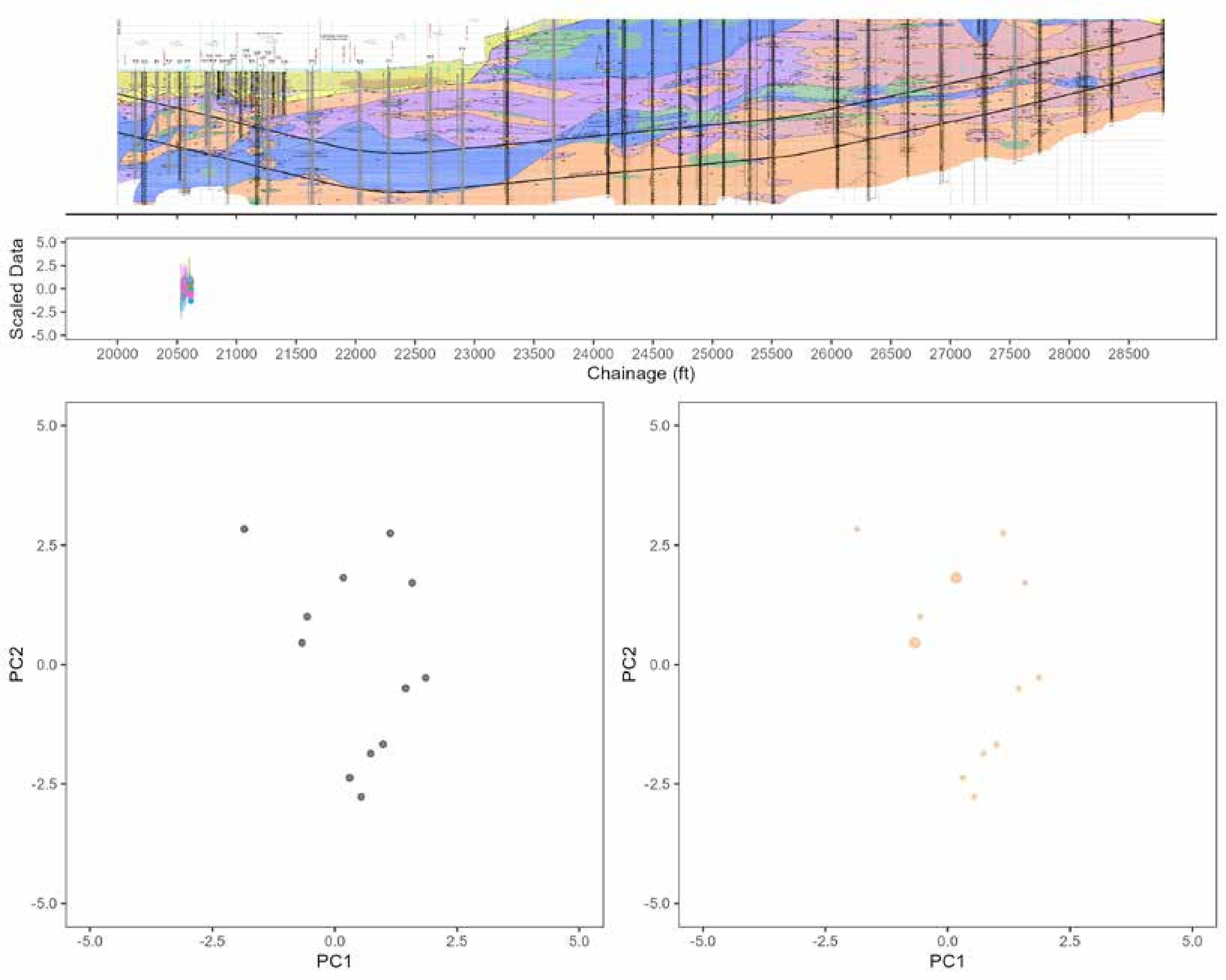
Unsupervised learning using EPBM data



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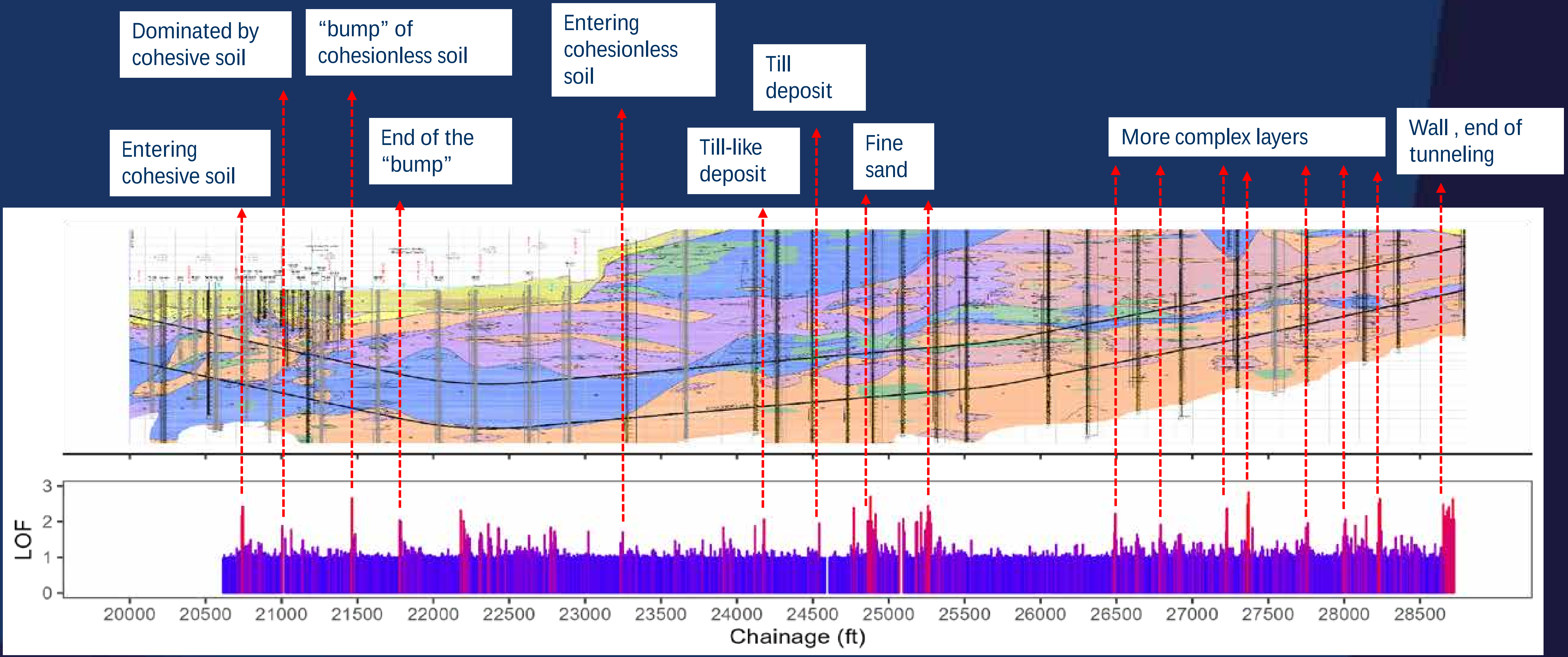

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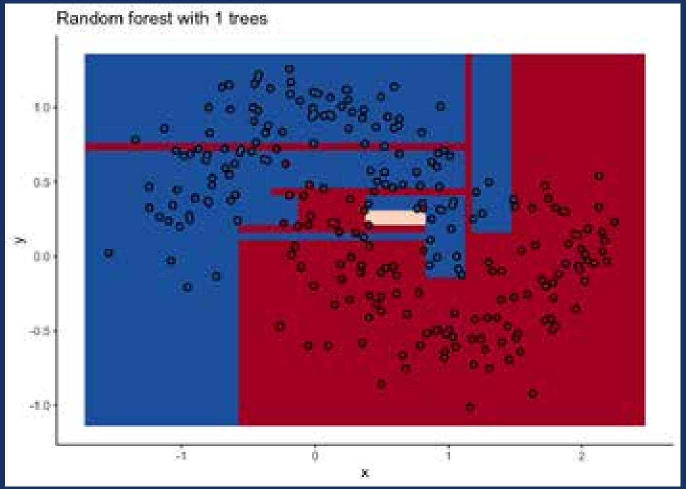
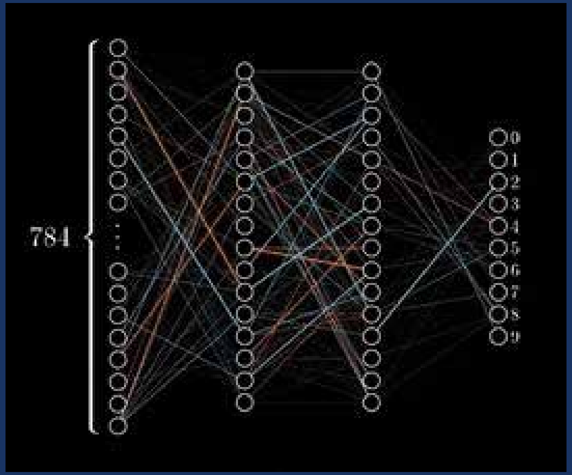
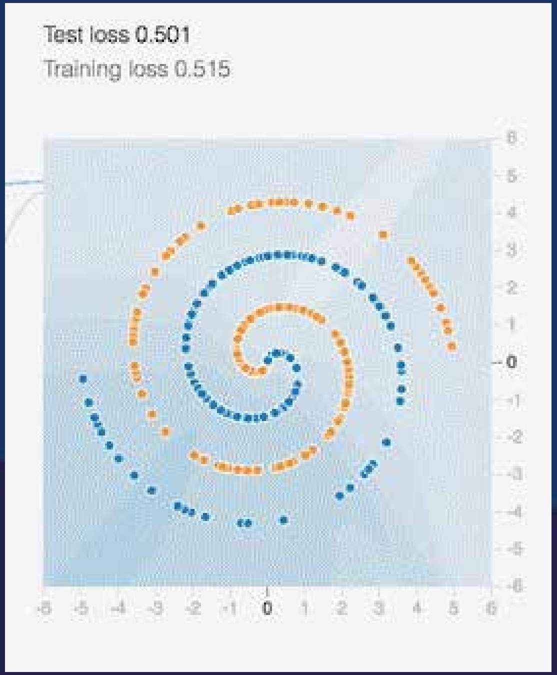
Random Forests



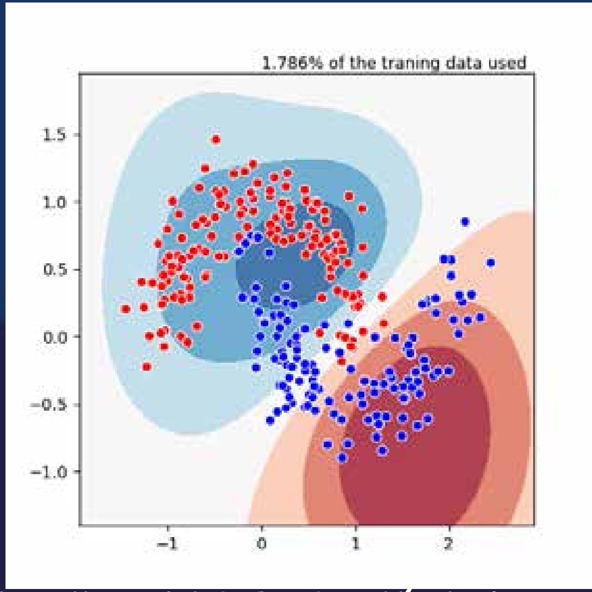
http://www.statistics.cool/post/why-do-random-forests-work/

Neural networks



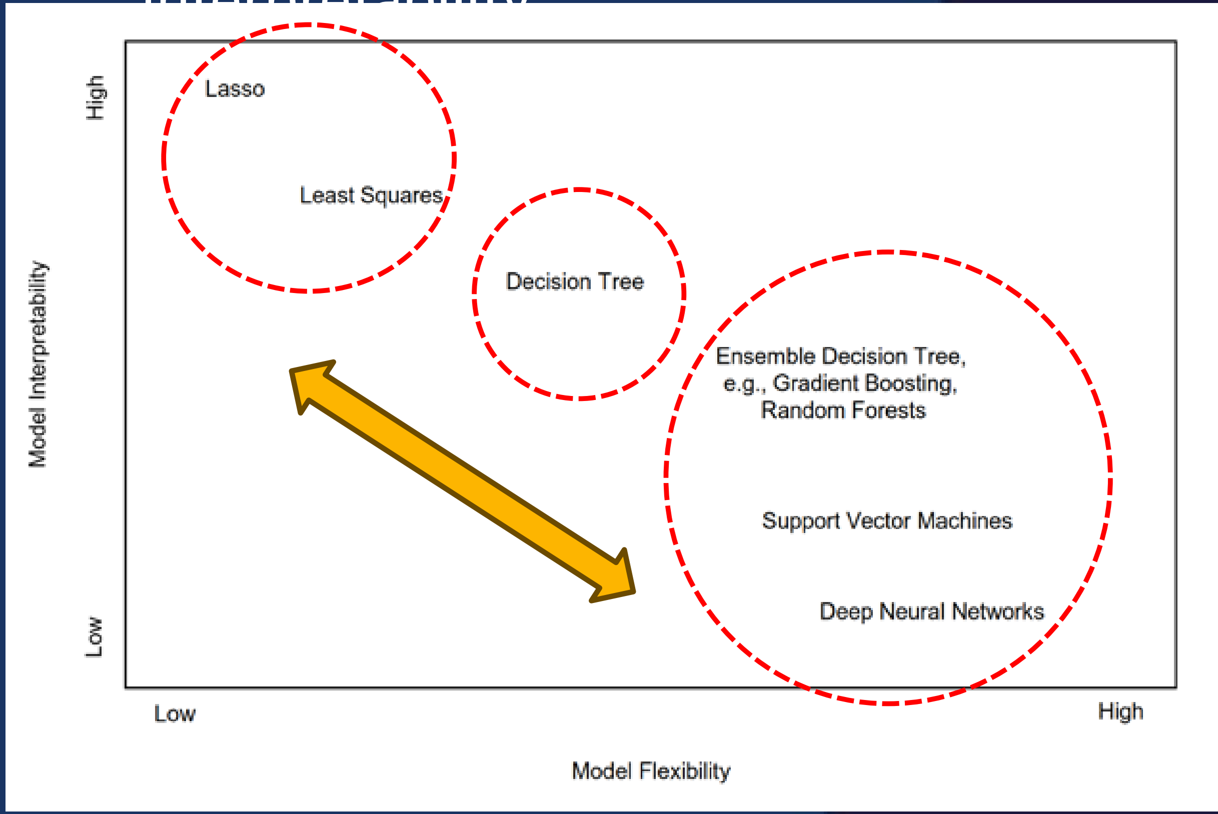


Support Vector Machine



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

Model flexibility versus Interpretability



現在および将来の世代に持続可能なインフラを提供するには…

- **監視　ー　Monitor**
    - リアクティブアクションではなくプロアクティブアクションの価値を示す
- **学習　ー　Learn**
    - パフォーマンスベースの設計と維持管理の価値を示す（インフラ個体から都市レベルへ）
- **予測そして応答　Anticipate and Respond**
    - アダプティブな（順応型）インフラによるさらなる安全性と持続可能性の価値を示す。
- **Smart and Connected Communities – 集団的認知と意思決定とは。**
    - 集団的認知と意思決定の多様性を理解する。
    - インフラの所有者とコミュニティとの信頼関係を構築する。
    - 5Rを考慮したテクノロジーを導入する。

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ご清聴ありがとうございました。

soga@berkeley.edu

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