Exponent®

Remote Sensing of GeoHazards for Distributed Infrastructure Systems

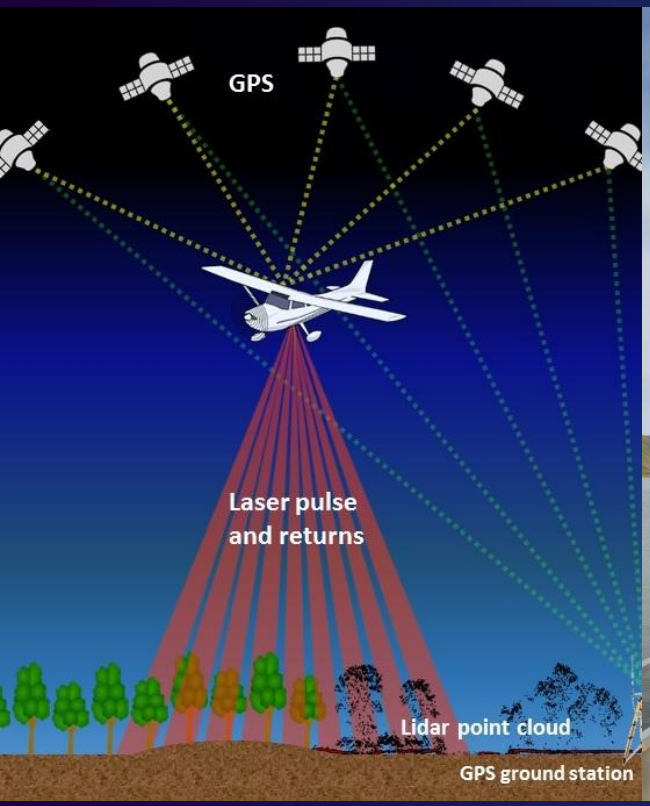
GeoVirginia

Juan F. Perri, Ph.D., P.E., G.E.

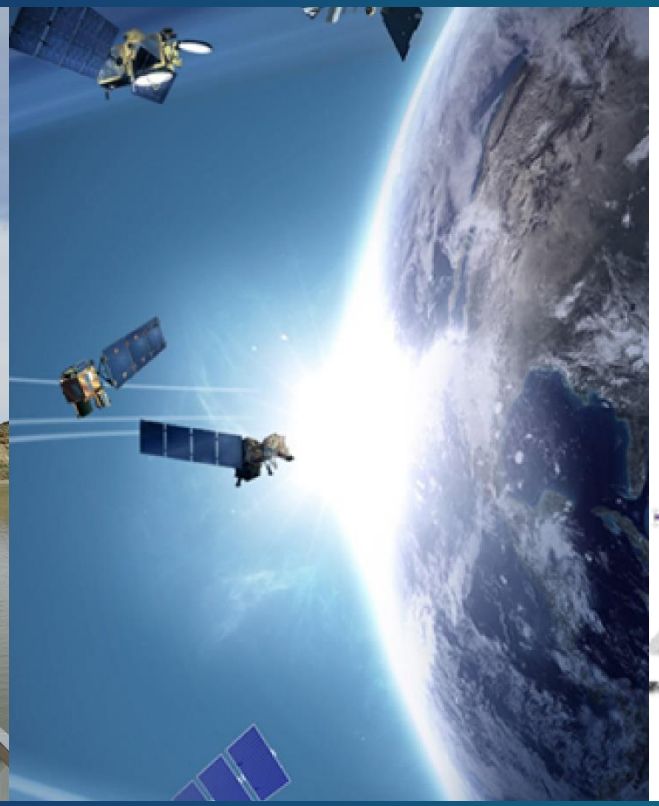
March 19, 2025

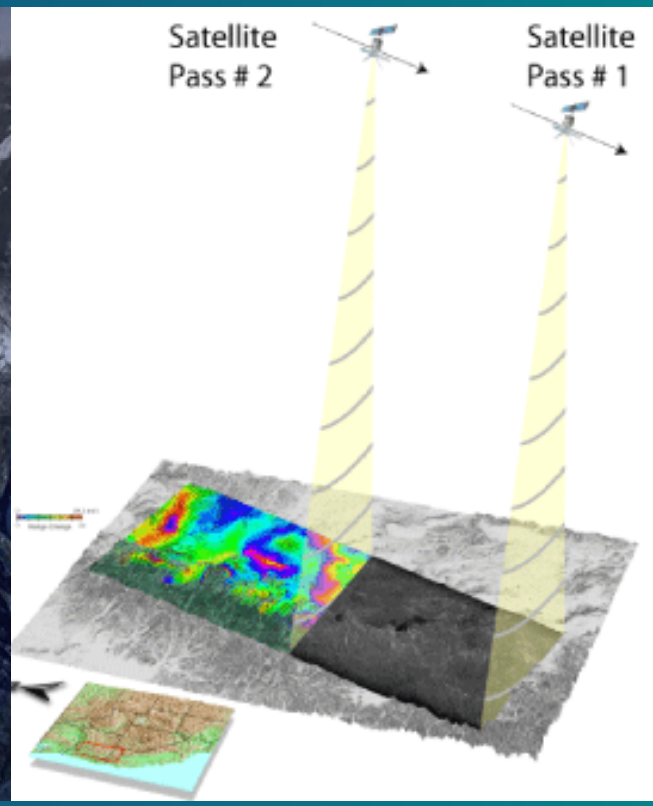
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Remote Sensing





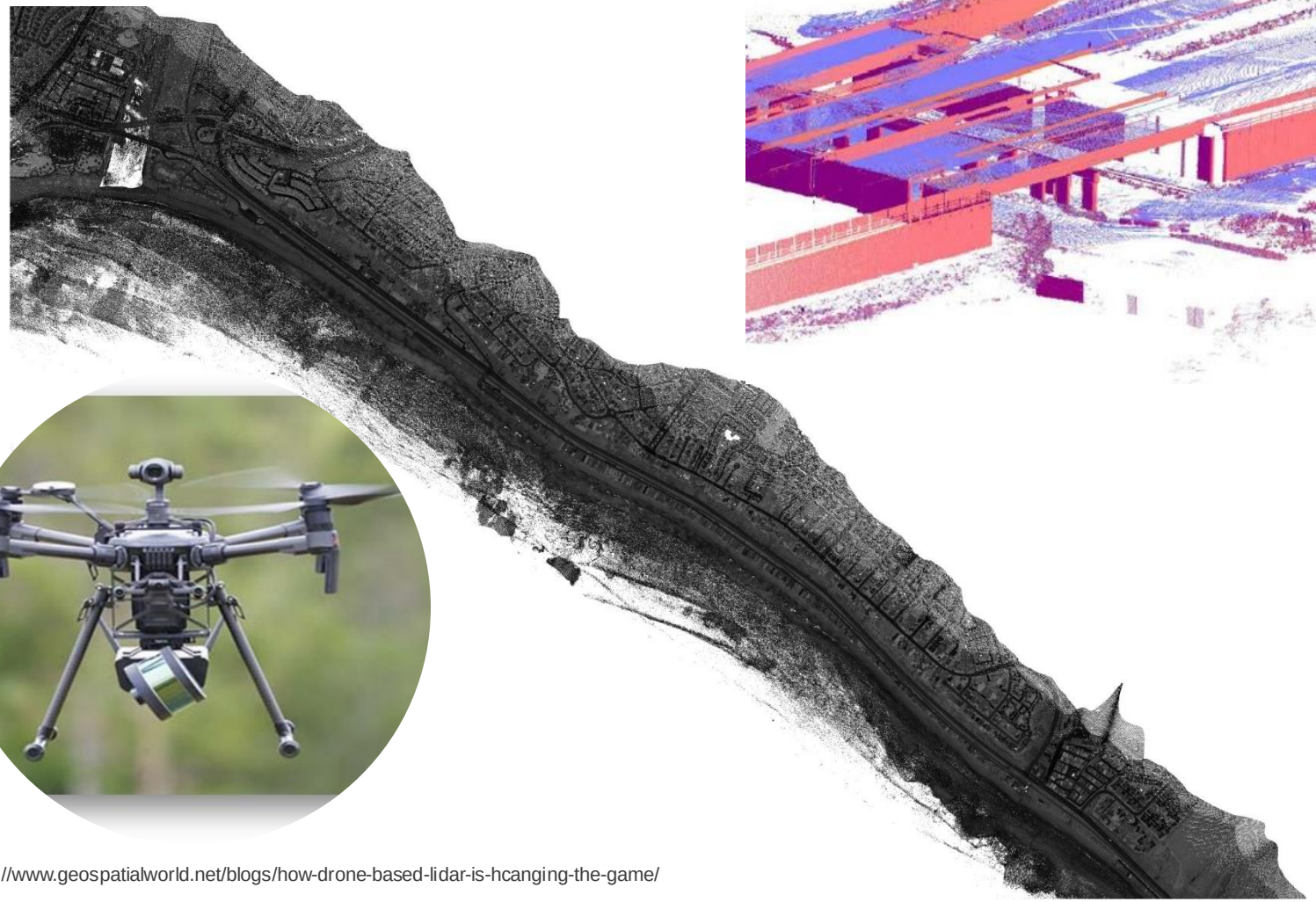




USGS
NASA illustration courtesy of Jenny Mottar

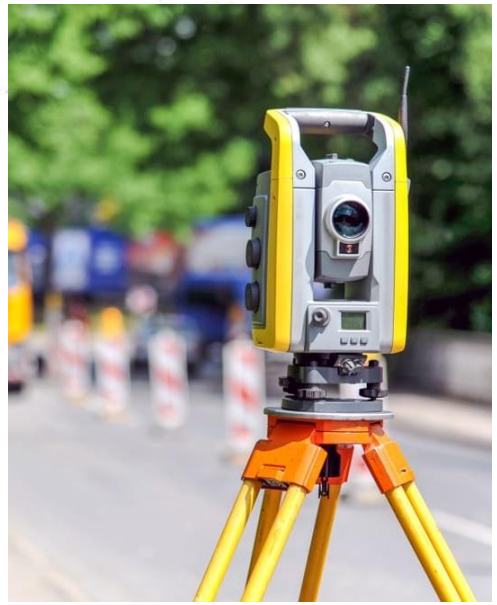
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Aerial & Land-based LiDAR





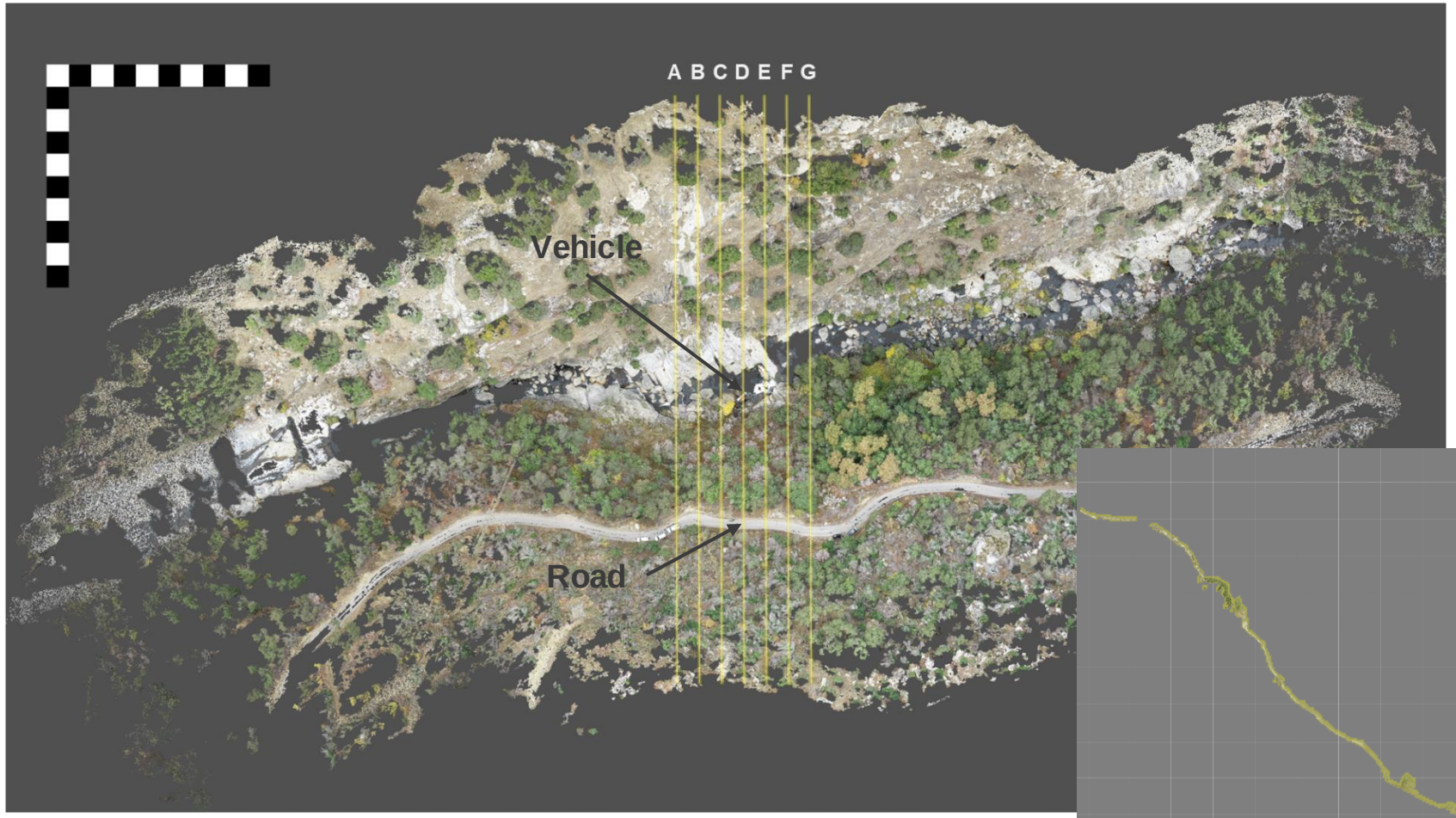
https://www.geospatialworld.net/blogs/how-drone-based-lidar-is-hcanging-the-game/



https://www.uk-blog.com/compelling-reasons-to-use-laser-scanning-technology/

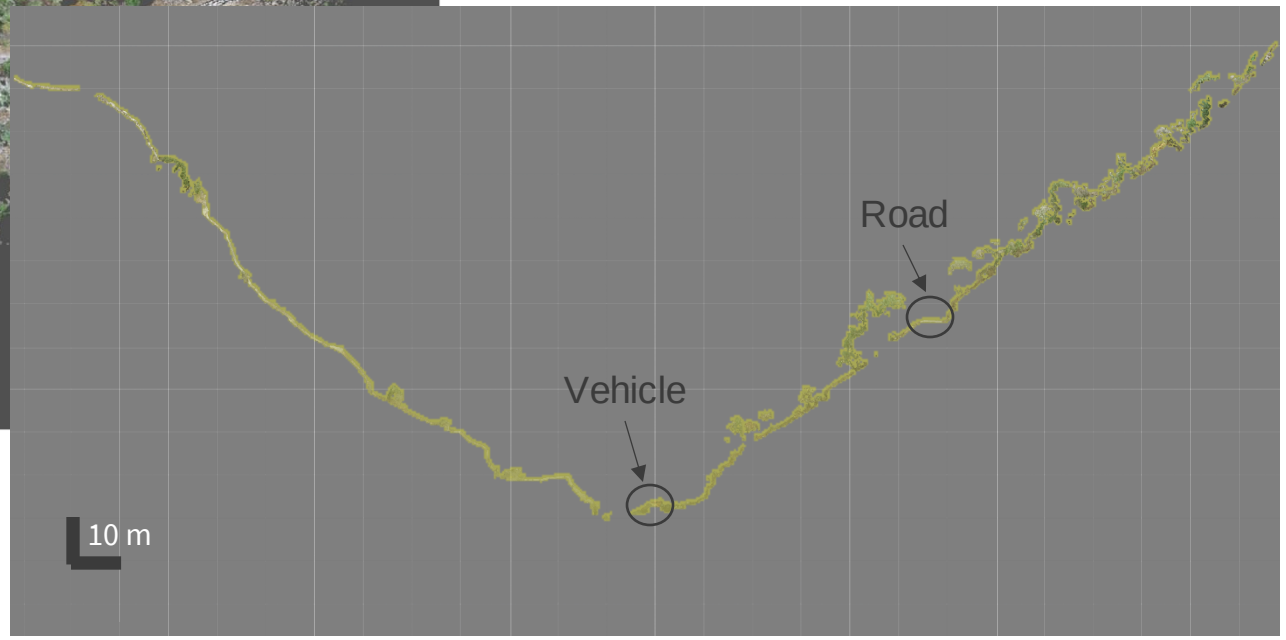
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Photogrammetry – Structure from Motion





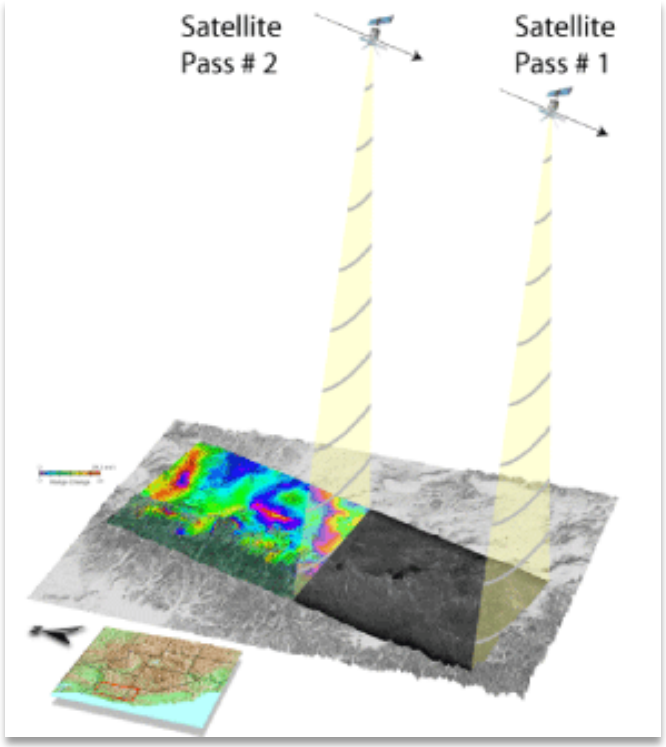




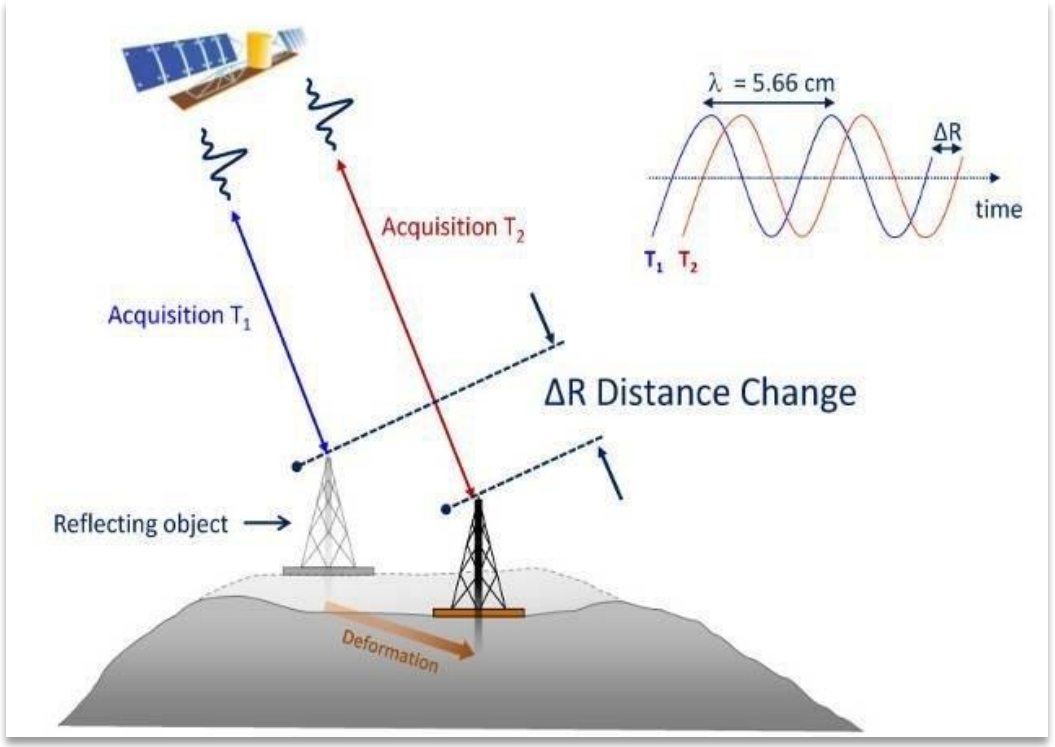
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Satellite-Based InSAR Monitoring

Satellite Data Collection

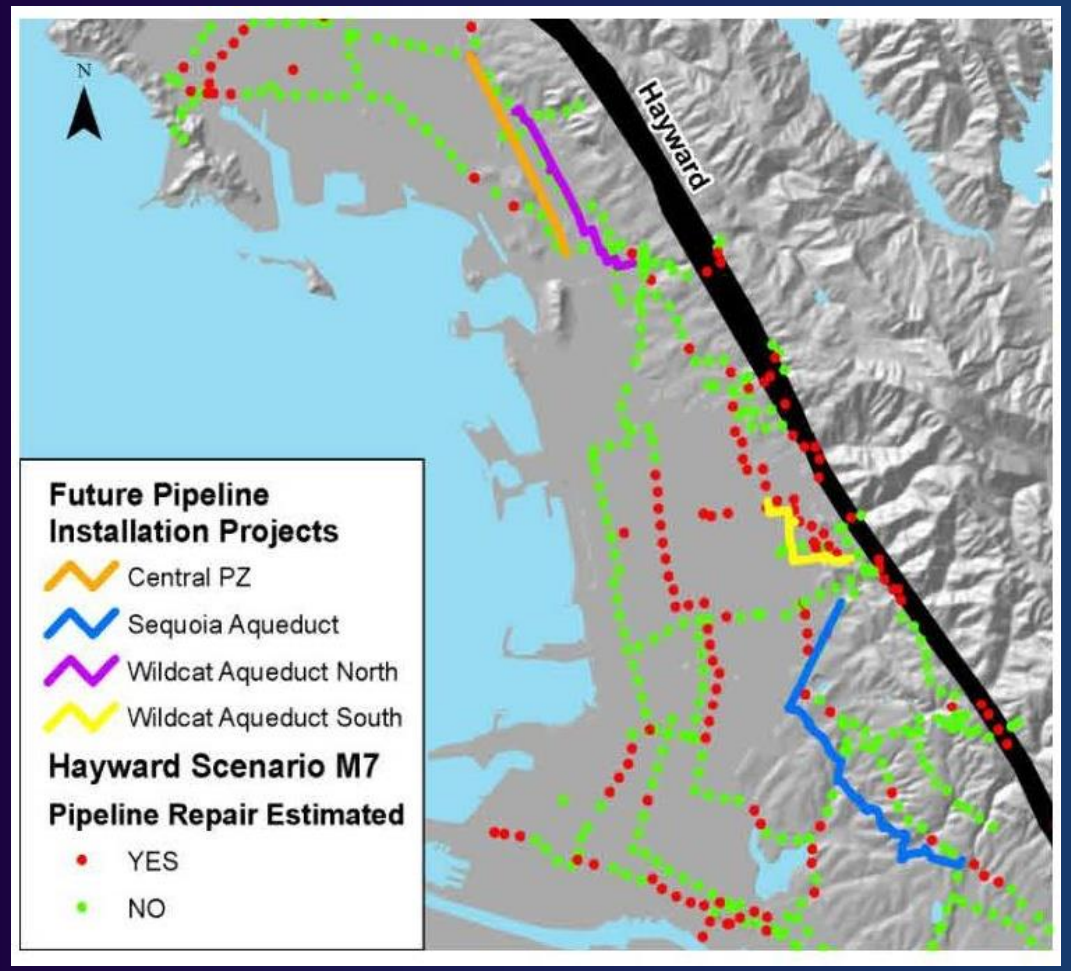


Data Processing – Ground Deformation

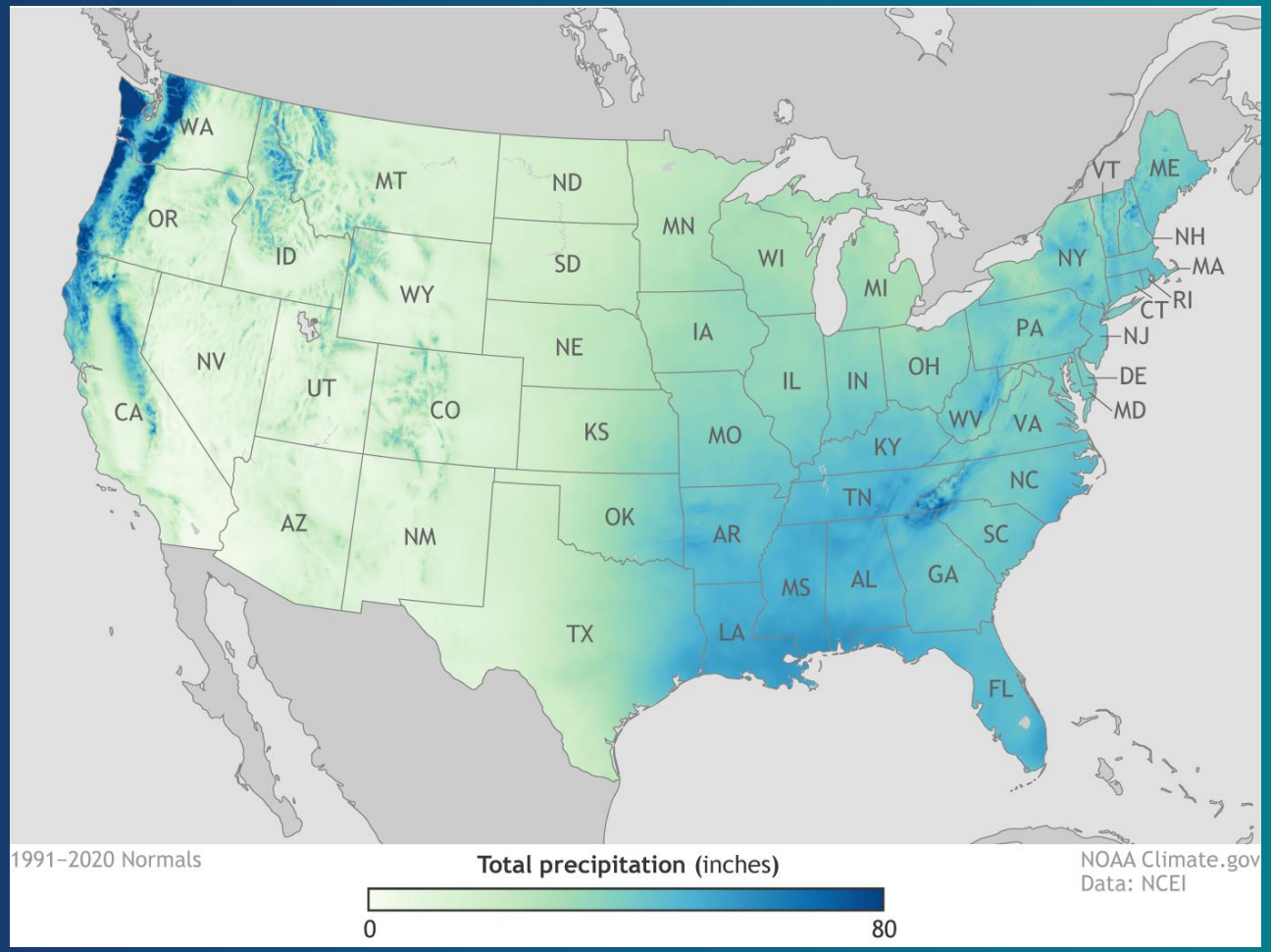


Andrea Tamburini, Sara Del Conte, Alessandro Ferretti, Stefano Cespa, TRE - Milano – Italy, **Advanced Satellite InSAR Technology For Fault Analysis And Tectonic Setting Assessment. Application To Reservoir Management And Monitoring**, International Petroleum Technology Conference held in Doha, Qatar, 20–22 January 2014.
USGS

GeoHazards Assessments



Terentieff et al. 2005

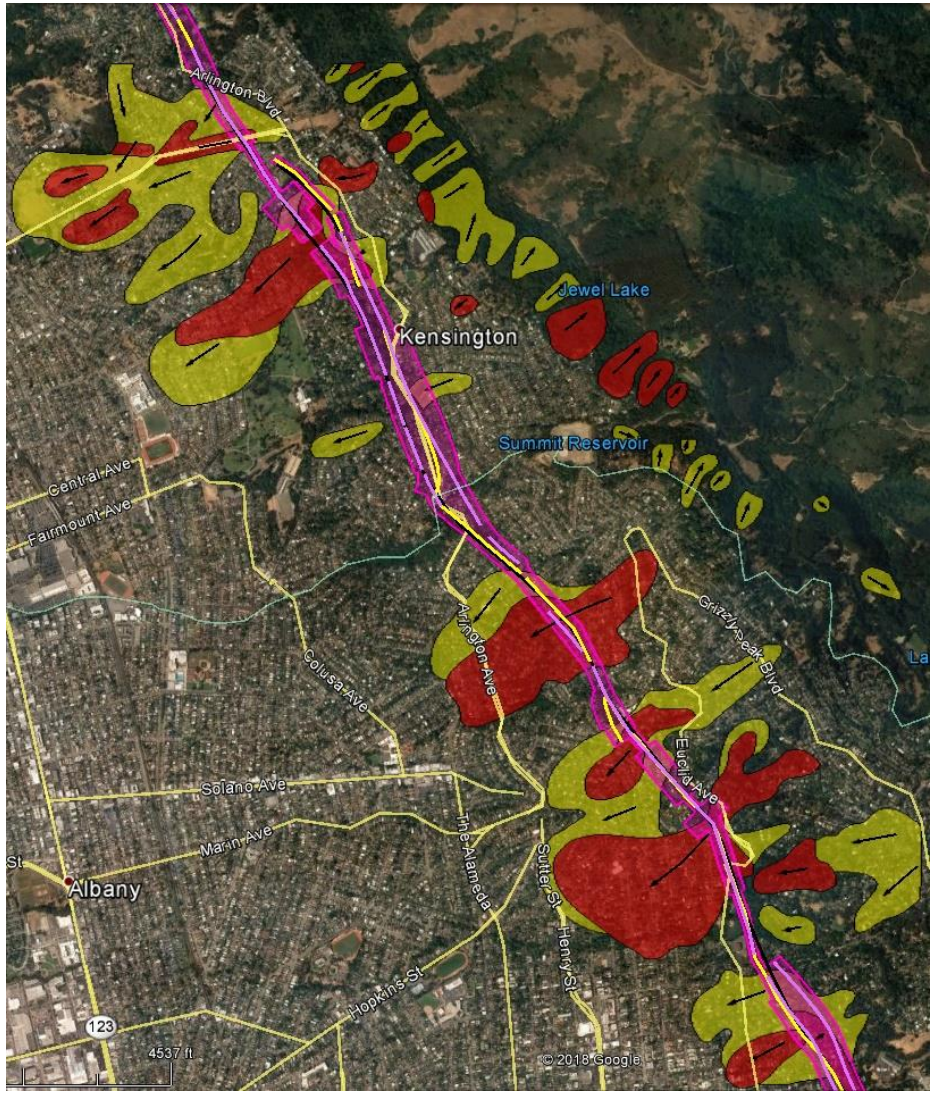


U.S. Climate Normals. Maps by NOAA Climate.gov, based on data from NOAA National Centers for Environmental Information.

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Purpose

- Implement a methodology to evaluate potential geotechnical threats to the integrity of existing infrastructure systems.
- Determine hazard zones and, if appropriate, identify remedial measure(s) to reduce those hazards.
- Applicability: geographically distributed infrastructure systems
  - Transportation arteries
  - Transmission/Distribution pipelines



Motivation to Establish a Framework

CHALLENGE

- Kilometers of systems
- Aging infrastructure
- Increased service demand
- Heightened risk of hazards

IDENTIFY HAZARDS

- Past performance
- Corrosion/Cracking
- Manufacturing/ Construction defects
- Third-party damage
- Improper operation
- Outside forces

BENEFITS

- Better compliance
- Risk reduction
- Accident prevention
- Cost savings
- Reliability improvement
- Prioritize work

- Between 1999 and 2018, gas pipeline incidents in the United States contributed to 291 fatalities and 1,267 injuries at a cost of over $9 billion.
- The vulnerability of our aging infrastructure is increasing over time.

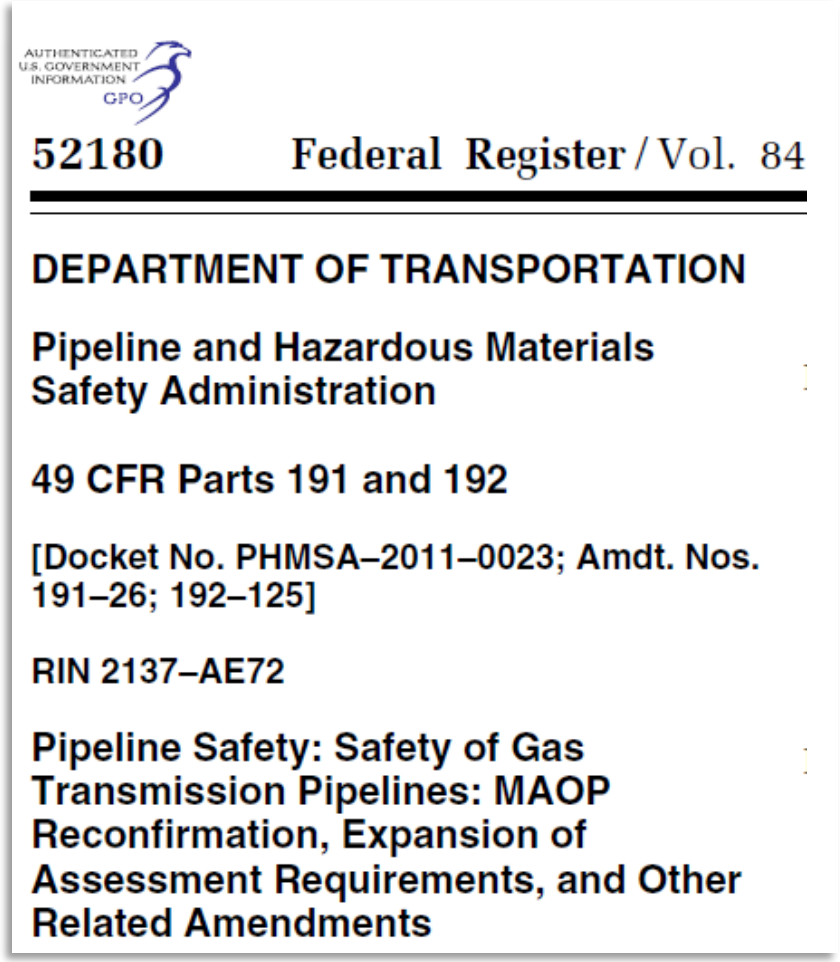
Sources: PHMSA, Annual Gas Transmission and Gathering Data 2018
PHMSA Annual Hazardous Liquid Data 2017

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Regulations – Federal

The “Mega Rule” explicitly requires the Operator to identify and evaluate all potential threats including:

> “***consideration of seismicity, geology, and soil stability of the area.***”


AUTHENTICATED U.S. GOVERNMENT INFORMATION GPO

52180 Federal Register / Vol. 84

DEPARTMENT OF TRANSPORTATION

Pipeline and Hazardous Materials Safety Administration

49 CFR Parts 191 and 192

[Docket No. PHMSA–2011–0023; Amdt. Nos. 191–26; 192–125]

RIN 2137–AE72

Pipeline Safety: Safety of Gas Transmission Pipelines: MAOP Reconfirmation, Expansion of Assessment Requirements, and Other Related Amendments

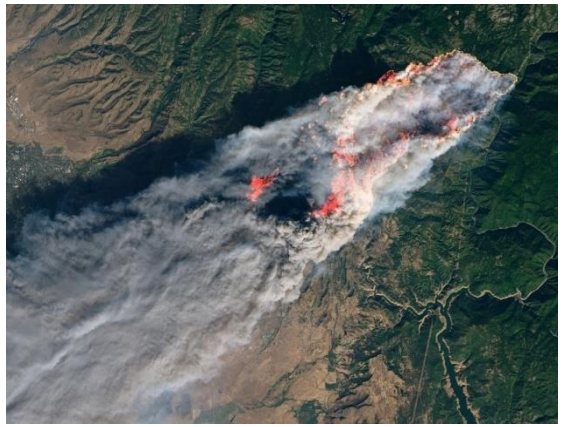
Source: https://www.exponent.com/knowledge/thought-leadership/2020/03/gas-transmission-pipelines

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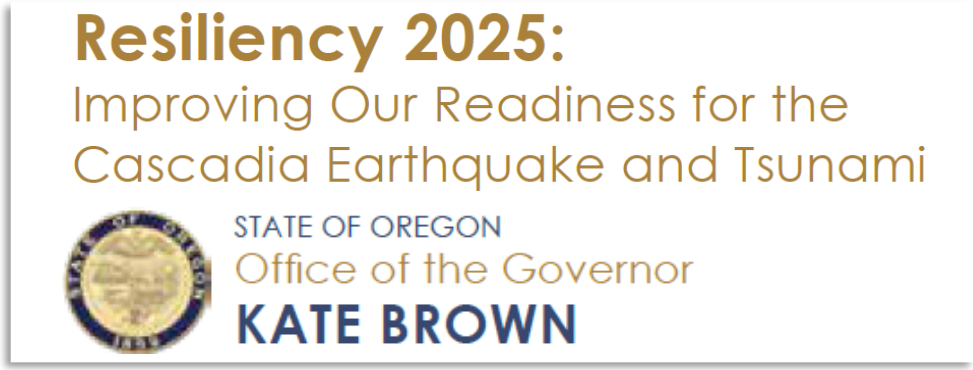
Regulations – State & Local

- **California PUC Rulemaking R.13-11-006**
  - Incorporated **risk-based decision-making** into the General Rate Cases (GRCs)
  - Requires funding requests to show how **safety and reliability** are connected to the **quantitative decisions in the GRC**
  - **Risk-based decision-making framework** RDF submitted in two filings: Safety Model Assessment Proceeding (S-MAP) and Risk Assessment Mitigation Phase (RAMP)



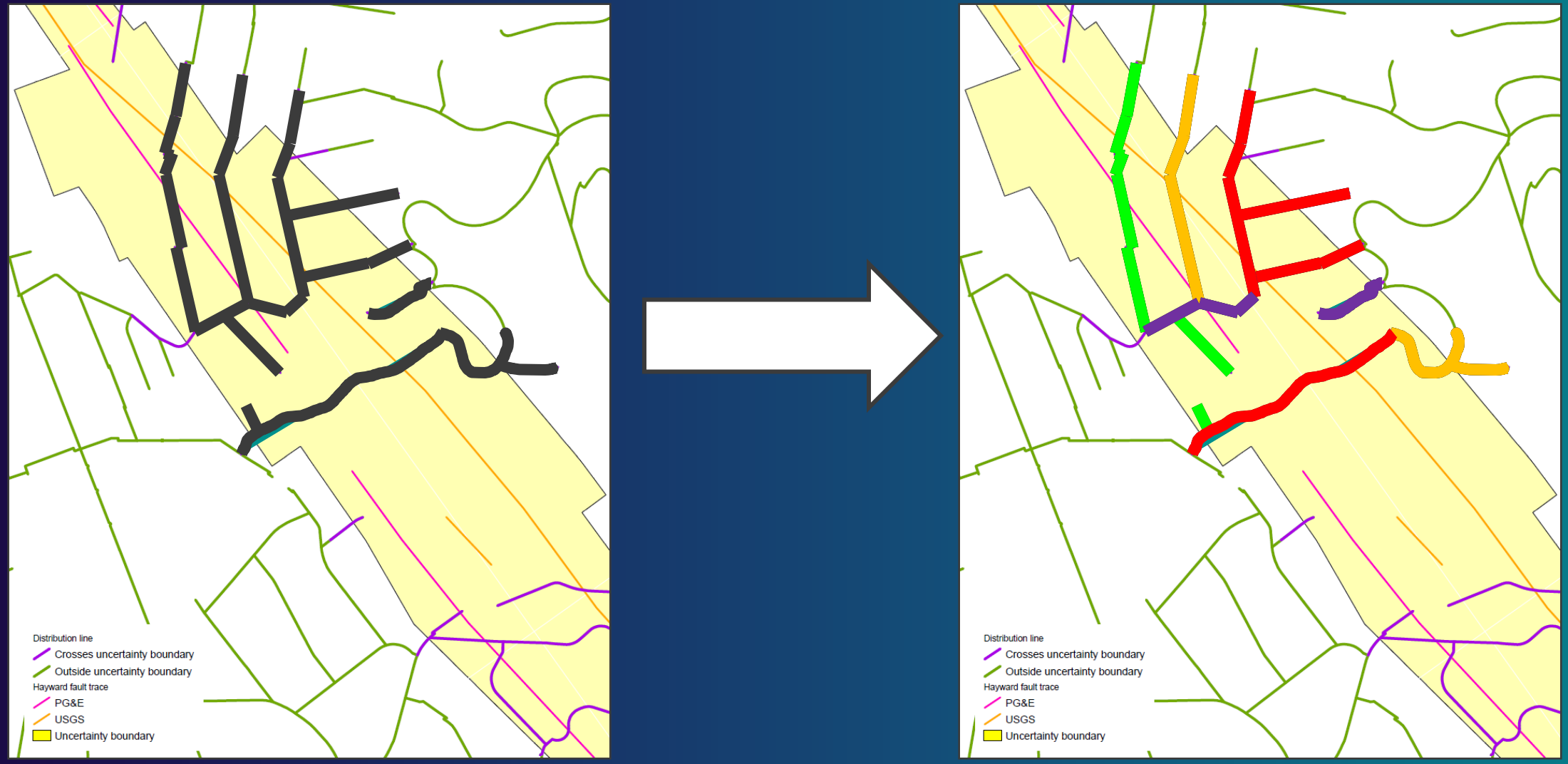


- **California PUC Rulemaking R.20-07-013**
  - Strengthens the risk-based decision-making framework that regulated energy utilities use to **assess, manage, mitigate, and minimize safety risks**



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Three Recent Examples



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Case Study 1

Golf Links Road Gas Release



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Golf Links Road Gas Release

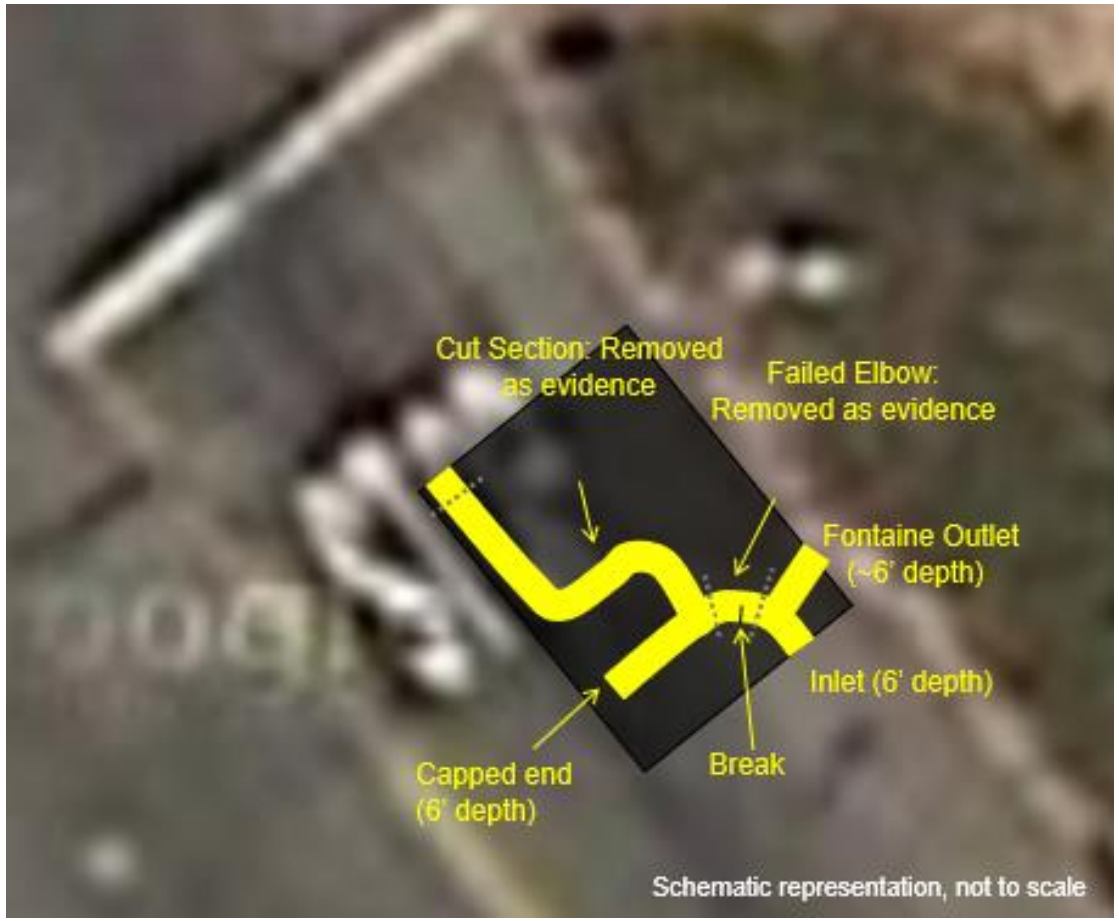


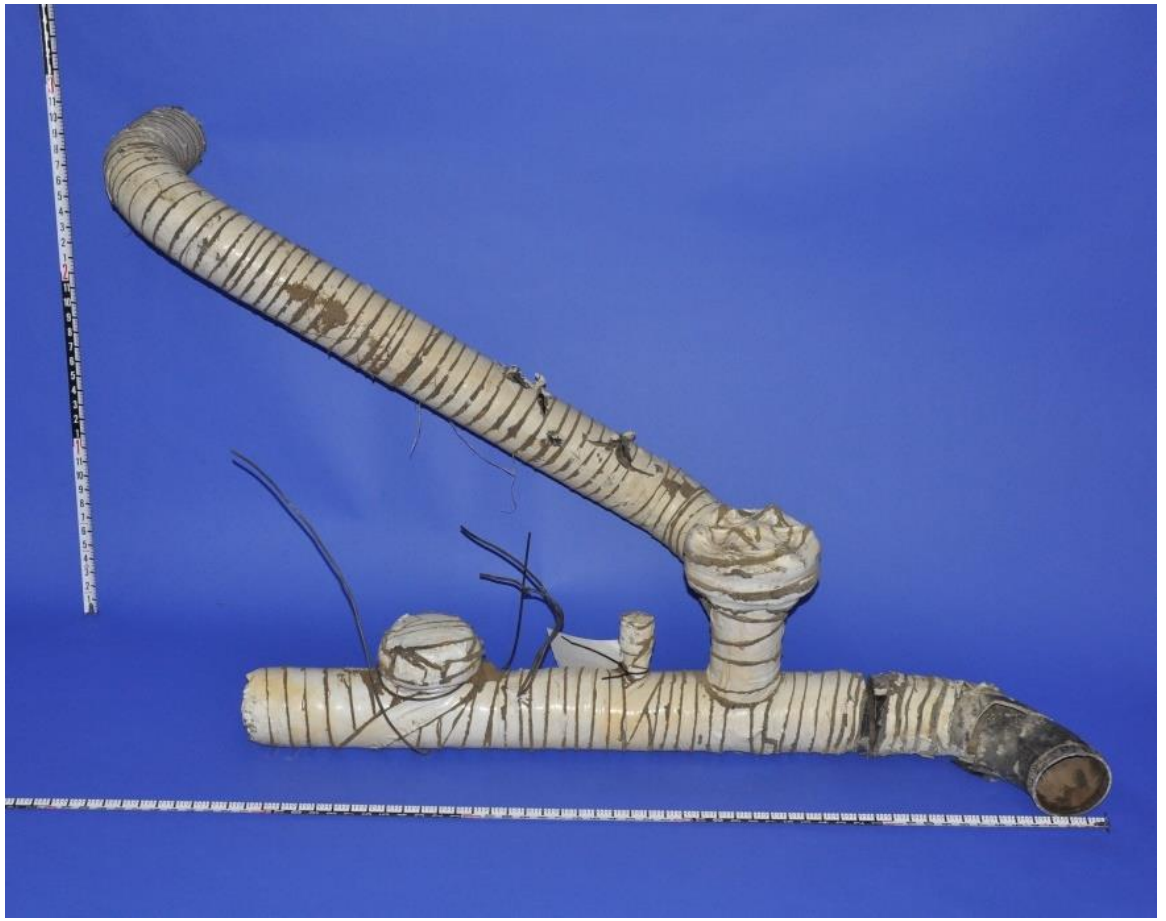


Photographs Source: PG&E

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Pipeline Rupture





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Pipeline Rupture at Hayward Fault

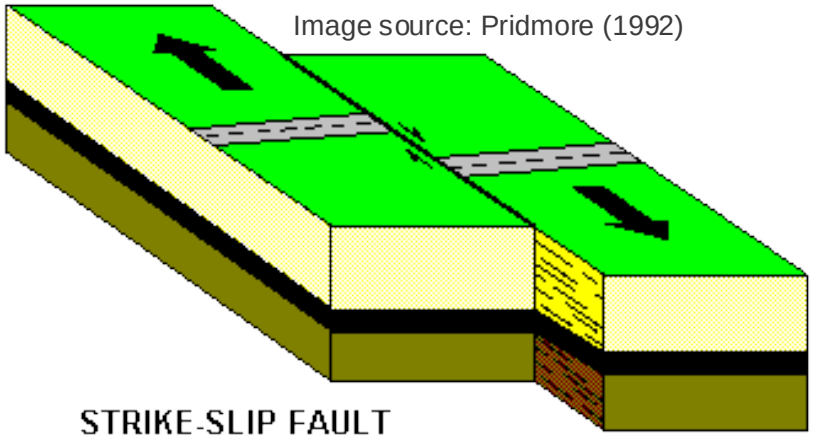
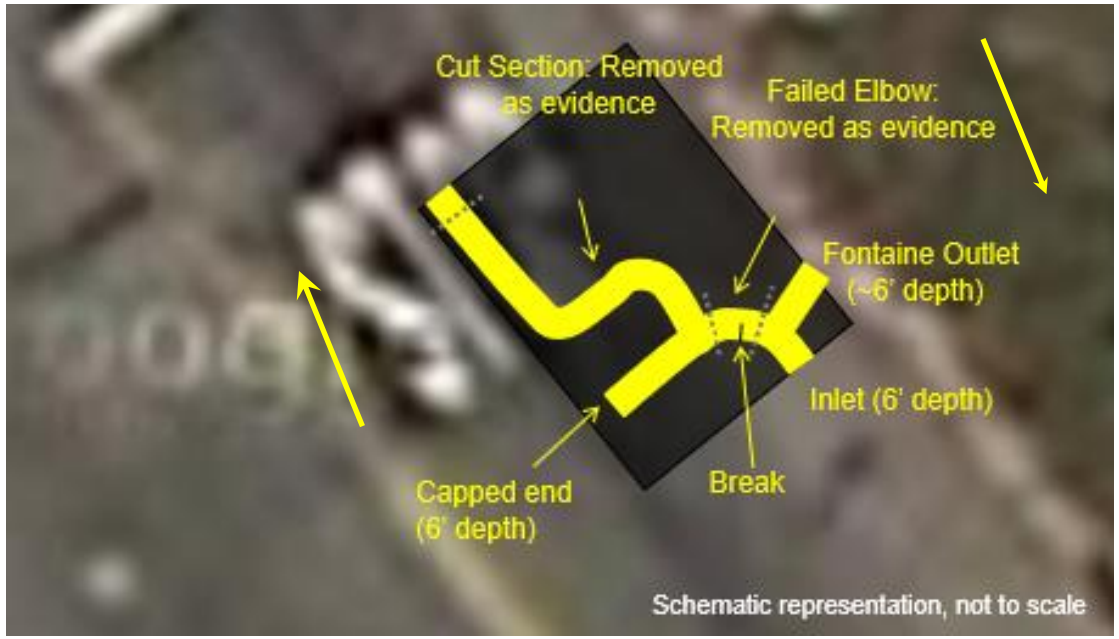


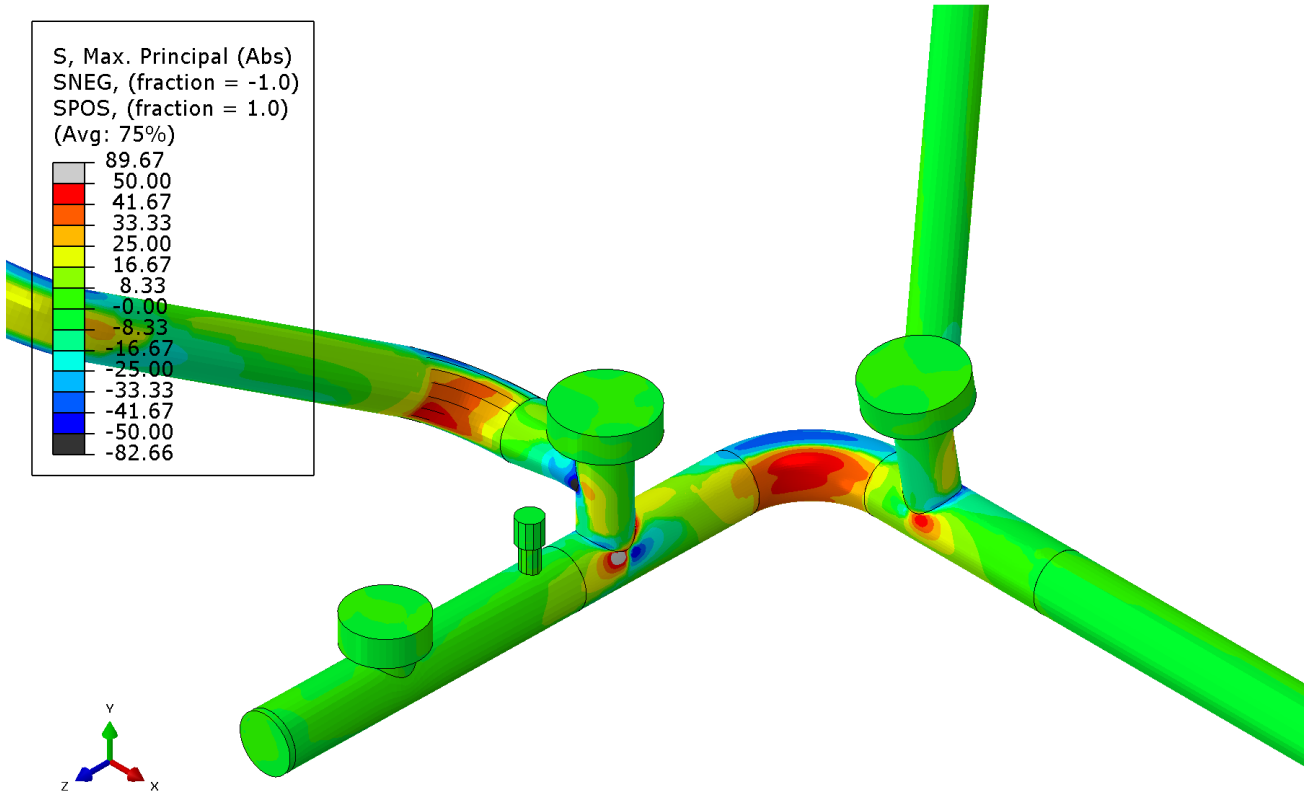
Image source: Pridmore (1992)



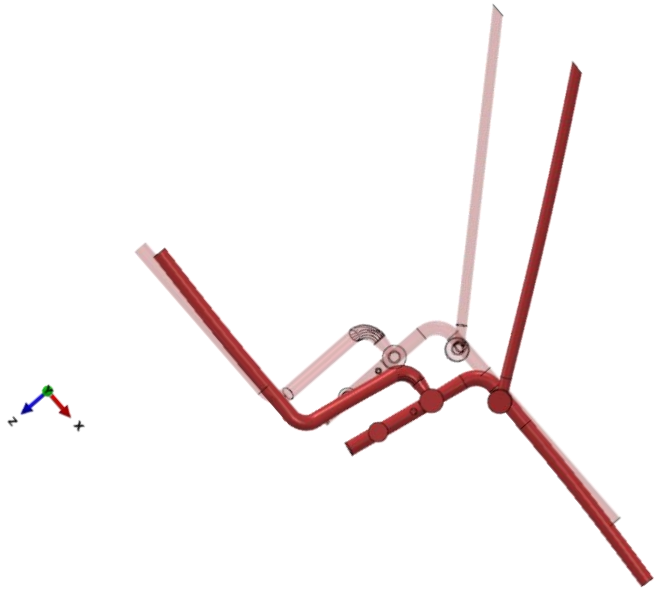


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Fault Creep Loading

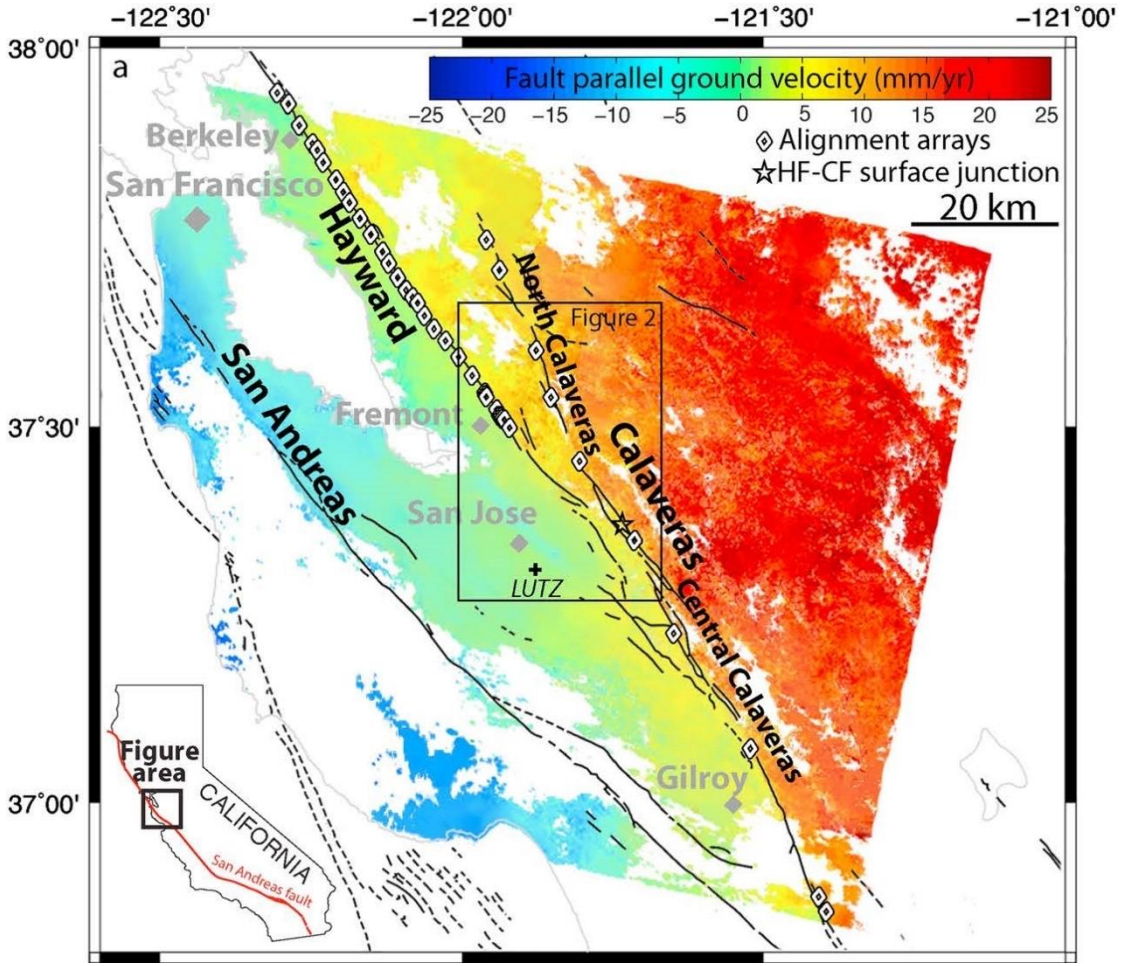


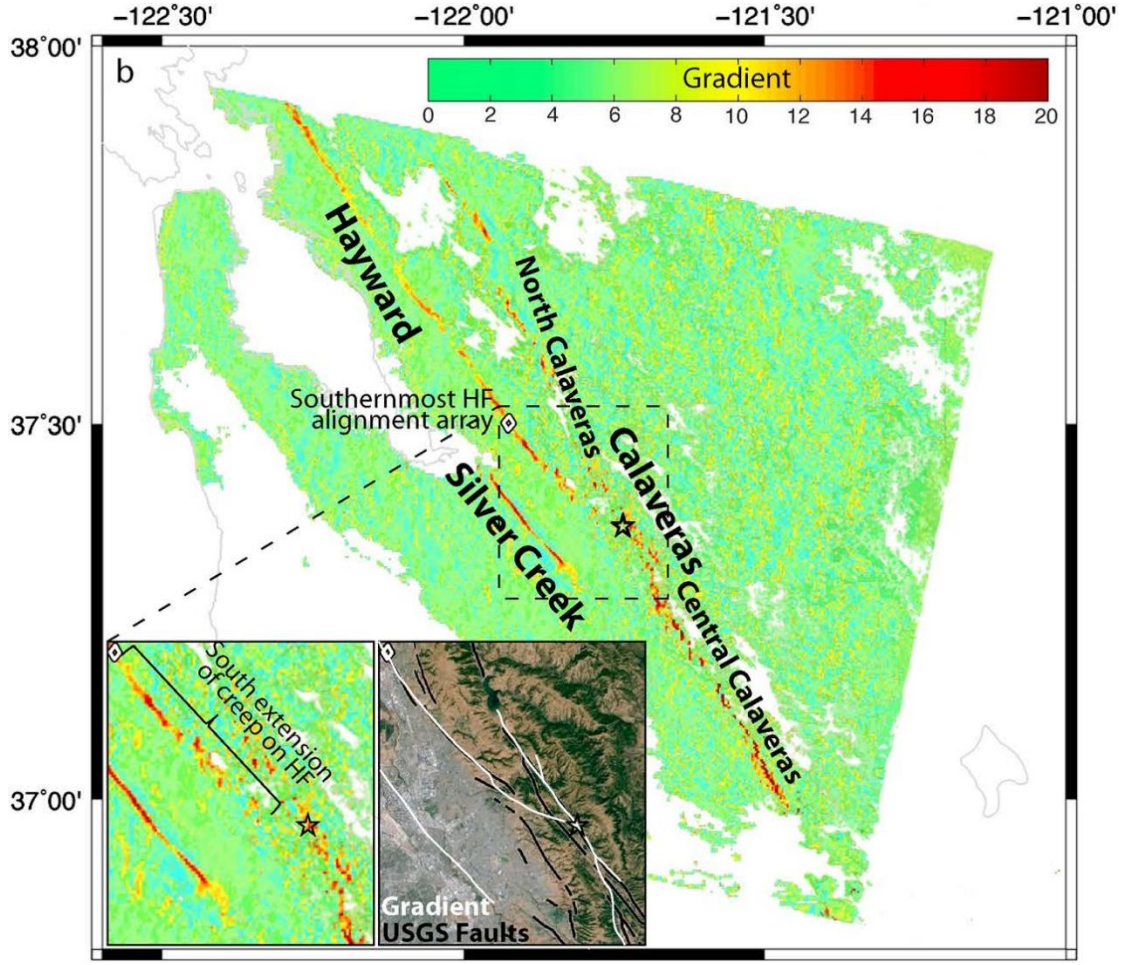




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Satellite Data – InSAR

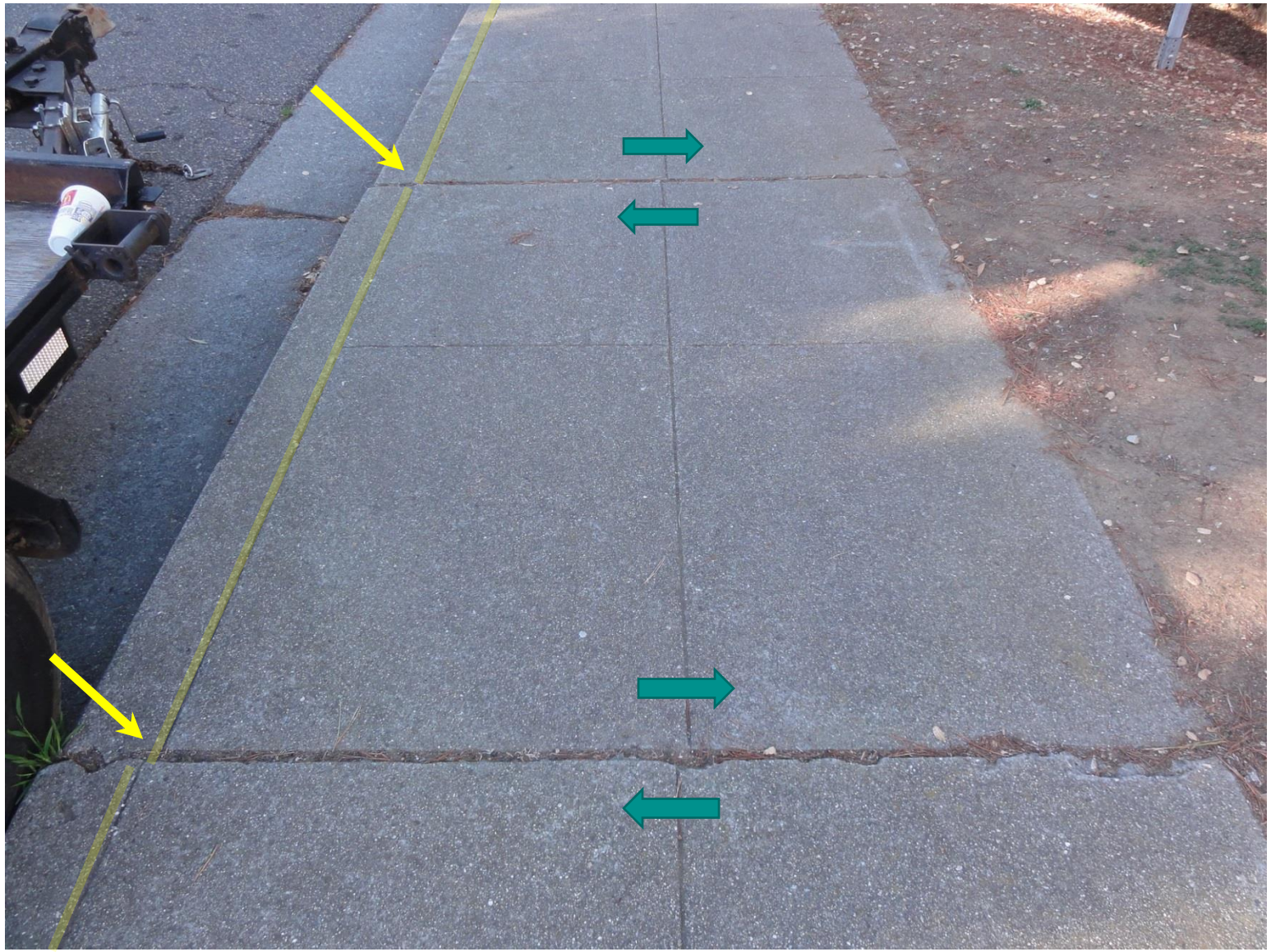




Chaussard, E, Bürgmann, R, Fattahi, H, Nadeau, RM, Taira, T, Johnson, CW, and Johanson, I (2015), Potential for larger earthquakes in the East San Francisco Bay Area due to the direct connection between the Hayward and Calaveras Faults. *Geophys. Res. Lett.*, 42, 2734– 2741.

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Evidence of Ground Movement in Vicinity of Site

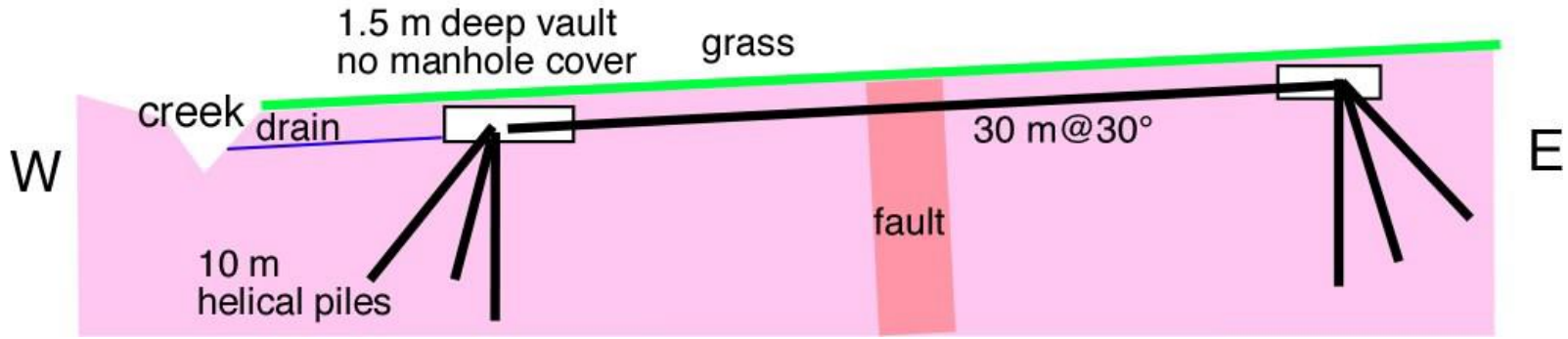


Encina Way

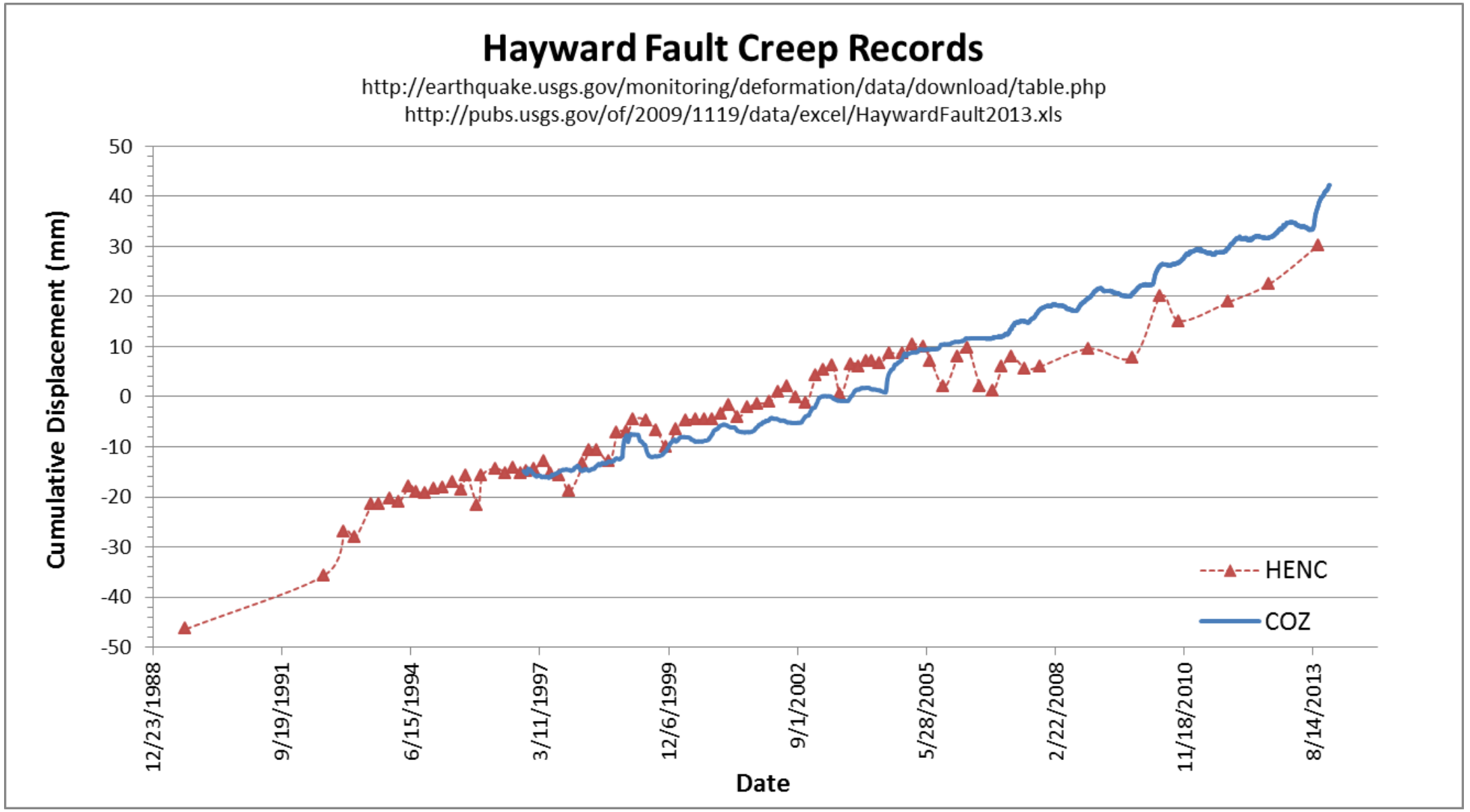
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Creepmeter – Oakland Zoo





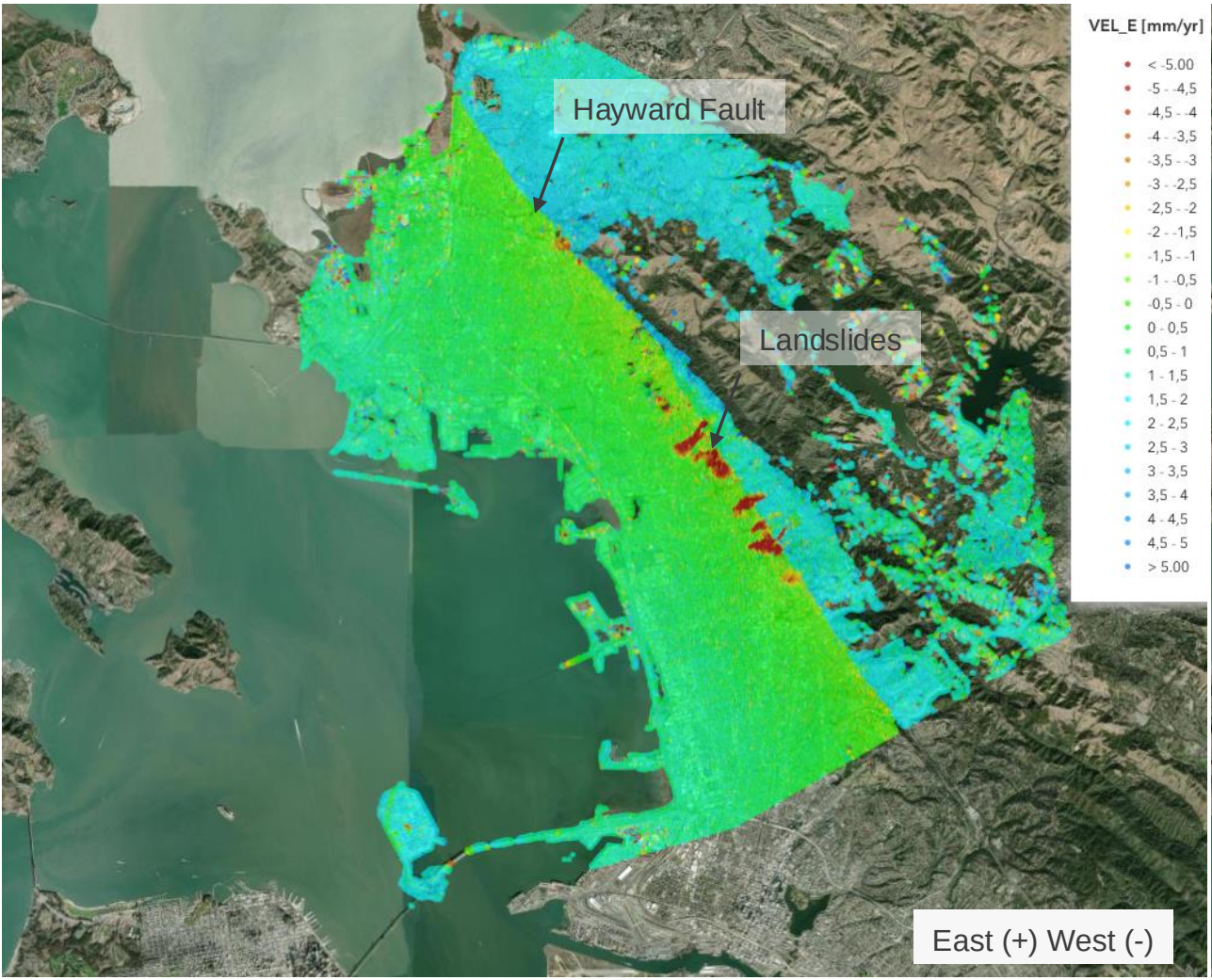
Source: Bilham, R. (2007?)

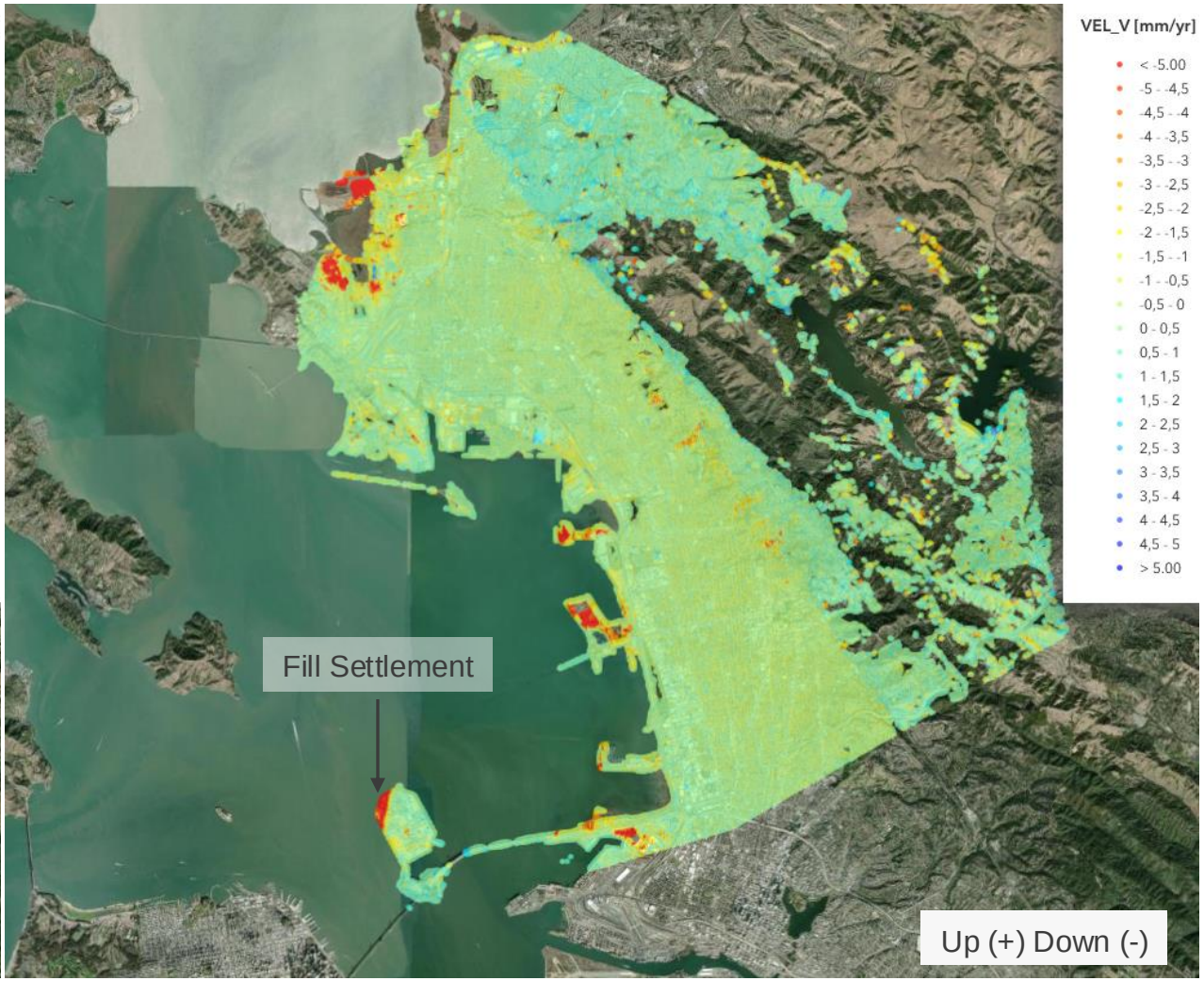


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Satellite Data – InSAR

2D TerraSAR-X Satellite 2009-2020





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Risk Assessments

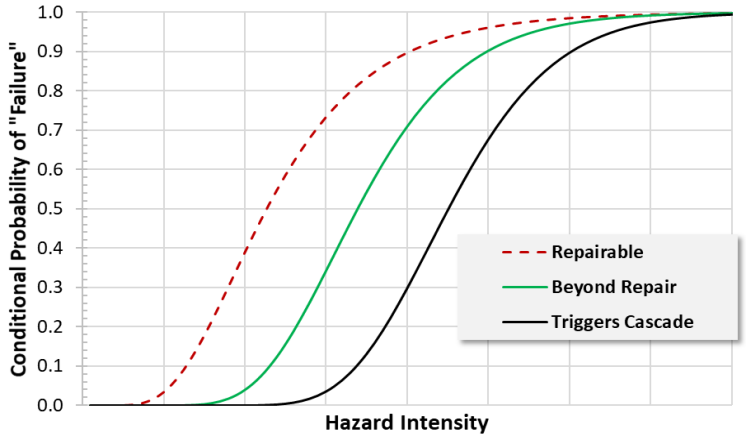
Qualitative Risk Assessment

Frequency of Occurrence	Severity of the Consequence: Negligible → Disastrous			
Almost Always	???	???	Very Bad	Severe
	???	???	Bad	Very Bad
	Very Good	Good	???	???
Almost Never	Excellent	Very Good	???	???

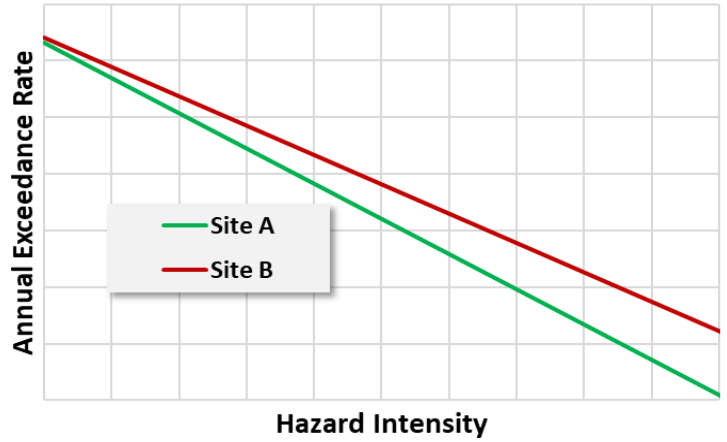
Quantitative Risk Assessment

Occurrence Rate, $\lambda = \int_0^\infty p(f|im) \left|\frac{dh}{dim}\right| dim$

Fragility Curves



Hazard Curves



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Geotechnical Pipeline Assessment Tool

Indicative Factor Weights by Hazard

Indicative Factor	Fault Creep	Liquefaction	Landslide	Subsidence	Expansive Soils	Geochemical
$IF_{material}$	25	30	5	5	5	
IF_{leaks}	10		5	10	10	40
$IF_{anchors}$	10	10	10	15		
$IF_{service}$	5	5	5	0	15	
IF_{d*a}	50					
IF_{SLHRF}		55				
IF_{LS}			50			
IF_{rain}			25			
IF_{sett}				70		
IF_{LinEx}					20	
IF_{PI}					20	
$IF_{haz-exp}$					30	
IF_{SC}						10
IF_{CP}						20
IF_{PA}						30
CHECK:	100	100	100	100	100	100

The sum of weights for each hazard should be equal to 100

Hazard Category Assignment Criteria

Hazard Level	Fault Creep	Liquefaction	Landslide	Subsidence	Expansive Soils	Geochemical
HL1: HF <	33	33	33	33	33	33
HL2: HF <	66	66	66	66	66	66
ID: HF_{Δ} >	40	40	40	40	40	40

Pre-1985 Aldyl-A pipes are, at a minimum, assigned to HL2

HL3 is assigned to all hazard levels greater than HL2

ID (Insufficient Data) is also assigned if the Hazard Factor cannot be calculated

HF_{Δ} is the difference between the MAX and MIN Hazard Factor (HF_{MAX} - HF_{MIN})

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Example of Landslide Hazard Assessment

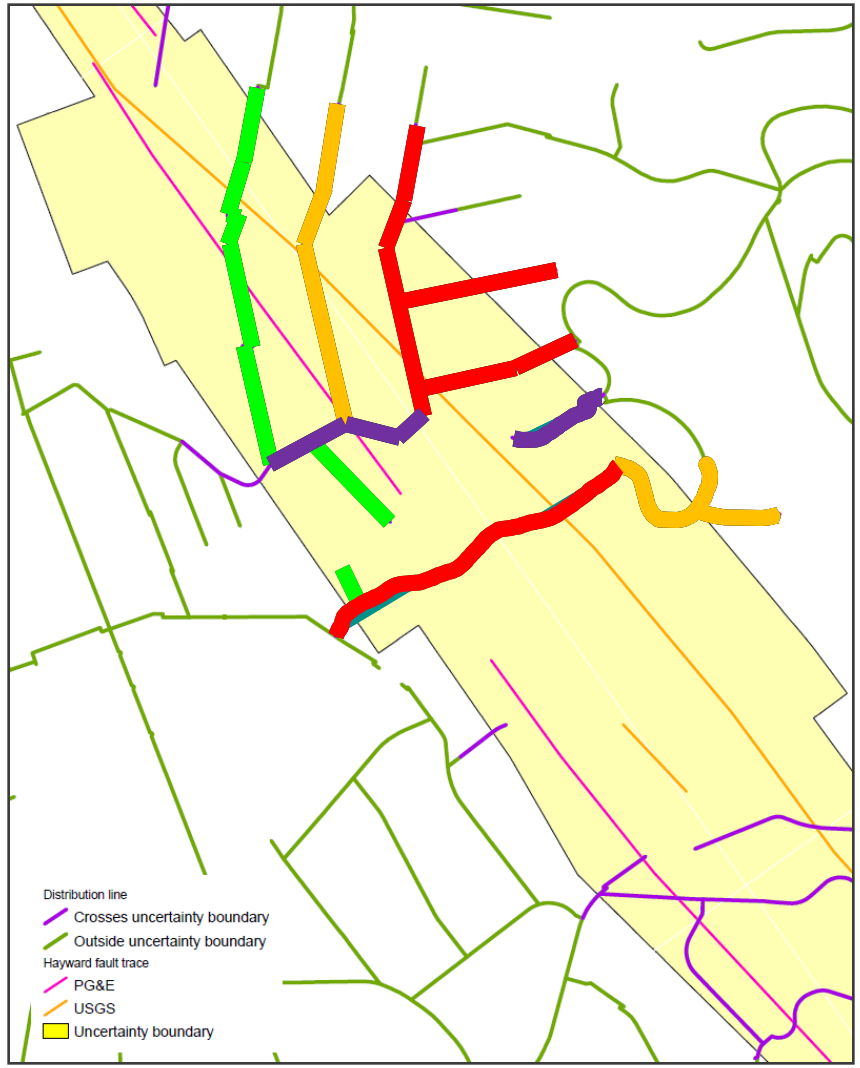
GPAT - Geotechnical Pipeline

IDENTIFIERS	LANDSLIDE HAZARD ASSESSMENT																				
	PARAMETERS		INDICATIVE FACTORS									HAZARD FACTOR			HAZARD CATEGORY						
GUID	MS58 Landslide Susceptibility Class	Mean Annual Rainfall (in)	F_{LS_min}	F_{LS_max}	F_{LS_median}	F_{rain_min}	F_{rain_max}	F_{rain_median}	$F_{anchors_min}$	$F_{anchors_max}$	$F_{anchors_median}$	MIN	MAX	MEDIAN	Preliminary	HL1 Support	HL2 Support	HL3 Support	ID Support	Final	Justification
{281A87CB-D469-41A7-9F45-DEC771C790C5}	5	24.2	0.5	0.5	0.5	0.606535433	1	0.806535433	0.312183116	0.624366233	0.624366233	46	59	54	HL2						
{919EFCAA-985B-4112-A87A-1C72DBB8B01C}	0	22.3	0.1	0.1	0.1	0.542637795	0.942637795	0.742637795	0.319345107	0.638690214	0.638690214	23	37	32	HL1						
{63DFD304-27E0-4CFB-8985-09E3FF11A6B9}	0	25.6	0.1	0.1	0.1	0.654934383	1	0.854934383	0.206468227	0.412936455	0.412936455	22	31	28	HL1						
{89F66D69-A017-49C7-8784-AF7D485C4D91}	0	23.8	0.1	0.1	0.1	0.59324147	0.99324147	0.79324147	0.5	1	1	24	37	33	HL1						
{AD9E0E41-A651-4E50-B41D-5B3A8B520577}	0	23.0	0.1	0.1	0.1	0.56523622	0.96523622	0.76523622	0.424862868	0.849725736	0.849725736	24	40	34	HL2						
{6B1BEEC9-B800-4079-9D2D-52506BF2347A}	0	22.2	0.1	0.1	0.1	0.539304462	0.939304462	0.739304462	0.271443833	0.542887666	0.542887666	21	35	29	HL1						
{372C4690-53AC-4ED5-BB43-F43E22244BB7}	0	22.1	0.1	0.1	0.1	0.537572178	0.937572178	0.737572178	0.5	1	1	23	37	33	HL1						
{73ED4A2C-60AD-483E-9878-DD770C85D6EC}	0	20.9	0.1	0.1	0.1	0.495708661	0.895708661	0.695708661	0.5	1	1	UNK	UNK	UNK	ID						
{523B4A7B-1927-43A0-9FE2-A07C3F4010AF}	7	24.2	0.7	0.7	0.7	0.606128609	1	0.806128609	0.5	1	1	61	75	70	HL3						
{51D29581-5A81-46C4-A4F8-6AEA758C86BC}	5	25.9	0.5	0.5	0.5	0.66175853	1	0.86175853	0.095830531	0.191661063	0.191661063	47	56	52	HL2						
{C92D6AB0-5A9C-4381-A6E9-E084E31E2BFE}	0	22.2	0.1	0.1	0.1	0.541036745	0.941036745	0.741036745	0.5	1	1	23	36	32	HL1						
{7D9778C1-E92A-4E48-BCAC-6E501FAA8802}	0	21.7	0.1	0.1	0.1	0.524304462	0.924304462	0.724304462	0.5	1	1	22	36	32	HL1						
{2D9DBE5D-B414-4BAE-B783-0476699E9198}	0	19.7	0.1	0.1	0.1	0.458175853	0.858175853	0.658175853	0.071043394	0.142086788	0.142086788	18	28	24	HL1						
{5075079B-7DFE-4431-92BC-F70B7C60A4FE}	5	21.7	0.5	0.5	0.5	0.522887139	0.922887139	0.722887139	0.5	1	1	47	62	57	HL2						
{11E2C560-DC96-4764-A30C-D009EA10665F}	0	23.6	0.1	0.1	0.1	0.586942257	0.986942257	0.786942257	0.5	1	1	24	37	33	HL1						
{138B4E2F-4ED8-43EA-9D8D-90DBB730E57A}	7	23.5	0.7	0.7	0.7	0.582821522	0.982821522	0.782821522	0.17458022	0.34916044	0.34916044	56	66	62	HL2						
{8F540EFA-E9D4-4E6B-A2B8-92F2014B3509}	0	23.6	0.1	0.1	0.1	0.587020997	0.987020997	0.787020997	0.5	1	1	UNK	UNK	UNK	ID						
{FB54D37D-4DE9-47C0-950C-93EA3CEDDAE7}	0	23.4	0.1	0.1	0.1	0.57839895	0.97839895	0.77839895	0.5	1	1	24	38	34	HL2						
{DB4D2BA5-5603-466F-A035-85A19F2297A4}	0	21.5	0.1	0.1	0.1	0.51816273	0.91816273	0.71816273	0.360509546	0.721019092	0.721019092	21	33	29	HL1						
{17B680C2-2130-44C0-8F22-A510687AE37C}	0	24.0	0.1	0.1	0.1	0.600734908	1	0.800734908	0.5	1	1	25	39	34	HL2						
{0F7DB551-0785-4BE8-B65C-230F33C466E7}	0	24.1	0.1	0.1	0.1	0.602716535	1	0.802716535	0.496045093	0.992090187	0.992090187	26	40	35	HL2						
{151B2EAB-F7ED-4F6D-B688-0393F7A72C12}	0	23.2	0.1	0.1	0.1	0.573451444	0.973451444	0.773451444	0.5	1	1	23	37	33	HL1						
{45C8E7B2-50A7-4CF7-B9A8-8F3AFD397AA4}	0	23.0	0.1	0.1	0.1	0.56660105	0.96660105	0.76660105	0.074375862	0.148751723	0.148751723	20	29	25	HL1						
{E057175D-4CAA-4990-8CD6-E5572BCD36EF}	5	24.3	0.5	0.5	0.5	0.611076115	1	0.811076115	0.5	1	1	UNK	UNK	UNK	ID						
{A6D844D2-A058-46DD-A888-47F3F568422A}	7	23.8	0.7	0.7	0.7	0.594908136	0.994908136	0.794908136	0.5	1	1	60	73	69	HL3						
{40CDB4EB-10A5-4373-A33E-469DA3371794}	0	23.7	0.1	0.1	0.1	0.590643045	0.990643045	0.790643045	0.5	1	1	24	38	34	HL2						
{56A79B25-72C8-47B7-A91B-BF367C6B7BA7}	0	23.5	0.1	0.1	0.1	0.582099738	0.982099738	0.782099738	0.220863123	0.441726246	0.441726246	23	34	29	HL1						
{C6C6299A-0BB8-4913-90B1-43010B7B88D0}	0	24.7	0.1	0.1	0.1	0.622887139	1	0.822887139	0.5	1	1	24	37	33	HL1						
{76F17D6E-F8B5-4FA2-9A0C-858C75F6F0C5}	0	23.0	0.1	0.1	0.1	0.565026247	0.965026247	0.765026247	0.312593633	0.625187266	0.625187266	21	33	29	HL1						
{30A0999D-ECC8-4321-B618-839E4FC22982}	0	23.5	0.1	0.1	0.1	0.583608924	0.983608924	0.783608924	0.5	1	1	24	37	33	HL1						
{C1ADBA63-9539-478D-A5CB-8F3DC0494AC5}	0	21.9	0.1	0.1	0.1	0.530708661	0.930708661	0.730708661	0.5	1	1	22	36	32	HL1						
{18EF5D24-06A3-42B3-BA5E-614176749F36}	0	23.8	0.1	0.1	0.1	0.594173228	0.994173228	0.794173228	0.5	1	1	24	37	33	HL1						
{427B3192-4824-49D5-95A1-81427FBC000F}	0	23.7	0.1	0.1	0.1	0.590643045	0.990643045	0.790643045	0.5	1	1	24	37	33	HL1						
{272ADB1B-3345-497F-98F4-CDC2F5791AA3}	5	24.9	0.5	0.5	0.5	0.630748031	1	0.830748031	0.5	1	1	49	63	59	HL2						
{E534639A-CC45-4721-A99C-22548549CAC9}	0	25.3	0.1	0.1	0.1	0.643215223	1	0.843215223	0.5	1	1	26	39	35	HL2						
{3EE32A5C-5BC6-462E-A9A5-6C3182B0F5B6}	0	25.5	0.1	0.1	0.1	0.649619423	1	0.849619423	0.5	1	1	UNK	UNK	UNK	ID						
{2BCB3FEA-B33B-460D-A7CF-DEA01AF0450D}	0	22.8	0.1	0.1	0.1	0.560839895	0.960839895	0.760839895	0.486437738	0.972875475	0.972875475	25	42	36	HL2						
{FCE998A6-151F-4071-AF36-378DF1D7834B}	0	22.2	0.1	0.1	0.1	0.539396325	0.939396325	0.739396325	0.142481646	0.284963291	0.284963291	20	30	26	HL1						
{F05327F3-35A1-4375-A38B-33B65CD0B60A}	0	22.8	0.1	0.1	0.1	0.560026247	0.960026247	0.760026247	0.5	1	1	25	42	36	HL2						
{19702B8B-6C90-4D49-9AE9-C7FD76B224E6}	0	23.4	0.1	0.1	0.1	0.580682415	0.980682415	0.780682415	0.332801469	0.665602939	0.665602939	25	40	34	HL2						
{BB59EDDA-95D5-48C9-91A0-B3305C39A7ED}	0	23.2	0.1	0.1	0.1	0.571706037	0.971706037	0.771706037	0.346481178	0.692962357	0.692962357	23	35	30	HL1						

Segments Categorization Example

Pipeline segments can be categorized by likelihood of pipeline failure:

- Hazard Level 1: low
- Hazard Level 2: moderate
- Hazard Level 3: high
- Insufficient Data: currently lacking sufficient data regarding past performance or hazard indicators



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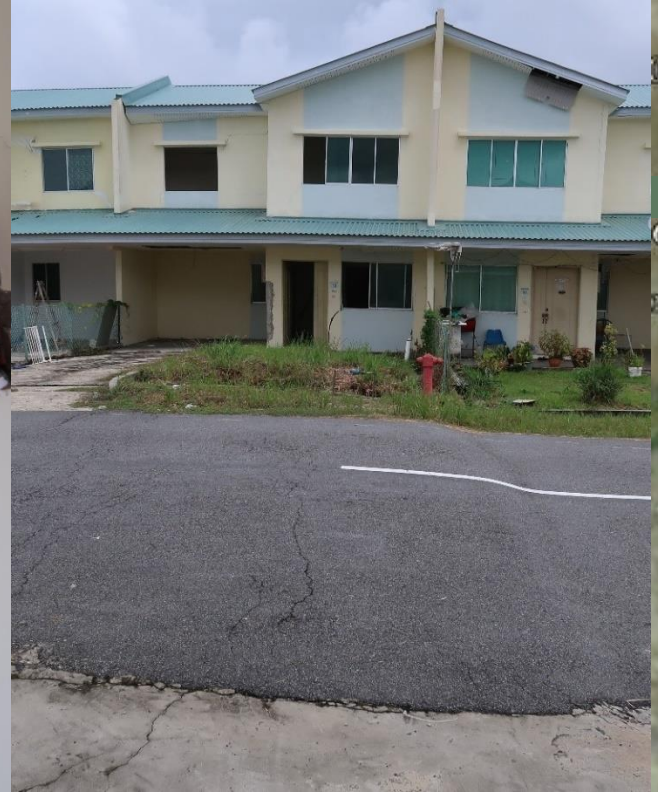
Case Study 2

Damage During
&
After Construction



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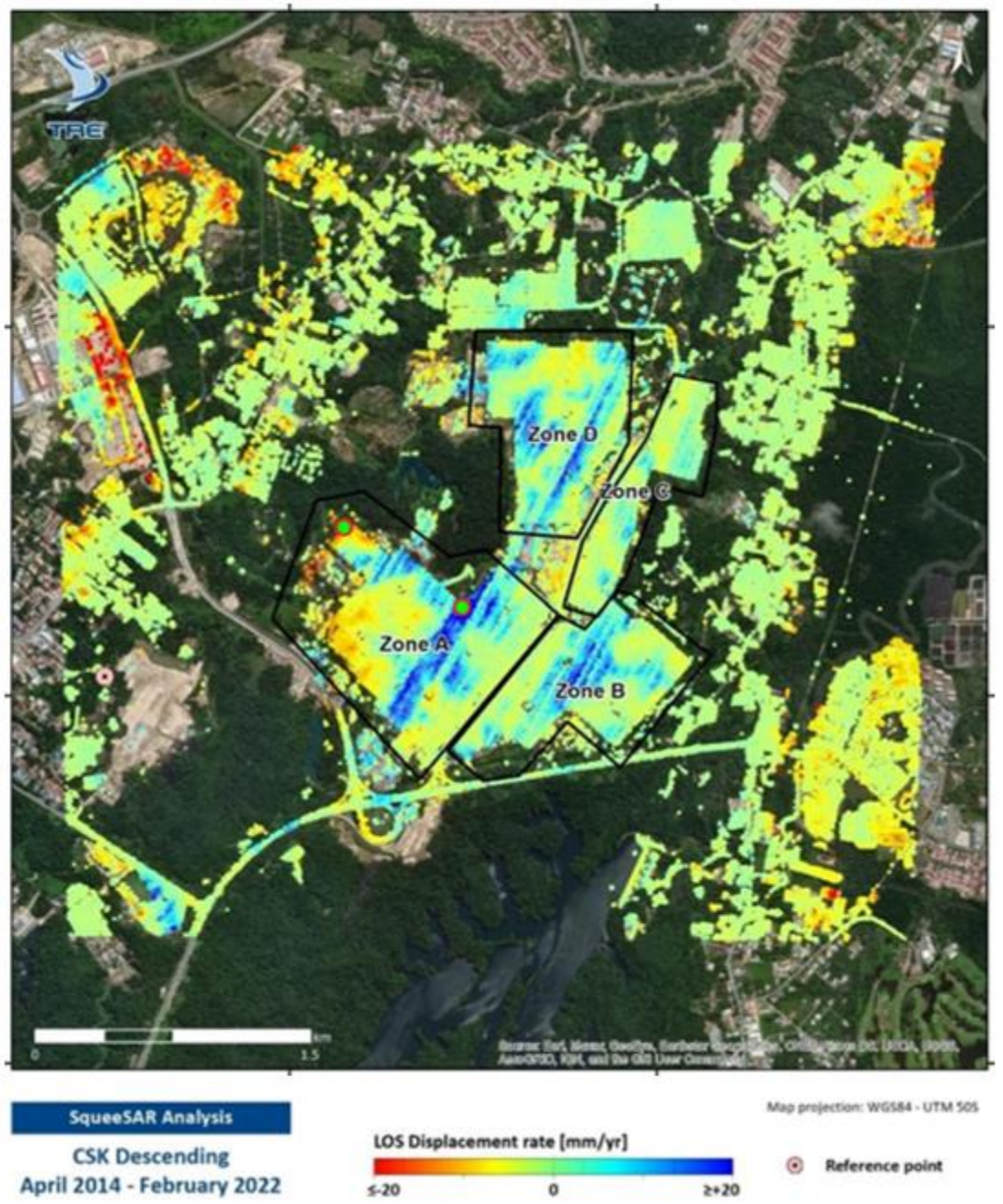



- Cracked walls & uneven floors in houses
- Heaved street & driveway pavements
- Damaged surface drainage works
- Damaged underground utilities

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Satellite Data

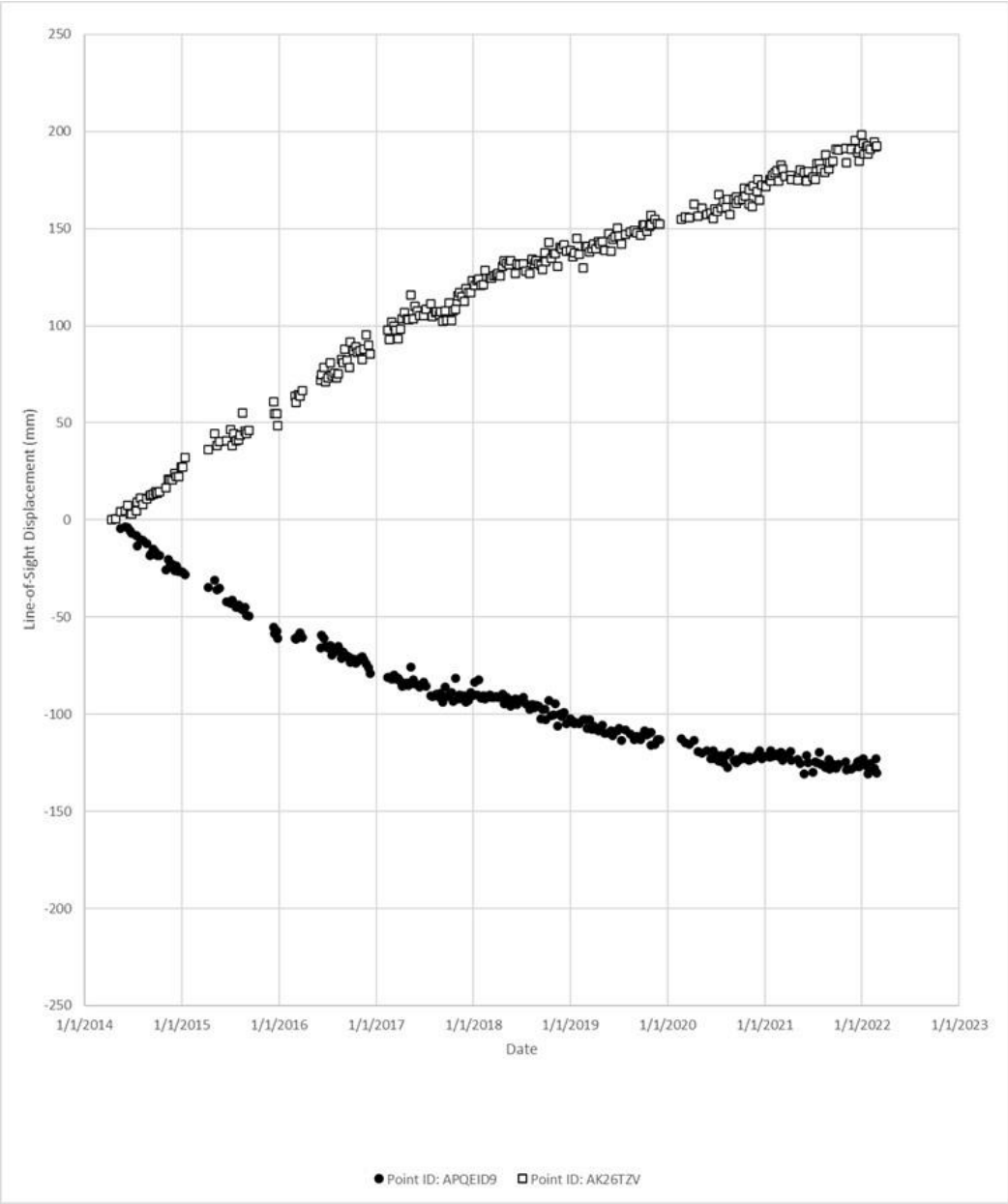
Site Wide Data



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Satellite Data

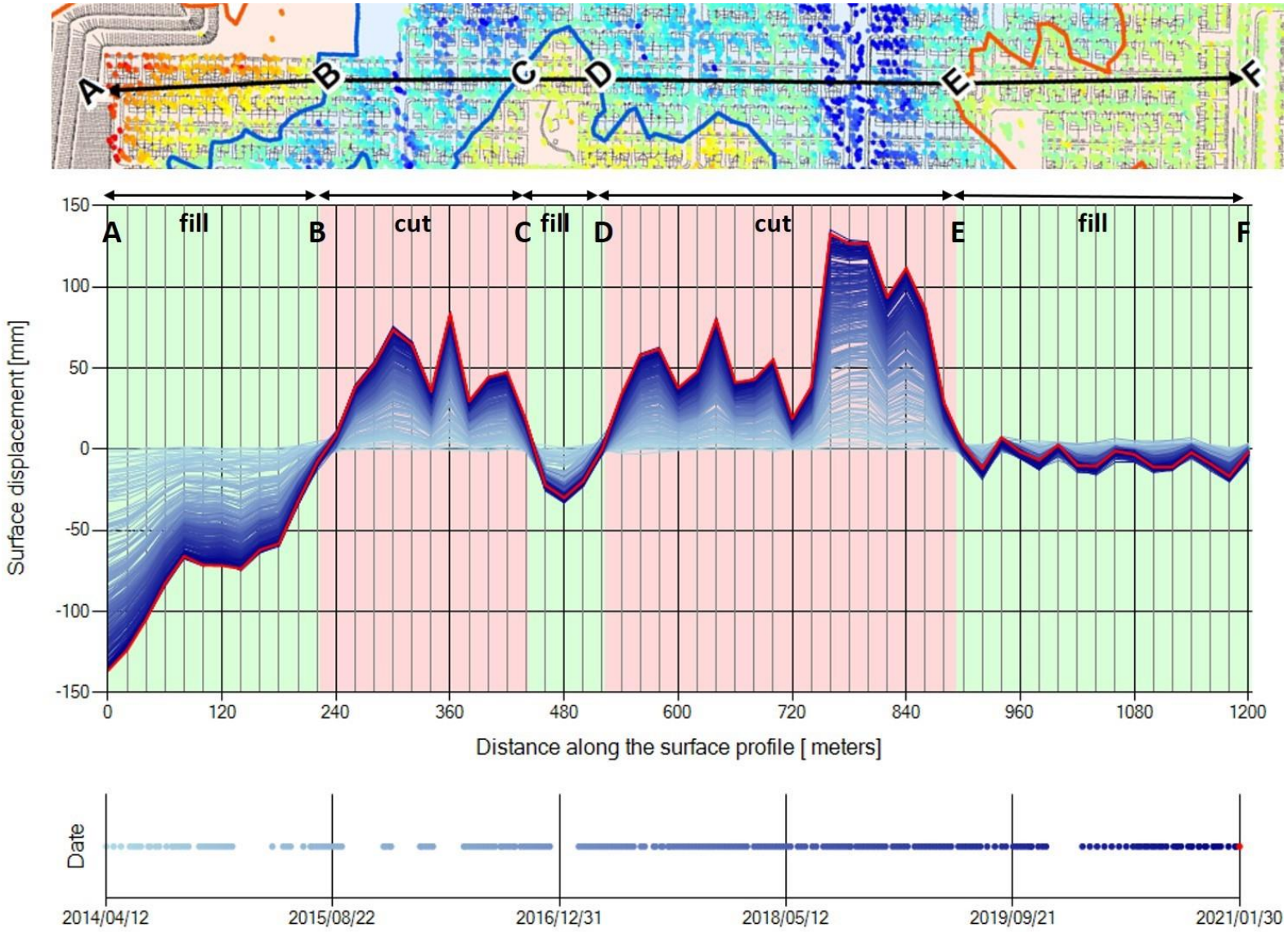
Time-history of Ground Movement at Specific Points



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Satellite Data

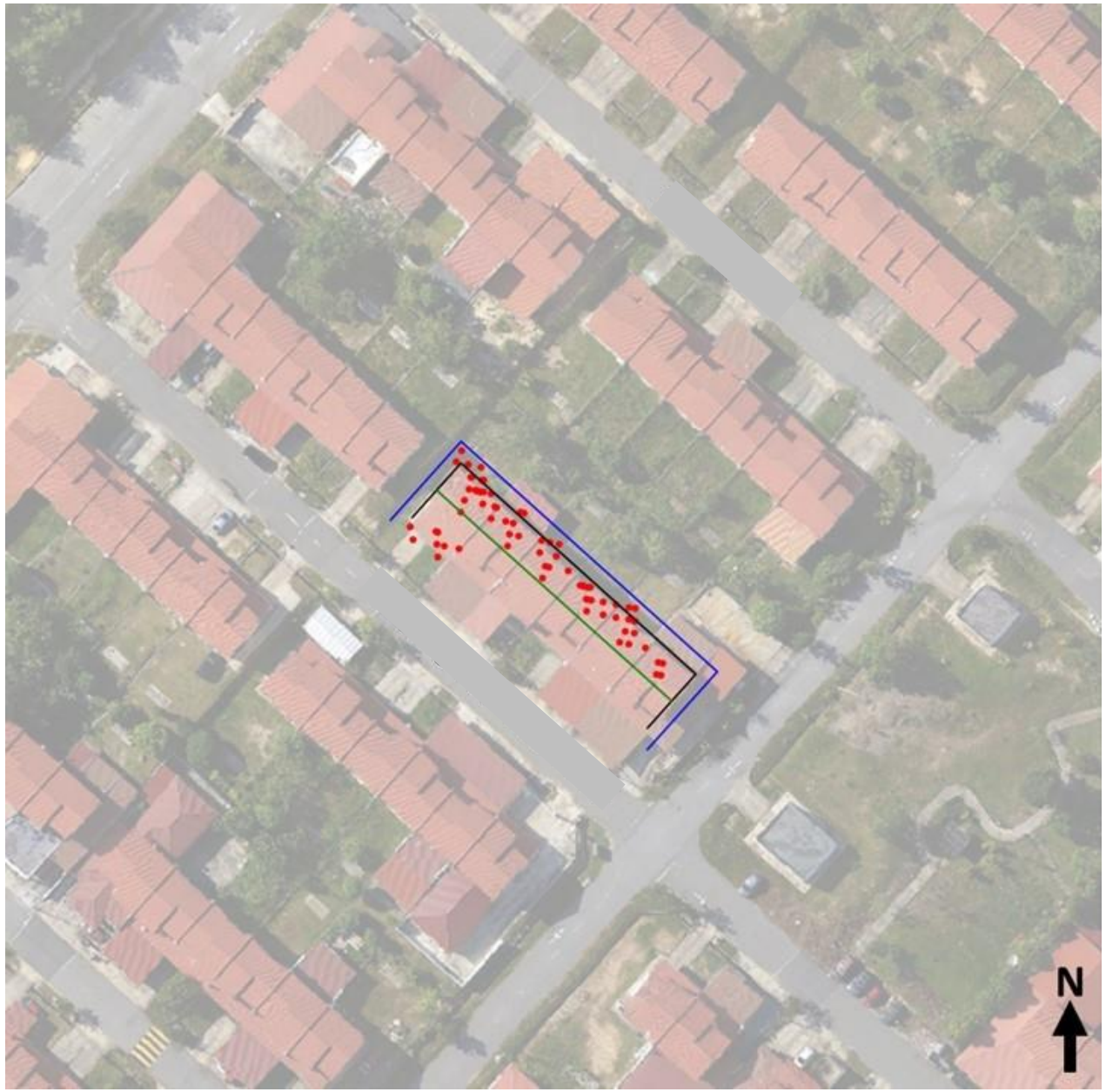
Profiles of
Ground Movement



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Satellite Data

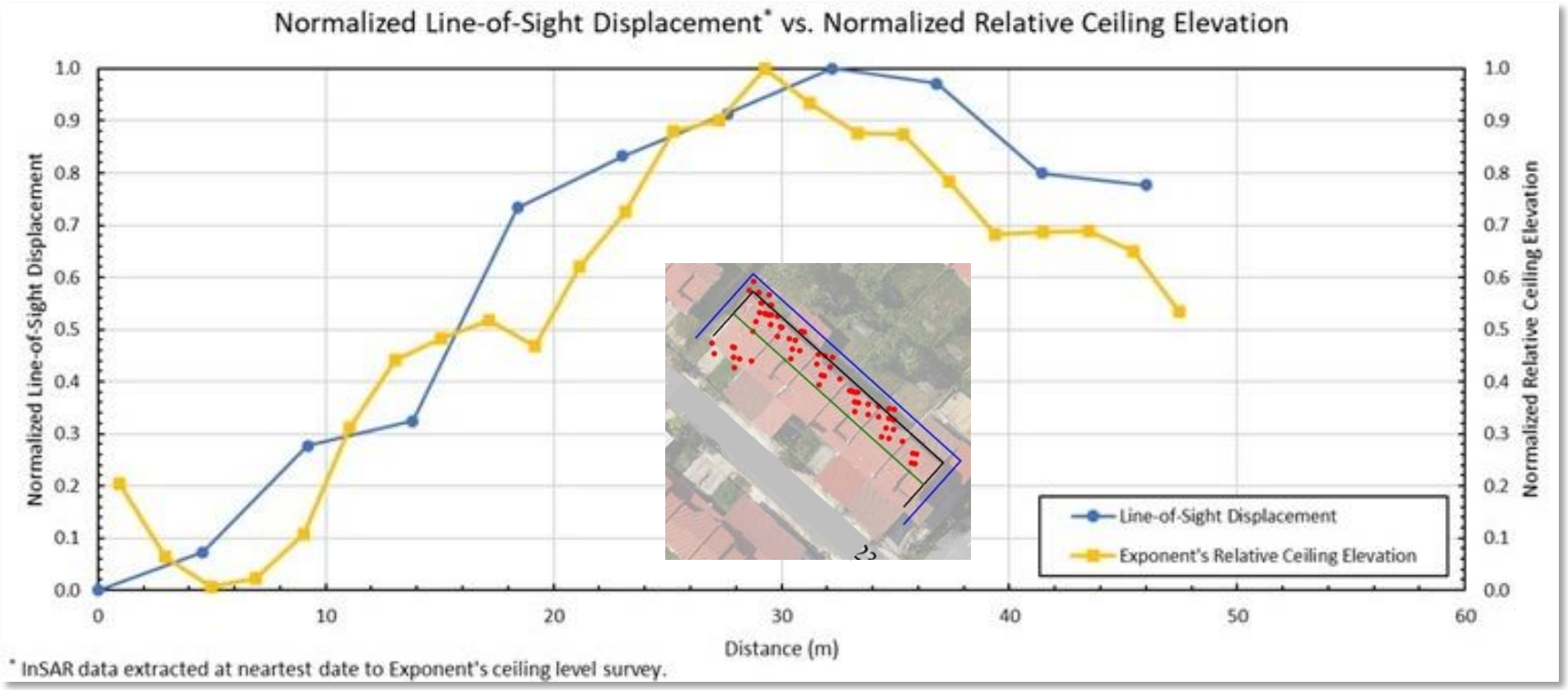
Ground Truthing



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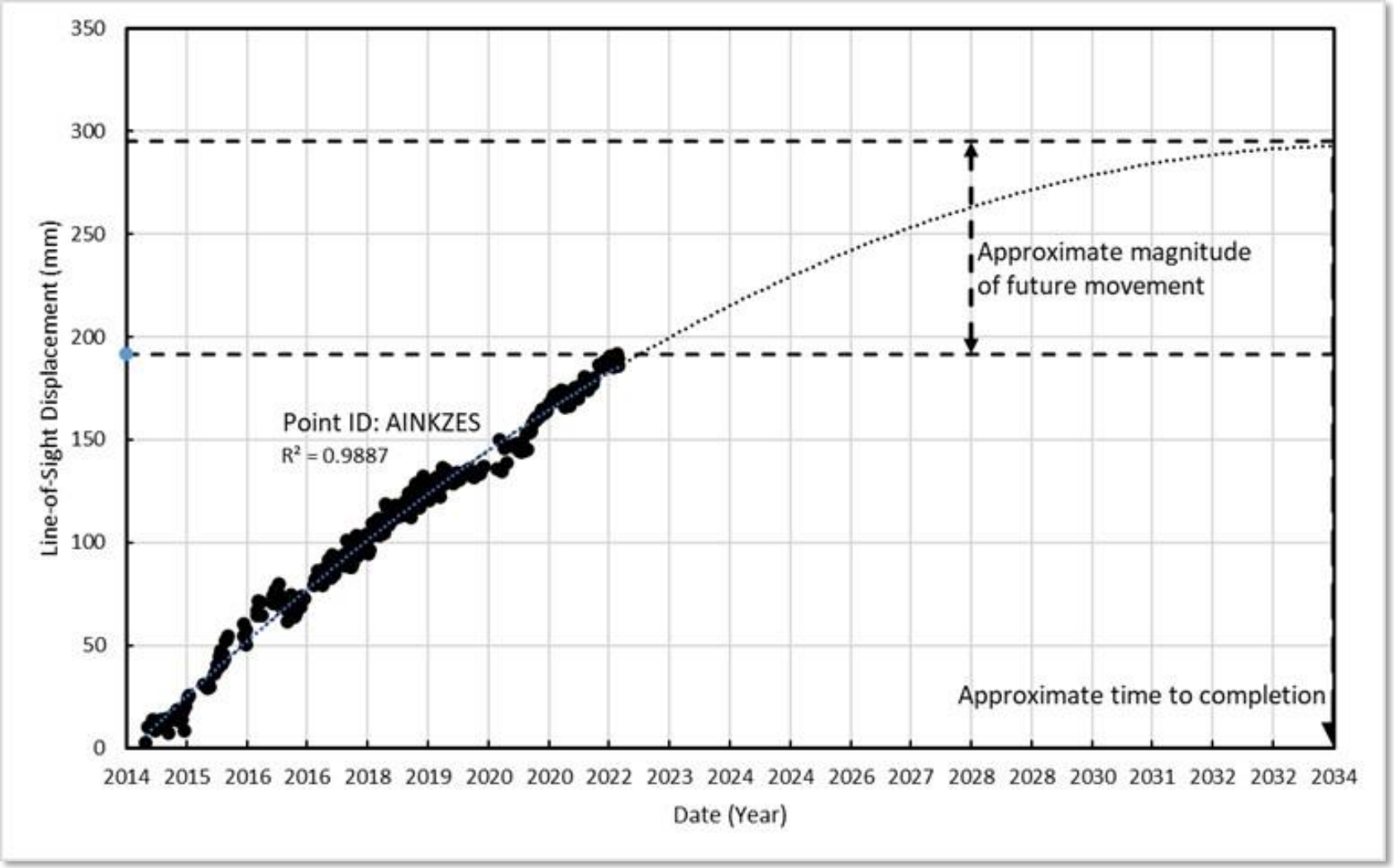
Ground Truthing



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Satellite Data

Looking into the Future



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Case Study 3

Tale of Two Uses:
Power of Data Visualization & Analyses Gone Awry



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Water Main Failure

During Failure

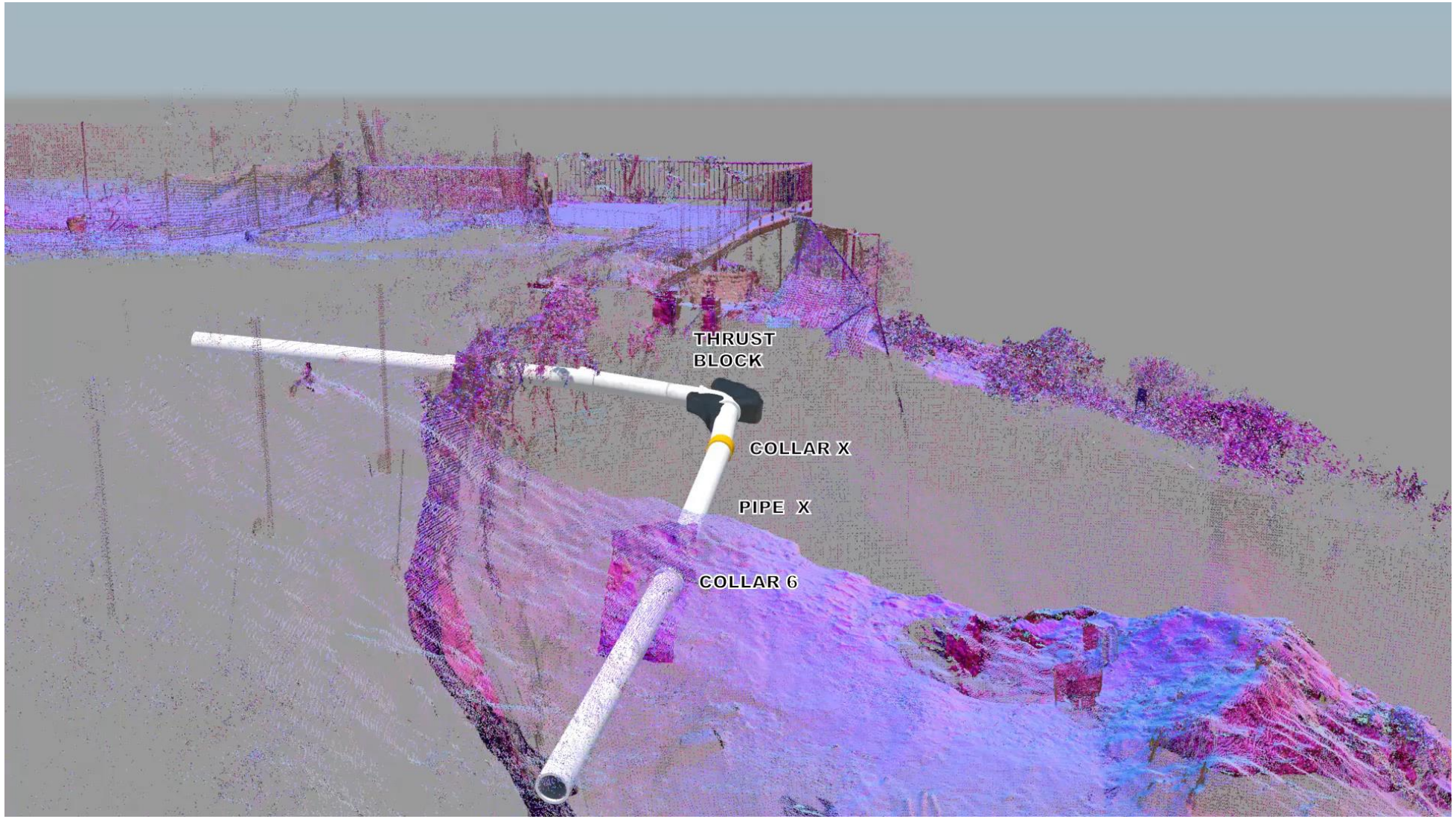


After Failure



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Data Visualization – Site Orientation



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Question?

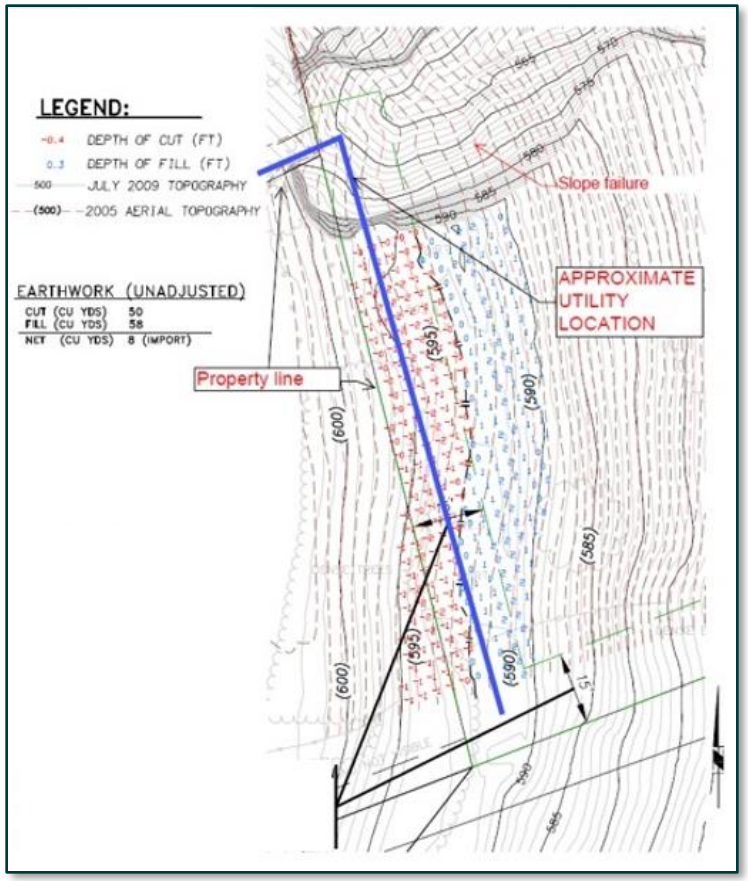
Did grading occur over pipe?



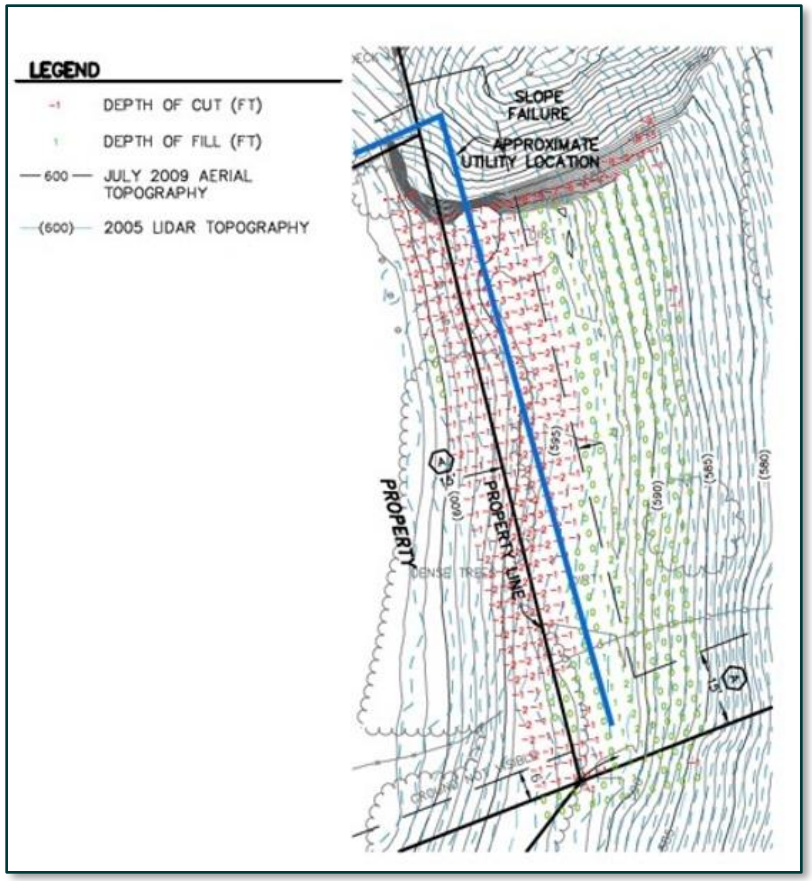
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Remote Sensing to the Rescue?

Consultant B



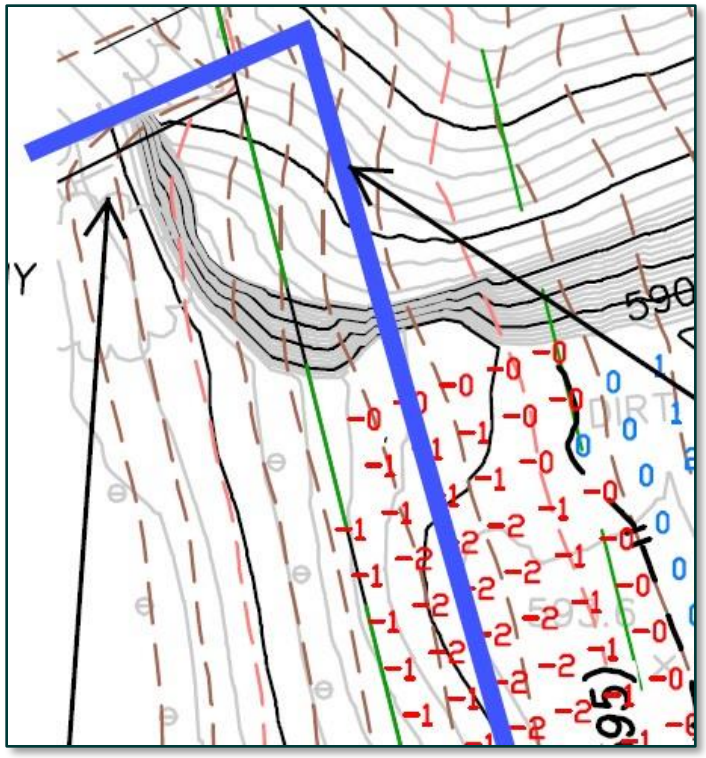
Consultant C



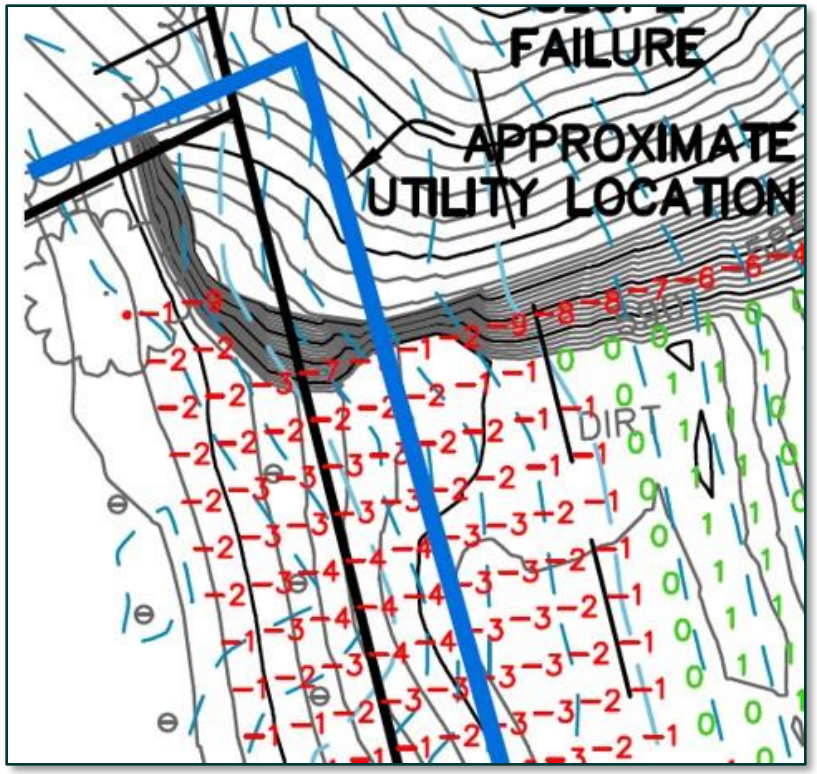
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Remote Sensing to the Rescue?

Consultant B



Consultant C



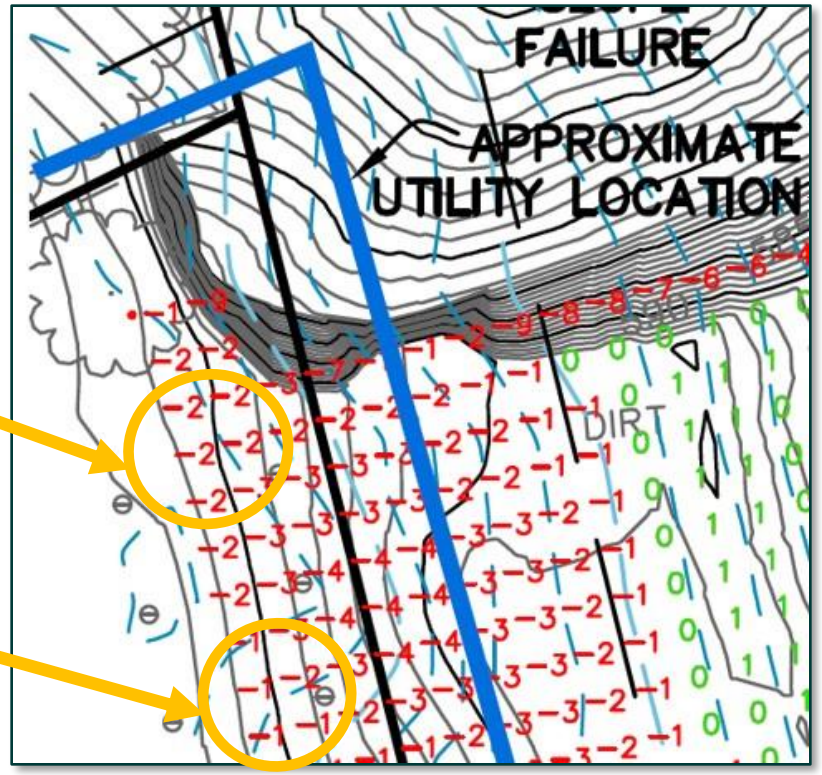
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Remote Sensing to the Rescue?

Consultant B



Consultant C



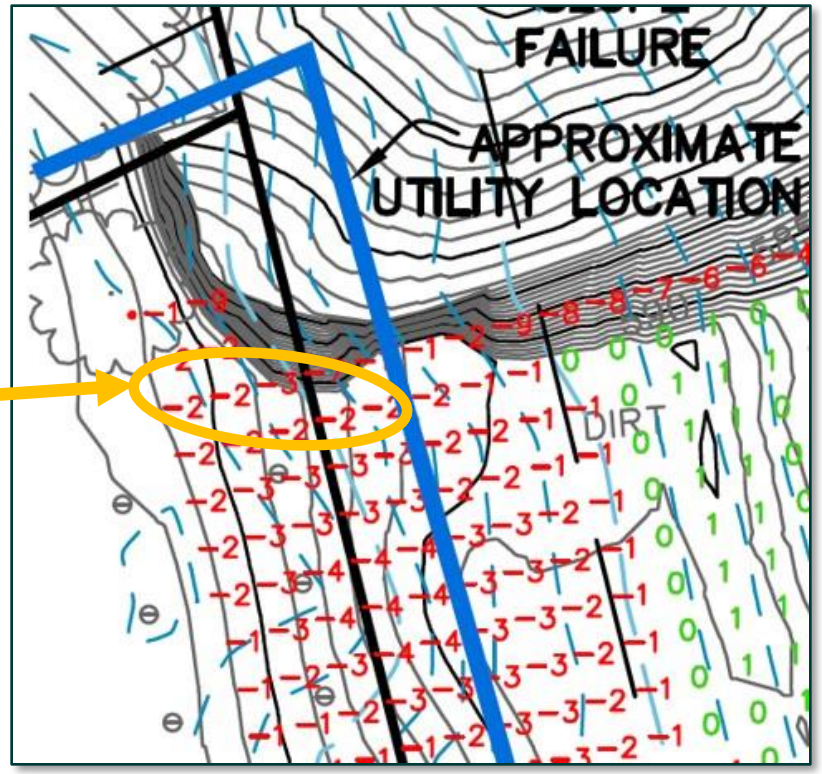
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Remote Sensing to the Rescue?

Consultant B



Consultant C



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Admissibility of Remote Sensing Data in Court

- Has the Technique Been Tested?
- Has it Been Subjected to Peer Review or Publication?
- What is the Known or Potential Rate of Error?
- Is the Methodology Generally Accepted in the Scientific Community?

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Conclusions

- Technological advancements in remote sensing allow:
  - Unprecedented potential for evaluating and monitoring distributed infrastructure systems.
  - Analyzing response to environmental stressors such as human activity, natural hazards, and climate change.
- Remote sensing has become commonplace, especially for large, distributed infrastructure systems such as pipeline and transportation corridors.
- Remote sensing can be integrated into a system-wide Hazards Assessment Framework.
- Remote sensing data is often collected on an automated and regular basis and can be used to assess present and past conditions.

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Conclusions (*cont.*)

- Remote-sensing tools can be used to:
  - Monitor surface and structural deformations to explain past performance.
  - Evaluate existing conditions.
  - Analyze potential future behavior.
  - Assist in diagnosing the cause of past performance problems or failures.
  - Demonstrate compliance with regulatory requirements.
  - Assist experts when controversies arise following the manifestation of undesirable events.
- Remote sensing is becoming a fundamental part of designs, risk assessments and mitigation strategies, construction monitoring, and expert opinions in disputes.
  - As a result, findings that rely on remote sensing data are increasingly a subject of scrutiny.

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Thank You



Juan F. Perri, Ph.D., P.E., G.E.

Principal Engineer

Exponent

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