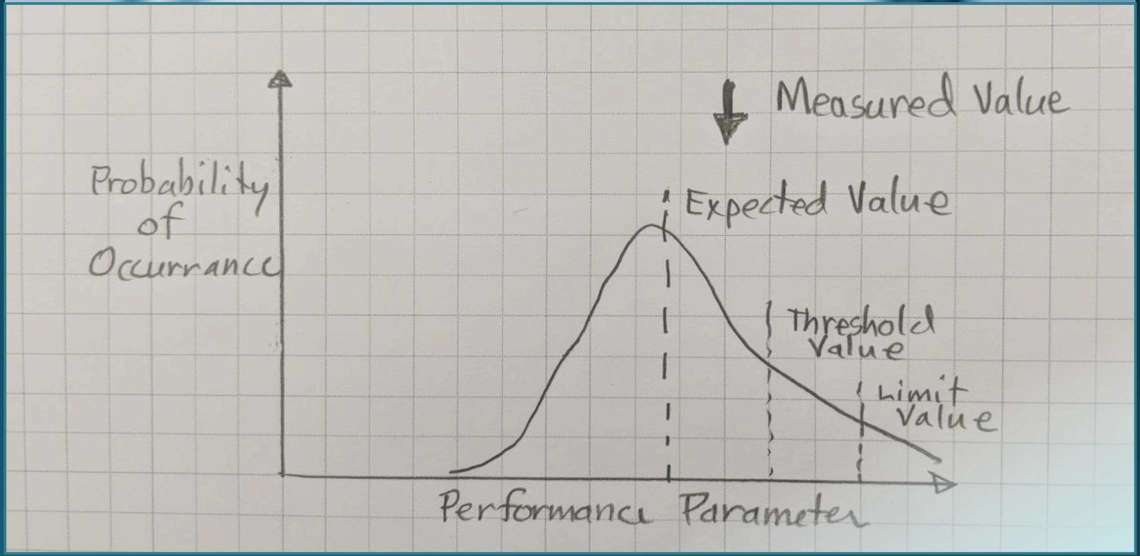
Challenges and Opportunities in Geotechnical Performance Monitoring in 2022

First Dunnicliff Lecture
11th FMGM
Imperial College
September 5, 2022



W. Allen Marr, PhD, PE, NAE
Founder and CEO of Geocomp
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- wam@geocomp.com

Contents

- Some memories of John Dunnicliff
- Evolution from “what is the question” to “help manage risk”
- Brief biased review of monitoring applications over past 20 years
- Some brief cases to illustrate key points
- Key components for successful monitoring
- Challenges
- Expanding the market for monitoring services
- Delivering with new technologies
- Champions
- Close

Recognition from the US civil engineering profession

Distinguished Membership in the American Society of Civil Engineers "for pre-eminent leadership in the field of geotechnical instrumentation and monitoring and for his long and distinguished career as a specialty consultant dedicated to the improvement of geotechnical practice."

For his contributions to education about instrumentation and monitoring through teaching more than 100 continuing education courses in geotechnical instrumentation and authoring three books including the famous Red Book – **Geotechnical Instrumentation for Monitoring Field Performance**

From John... via his many short courses in US and Europe

- Define the geotechnical questions that need to be answered
- Every instrument should have a clearly defined purpose
- Use a systematic approach to every instrumentation program

  See paper by Dunnicliff in Proceedings of the 5th International Symposium on Field Measurements in Geomechanics, FMGM (Singapore) 1999
- The people having the greatest interest in the answers to these questions should have a significant involvement in the monitoring.
- Geotechnical instrumentation and monitoring should be procured as a professional services contract with qualified entities, rather than a lowest-bid construction item.

  See paper by Dunnicliff and Powderham (2001) GIN 19:3.

What are some important questions?

- Is the facility performing as expected?
- Are the current conditions safe?
- Is an emergency condition developing?
- Is a critical failure mode likely to develop?
- Are the existing conditions deteriorating and if yes, when might these conditions become unsafe?
- Why are the emerging conditions developing?
- Will the structure remain safe for future changes in loads, geometry, properties)?
- What actions should or can be taken to preserve or restore the safety of the facility?
- What remedial actions might be effective?

Uncertainties and Unknowns are Sources of all Risks

- Known knowns – what we know we know
- Known unknowns –what we know to be unknown
- Unknown unknowns – what we don't know

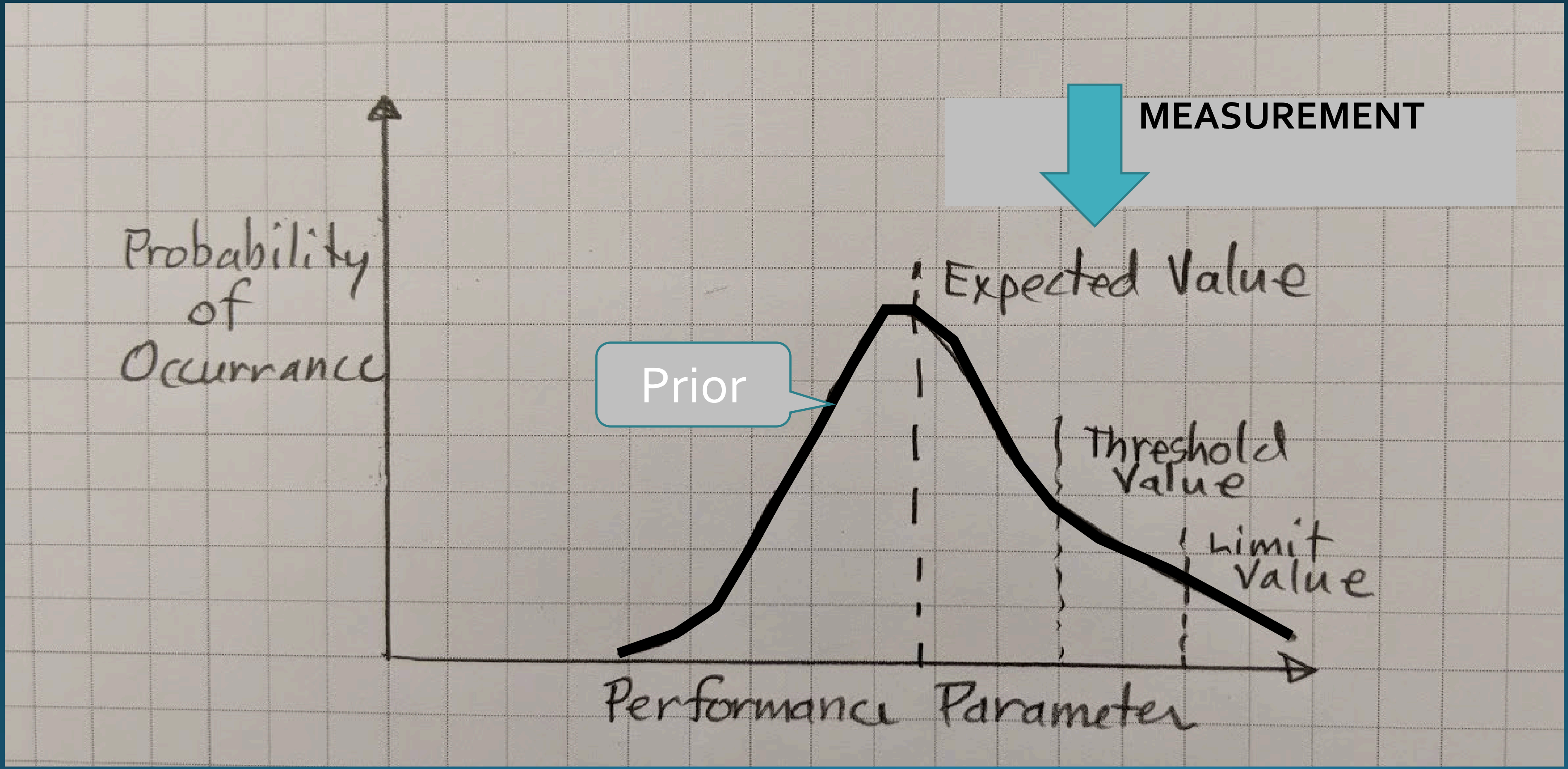
} Rumsfeld's risk characterizations

- Missed knowns – what is known but we missed (errors and omissions)
- Unknown knowns – what others know but we fail to acknowledge (defective judgment)

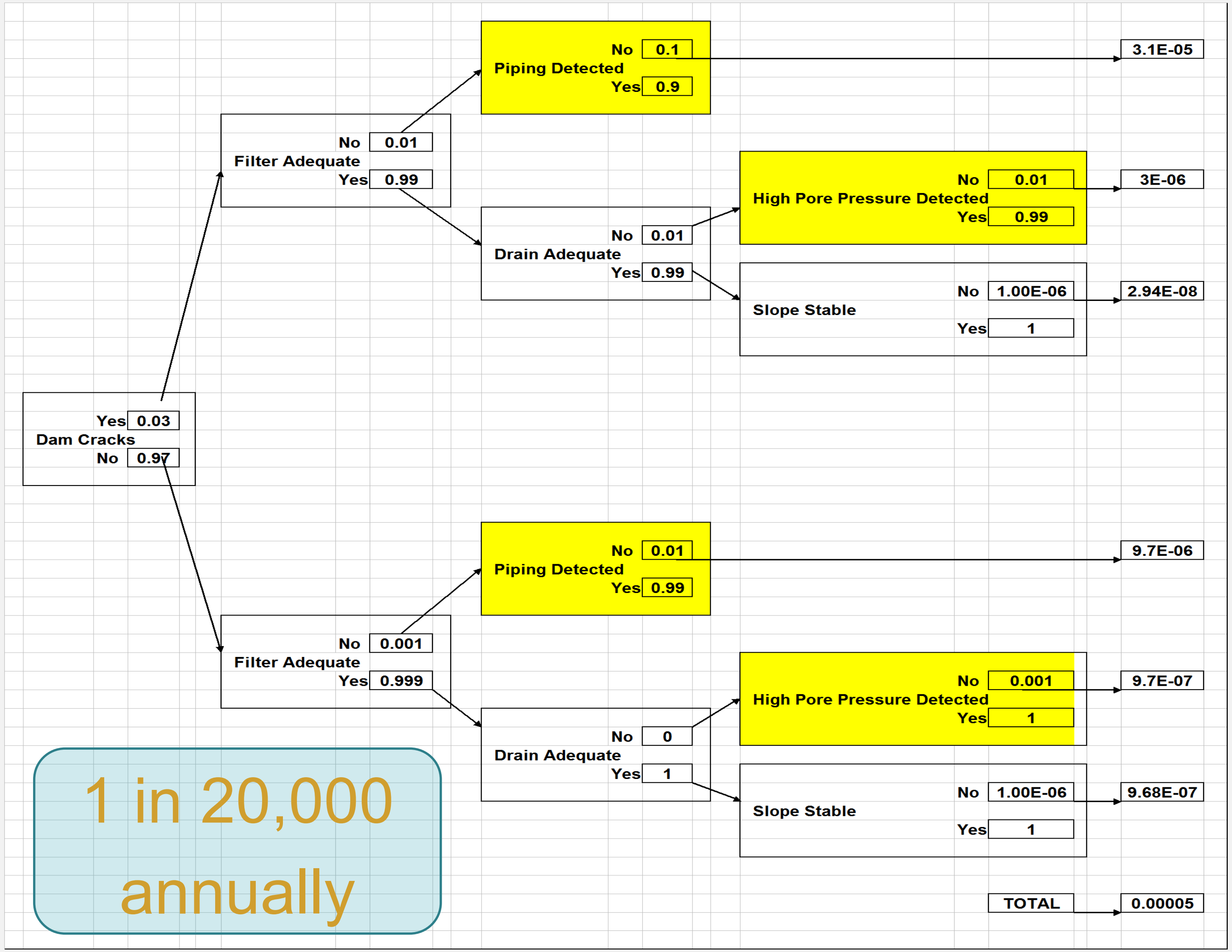
Too expensive to instrument every structure to reduce these unknowns.

Measurements can reveal performance from these unknowns that might be important to the facility even before we know much about their existence.

Effective monitoring reduces uncertainty



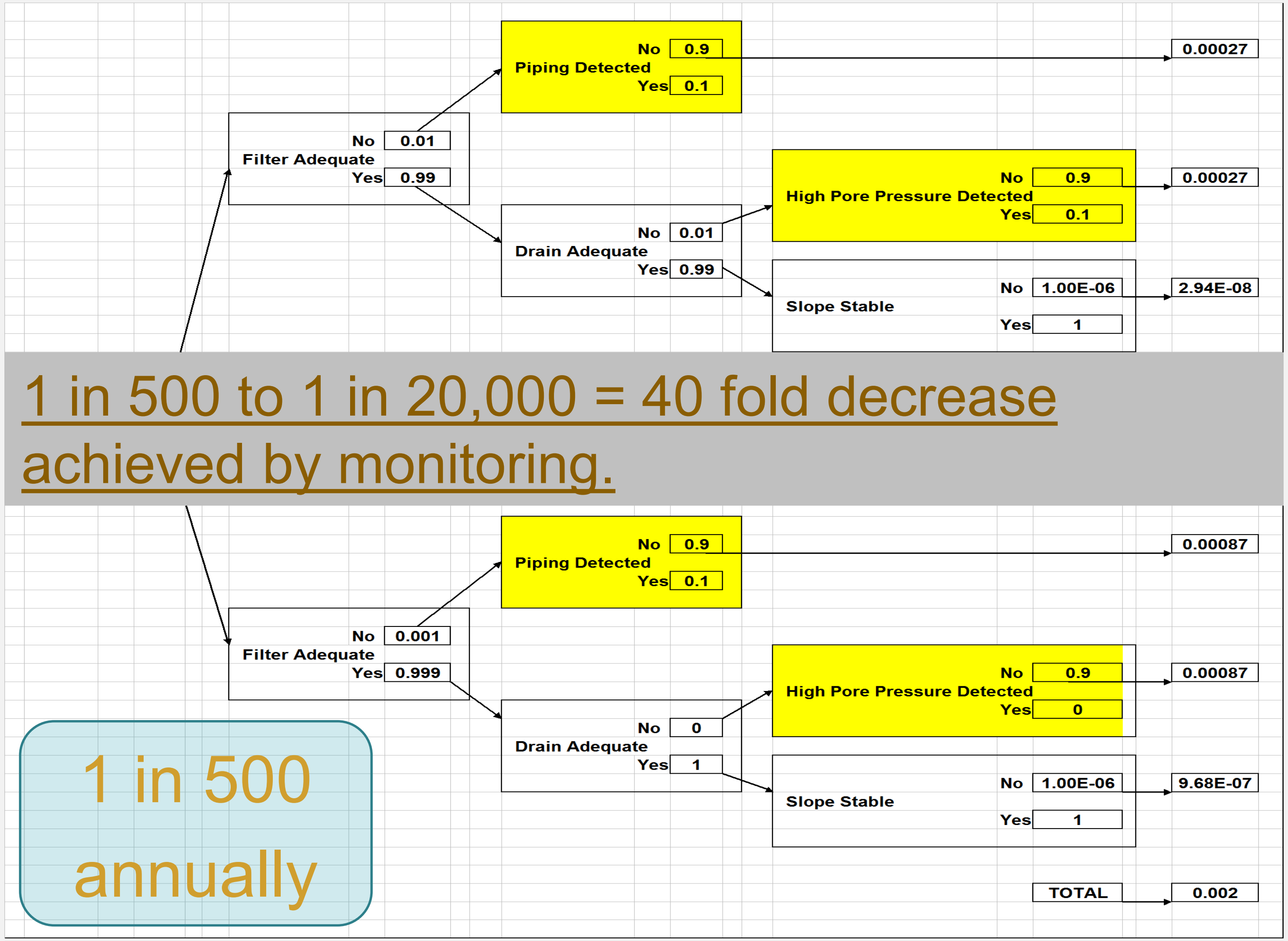
Proof Points of Risk Reduction by I-M-M Dam Failure by Cracking



1 in 20,000 annually

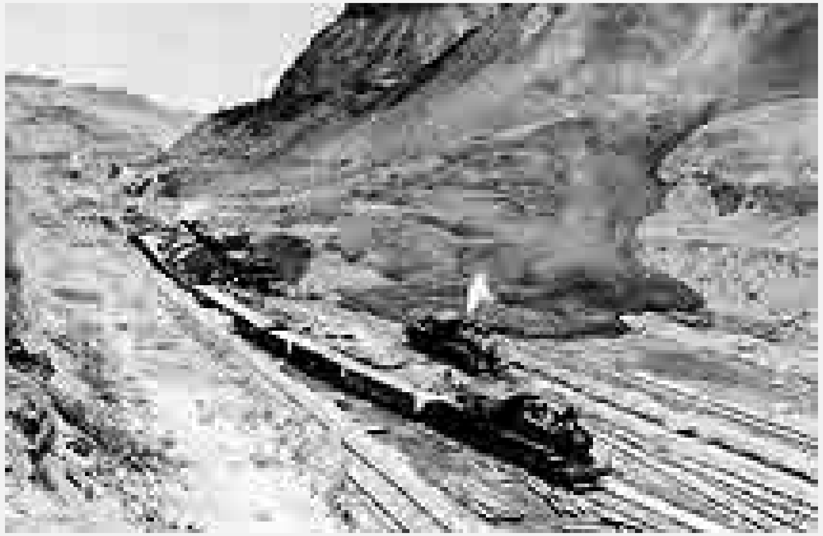
Earth Dam with good, conservative practice, Whitman, 1984

Proof Points of Risk Reduction by I&M Dam Failure by Cracking
(Whitman 1984, Poor Monitoring)



Earth Dam with good, conservative practice, Whitman, 1984 – poor monitoring

Proof Points of Risk Reduction by I-M-M

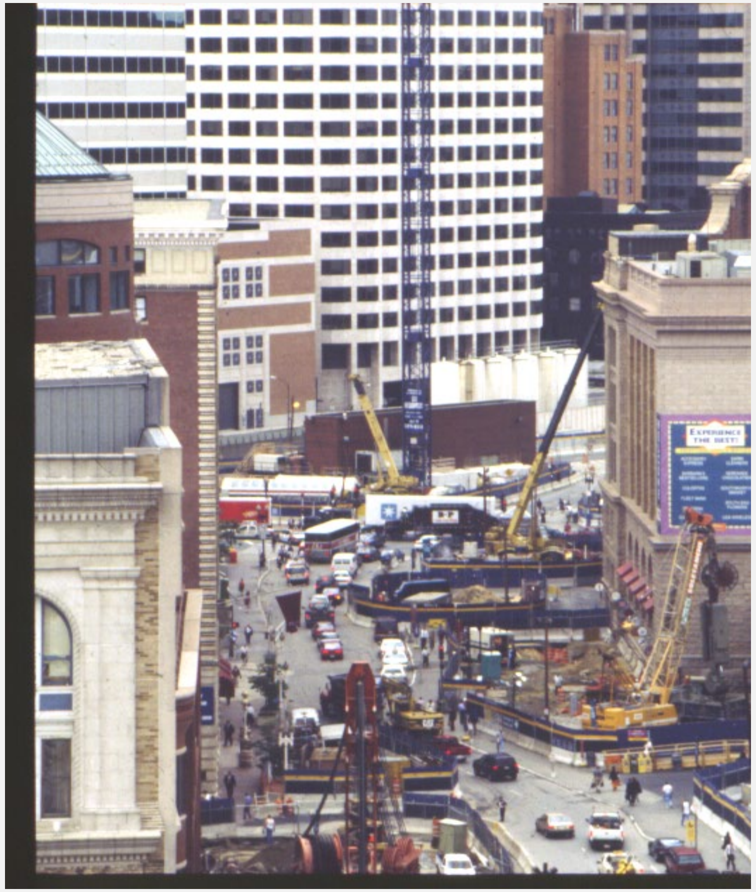


Panama Canal Landslide Control Program

- Landslide Control Program consists of visual inspections, instrumentation and monitoring and proactive stabilization activities whenever slope instability is first indicated.
- Landslide Control Program has reduced the probability of slope instability on the Panama Canal by roughly <u>one order of magnitude</u>.
- With additional I-M-M measures may be able to reduce by another order of magnitude.

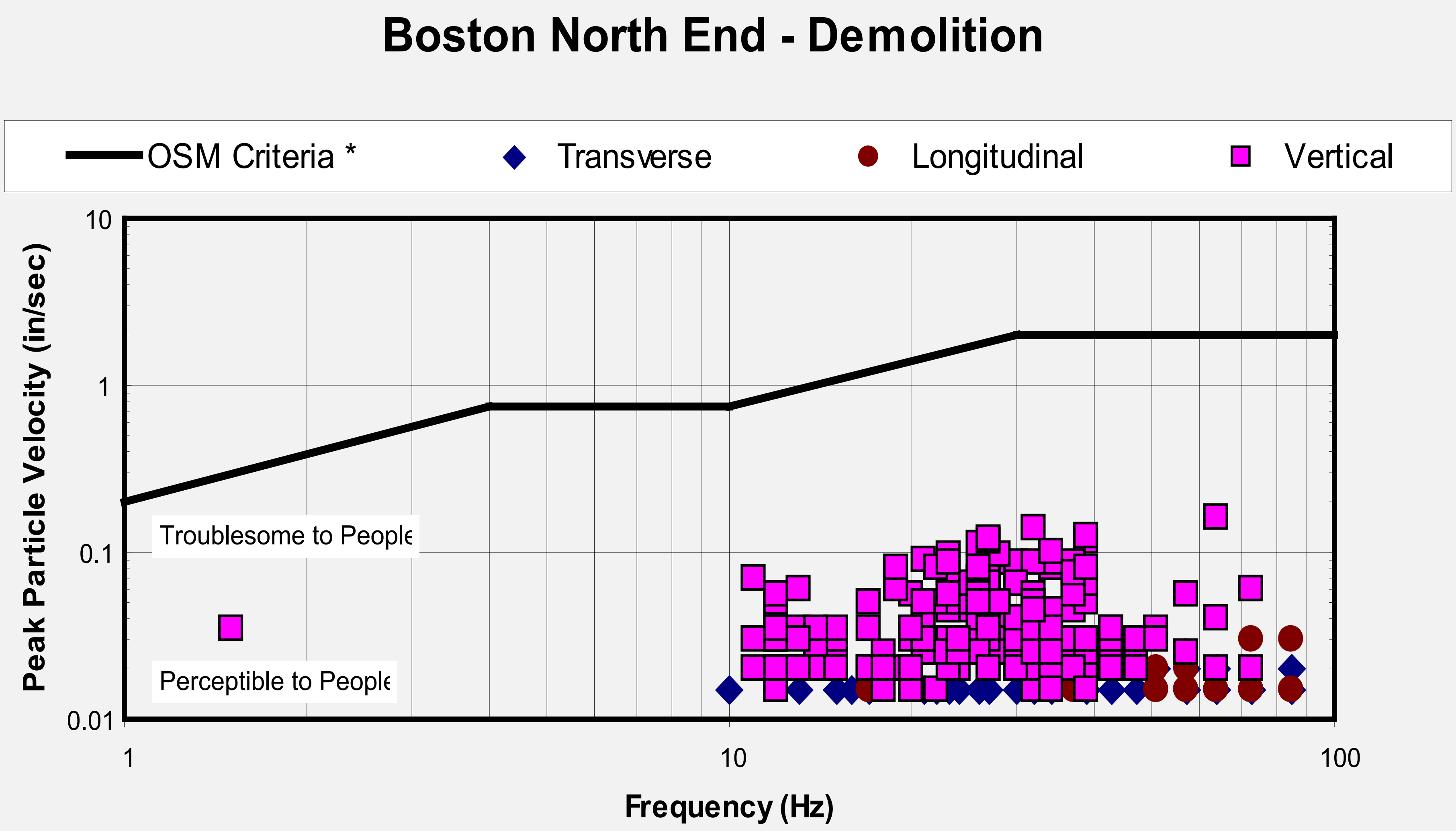
With permission from Luis D. Alfaro of the Panama Canal (1988 document)

Boston's "Big Dig" –
Protecting Adjacent Structures and Minimizing Litigation



- Horizontal movement
- > ¾" triggered review
- >1.5" stopped work

Vibration Monitoring –
Communicate to Stakeholders that we are meeting project commitments



Summary of Risk Cost Analysis – Protecting 150 Structures

Table 5: Summary of Risk Cost Analysis for CA/T

Outcome	Consequence	Probability of Occurrence without Monitoring	Risk Cost
Collapse	$5B	.03	~$150M
Major damage and disruption	$700 M	0.3	~$200M
Construction delays from unexpected performance	$500 M	0.2	~$100M
Architectural to structural damage	$100M	~1	~$100M
		Total:	$550,000,000

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CA/T Instrumentation Program (Marr, 2007)

- Estimate of risk without monitoring = $550 million plus potential for significant loss of life and injury.
- At completion of construction amount paid for repairs of damages = $9M
- Total cost of monitoring program = $60M
- Monitoring program potentially saved the project $500M in avoided risk costs.

KEY MESSAGE

Effective performance monitoring can reduce geotechnical risks by one to two orders of magnitude (10 to 100 times)

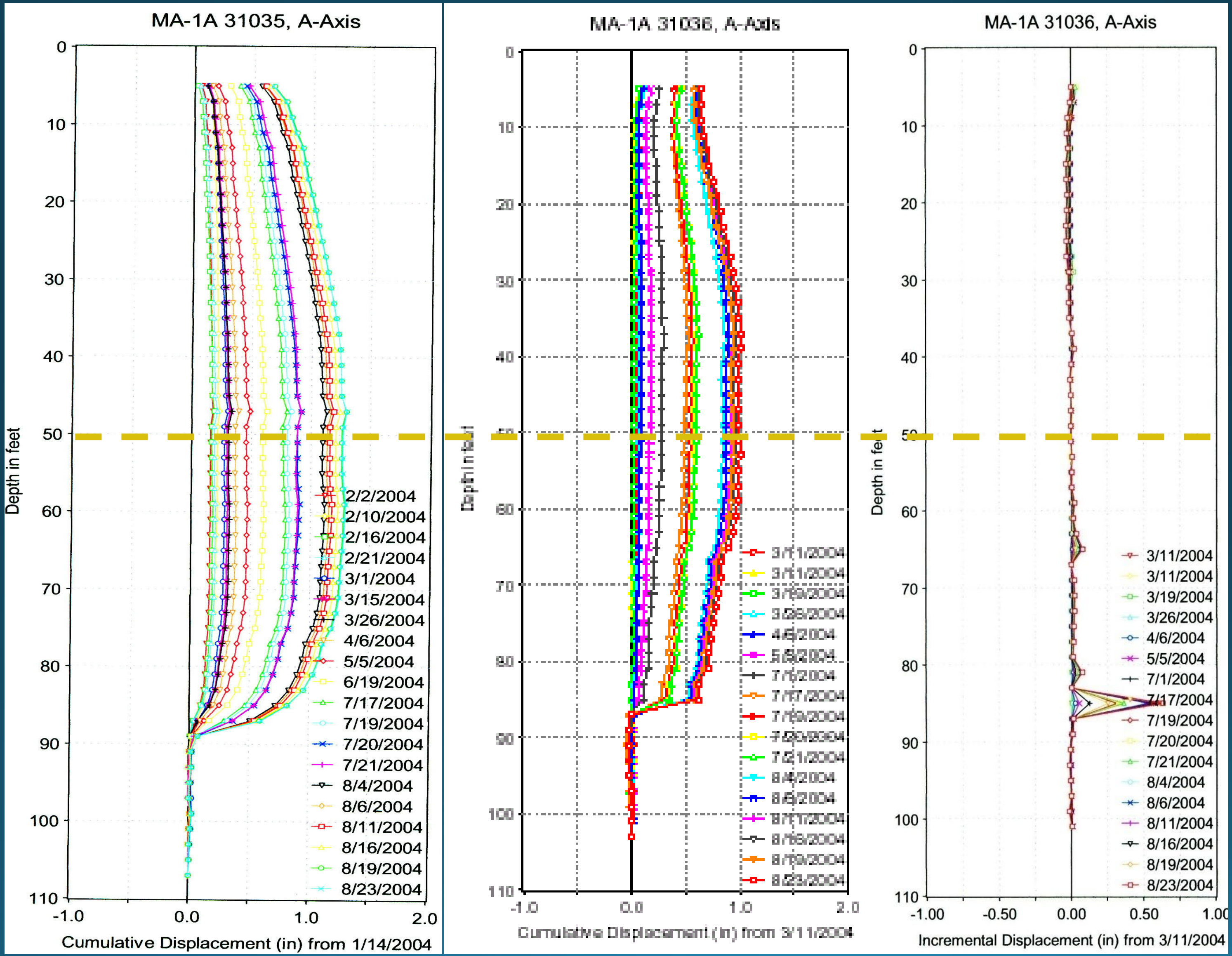
Performance monitoring can be very cost effective.

Woodrow Wilson Bridge

prove high strength geogrid is providing needed stability

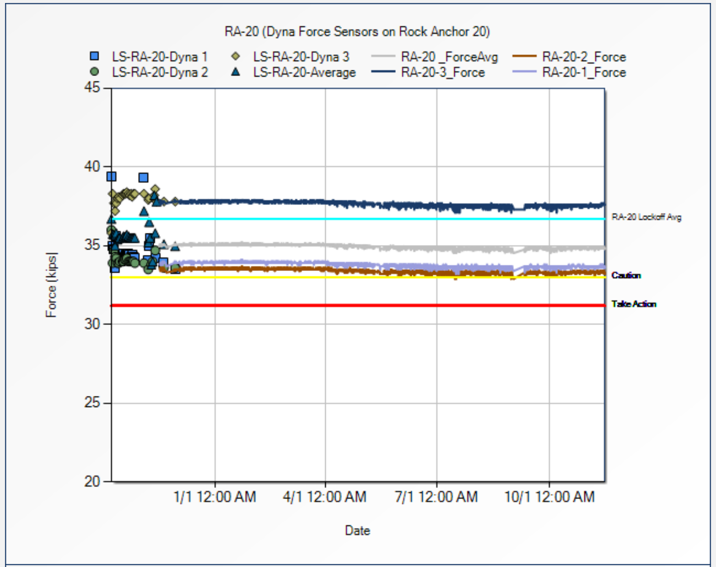
Woodrow Wilson Bridge

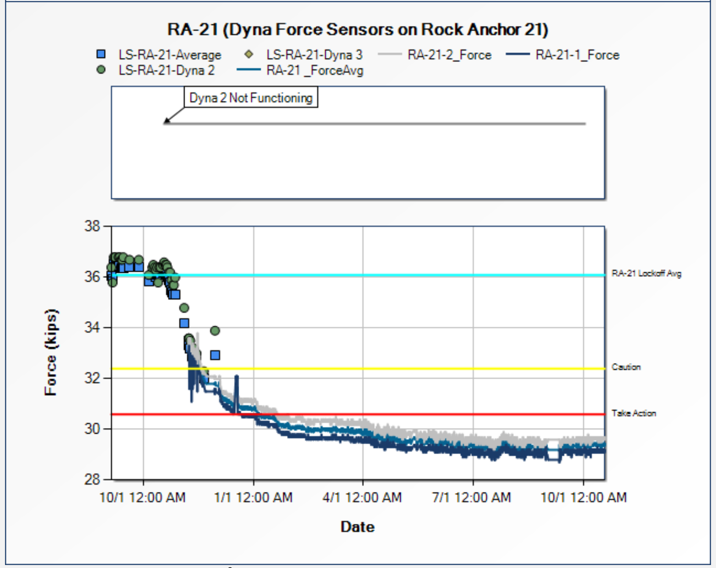
Inclinometer into foundation to detect if instability at reinforcement level



Willow Island Low Head Hydro Plant

protect existing dam structure from damage during construction





Monitoring to confirm design and manage construction sequencing

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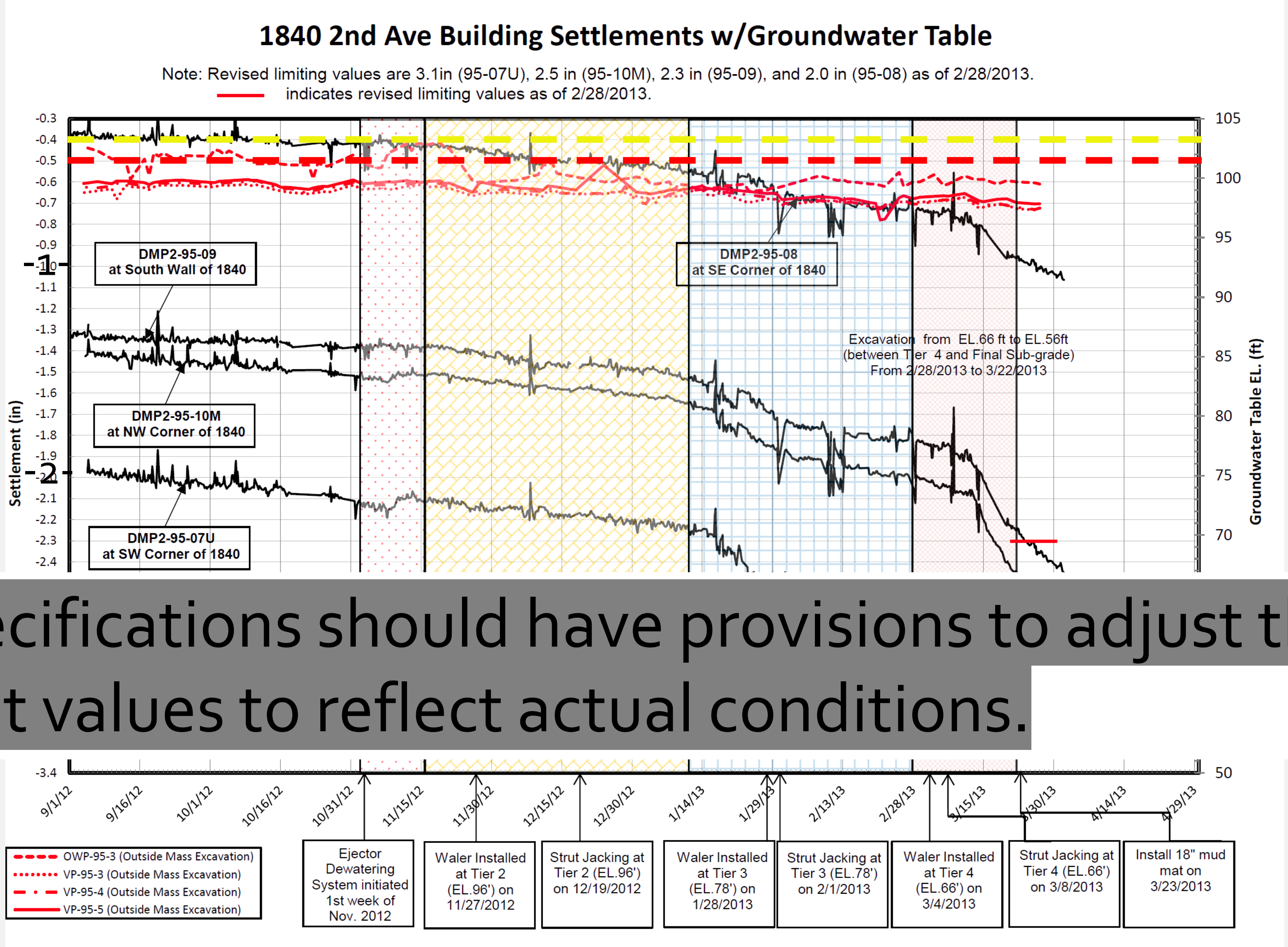
2nd Ave Subway - New York City

Protect adjacent structures during construction off deep excavations

2nd Ave Subway - New York City
Protect adjacent structures during construction off deep excavations



Specifications should have provisions to adjust the limit values to reflect actual conditions.

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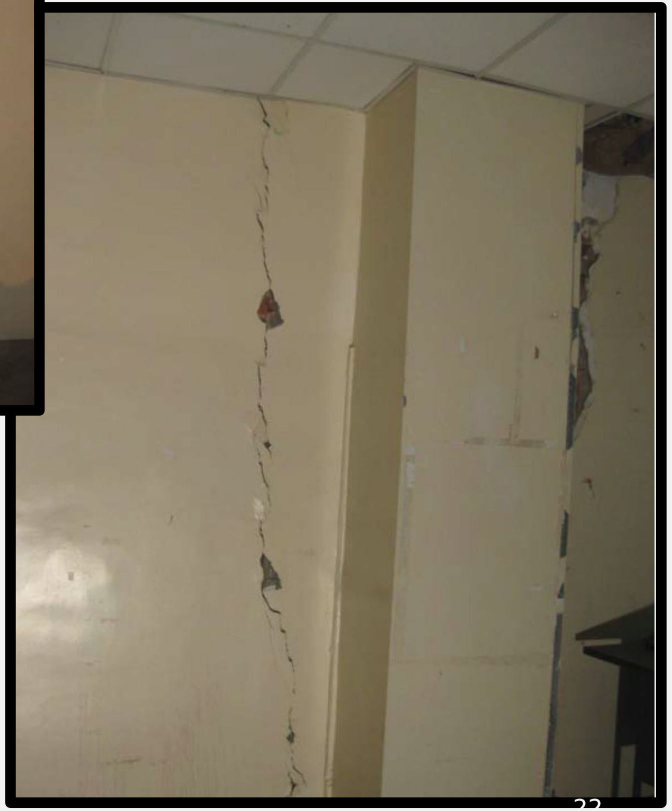
2nd Ave Subway - New York City

Protect adjacent structures during construction off deep excavations



Sakonnet River Bridge Replacement – Rhode Island

Protect old bridge from damage during new construction

Total station – mounting enclosure with solar engine adjacent to unused railway

dGPS station – GPS, spread-spectrum radio, solar engine

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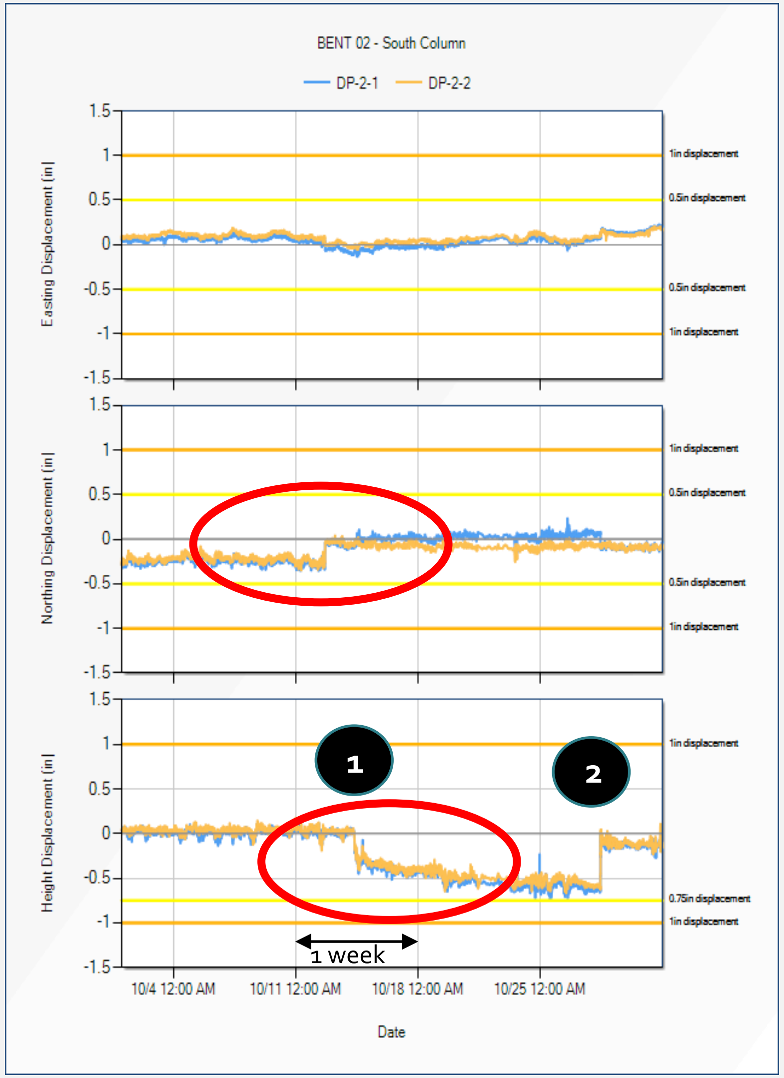
Sakonnet River Bridge Replacement – Rhode Island

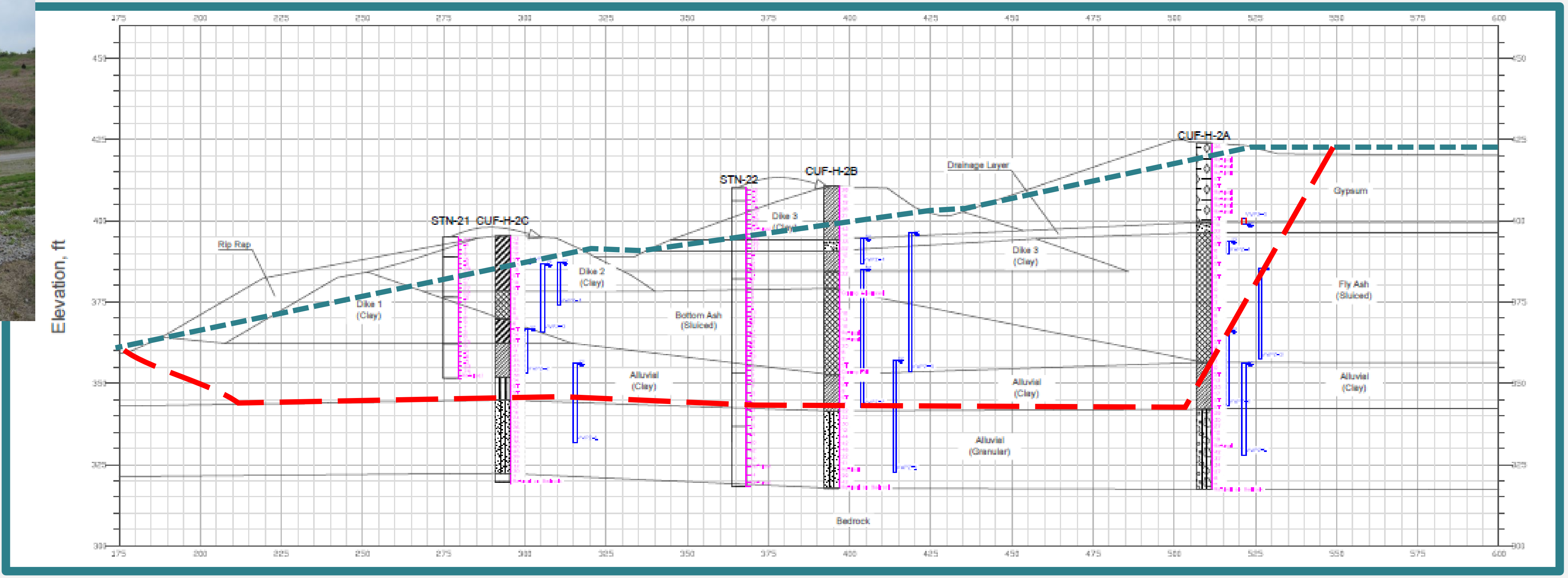
AMTS data showing settlement of Bent 2 South Column during sheet piling



Cause for Alarm:

- Driving sheet piling within 15' of existing Bent 2 South Column
- AMTS data taken every 5-15 min showed settlement of column reaching 0.5"
- Bridge jacked back into place
- Strain gauges on structure showed no damage.

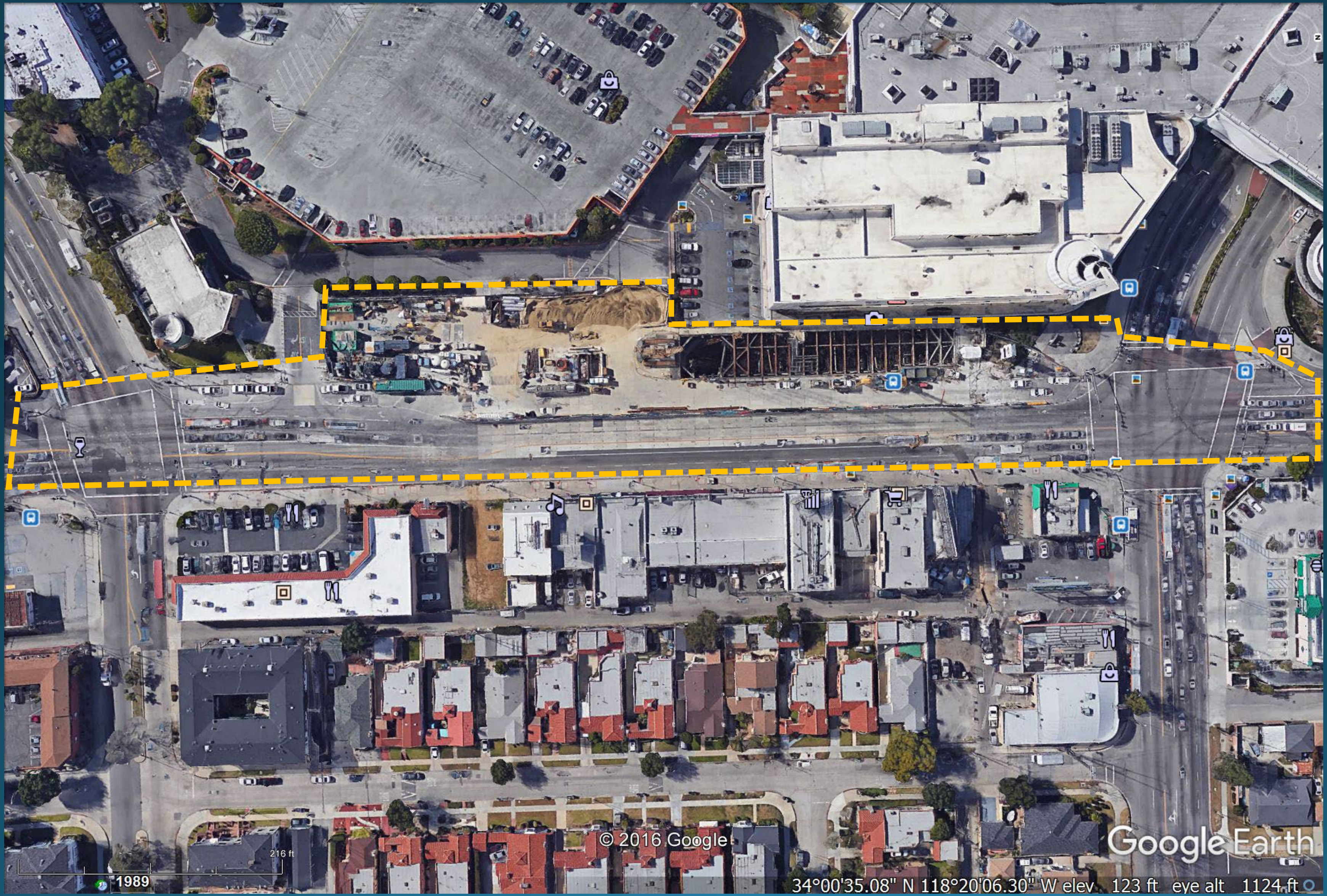
Determine Baseline conditions for stability assessment:
Using Monitoring data to reduce unnecessary conservatism



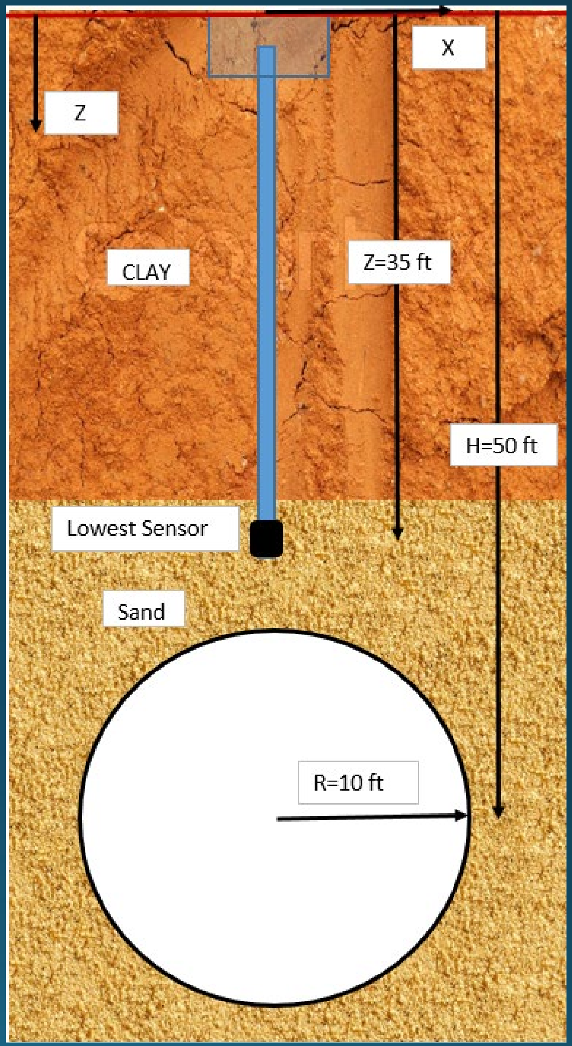
With measured pore pressures, calculated FS increased from 1.2 to 1.5.
Problem went away saving > $10,000,000 in unnecessary buttressing.
Automating monitoring allowed client to reassign 9 full-time people and get monitoring every 15 minutes on 5000 instruments.

LA Metro Crenshaw Line – MLK Station

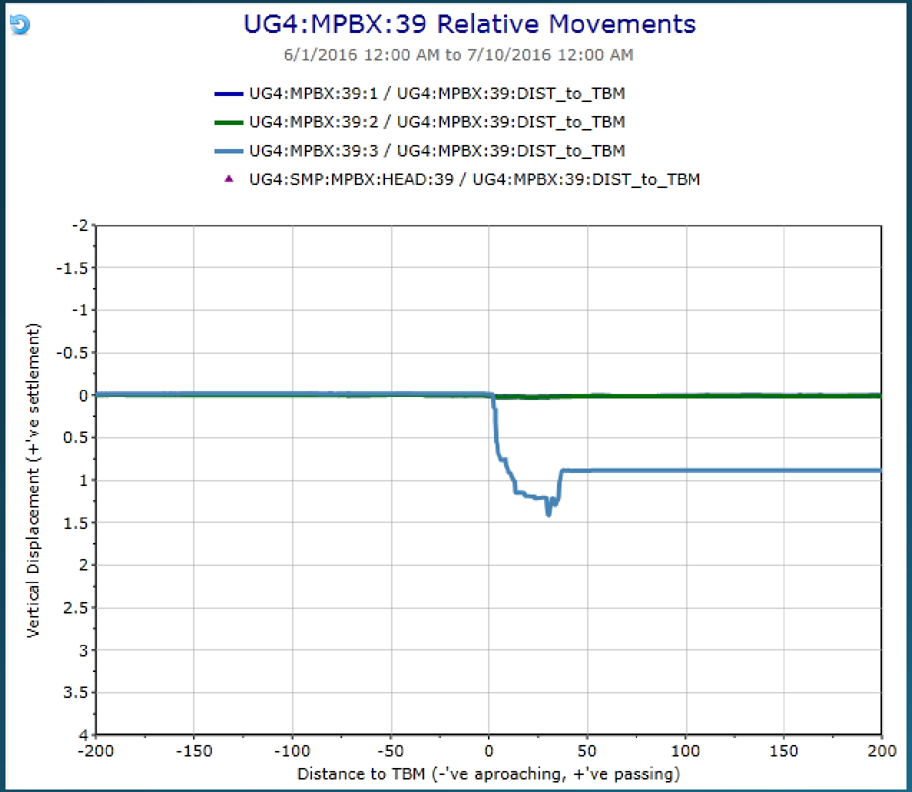
Limit effects on adjacent structures to avoid costs and delays from lawsuits.

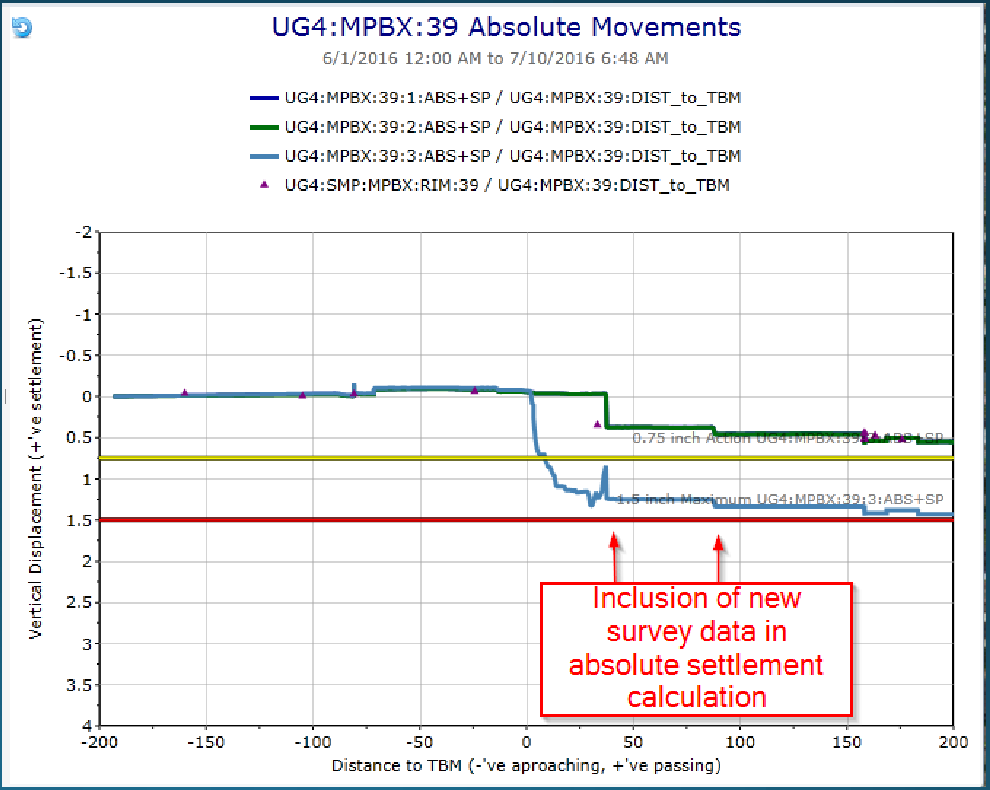


Crenshaw TBM - Harriet

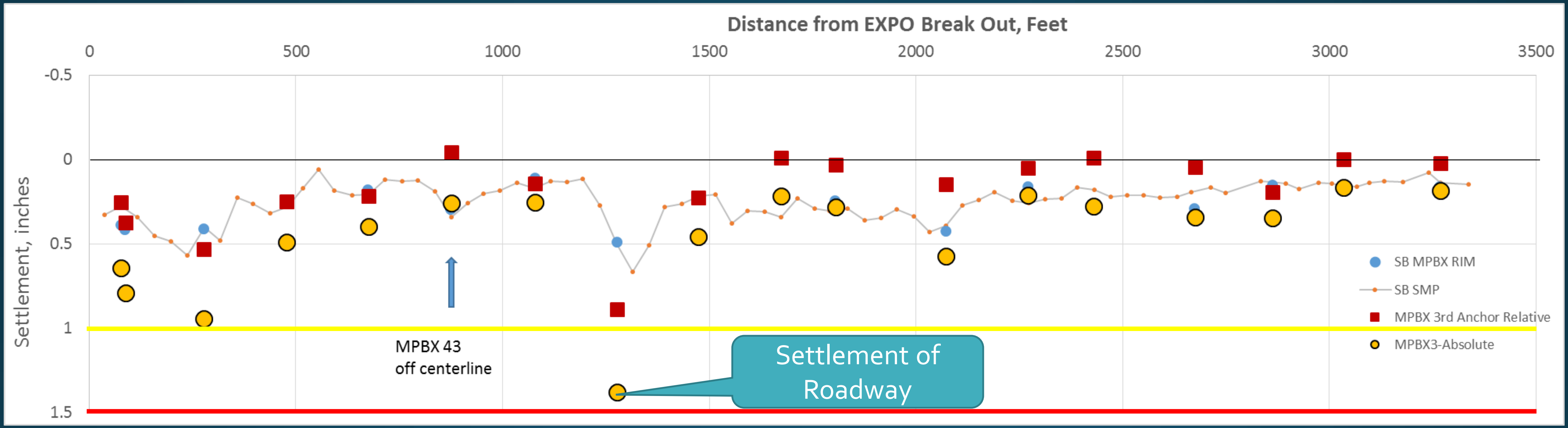


Control settlement of ground above tunnel crown to limit damage





Settlement above TBM with tunnel advance



Note the clear trend of decreasing ground settlements with time as TBM procedures are improved.

Settlement during station excavation

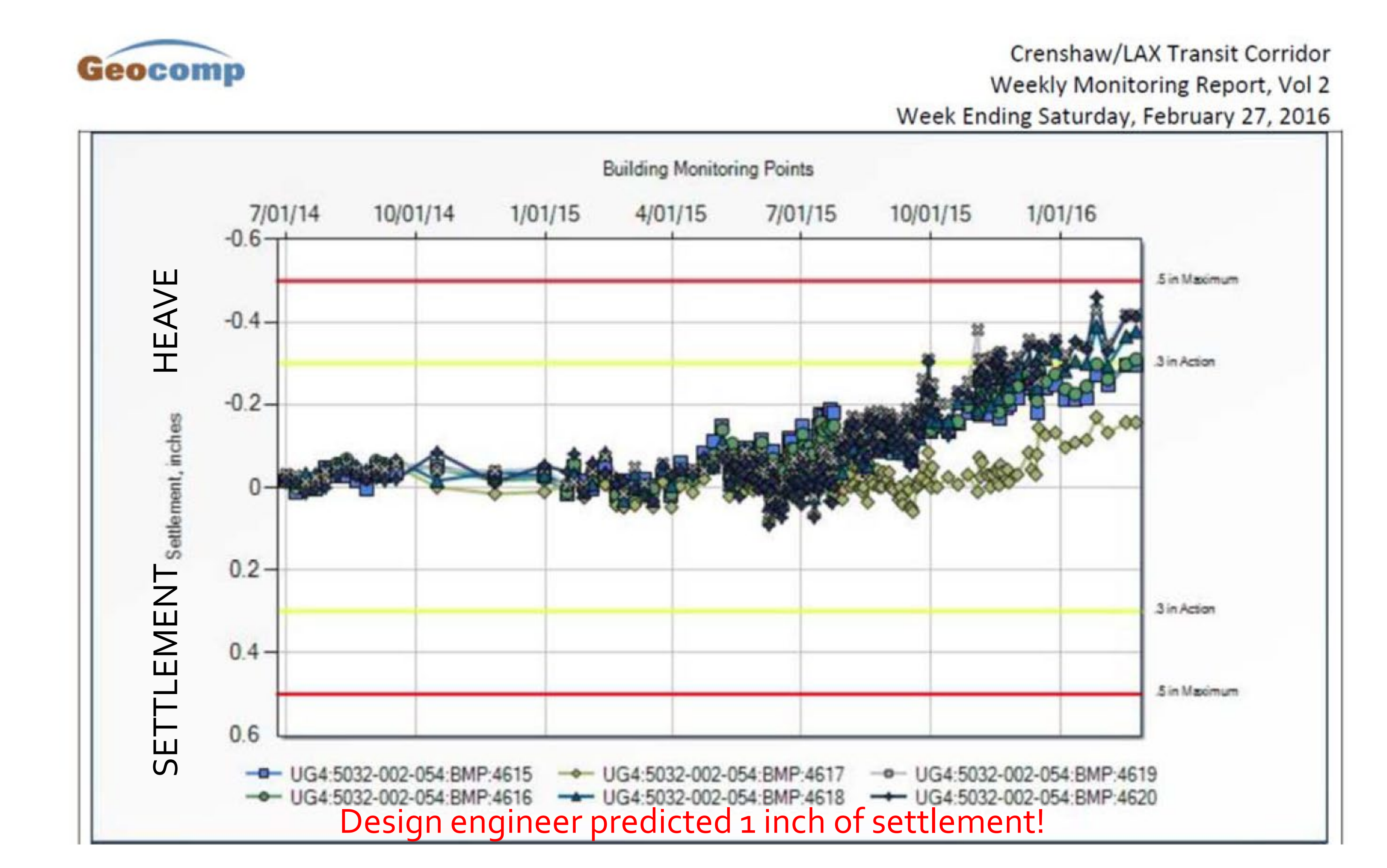


Figure 2: Heave measured at Points 4615 to 4620

Landslide on New Highway in Mountainous Area

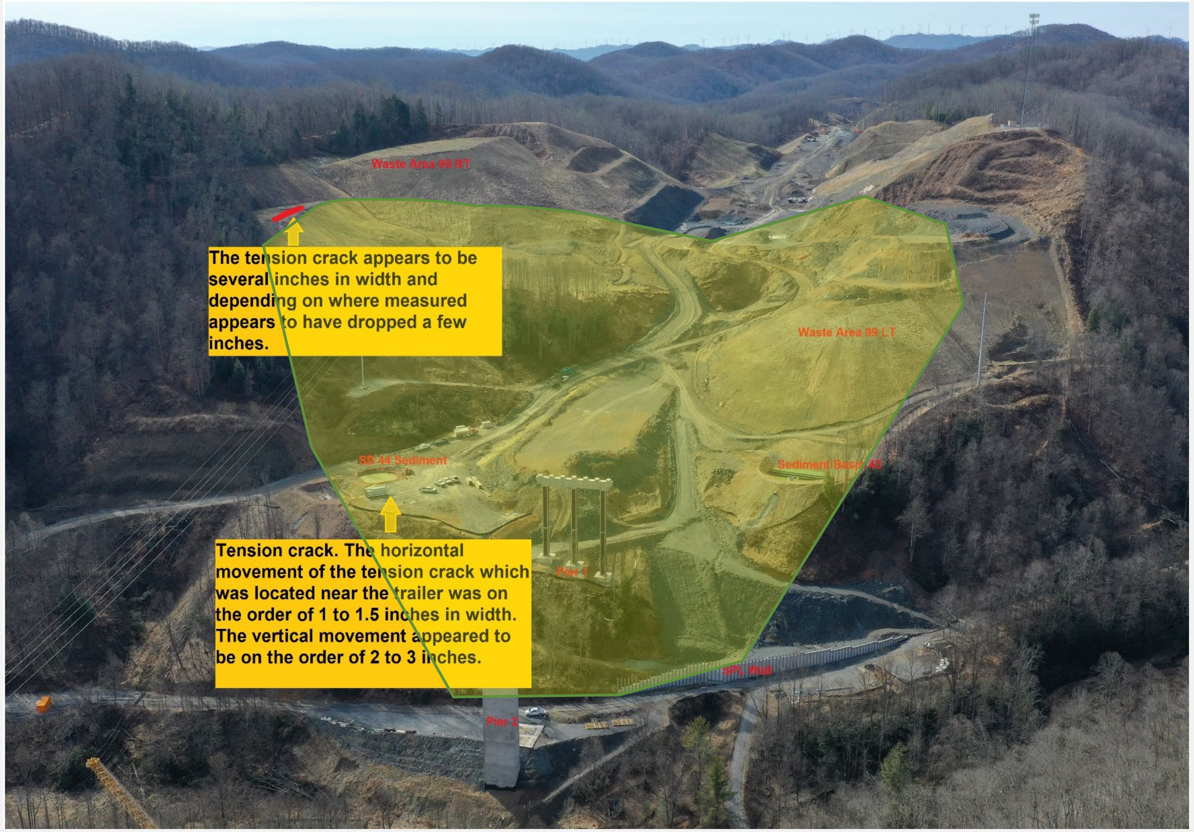
Why is newly constructed bridge pier out of position?

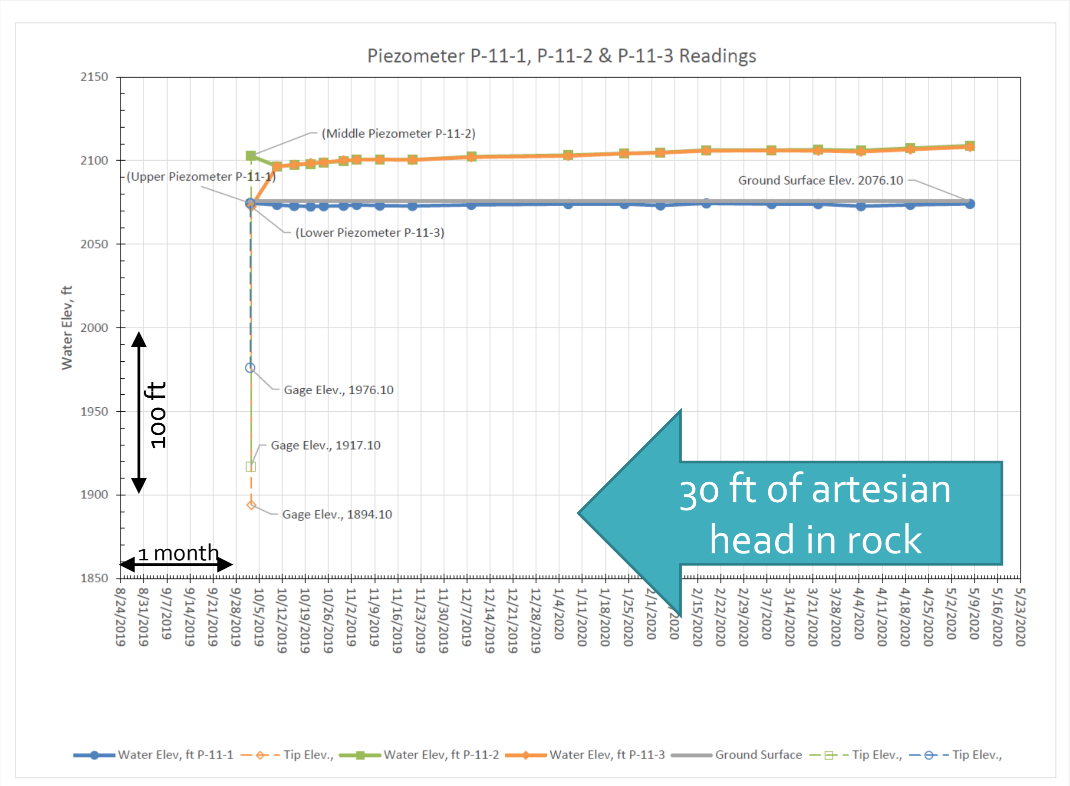
Major cut and fill with construction of bridge piers.

Pier found to be 12" out of position.

Contact borings show dry holes.

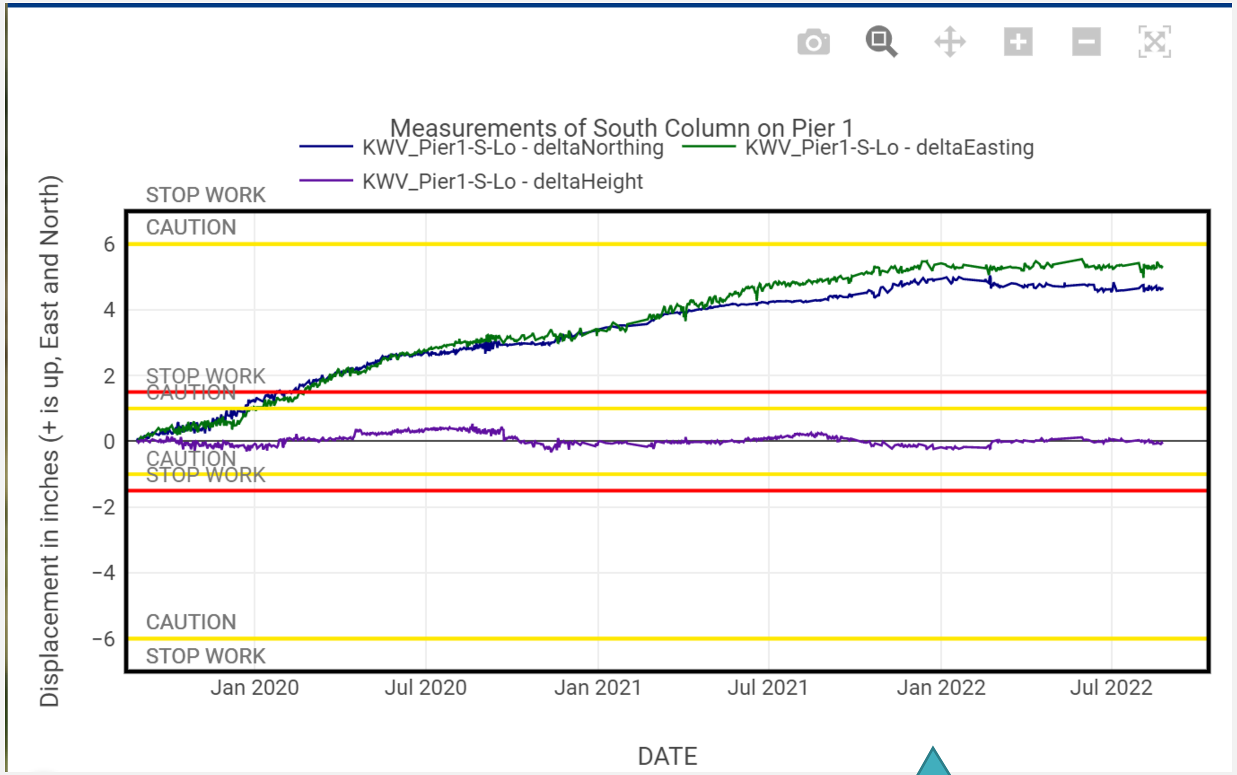
Piezometers showed artesian pressures.





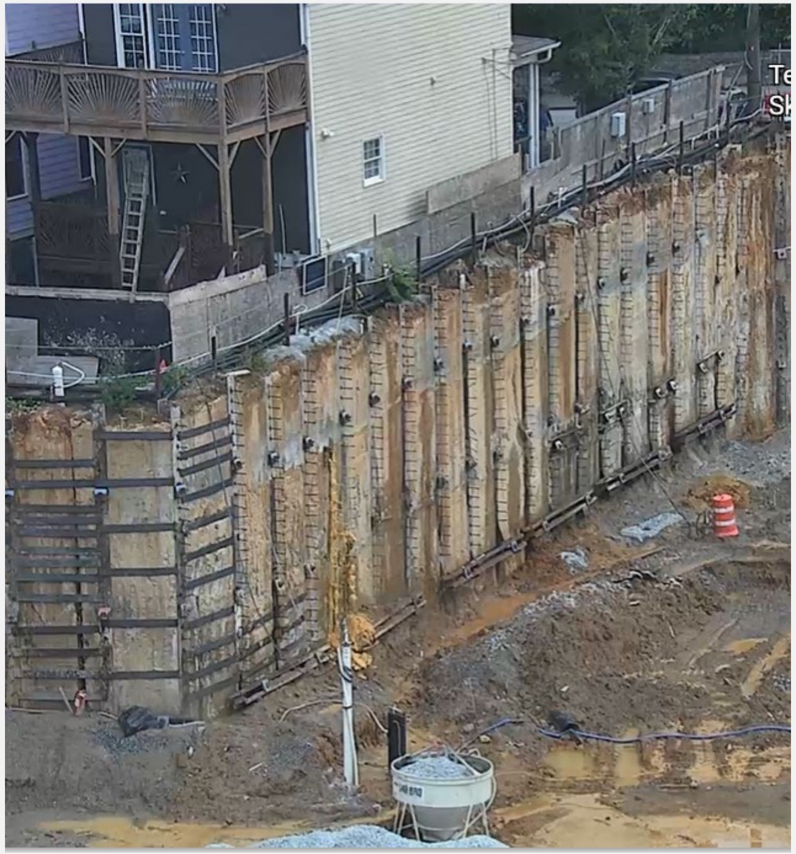
Instrumentation Showed Drainage was Essential to Stabilize

200 gpm (1,100 m^3/day) for all drains after rain



Horizontal Drains completed

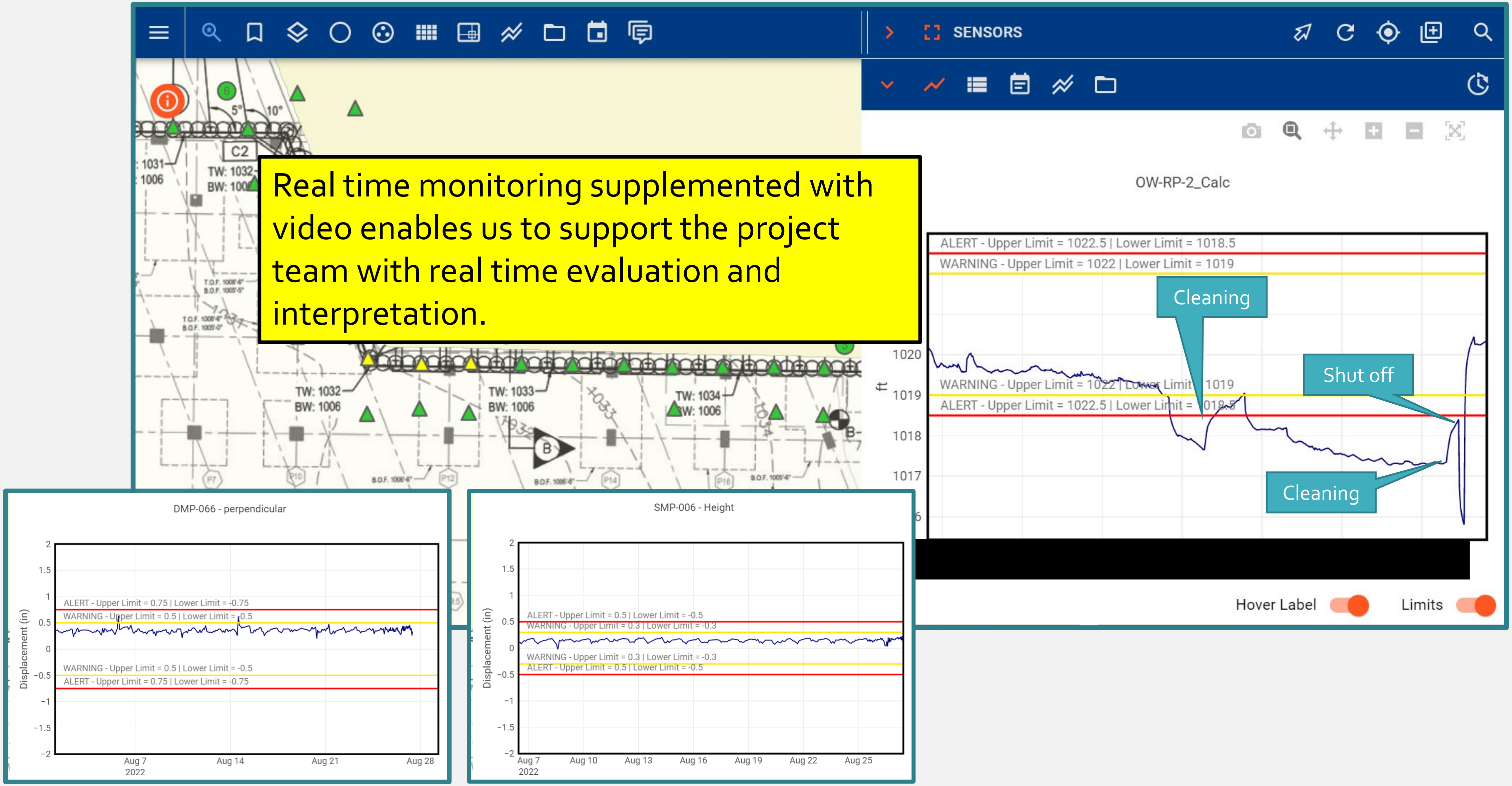
Real-time monitoring helps monitor for emerging risks during construction



Remote video in real time with Pan-Zoom-Tilt enhances the visual surveillance component of Monitoring

Real-Time Monitoring to Inform Construction on the Fly

Real time monitoring supplemented with video enables us to support the project team with real time evaluation and interpretation.



KEY MESSAGE

Monitoring delivers value in
improved safety,
saved time,
saved money,
and/or reduced risk.

We need to develop and execute every monitoring project with these objectives in mind, then document the value provided.

Some Key Components of Monitoring

- Visually surveilling
- Putting appropriate and reliable instruments in the right places
- Collecting data
- Evaluating data
- Interpreting data
- Communicating results and their meaning
- Acting when indicated with appropriate speed

Visual surveillance

- Human eye
  - Peck said the most valuable instrument is the human eye connected to a working brain
- Mounted remote PTZ Video Cameras
- Drones with camera and positioning software

Key Requirement: Data Must be Evaluated and Interpreted

Evaluate

(identify and remove invalid data)

- Are the data correct and believable?
- Is the information valid and complete?
- Are more data needed?
- What steps are needed in improve quality of the data?

Interpret

(what actions are needed)

- What do the data mean?
- What is the cause and effect?
- What are the implications of the data?
- What actions are required?

These tasks can take considerable time and require well-trained people.
Can AI and ML technologies help us without giving off false alarms?

Needs for improvement in our monitoring programs

- Reduce uncertainties, glitches and false alarms
- Deliver more results in ways that provide more value (believable, to be trusted, understandable, actionable)
- Go beyond green, yellow, red to predictive assessments
- Capture, explain and broadcast the value statements for monitoring projects

Challenges: Hinderances to Better I&M Projects

- No clear purpose given
  - Client or Contractor doesn't see the value
  - Instrumentation sub doesn't have a clear objective
- Poor contract terms
- Inadequate specifications
- Poor or inappropriate design
- Poor planning
- Poor implementation of best laid plans
- Inexperienced instrumentation team
- Insufficient evaluation of the data before it is passed for interpretation
- Incorrect or incomplete interpretation of the data
- No value generated or demonstrated
- No champion for continuance of good monitoring and drive for success
- Unrealistic expectations leading to disappointments and wrong assessments
- Erroneous beliefs prevent adoptions of better solutions

Embedded Opinions we need to overcome

- I&M is expensive to procure and install
- Instruments don’t work reliably
- Systems require a lot of maintenance and have an unknown life
- Too much data
- People don’t understand or know how to use the data
- Insufficient resources to monitor and maintain
- Equipment prone to damage and vandalism
- Inexplicable changes in the data diminish believability
- Setting limit values (threshold limits and alarm limits) is challenging and can’t be trusted if they are changed.

A sobering observation……..

Brumadinho Dam B I VALE Expert Panel Final Report

The failure is also unique in that it occurred with no apparent signs of distress prior to failure. High quality video from a drone flown over Dam I only seven days prior to the failure also showed no signs of distress. The dam was extensively monitored using a combination of survey monuments along the crest of the dam, inclinometers to measure internal deformations, ground-based radar to monitor surface deformations of the face of the dam, and piezometers to measure changes in internal water levels, among other instruments. None of these methods detected any significant deformations or changes prior to failure.

What does this case say about the value of monitoring?

Increasing the market for I&M services

- Deliver value
- Demonstrate and communicate value
- Deploy new technologies when they work and provide value.
- Develop broader applications for our work

Delivering Value

- Set realistic client expectations and deliver on those.
- Integrate design, construction and monitoring teams for interpretation and contingency works.
- Under promise and overdeliver
- Recognize that schedule and cost are big drivers in our industry that we cannot avoid – how to manage expectations and still deliver a qualify service that adds value within the project constraints.
- Determine value added and develop value added statements:
  - The monitoring program saved the project xxx.
  - The monitoring program helped avoid a collapse, which if it had happened would have delayed the project xxxx months.
  - Data from the monitoring program helped validate a design change that saved xxx months and yyy dollars.
- Communicate value added in meaningful terms to the client and to the business community.

How to Deliver Value

- Use a systematic approach to obtain reliable systems.
- Add redundancy for the most important measurements.
- Employ designs with components that don’t fail or at least help identify and fix failed points quickly.
- Keep clarity on differences between evaluating and interpreting the data, who is responsible for each.
- Use methods to minimize questionable data and false alarms.
- Track the data incidents , summarize experiences, develop continuous improvements and synthesize value statements as the project progresses.

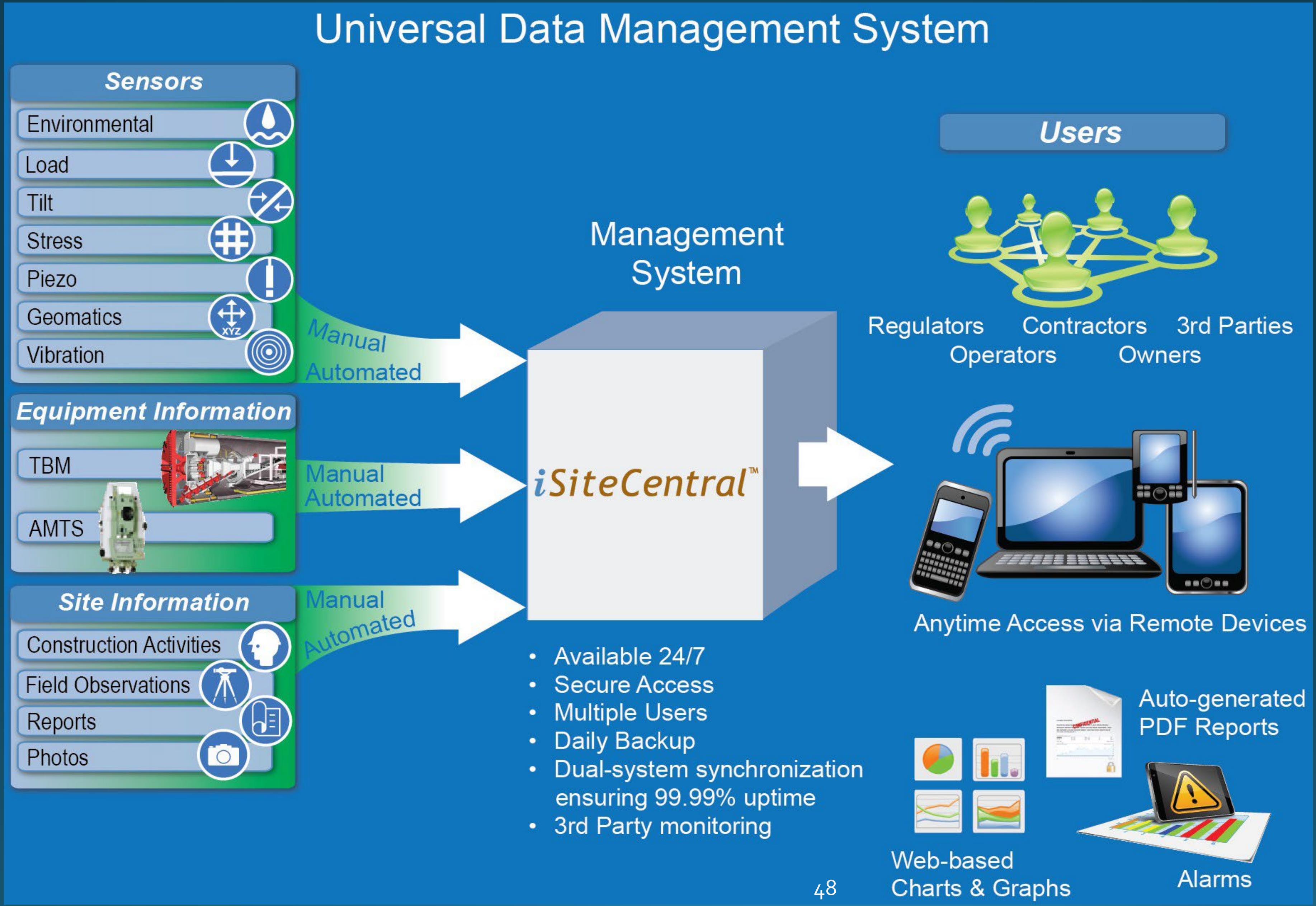
KEY MESSAGE:

We can improve our future by creating more value from Monitoring services, prove the value generated and tell the story often.

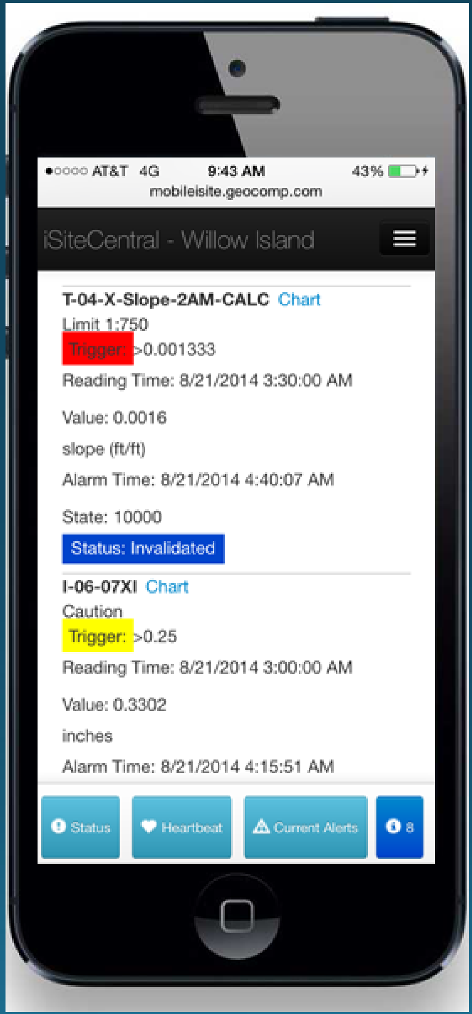
Expand the market

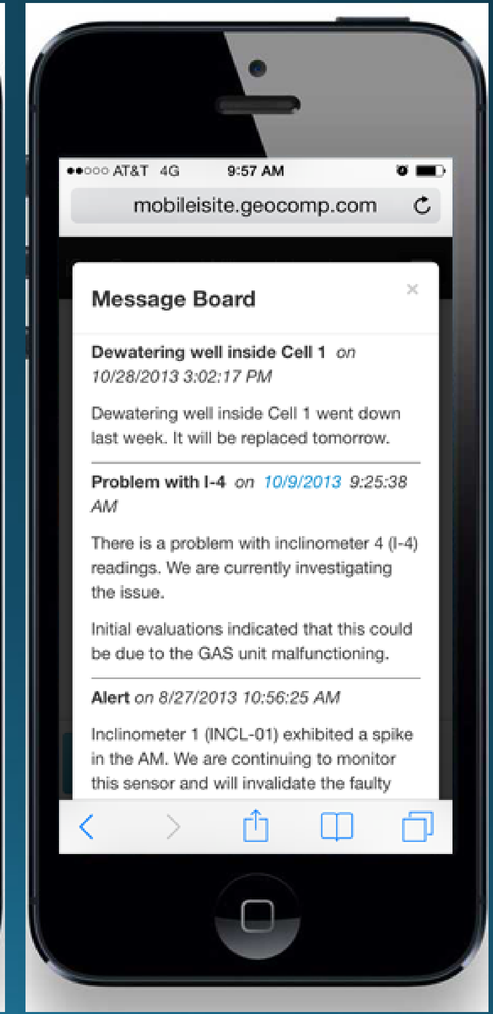
- Make every project a success story of value generated and delivered.
- Make monitoring an integrated part of risk management
- Use appropriate technologies to enhance value generation
  - INSAR
  - LIDAR
  - DFOS
- Add context to data from measurements
- Work monitoring into an acceptable part of Asset Management
- Use monitoring to deliver Structural Life Extension to existing assets
- Use monitoring to validate, calibrate and update Digital Twins
- Communicate more broadly in layman's terms the benefits and values for monitoring.

Integrating data and context



Mobile Apps for data collection, consumption, diagnostics and action





Interpreting and Communicating results in near Real-Time Monitoring Add greatly to the value monitoring can deliver

Design and Installation

Deformations, strains, stresses, forces, water pressures, water flows, weather, vibrations, surface geometry changes, video

Sensor selection and installation procedures

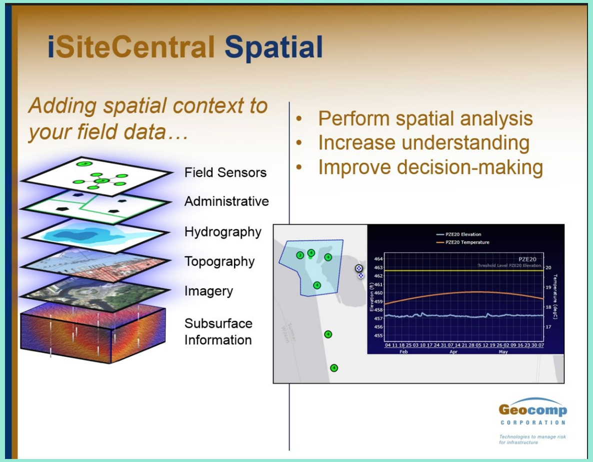
Installation oversite

DATA MANAGEMENT

Real-time collection and processing of data and related context information.

Powerful data bases that store and retrieve data in a secure way and serve it up without delay

Redundant and backed up

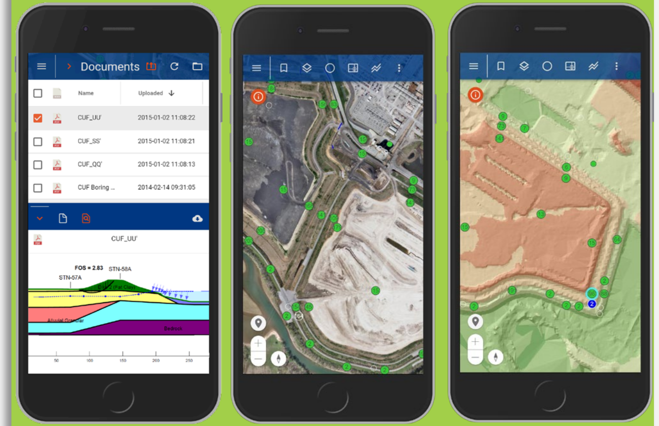


REPORTING

Real-time alert messaging of warning and exceedance states via email and personal devices.

Automated report generation with templates to customize contents.

Document repository to call up emergency procedures, contingency plans, instrumentation details, etc.



Add Risk Monitoring Column to Risk Register (1)

Risk No.	Risk Name	Description		Consequence Description	Consequence (money, time) (see Sheet 2 for	Relative Liklihood (See Sheet 2 for Scoring)	RISK INDEX	Risk Monitoring Responsibility	Emerging Indicator
1	DEWATERING WELLS								
1-7		Maximum water level is less than 5 ft below subgrade		Potential water intrusion impact in nearby area	1	3	3	DC	monitor pore pressures in soil
1-9		Loss of all pumps (loss of power)		Depending on water level, spillage could occur onsite and saturate the surround area. Upward flow could soften subgrade	2	2	4	DC	monitor power
2	SHORING WALL								
2-1		Tieback won't take up load during prestress		Time impact to potentially add additional tieback	2	2	4	WC	measurements during prestressing
2-2		Tieback lock-off slips		Time impact to re-load tieback lock-off	2	2	4	WC	visual observation
2-5		Tieback fails proof testing		Time impact to potentially add additional tieback	2	2	4	WC	measurements during proof testing
2-7		Tieback fails		Time impact to potentially add additional tieback	2	2	4	WC	visual observation
2-13		Tieback hits recharge well or monitoring Piezometer		inadequate recharge, increased risk of settlement behind the wall (recharge well). Lack of monitoring data- inability to monitor effectiveness of recharge system and/or impact of dewatering	3	2	6	WC	visual observations; monitoring system data
3	EXCAVATION								
3-1		Encounters manmade objects larger than 3 cubic yards		Time impact assess and remove object. This situation could impact the excavation schedule.	2	2	4	EC	visual observation
3-2		Excavation encounters hard stuff that can't be removed with excavator		Time impact assess and remove object. This situation could impact the excavation schedule. Contractor may need hammer drill or blast material in extreme	3	2	6	EC	visual observation
3-3		Encounters soupy soils in the hole		This situation could have a multitude of impacts depending on the location of the soupy soils. May need to mix with lime. Could have time and cost	2	3	6	EC	visual observation
3-4		Causes boiling and/or heaving of the bottom		Potential wall failure at impacted area could cause a water intrusion scenerio	2	2	4	EC	visual observation
3-5		Observe water spouts, boils, seeps or heaving up of the bottom of the excavation within 30 ft of the wall		Potential wall failure at impacted area could cause a water intrusion scenerio	2	2	4	EC	visual observation
3-6		Exposes weak section of the shoring wall		Time impact to fortify shoring wall with waler or other mechanisms would be a time impact	2	2	4	Geocomp	visual observation
3-9		Portion of ESS damaged by excavation activities		Time impact to remediate damage to wall	2	2	4	EC	visual observation
3-10		Dewatering well damaged by excavation activities		Time impact to remediate damage to well	2	3	6	EC	visual observation
3-11		Soft areas, weak areas in the subgrade after final cut		Time and cost impact to fortify weak areas of soil	2	3	6	EC	visual observation
3-12		Tearing of geocomposite before it is		Time impact to remediate damaged geocomposite	2	3	6	EC	visual observation

Add Risk Monitoring Column to Risk Register (2)

Risk No.	Risk Name	Description	Consequence Description	Consequence (money, time) (see Sheet 2 for	Relative Liklihood (See Sheet	RISK INDEX	Risk Monitoring Responsibility	Emerging Indicator
4	**RECHARGE WELLS**							
4-3		Well won't take water	Additional cost to discharge water from site	0	0	0	DC	visual observation
4-4		Water boils up around the outside of the well???	Water intrusion to nearby property and site	1	1	1	DC	visual observation
5	**MAT FOUNDATION**							
5-1		Can't control the uplift on bottom of matt	Mat foundation lifts and potentially settles in an irregular fashion	3	2	6	Geocomp	visual observation; level survey
5-2		Mat starts to heave during construction	Mat foundation lifts and potentially settles in an irregular fashion	3	2	6	Geocomp	visual observation; level survey
5-3		Mat settles unexpectedly more than 3 inches??	Major design implications and impact	3	1.5	4.5	Geocomp	level survey
5-4		Mat shows leakage as dewatering is shut down	Water infiltration of subsurface and mat slab	2	3	6	GC	visual observation
5-5		Final uplift pressures are higher than	Mat foundation lifts and potentially settles	2	3	6	Geocomp	visual observation; measurements at
5-6		Can't keep water level deep enough to pour the slab	Water presence impacts ability to pour slab and has negative time and cost impact	2	3	6	Geocomp	visual observations; pore pressure measurements
6	**EXTERNAL ELEMENTS**							
6-1		Street settles more than ??? Inches	Time and cost impact to assess situation and repave street	3	2	6	Geocomp	visual; monitoring system, manual survey
6-2		Building settles more than Alert Level	Time and cost impact to assess situation and potential major rehabilitation effort	3-4	2	7	Geocomp	monitoring system
6-4		Settlement of sidewalk of more than ??? Inches	Time to assess cause for settlement and modification to hardscape	2	2	4	Geocomp	visual; monitoring system, manual survey
6-5		Gas line punctured by construction activity	Time and cost impact for City to address situation and affected properties lack of gas	2	2	4	GC	visual observation
6-6		Gas line develops leak	Time and cost impact for City to address situation and affected properties lack of gas	2	2	4	GC	visual observation
6-7		Older water main breaks	Time and cost impact for City to address situation and affected properties lack of water / water intrusion to nearby properties	3	1	3	GC	visual observation
6-8		Newer water main breaks	Time and cost impact for City to address situation and affected properties lack of water / water intrusion to nearby properties	3	1	3	GC	visual observation
6-9		Sewer line breaks	Time and cost impact for City to address situation and affected properties lack of plumbing / sewer back up	3	2	6	GC	visual observation
6-11		Vibration levels exceed limits	Potential to cause cosmetic damage to structure; distress to neighbors	3	2	6	Geocomp	monitor with seismographs
6-12		Water levels in external piezometers (non recharge areas) drop below threshold limits.	Potential to cause cosmetic damage to structure; distress to neighbors	1	3	3	Geocomp	monitor with external piezometers and visual observations of structures

Future Opportunities on existing infrastructure

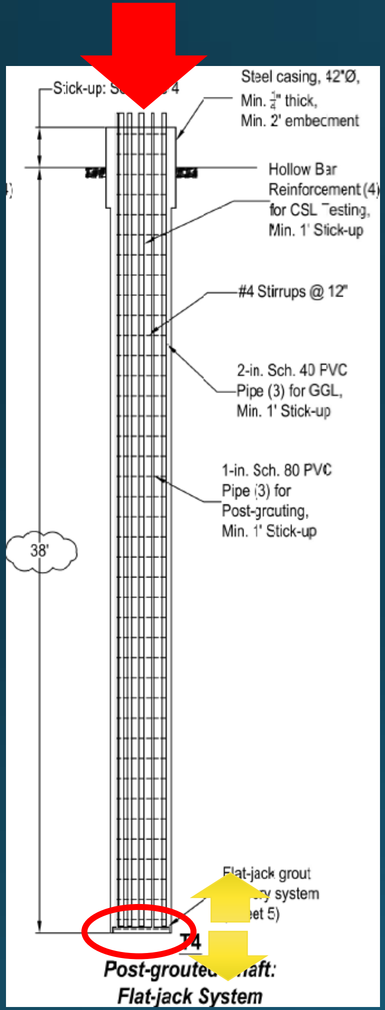
Early Warning Systems (eWS)

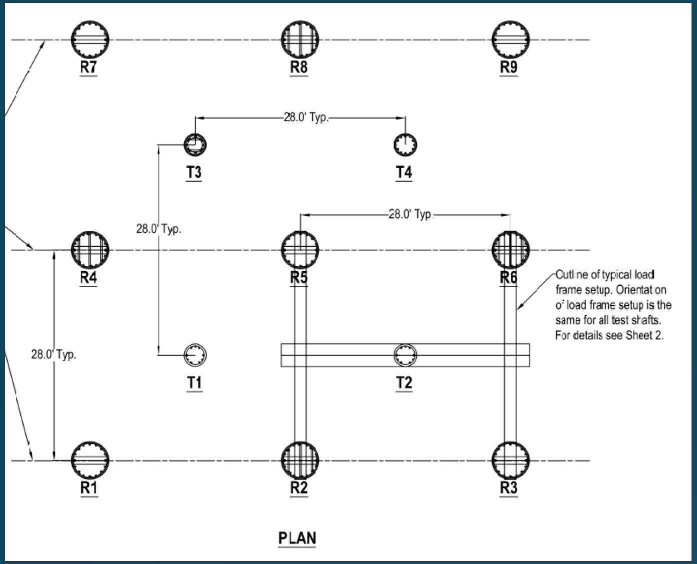
Determine if an unsafe condition exists or is developing and what to do to reduce risk to people and facilities.

Emergency Warning System (EWS)

Alert people to get out of potential inundation zone as quickly as possible following detection of an emergency condition.

Deployment of new technology when it works
Post Grouting Technique to improve Drilled Shaft End-Bearing Resistance

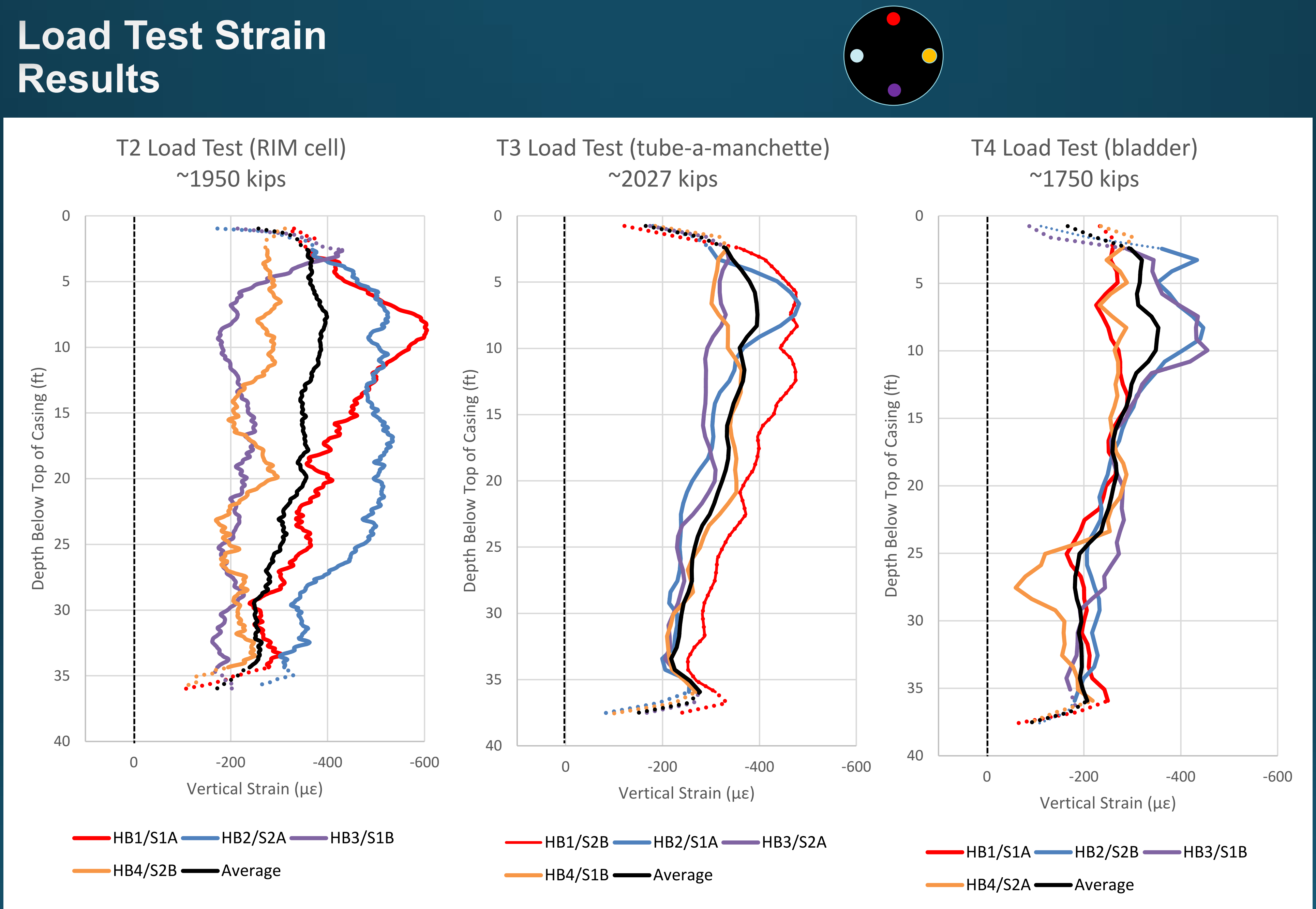




Andrew Yeskoo

From Kenichi Soga, UC Berkeley

Load Test Strain Results



From Kenichi Soga, UC Berkeley

San Luis Dam and Reservoir, CA

Improve seismic resistance
Increase height 10 ft (3 meters)
Add 10,000,000 cy of earthfill
Add 130,000 acre ft of storage

382 ft high
2,041,000 acre-ft of storage
Length of 18,600 ft (5,700 m)

- Excavate at toe of dam to install seismic retrofit measures
- Instrument to monitor movements during this risky work
- How will changes in reservoir level affect these measurements?

Use INSAR data from satellites for measure movement of earth surface from 2018 to now to measure movement of dam with changes in reservoir level.
(data provided by CGG)

INSAR East-West Displacement Feb 2018-May 2022.

3.2 East-West Displacement Rate February 2018 - May 2022

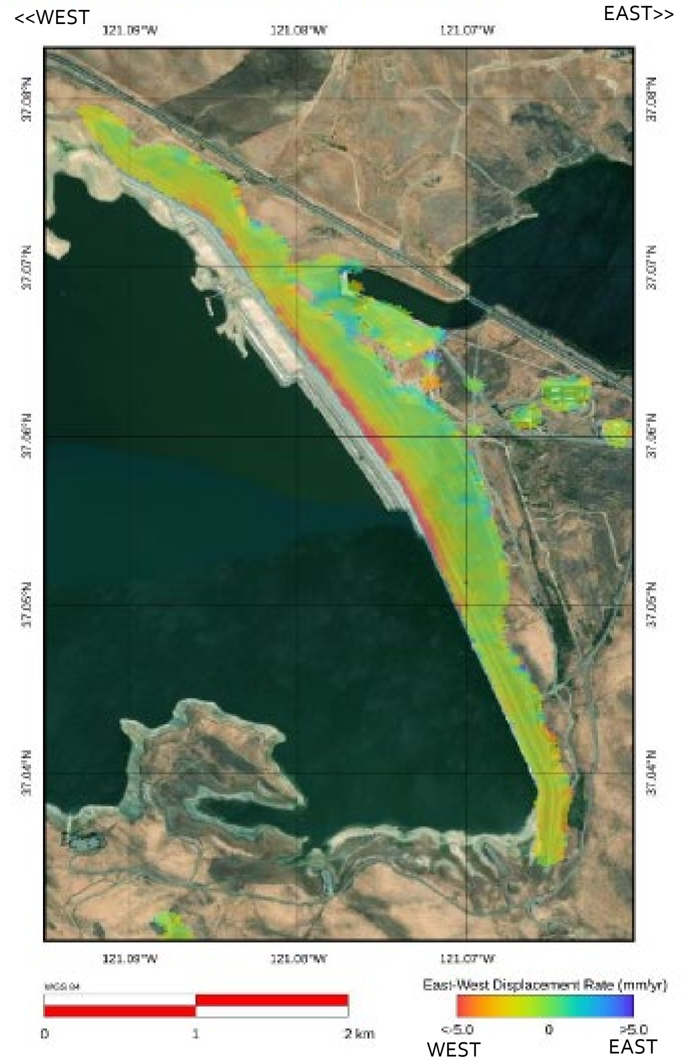


Figure 7 – East-West InSAR displacement rate result spanning February 2018 – May 2022

© CGG 2022. Copernicus Sentinel data 2018-2022.

Base Image © Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USGS, AeroGRID, IGN, and the GIS User Community.

Result	Uncertainty
Feb18-Jun22 Vertical Displacement Rate	±2 mm/yr
Feb18-Jun22 East-West Displacement Rate	±2 mm/yr

Table 2 – Uncertainty estimates

From INSAR point clouds to measurements at point source sensor locations.

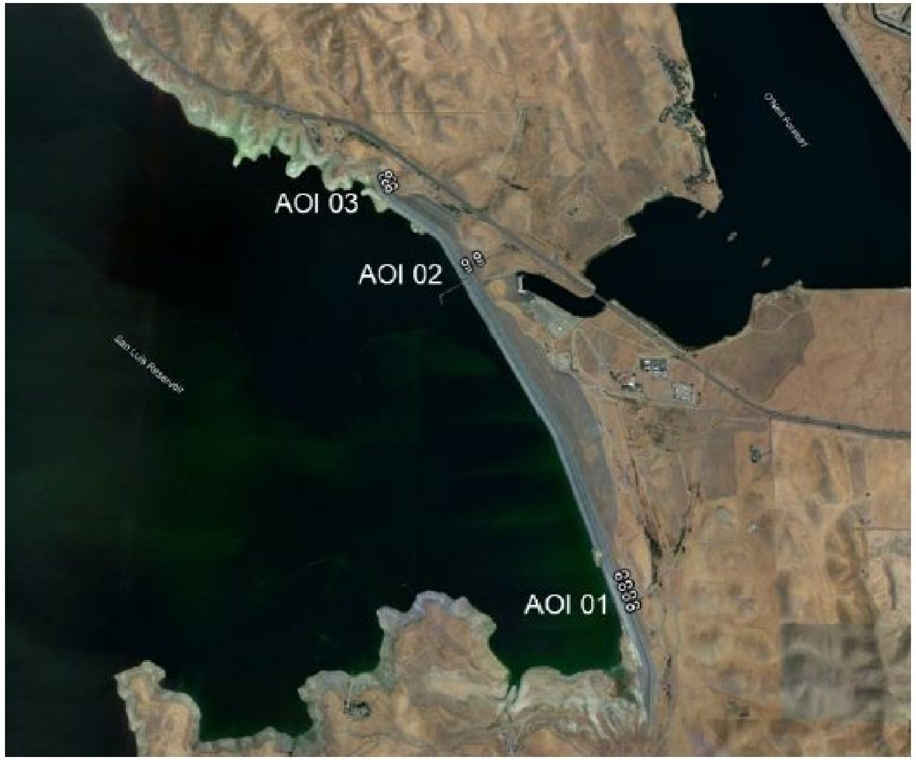


Figure 12 – San Luis Dam Areas of Interest. Circles indicate proposed inclinometer locations which are distributed into three AOIs.
Google Earth, Image © 2022 Maxar Technologies

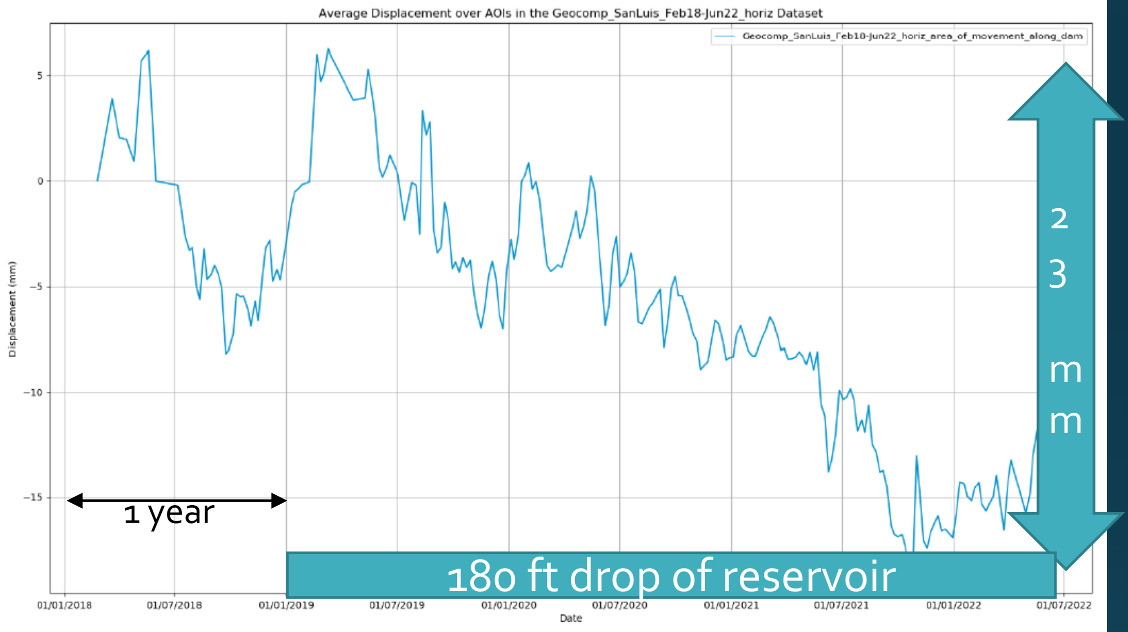


Figure 25 – Average east-west InSAR timeseries spanning February 2018 – May 2022 for the inner western edge of the dam as highlighted above.
© CGG 2022. Copernicus Sentinel data 2018-2022.
Base image © Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USGS, AeroGRID, IGN, and the GIS User Community.

KEY MESSAGE:

New technologies will bring great value provided we use them properly, don’t oversell them, and provide results in understandable and actionable form that can be trusted.

Monitoring programs without a champion mostly fail.

Success requires someone with access to budget control to explain the purpose and benefits of monitoring to the project and fight for a reasonable and continued budget.

Someone to explain the purpose and expected benefits of the work and help keep it focused.

Someone to communicate the status and benefits derived from monitoring across the project on a continual basis

Someone with a shared commitment to make the monitoring program a success and demonstrate delivered value.

Articulating Value

We need to express value in terms owners and stakeholders understand.

"We installed 36 piezometers, 5 inclinometers and a weather station all connected to a real-time automated data collection and management system delivering data to users' phones" is not a value statement.

"We provided a monitoring system that delivers status of the dam's safety to stakeholder's phones in real time" has meaning to non-technical people who are the ultimate beneficiaries of the work.

"The monitoring system provided data to show that a full level of bracing could be removed without affecting adjacent buildings or endangering safety, thereby saving $1,200,000 in construction costs and 2 weeks of construction time."

"The monitoring system revealed a developing crack in the wall leading to additional support being installed, thereby avoiding a potential collapse, safety issues, and weeks of delay to the project."

"The monitoring system indicated that consolidation of the 30-meter-thick layer of clay was proceeding faster than expected, thereby allowing the surcharge to be removed 3 weeks earlier than planned. "

"The monitoring system indicated that the soft foundation for the MSE wall was approaching failure which caused the engineer to recommend a halt to further construction to await further strength gain, thereby avoiding a failure that could have delayed the project by up to a year."

IN GENERAL:
"Performance monitoring saved xxxx time and yyy money."
"Performance monitoring helped us monitor and manage significant risks to the project."

Closing Remarks

- One of most valuable results of an effective monitoring program is when it reveals unknowns we didn't consider and gives us information in time to implement responses to manage safety, risk, time and money.
- We need to extract value derived and lessons learned from Monitoring (both successes and failures) as a project progresses.
- We need to quantify value provided by monitoring in terms of improved safety, saved money, reduced time and managed risk, then broadcast the results.
- We can expand the market for Monitoring by delivering actionable data that are understandable and believable
- We should be alert to delivering value in ways that were not envisioned during planning and articulate this benefit, so client recognizes it.