EPRG-PRCI-APGA
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JTM-23-p35
A Comparison of Remote Sensing Technologies for Slope Monitoring

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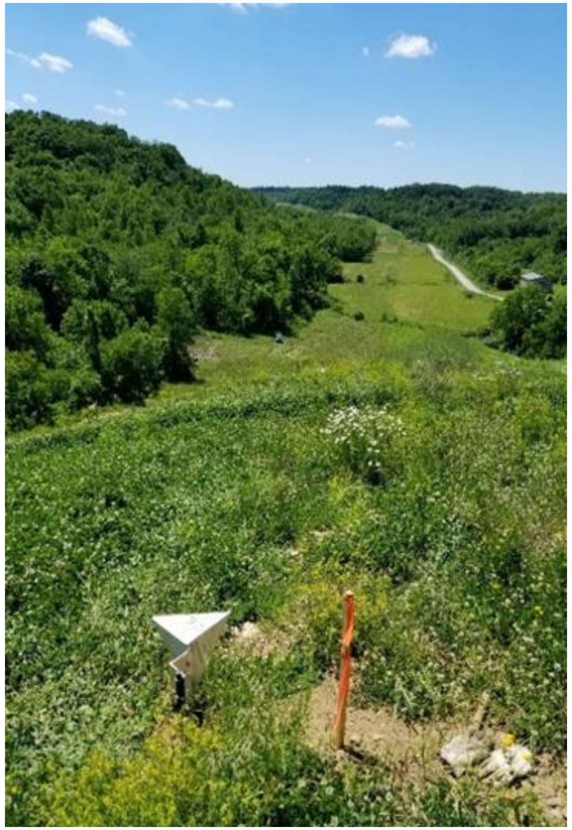
Introduction

Geohazards, including unstable slopes and landslides, are having an increasing impact on our infrastructure in the United States and globally. Infrastructure, such as natural gas pipelines, are sometimes located in difficult terrain with poor soil conditions, which are susceptible to potential slope movement (i.e., creep) and landslides.



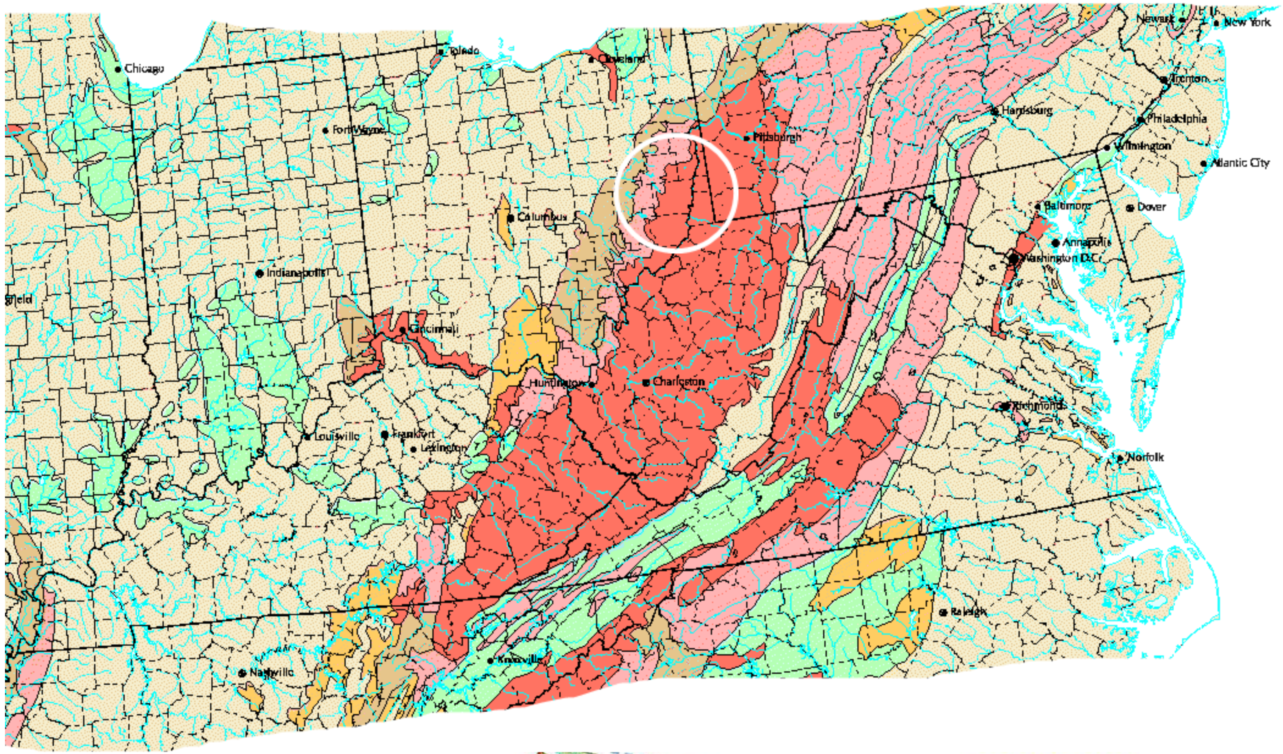
- This research project focused on a comparison of several in-situ instrumentation methods and two remote sensing technologies, GBInSAR and InSAR.
- **The overall objective of the comparison research was to determine the reliability of the remote sensing methods (GBInSAR and InSAR) compared with the in-situ instrumentation for slope monitoring, that will ultimately reduce risk and increase pipeline infrastructure integrity.**

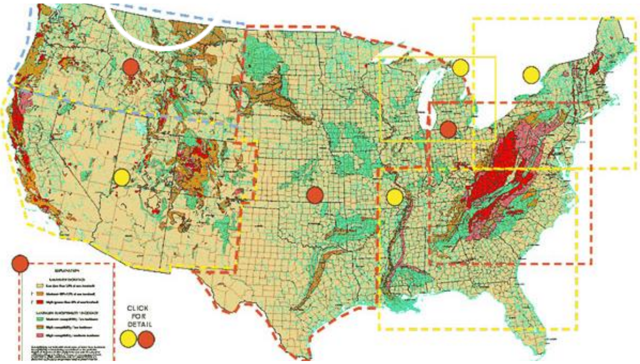
Introduction - II

- Recent advances with remote sensing techniques have made it possible to obtain measurements in soil and rock surfaces in three dimensions without in-situ instrumentation.
- Ground based (GB) InSAR (Interferometric Synthetic Aperture Radar) has been widely used in the mining industry to monitor slopes for movement. GBInSAR utilizes microwave technology to continuously scan a slope and monitor displacement and velocity in near real time.
- Satellite based InSAR is a remote sensing technology for slope monitoring that has not been fully utilized by oil and gas operators.
- This research presentation will include:
  - Introduction/Overview
  - Field Investigation
  - Data Analysis/Results
  - Conclusions/Recommendations

Overview – USGS landslide Map

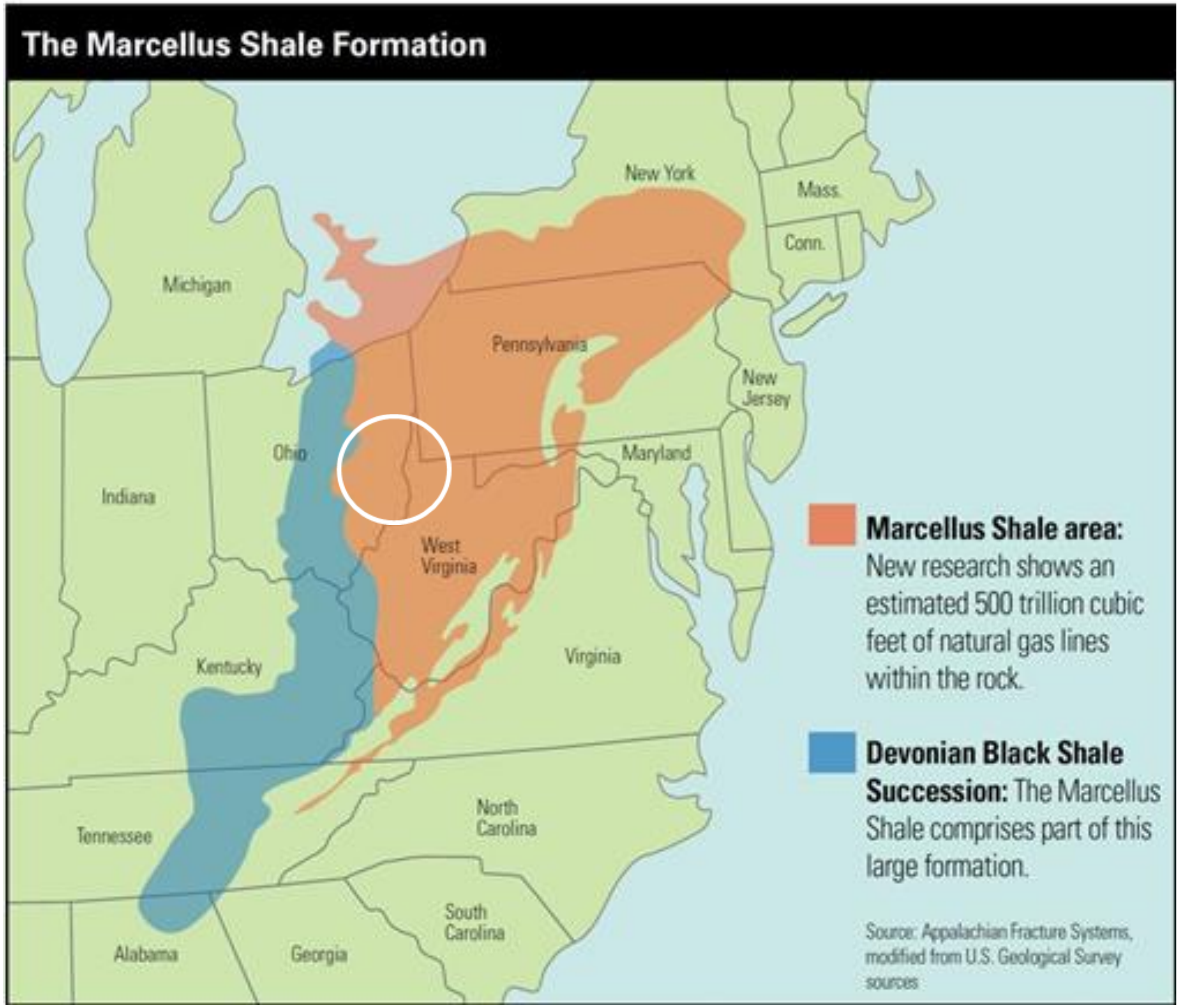
- Slow earth flow or slump are the most common types of landslides within the Appalachian Plateaus Province, which is the most severe for landsliding in the US.
- Precipitation in the Appalachian region ranges from 890 to 1140 mm per year (35 to 45 inches per year), which generally occurs in late winter and early spring, which then contributes to an area of major landslide severity.





Overview – Marcellus Shale Formation

The Marcellus Shale is located within the Appalachian Plateau and Basin and is a organic rich formation that has been extensively explored and drilled and is currently a vital natural gas producing formation in the United States.

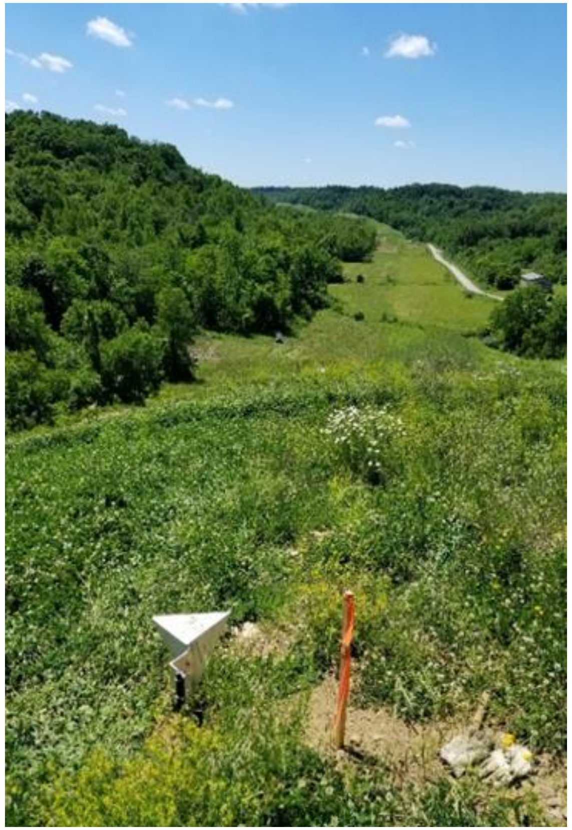


Site History/Geology

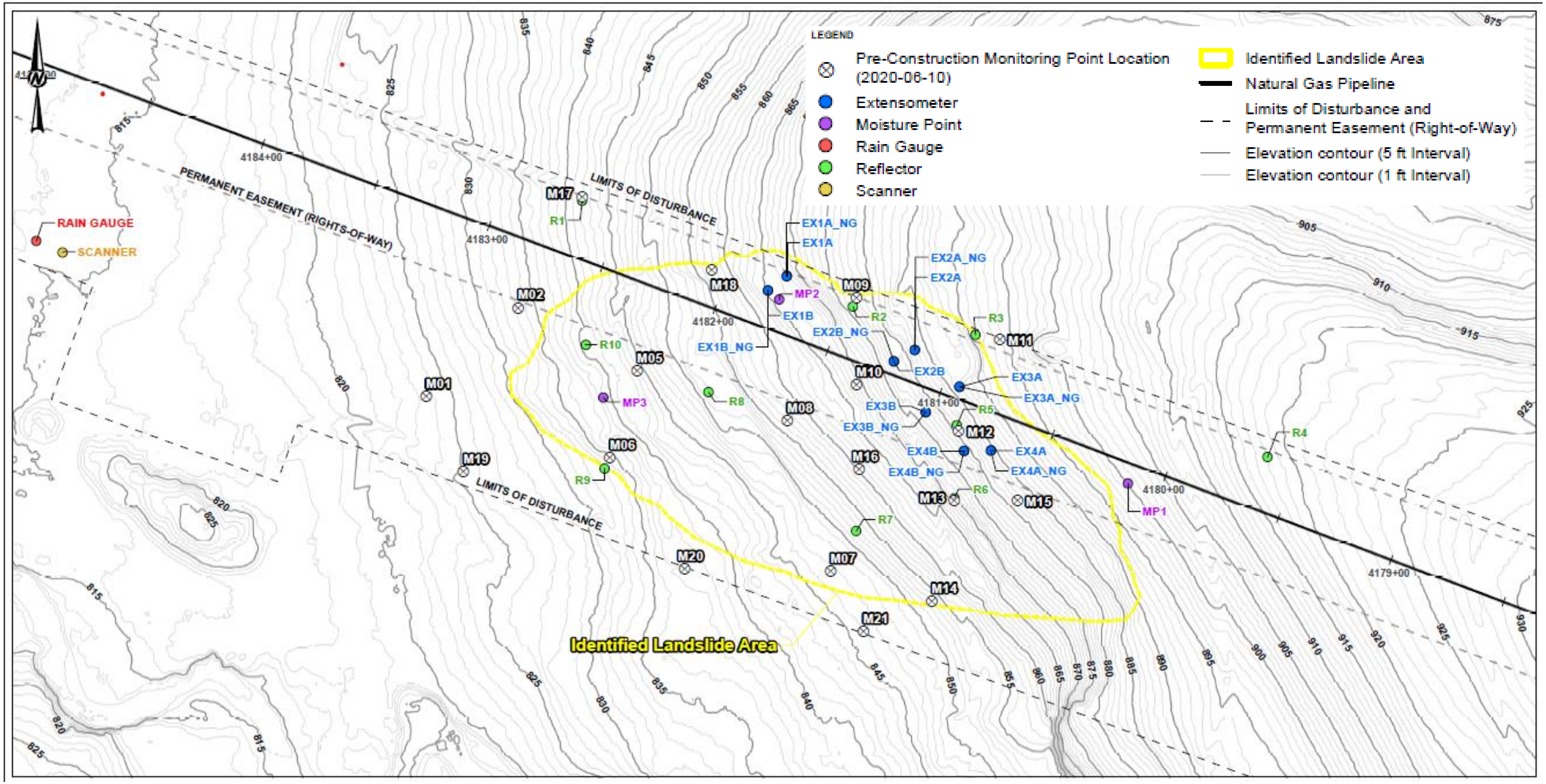
- The project site is located in eastern Ohio and within the Marcellus Shale region. The area in Ohio is known for steep and narrow valleys which makes it difficult to construct pipelines.
- According to the USGS the site is underlain by the Conemaugh Group.
- The Ohio Geological Survey (Slucher et al, 2006) defines the Conemaugh Group (Pc) of Pennsylvanian age and consisting of shale, siltstone, and mudstone. The group also contains minor amounts of sandstone, limestone, and coal.
- The Conemaugh Group contains the well-known Pittsburgh red beds, which have a relative susceptibility to land sliding (Pomeroy, 1982).
- The research study site includes a natural gas pipeline which was installed in the slope in 2017.

Site Background

- The research field site was located at a previously identified unstable slope along a pipeline ROW in eastern Ohio.
- The research was carried out over the course of a five-month monitoring period which included a post-construction monitoring period along with InSAR data report of the field site.
- The GBInSAR commenced with collection of data **on June 10th, 2021**. Ten reflectors were installed throughout the slope and the site rain gage, moisture point sensors (3), and extensometers (4).
- Weekly to bi-weekly visits were made to the site to download the rain gage data, obtain extensometer measurements, check on the GBInSAR (including the solar panels), and to check on the general slope conditions (i.e., tension cracks, etc.).



The Research Site

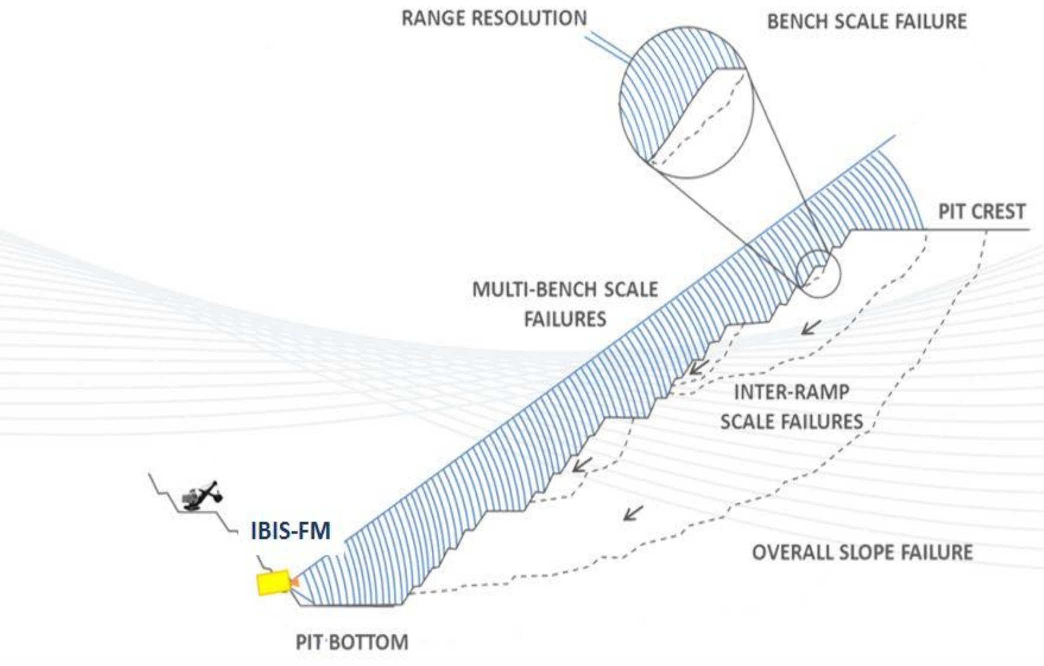


Remote Sensing - GBInSAR

- The GBInSAR monitoring system for this research project is the IBIS-Rover by IDS GeoRadar. IDS designed the IBIS-Rover for a real time monitoring system that uses synthetic aperture radar.
- Some of the hardware features of the IBIS monitoring system include: high spatial resolution (0.75m x 8.8m resolution cell at 1000m), long operating range (10m to 2500m), rapid scan (every 90 seconds), and fully remote.

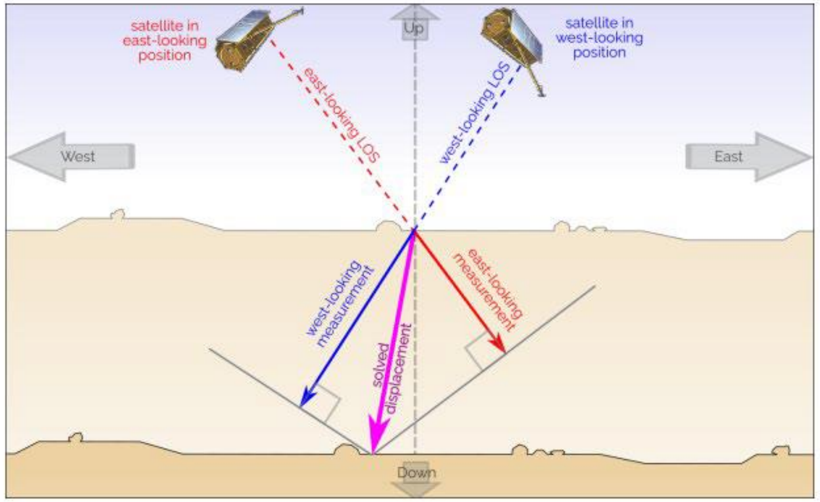
IBIS-Rover vs. typical slope instability scales

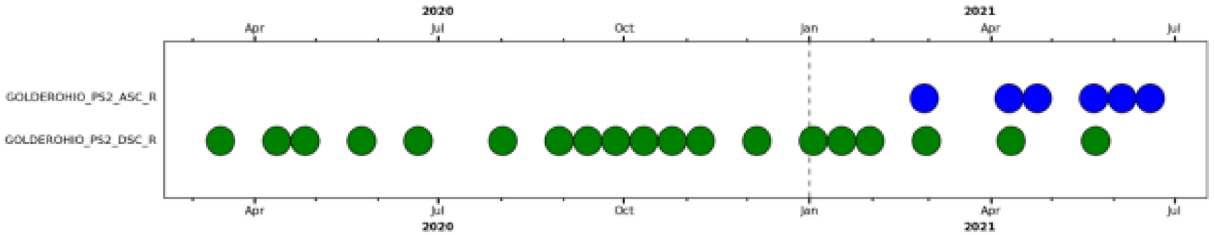
High resolution enables the identification within a **single bench** of **several pixels**, allowing the detection of small failures.



Remote Sensing - InSAR

- Interferometric synthetic aperture radar or InSAR is a satellite-based remote sensing technology that is used to monitor ground displacement/movement, generally over large geographic regions.
- 3VGeomatics was subcontracted to provide satellite images and analysis of the site, before, during and after the research monitoring period.
- A total of 19 descending (west-looking) images acquiring from March 2020 to May 2021, and 6 (six) ascending (east-looking) images acquired from February 2021 to June 2021.





Survey Points/Instrumentation

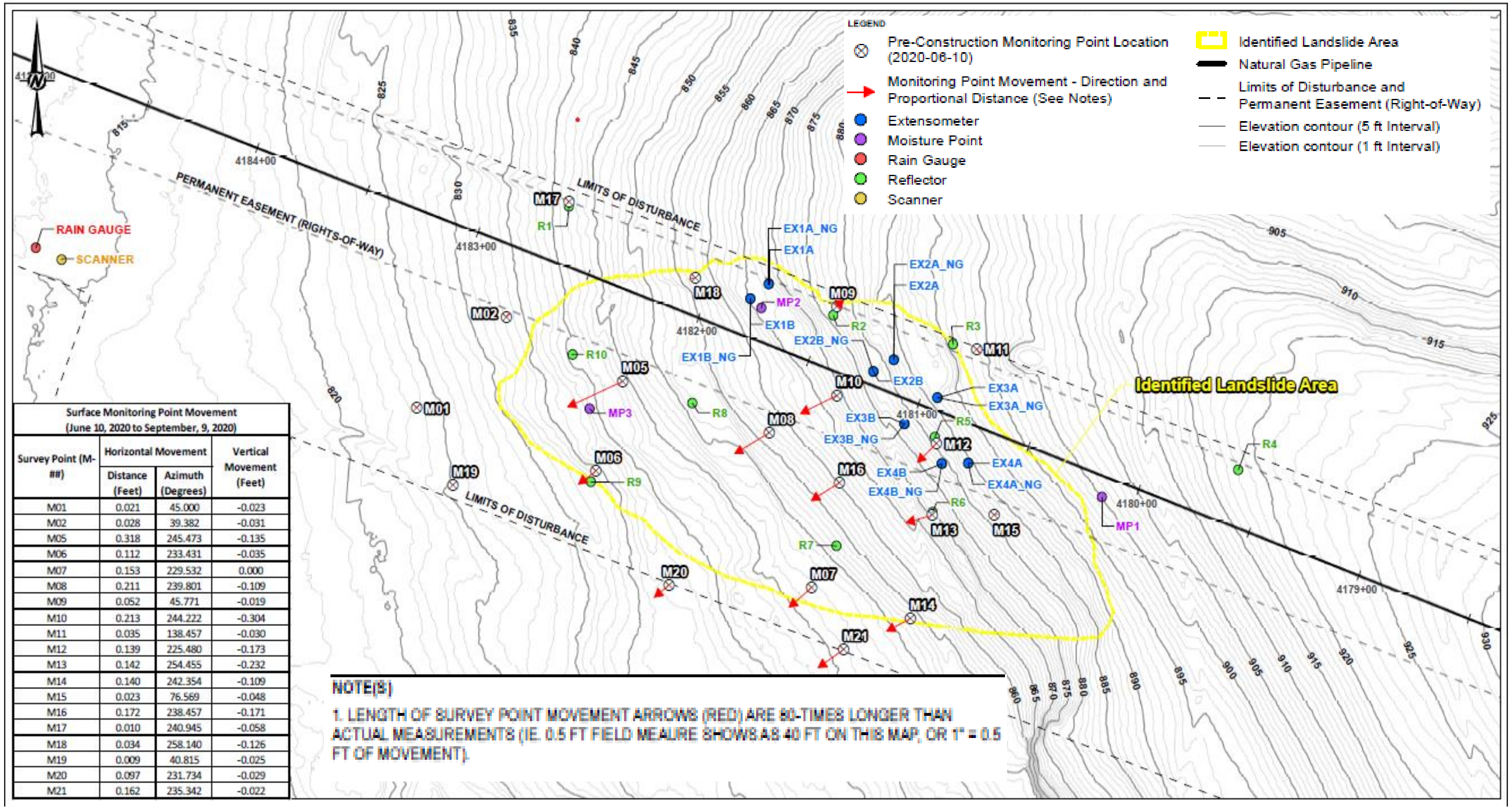
- Survey Points (19) – Surveyed every week for changes in x, y and z.
- Extensometers (4 sets) – measurements obtained once a week. Installed over tension cracks.
- Soil Moisture Probes (3) – data obtained every hour and relayed via cell service.
- Rain Gage – automatic data recorder (7 day cycle)

Field Investigation

The field investigation was divided into two parts: pre-construction and post construction. This presentation will focus on the pre-construction period, June 10, 2021 to September 10, 2021.

Results - Survey Points - Vector Movement Analysis

The survey point data were used as a method to track survey control movement against the GBInSAR displacement data. **Adjacent figure shows a vector arrow map of the magnitude of the monument movement over the survey timeframe.** Based on the data received from the survey company the **movement of the survey monuments** over the monitoring period ranged from **0.25 to 9.65cm (0.1 to 3.8 inches).**

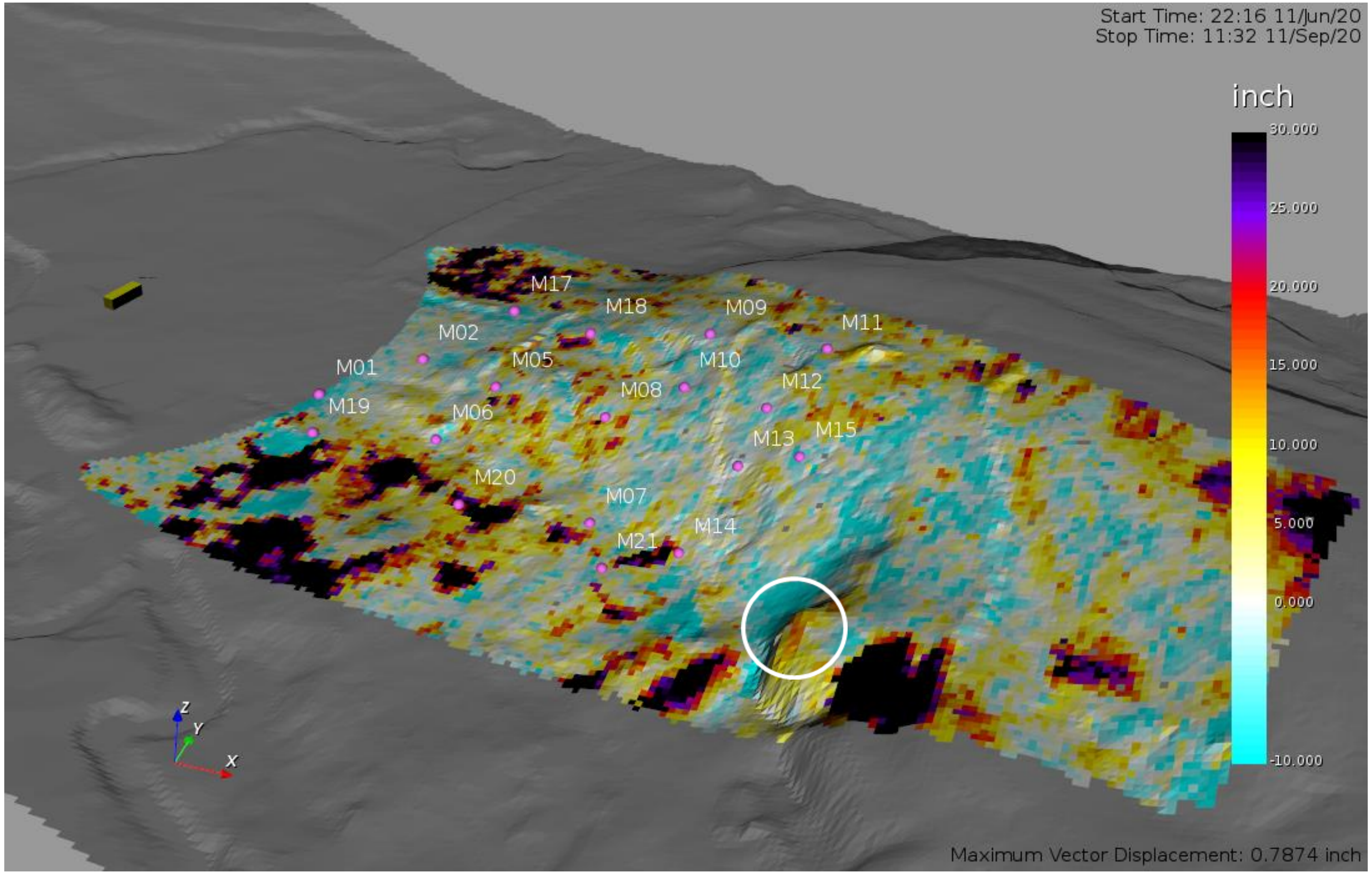


Surface Monitoring Point Movement
(June 10, 2020 to September, 9, 2020)

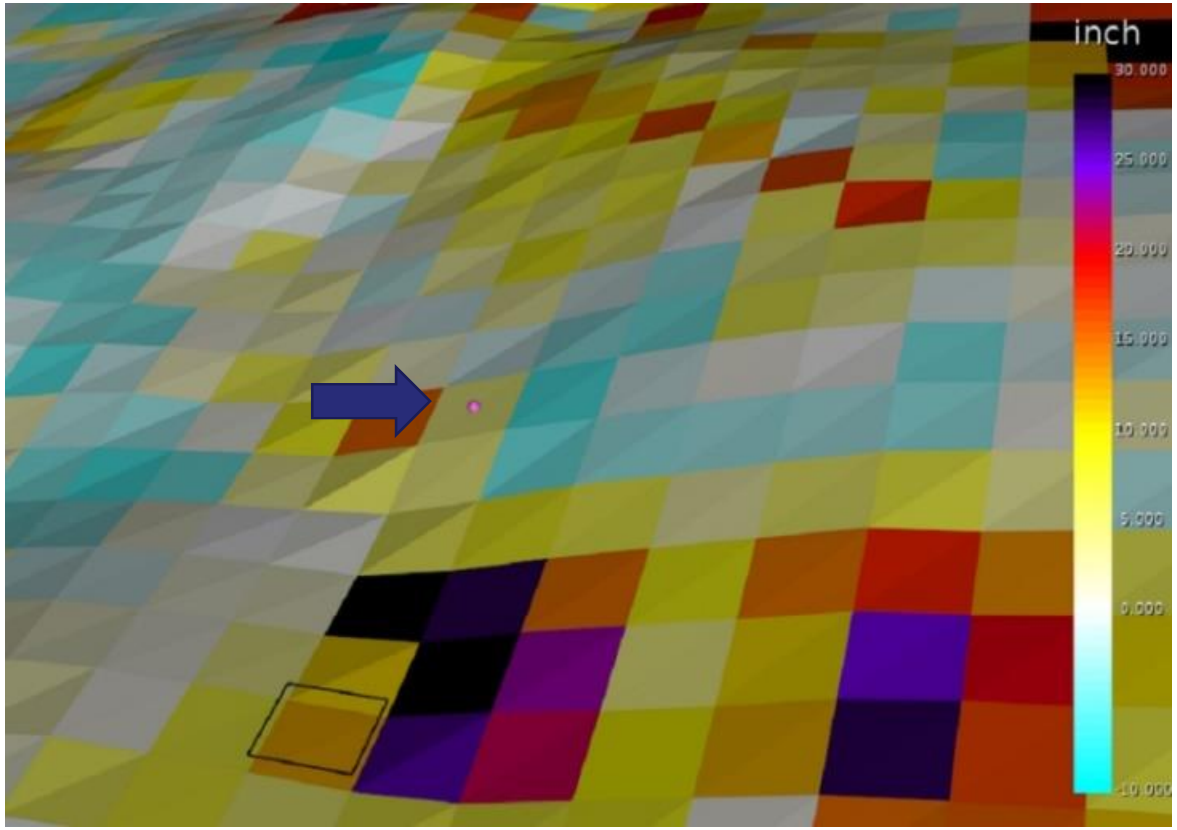
Survey Point (M-##)	Horizontal Movement		Vertical Movement (Feet)
	Distance (Feet)	Azimuth (Degrees)	
M01	0.021	45.000	-0.023
M02	0.028	39.382	-0.031
M05	0.318	245.473	-0.135
M06	0.112	233.431	-0.035
M07	0.153	229.532	0.000
M08	0.211	239.801	-0.109
M09	0.052	45.771	-0.019
M10	0.213	244.222	-0.304
M11	0.035	138.457	-0.030
M12	0.139	225.480	-0.173
M13	0.142	254.455	-0.232
M14	0.140	242.354	-0.109
M15	0.023	76.569	-0.048
M16	0.172	238.457	-0.171
M17	0.010	240.945	-0.058
M18	0.034	258.140	-0.126
M19	0.009	40.815	-0.025
M20	0.097	231.734	-0.029
M21	0.162	235.342	-0.022

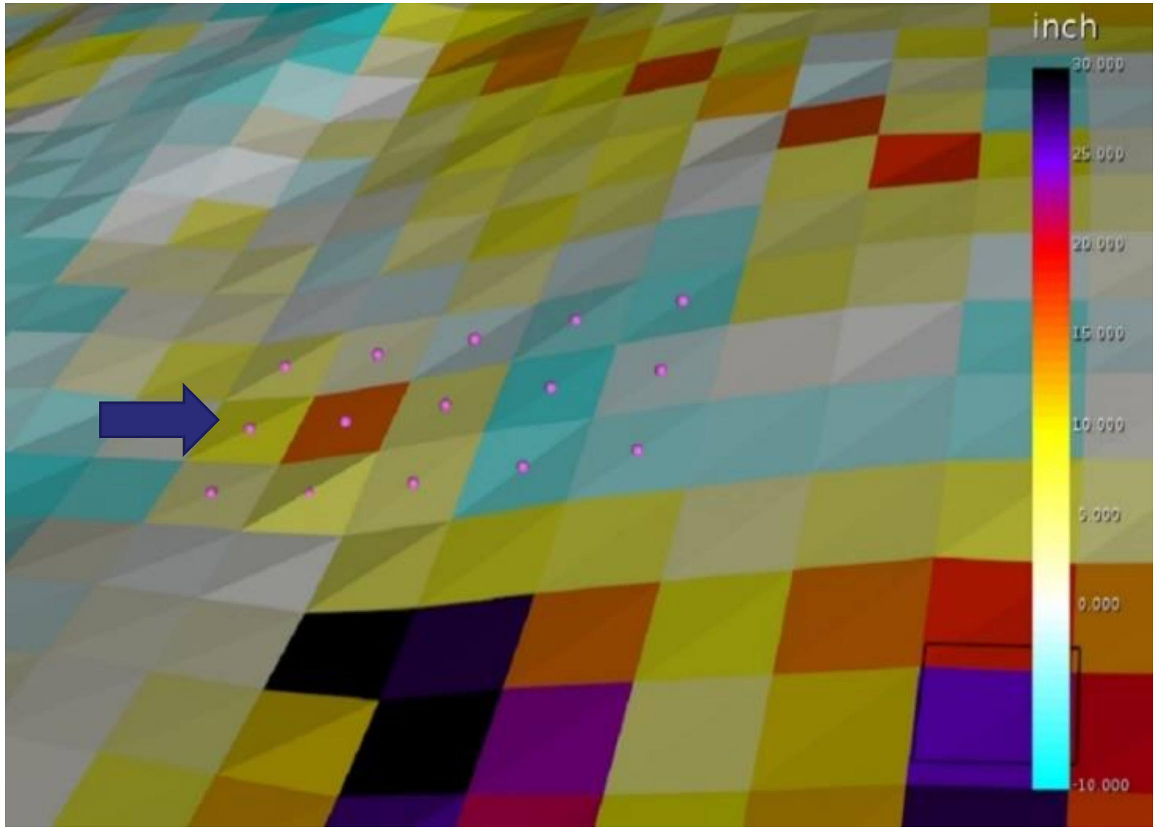
Results – GBInSAR

Total displacement map over the three month monitoring period (north is in the direction of the Y axis). The white circle indicates the sandstone outcrop.



Data Anaysis Approach - Single/Multiple Pixel‘s





Example of single pixel (left) and multiple pixels (right) analysis (pink dots)

Reserach Results

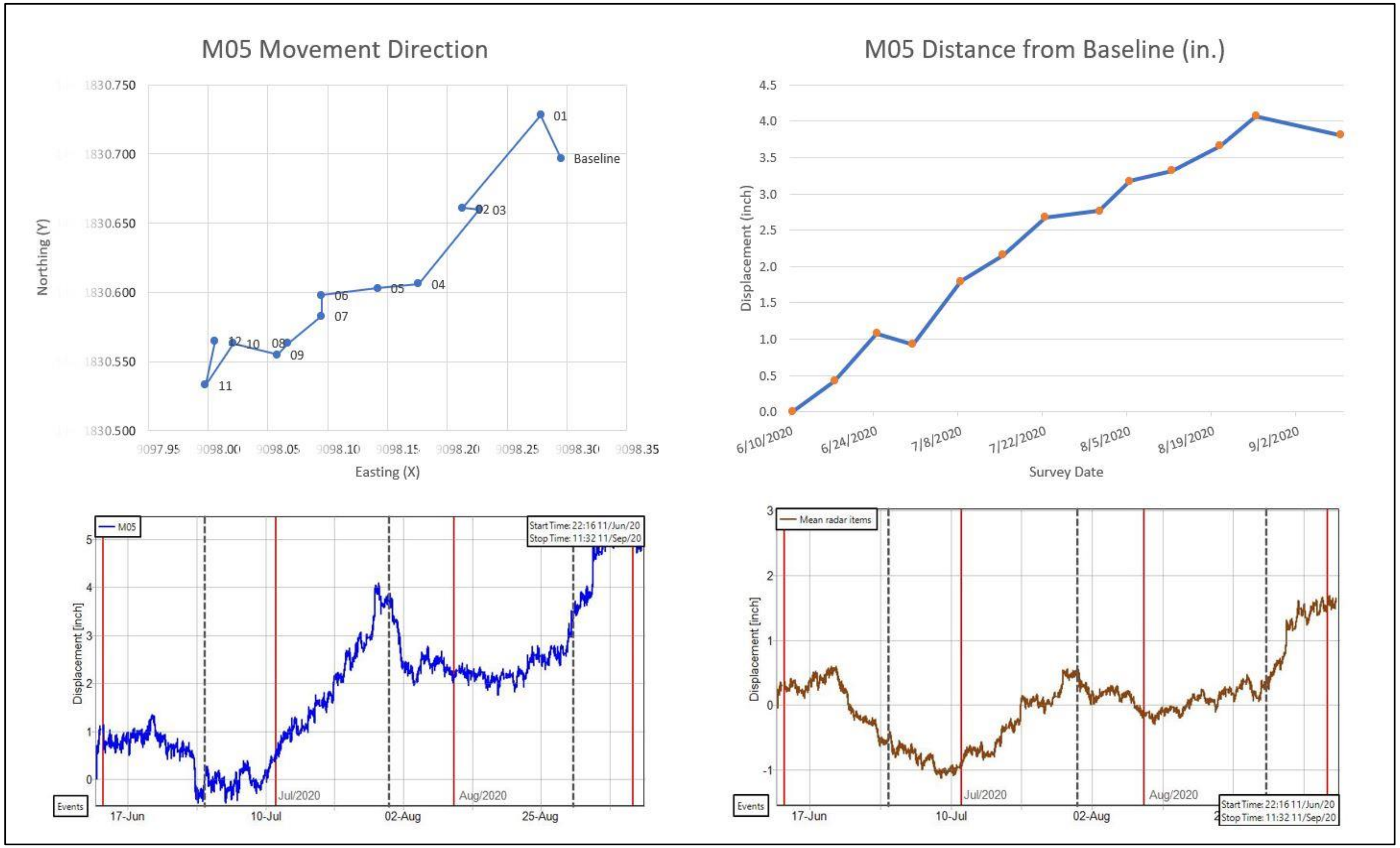
Based on the results observed from the survey monuments and GBInSAR displacements it was decided to categorize the agreements based on three levels. The levels of agreement are 1, 2, and 3 and summarized below:

- **Level 1** – agreement indicates the monument movement direction and displacement matches well with the GBInSAR pixel movement direction and displacement.
- **Level 2** – agreement indicates either the monument movement direction or displacement matches well with the GBInSAR pixel movement direction or displacement.
- **Level 3** - neither the monument movement direction or displacement matches well with the GBInSAR pixel movement direction and displacement.

Rank 1 (6)
M02
M05
M09
M11
M15
M21
Rank 2 (11)
M06
M07
M08
M10
M12
M13
M14
M16
M18
M19
M20
Rank 3 (2)
M01
M17

Data Analysis – Level 1

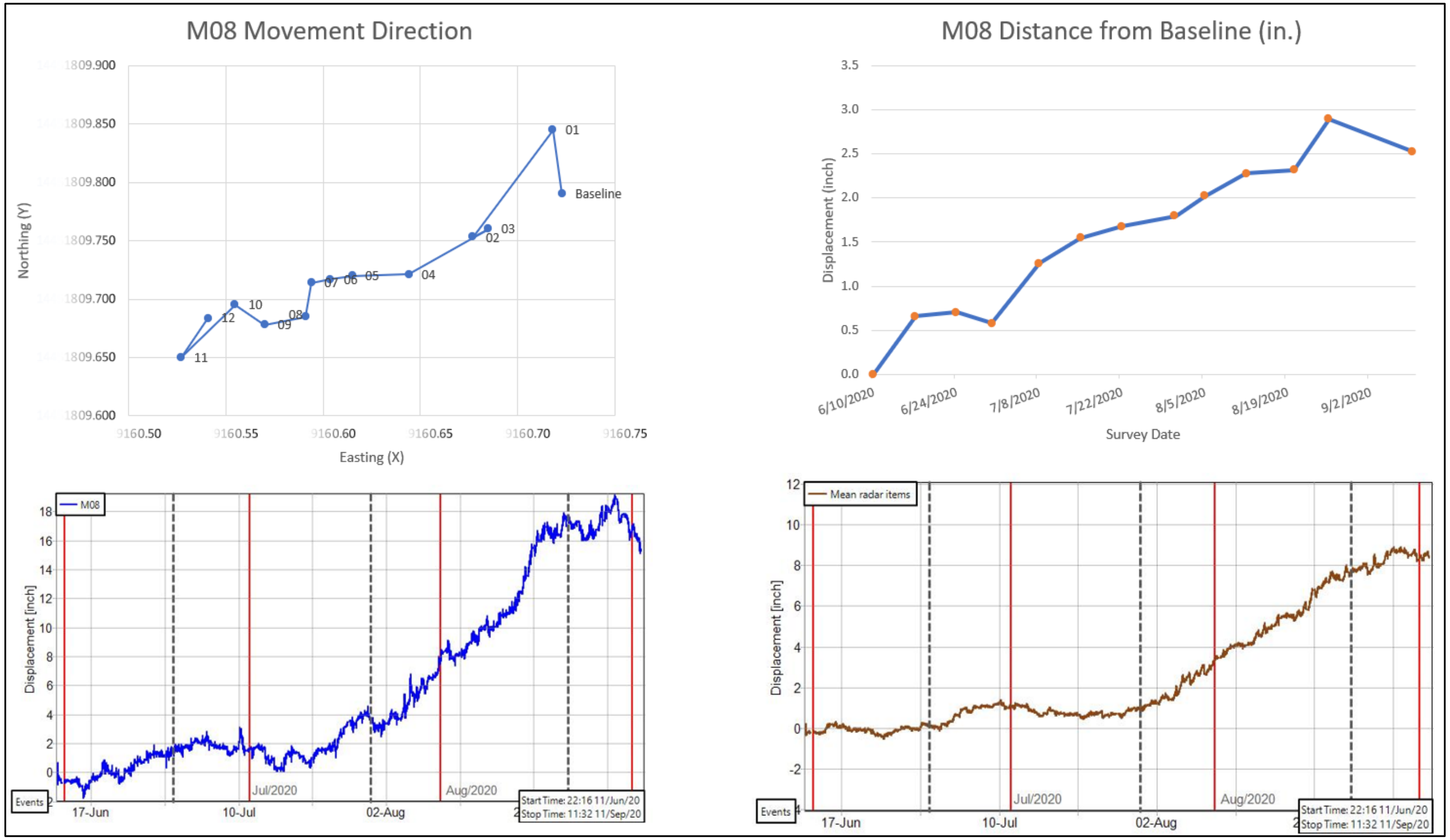
Level 1 – agreement indicates the monument movement direction and displacement matches well with the GBInSAR pixel movement direction and displacement. Example: SP05 Survey Point and GBInSAR Comparison.



Level 1 (6)
M02
M05
M09
M11
M15
M21
Level 2 (11)
M06
M07
M08
M10
M12
M13
M14
M16
M18
M19
M20
Level 3 (2)
M01
M17

Data Analysis – Level 2

Level 2 – agreement indicates either the survey point movement direction or displacement matches well with the GBInSAR pixel movement direction or displacement. SP08 Survey Point and GBInSAR Comparison.



Level 1 (6)
M02
M05
M09
M11
M15
M21
Level 2 (11)
M06
M07
M08
M10
M12
M13
M14
M16
M18
M19
M20
Level 3 (2)
M01
M17

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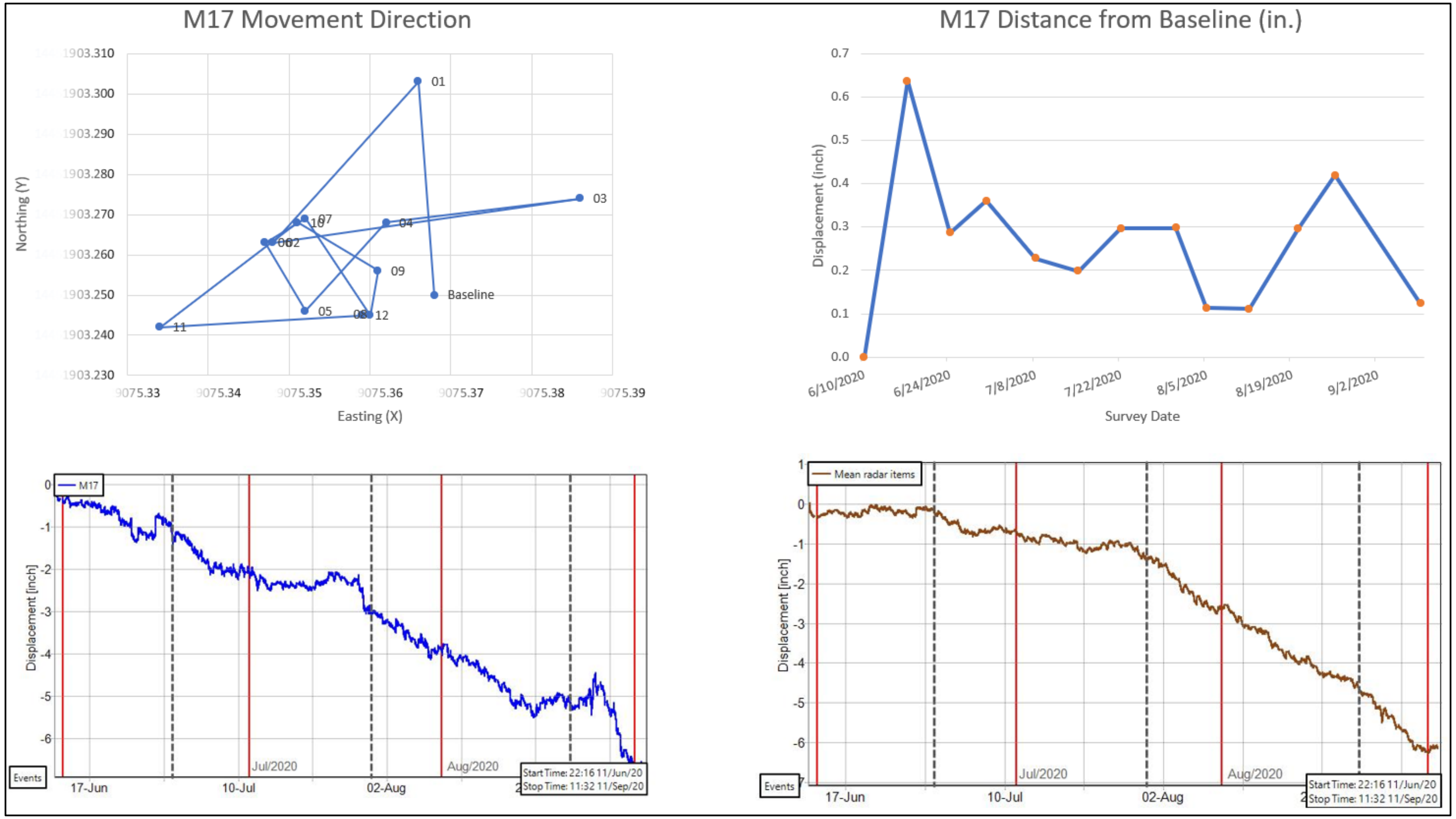
Data Analysis – Level 3

Level 3 - neither the monument movement direction or displacement matches well with the GBInSAR pixel movement direction and displacement. SP17 Survey Point and GBInSAR Comparison.



Level 1 (6)
M02
M05
M09
M11
M15
M21
Level 2 (11)
M06
M07
M08
M10
M12
M13
M14
M16
M18
M19
M20
Level 3 (2)
M01
M17

Extensometer Readings/Results – Example 2AB Data

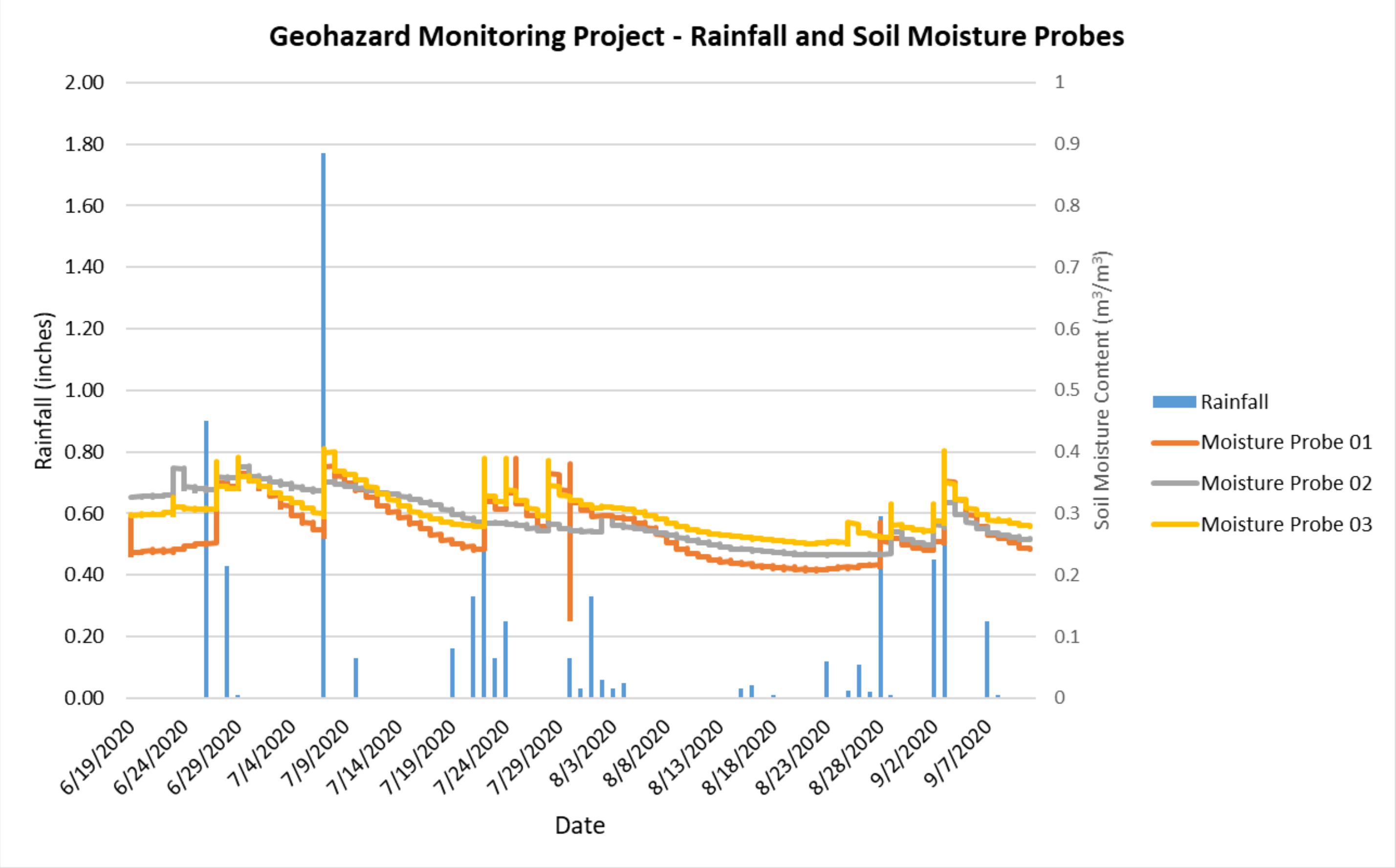
- Extensometers sets 1AB – 4AB each showed elongation across the two fixed rods of between 15 and 28 mm (0.6 inches and 1 inch).

- This is good agreement between the two different data types in this location. These two points were the only instance where an extensometer set was within 3m (10 feet) of a survey point.

Date	Serial #	Temp °F	Temp °C	Reading (mm)	Time	Difference from prior read (mm)	Difference from prior read (in)
6/19/2020	2004219	75	24	3180.71	12:05 PM	--	--
6/24/2020	2004219	82	28	3185.71	2:45 PM	5.00	0.20
7/2/2020	2004219	85	29	3186.70	10:55 AM	0.99	0.04
7/10/2020	2004219	75	24	3191.42	9:55 AM	4.72	0.19
7/17/2020	2004219	84	29	3195.53	2:50 PM	4.11	0.16
7/23/2020	2004219	74	23	3198.76	9:55 AM	3.23	0.13
8/5/2020	2004219	72	22	3202.28	2:50 PM	3.52	0.14
8/20/2020	2004219	78	26	3206.10	1:10 PM	3.82	0.15
9/3/2020	2004219	74	23	3206.37	10:00 AM	0.27	0.01
9/11/2020	2004219	69	21	3208.49	9:55 AM	2.12	0.08
			Difference from Original Reading			27.78	1.09

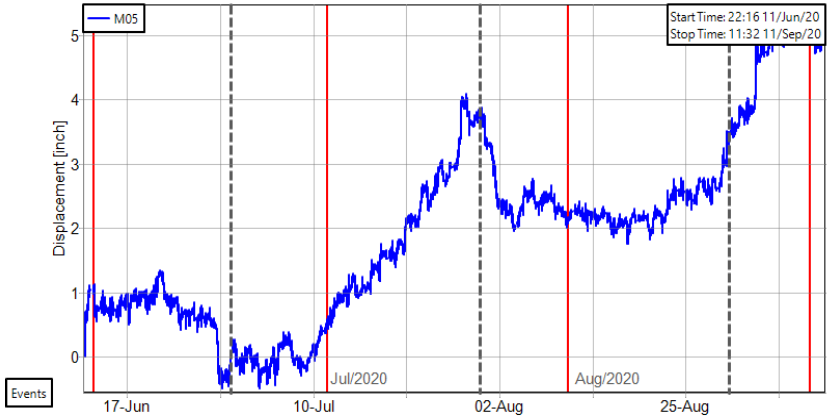
Data Analysis – Rainfall and Soil Moisture Probes

- Soil moisture probes data shows good correlation with the rain gauge rainfall events.
- The GBInSAR data were examined for correlations in displacement across rain events and increase in soil moisture content and there was no identified increase in movement observed in the time frames around precipitation on site.
- Long-term analysis of surface water infiltration and groundwater recharge should be performed in order to assess the interactions between the groundwater and slope movement/shear zone.



Conclusions

- GBInSAR data showed good agreement between the displacement time series and monument points. There are several points that did not show good correlation, and this can mostly be attributed to high vegetation on the slope during monitoring. The high irregular vegetation causes low amplitude and inconsistent radar reflections reducing the reflected amplitude.



- Rain data and soil moisture probe data show good agreement with each other; however, no discernible correlation was observed with the GBInSAR data. Overall, the amount of rainfall observed over the three-month monitoring period was not considered significant with the largest single event at 4.6 cm (1.8 inches).

Conclusions

- The extensometer data set showed elongation between 1.5cm (0.6 inches) and 2.5cm (1 inch). This amount of displacement over the monitoring period is small and correlates well with the localized minimal movement of the GBInSAR data near these locations.
- The GBInSAR and InSAR data both showed displacement over the site. In general, the InSAR data showed better than expected results and correlation with the GBInSAR. The InSAR displacement map shows clear movement between 5.1cm to 25.4cm/year (2 -10 in/year) over the field site in correlation with observed GBInSAR values on average between 12.7cm to 25.4cm (5-10 inches) near SP 5 and SP 8.

Conclusions

- The project was a unique opportunity to examine and monitor an unstable slope both during and after construction remediation activities.
- In general, the remote sensing technologies were able to capture movement over the area of interest and show displacement trends in the data over their respective time series.
- However, both the GBInSAR and InSAR datasets measured slope movement trends over their respective time series. Both GBInSAR and InSAR were affected by slope vegetation to varying degrees.
- Based on these results both remote sensing technologies can serve to collect meaningful data along unstable slopes on pipeline ROWs, for both short-term (high-risk slopes) and long-term monitoring.

Recommendations – Future Projects

- **Deployment of an automated total station adjacent to the GBInSAR for automated survey control.** The purpose is to establish a suitable number of reflector monuments across critical parts of the slope to provide true movement and ground truth to the GBInSAR.
- Deploy instrument in-line with the slope movement.
- **Vegetation management of the slope is required to control backscatter of the radar signal.** Vegetation growth can cause inaccurate slope radar returns. The GBInSAR manufacturer is currently working on enhancing algorithms that may be able to deal with vegetation, however, this is still in the developing stages.

Recommendations

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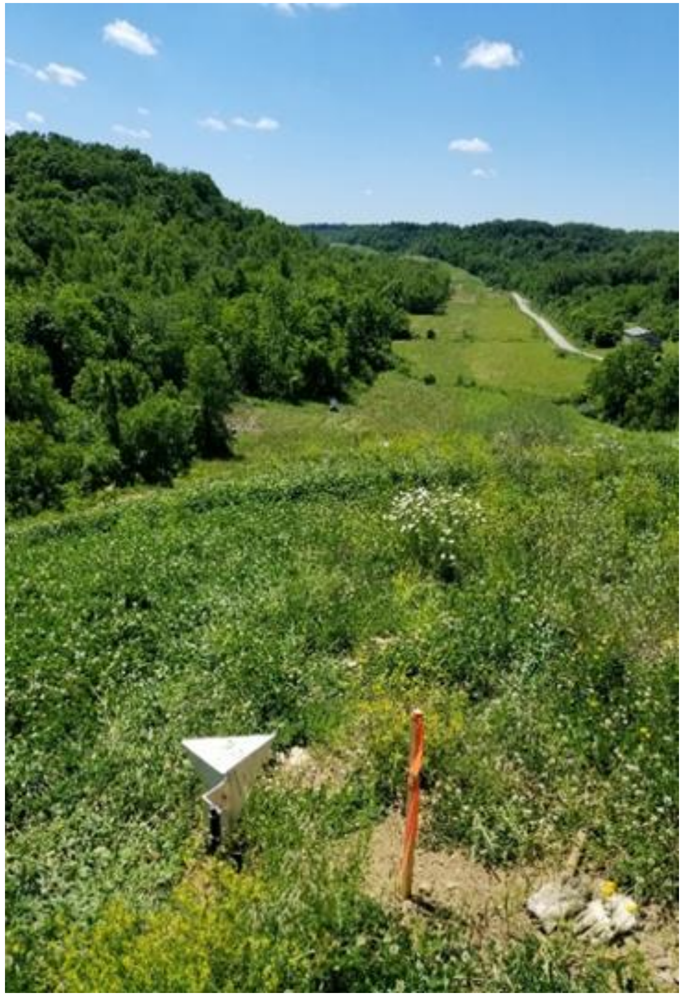
- **Attempt to coordinate monitoring around the early springtime months.** This has two potential benefits, the first is vegetation is usually at a low level and second springtime is typically the time when the highest amount of precipitation occurs from winter snow melt and early spring rains.
- InSAR has provided data to support the use of monitoring slopes over large geographic regions. InSAR is a reliable method for long-term monitoring of low or medium risk slopes. **If a slope requires near real-time data due to an elevated threat level (i.e., high risk), then GBInSAR is an appropriate technology to provide high data density in near real-time within the constraints listed above.**



Thank you for your attention.