PUERTO RICO HIGHWAYS & TRANSPORTATION AUTHORITY

Terrestrial Laser Scanning for Measuring Rock Slope Deformation and Discontinuity Orientation

52nd Southeastern Geotechnical Engineering Conference

Charlotte, North Carolina

Ricardo J. Romero-Ramírez, PhD CE, PhD GE, PE

María Elena Arroyo-Caraballo, MSCE, PE

Agenda

- Introduction
- Background
- Methodology
- Discussion of Results
- Documenting an Archaeological Petroglyph
- Conclusions
- Recommendations for Future Work

PUERTO RICO HIGHWAYS & TRANSPORTATION AUTHORITY

Introduction

- Rock slope movements cost millions of dollars and can cause the loss of property and human life.
- Traditional methods to detect rock slope movements and to measure rock discontinuity orientation are useful for small areas, but they may not be enough or cost-effective for large areas.
- A terrestrial laser scanner will be used to measure rock slope deformations and determine the orientation of rock discontinuities.
- The results of the terrestrial laser scanner will be compared to the results obtained from traditional methods.

PUERTO RICO HIGHWAYS & TRANSPORTATION AUTHORITY

Background

Acronyms

- Laser – Light amplification by the stimulated emission of radiation
- LIDAR – Laser Induced Detection and Ranging
- TLS – Terrestrial Laser Scanner
- RDS – Rock Displacement Simulator
- DTM – Digital Terrain Model

Background (cont.)

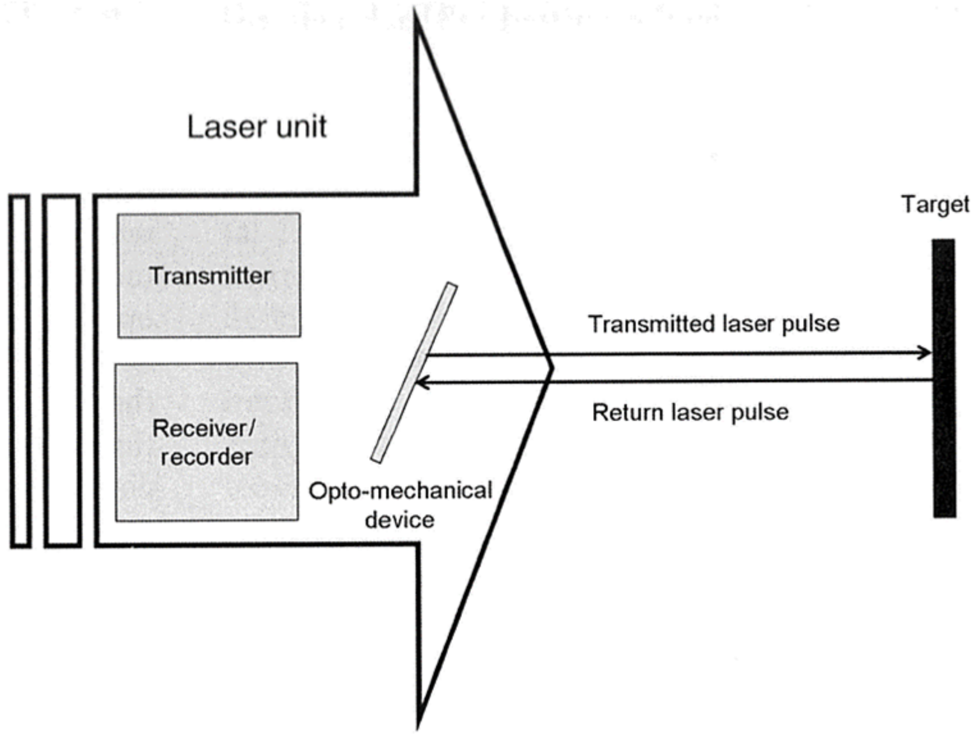
Previous Research

- Rosenblad et al. (2016) demonstrated that TLS was capable of detecting centimeter-scale movements of boulders.
- Maerz et al. (2016) measured sub-mm scale movements of soil slopes using TLS.
- Romero (2019) found that sub-mm movements of a rock displacement simulator can be measured using TLS and post-processing software.

Background (cont.)

TLS components

- a transmitter;
- an opto-mechanical device; and
- a receiver/recorder unit



Basic components of a TLS instrument
(Heritage and Large, 2009).

PUERTO RICO HIGHWAYS & TRANSPORTATION AUTHORITY

Background (cont.)

Point Cloud

- The TLS transmits a laser pulse to a target of interest, where some of the energy is reflected to the recorder unit.
- This procedure continues until the TLS has completed scanning the entire surface of the target of interest.
- Millions of points are acquired in a short time.
- The closer the points are together, the more the image looks like a photograph.

Background (cont.)

Advantages of TLS

- Discontinuous measurement campaigns can be carried out without concerns for changes in the position of the instrument because the reference system of the models is "fixed" on the markers.
- Comparison between multitemporal scans allows the detection of 3-D displacements.

Limitations of TLS

- Campaigns must be performed during good weather conditions, and good illumination is necessary when digital images are needed.

PUERTO RICO HIGHWAYS & TRANSPORTATION AUTHORITY

Methodology

Equipment

- Riegl Model VZ-2000i
- Software RiScan Pro with LIS Geotec Plugin
- Acquired in April 2023 with STIC funds to further develop our Unstable Slope Management Program (USMP).

Methodology (cont.)

PUERTO RICO HIGHWAYS & TRANSPORTATION AUTHORITY

Riegl VZ-2000i Specifications

- Data acquisition up to 500,000 measurements/sec
- Field of view 100ºV x 360ºH
- Range up to 2,500 m
- Integrated GNSS RTK Receiver

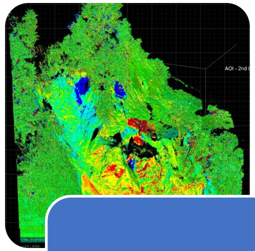
PUERTO RICO
HIGHWAYS & TRANSPORTATION
AUTHORITY

Methodology (cont.)

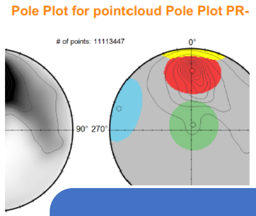
Measurement Validation

Field Data

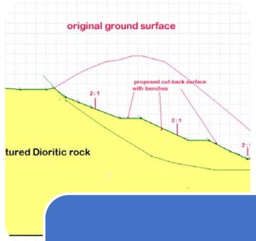
Data Processing



Movement Detection



Discontinuity Orientation



Mitigation

PUERTO RICO HIGHWAYS & TRANSPORTATION AUTHORITY

Methodology (cont.)

Rock Displacement Simulator (RDS)

Front 23 x 24 in plate

Back 23 x 24 in plate

Methodology (cont.)

First Controlled Experiment

- 10 ¾ x 8 in Aluminum Plate
- Distance to target 31.82 m
- 1st campaign
  - Scans 1 – 5
- 2nd campaign
  - Scan 6
  - Offset 12 inches
- <u>Sub-millimetric accuracy</u>

Table 1. Measured TLS Displacements vs. Ground Truth Data (10 ¾ x 8 in Plate)

Scan	Campaign	True Δ (mm)	TLS Measured Δ (mm)	Absolute Error (mm)	Relative Error %
1	1	0	0	0	--
2	1	1.06	1.00	-0.06	5.7%
3	1	5.17	5.00	-0.17	3.3%
4	1	12.14	12.25	0.11	0.9%
5	1	21.39	21.50	0.11	0.5%
6	2	21.39	21.25	-0.14	0.7%

Methodology (cont.)

Second Controlled Experiment

- 23x24 in Aluminum Plate
- Distance to target 33.32 m
- 1st campaign
  - Scans 1 – 6
- Sub-millimetric accuracy

Table 2. Measured TLS Displacements vs. Ground Truth Data (23x24 in plate)

Scan	Campaign	True Δ (mm)	TLS Measured Δ (mm)	Absolute Error (mm)	Relative Error %
1	1	0	0	0	--
2	1	1.84	1.75	-0.09	4.9%
3	1	3.8	3.75	-0.05	1.3%
4	1	7.69	7.75	0.06	0.8%
5	1	13.46	14.25	0.79	5.9%
6	1	19.47	19.25	-0.22	1.1%

PUERTO RICO HIGHWAYS & TRANSPORTATION AUTHORITY

Methodology (cont.)

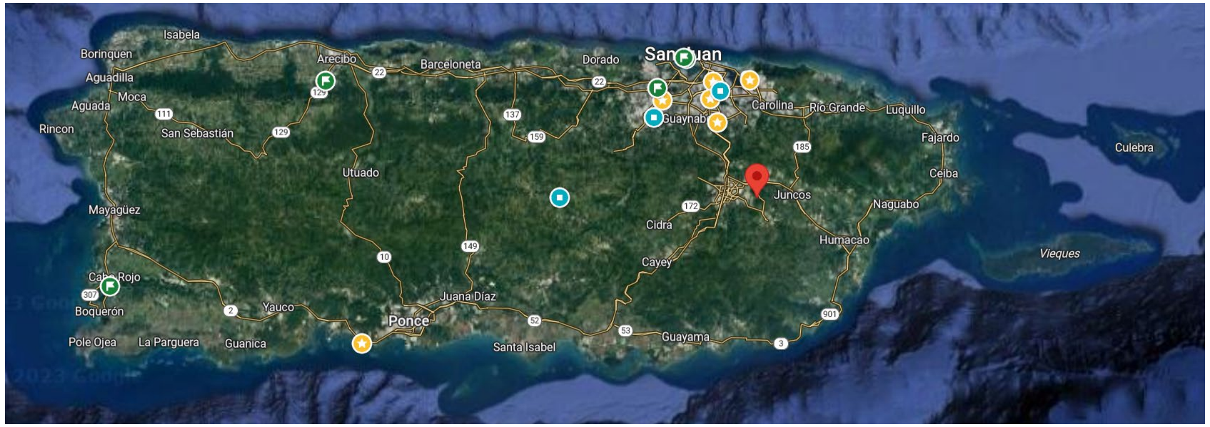
Table 3. Case Studies

Landslide	Purpose	Height (m)	Width (m)	1st Measurement Campaign	2nd Measurement Campaign	3rd Measurement Campaign	4th Measurement Campaign
PR-203 Km 2.5 San Lorenzo	Movement detection	50	30	June 12, 2023	June 20, 2023	June 27, 2023	October 13, 2023
PR-129 Km 10.9 Hatillo	Documentation of an archeological petroglyph	25	125	July 6, 2023	July 12, 2023	N/A	N/A

Methodology (cont.)

Details of the PR-203 rock slope failure

- PR-203, Km 2.5, San Lorenzo



- Jointed undifferentiated Cretaceous volcanic rock along the Northwestern end of the San Lorenzo Batholith granodiorite intrusion (Joyce, 2023).

PUERTO RICO HIGHWAYS & TRANSPORTATION AUTHORITY

Methodology (cont.)

PR-203 Km 2.5 slope

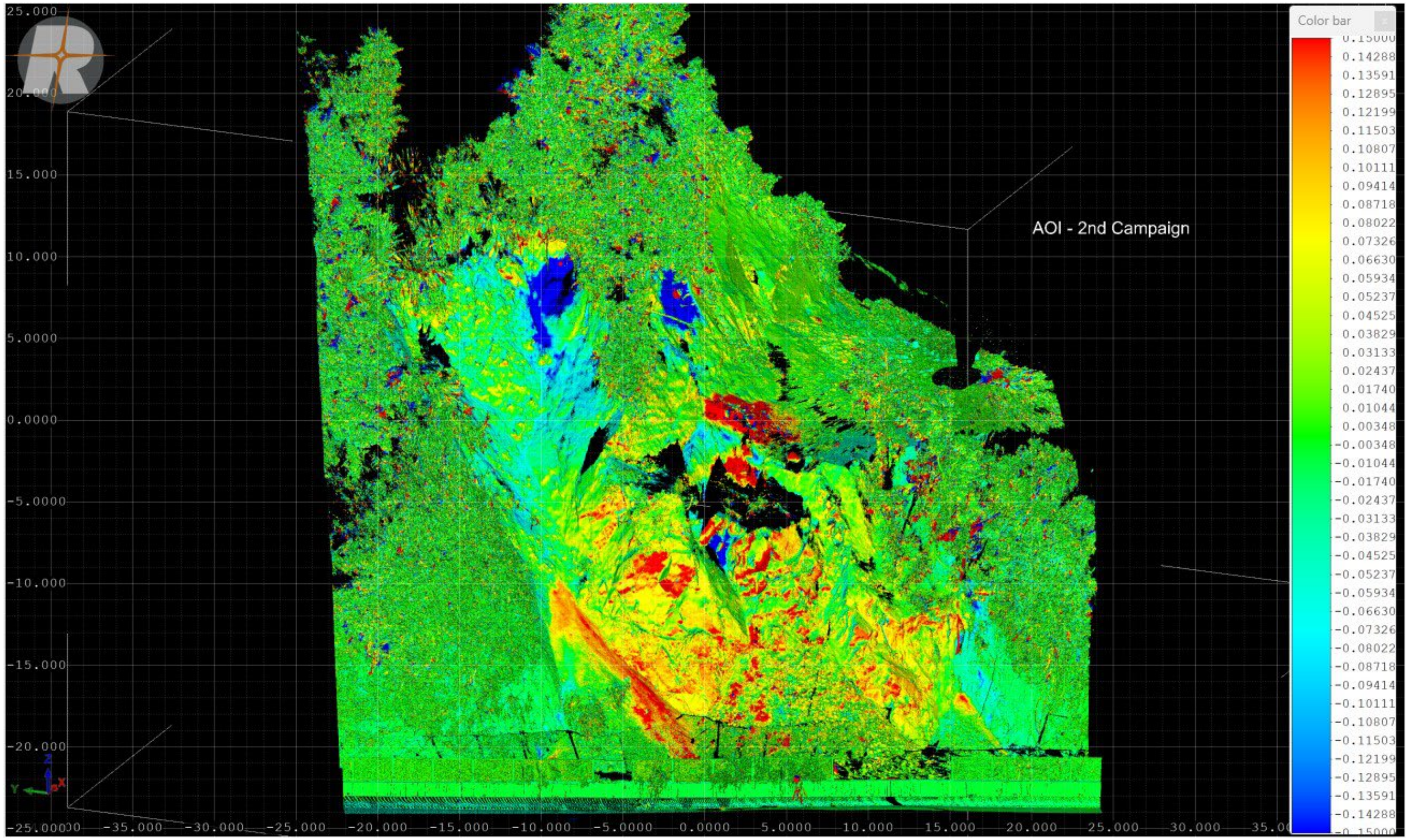
- 1st campaign
  - Used 50 mm flat reflectors and 100 mm cylindrical reflectors
  - RTK fixed @ 1.4 cm horizontal accuracy and 1.5 cm vertical accuracy
  - NTRIP Caster @ 11.5 miles
- 2nd and 3rd campaign
  - Added 150 mm flat reflectors

Methodology (cont.)

Scan Positions

PUERTO RICO
HIGHWAYS & TRANSPORTATION
AUTHORITY

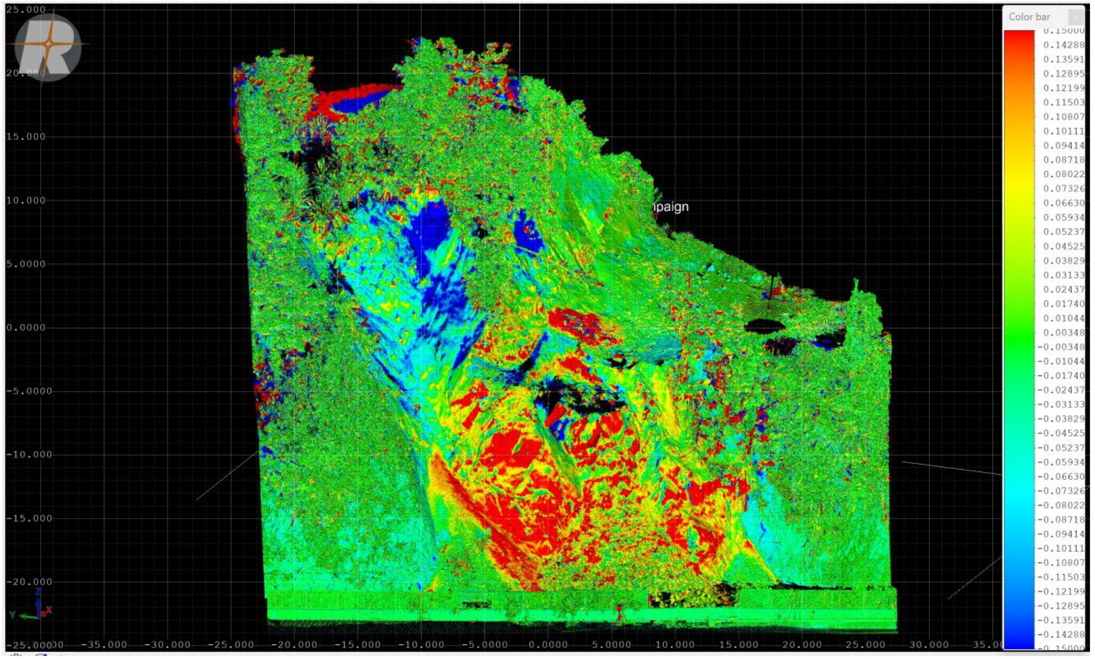
Discussion of Results



Cloud Comparison PR-203 1st vs 2nd

- Time lapse - 8 days
- Blue represents negative (decrease in volume) movements up to -0.497 m
- Red represents positive (increase in volume) movements 0.164 m

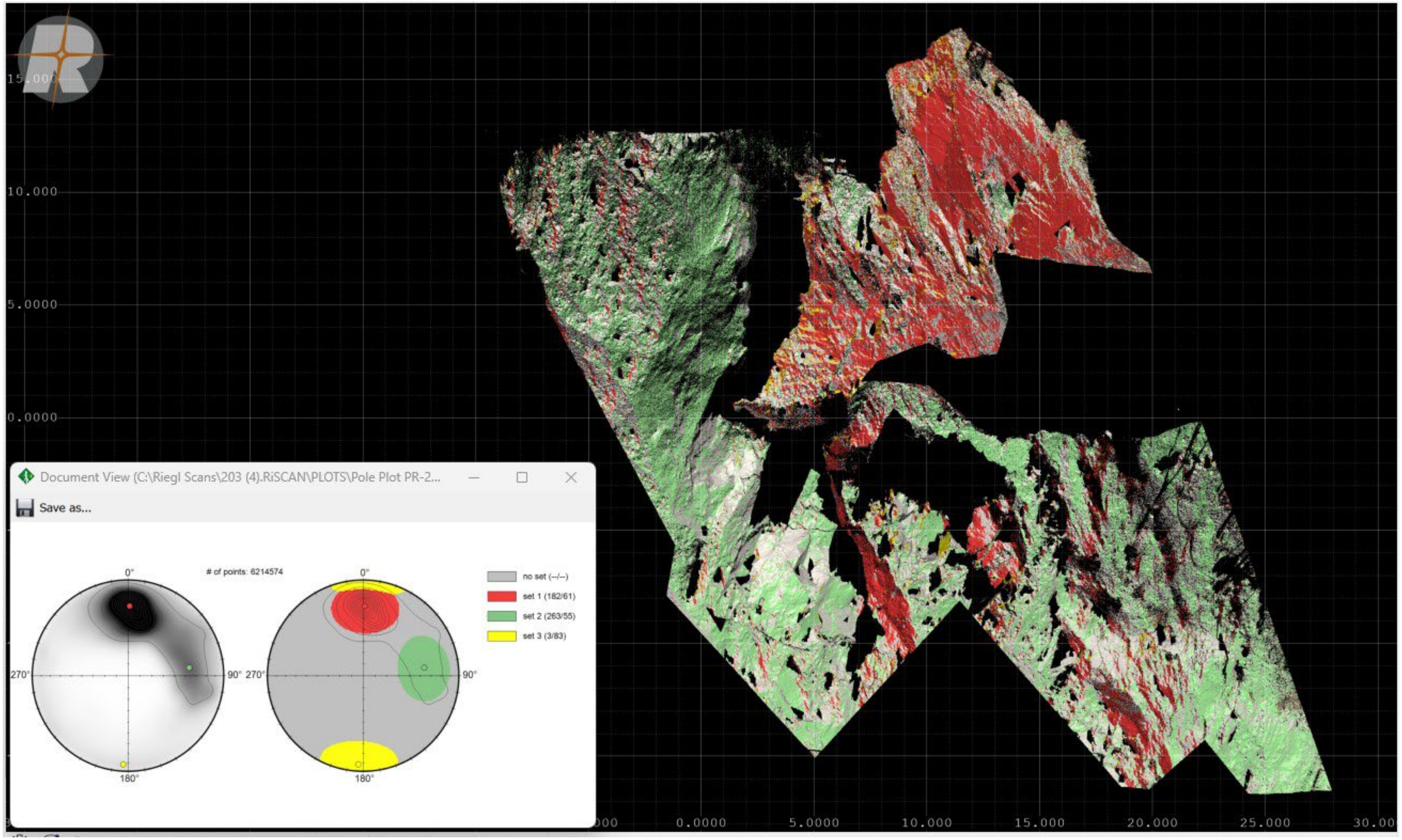
Discussion of Results (cont.)



Cloud Comparison PR-203 1st vs 3rd

- Time lapse – 15 days
- Negative (decrease in volume) movements up to -0.543 m
- Positive (increase in volume) movements 0.302 m

Discussion of Results (cont.)



Pole Plot PR-203

- 182/61
- 263/55
- 3/83

Discussion of Results (cont.)

Joyce, 2023 - “Point cloud joint set poles from the LiDAR scans from Figure 5 are plotted in blue along with the measured joint data on the stereonet in Figure 4. Intersection of the dominant joint set 1 plane with the measured data is coincident with measured joint set intersection at 248, 36°.”

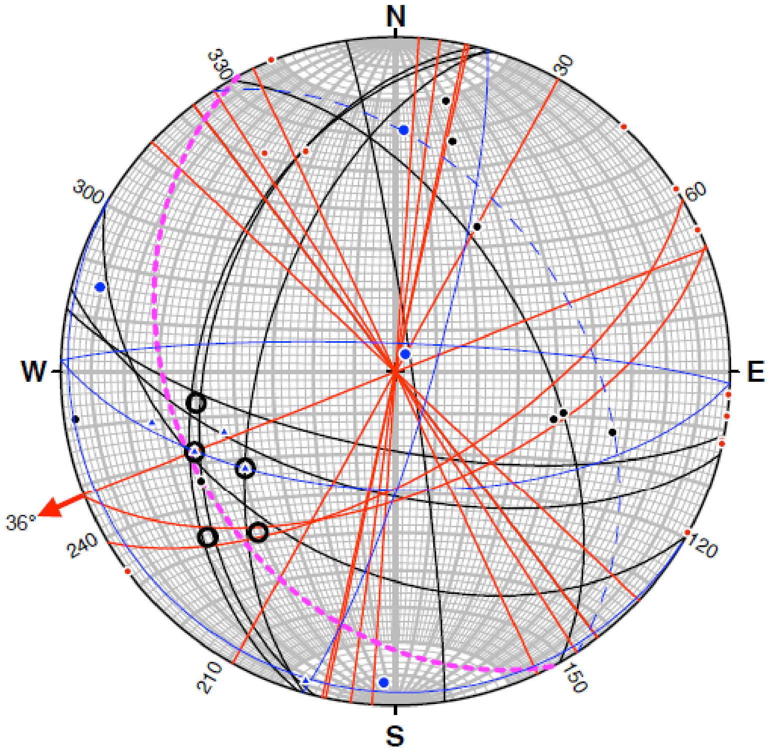
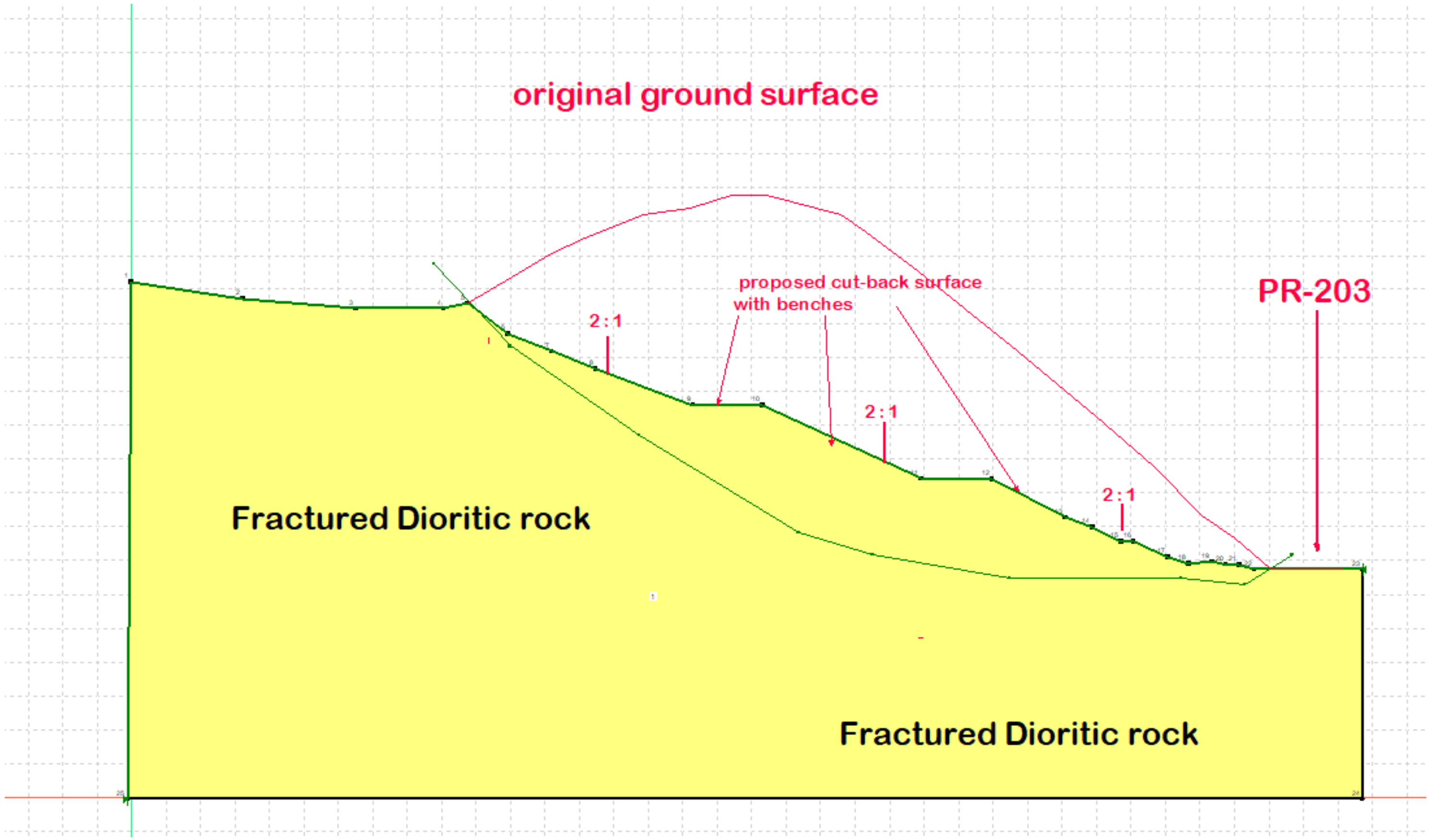


Figure 4 Stereographic projection of geologic and landslide structures
Red lines and curves fissure and escarpment measurements, circles-poles
Black curves systematic joint plane measurements, filled circles-poles
Blue curves planes drawn to Lidar data poles shown as circles, dashed curve-pole distribution, triangles-intersections between lidar and measured data
Black large open circles drawn to systematic joint set intersections
Magenta dashed curve is the slope angle and direction from topographic plan

Discussion of Results (cont.)

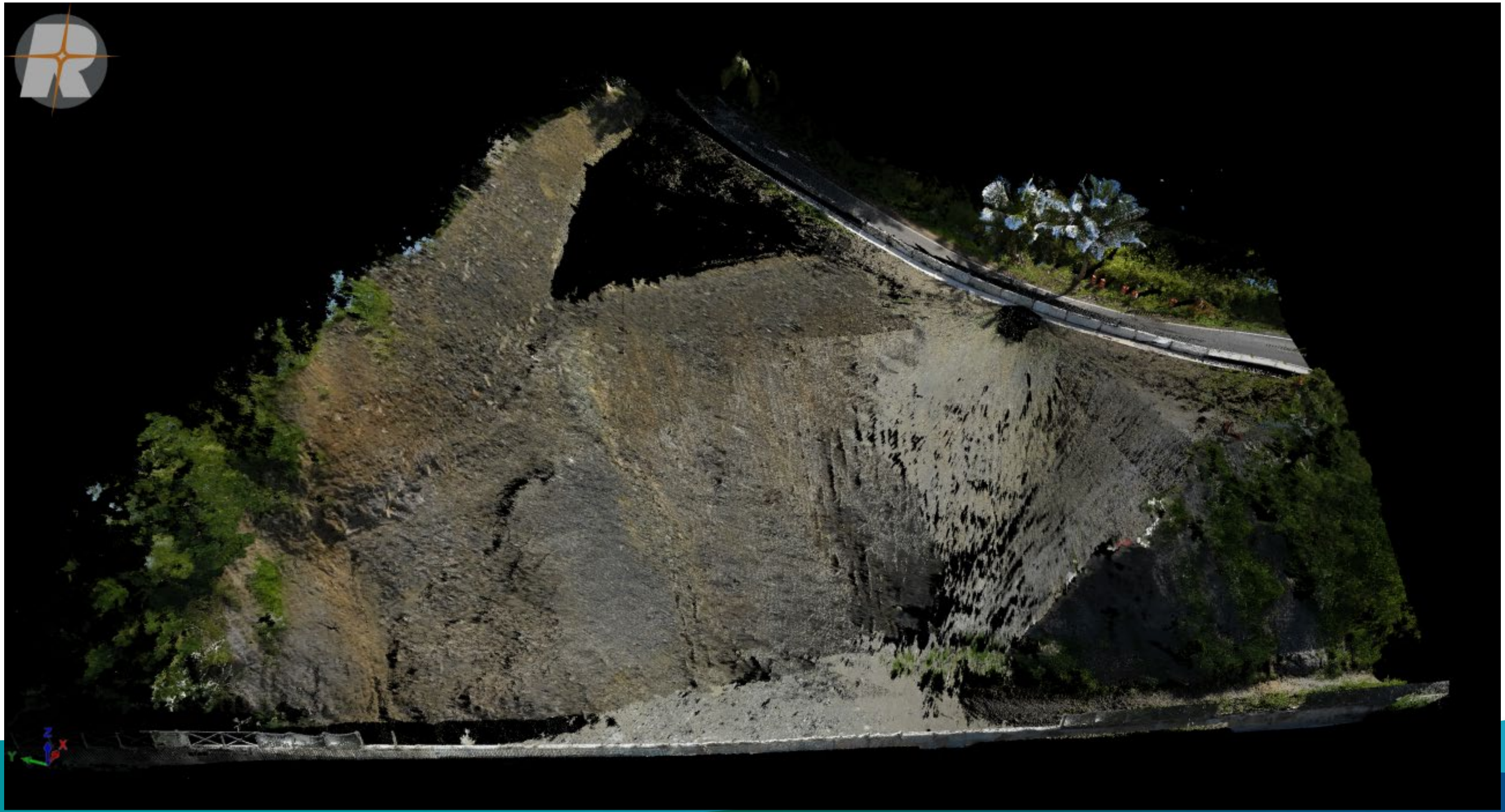
PR-203 Km 2.5 Proposed Remediation



Modified from Suelos, 2023.

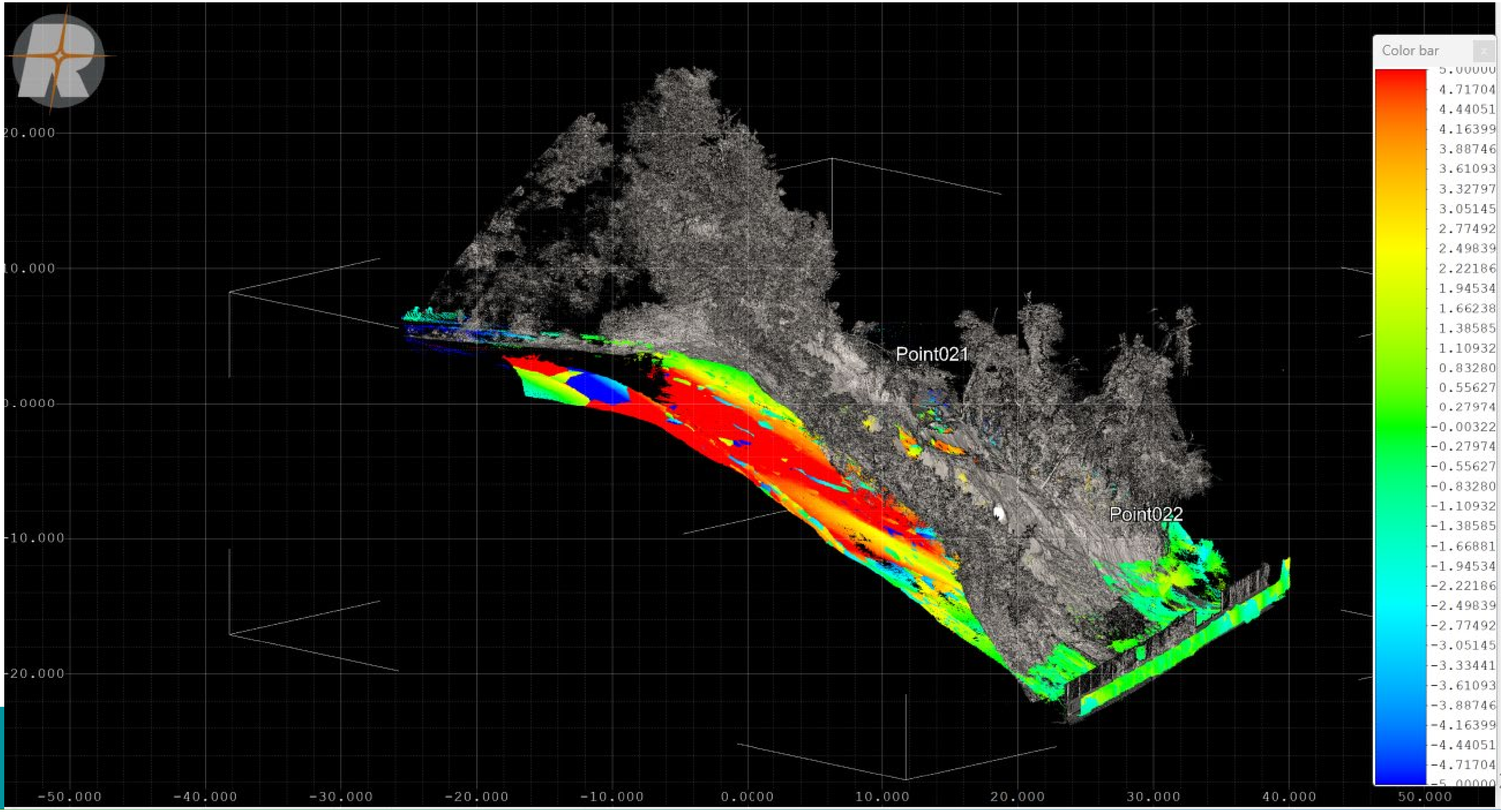
Discussion of Results (cont.)

PR-203 Km 2.5 Actual Remediation

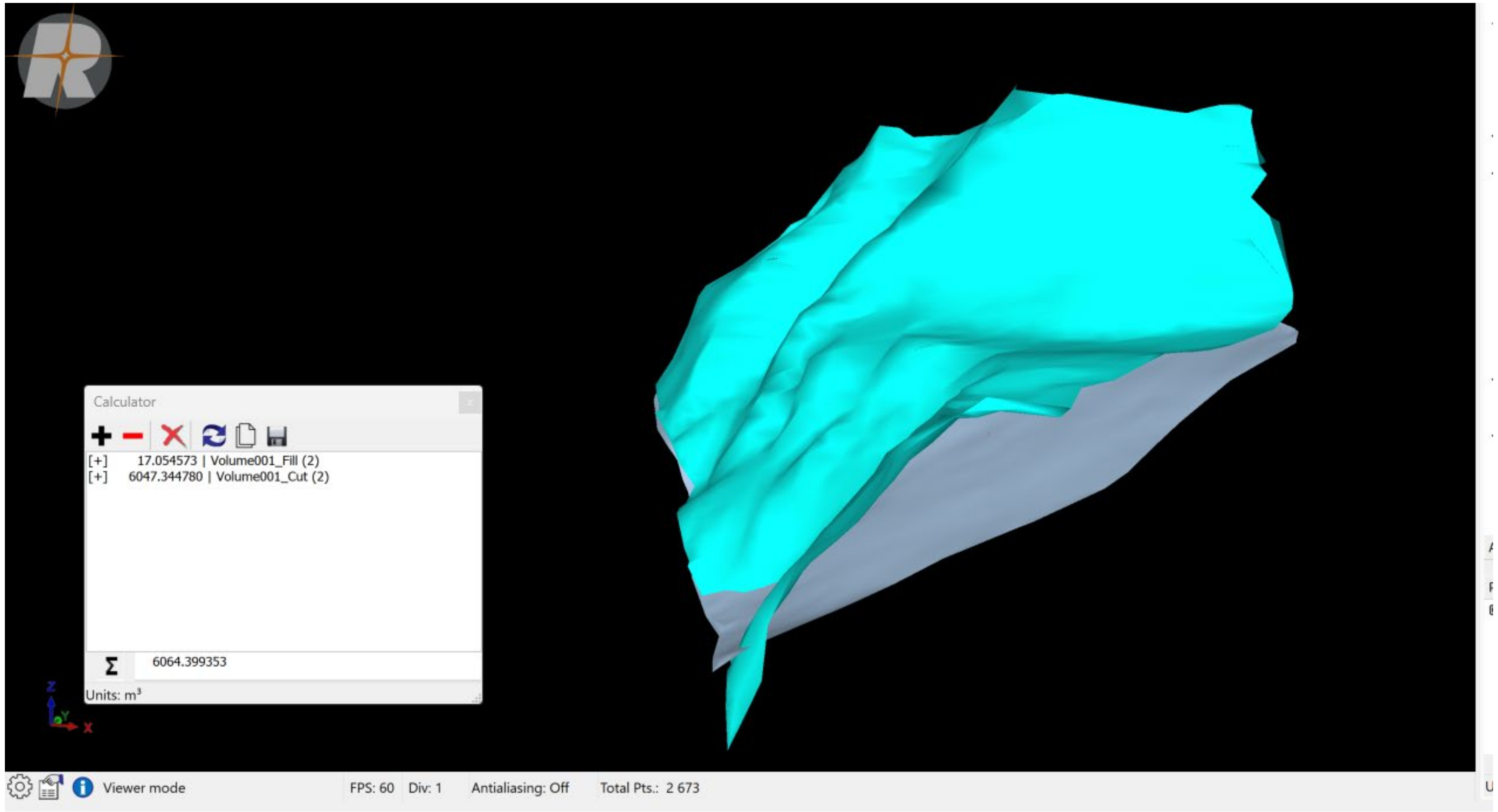


Discussion of Results (cont.)

Failed vs remediated slope



Discussion of Results (cont.)



Aqua – DTM of Initial surface
Gray – DTM of Remediated slope
Cut volume = 6,047 m^3

Discussion of Results (cont.)

Before Remediation

After Remediation

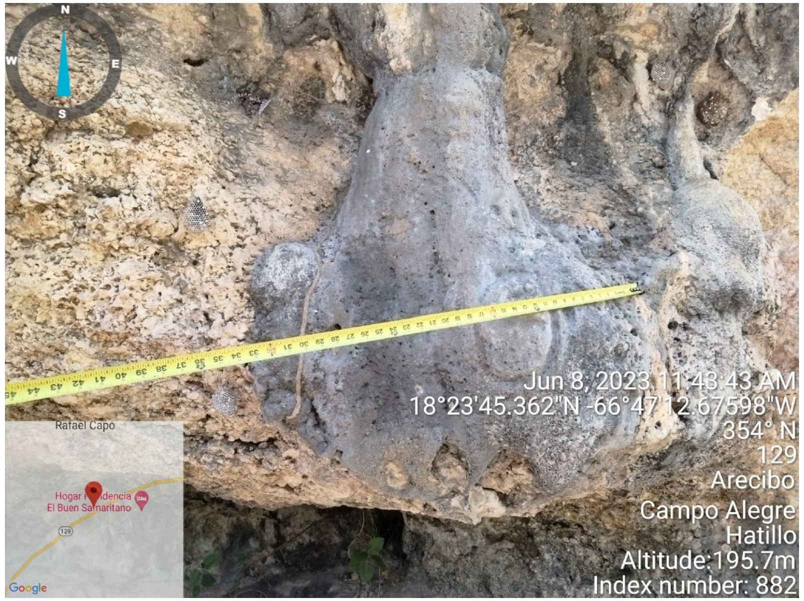
Documenting an Archaeological Petroglyph using TLS

Objectives

- Perform TLS measurements of a petroglyph found on a road widening project on PR-129, Km 10.9, Hatillo, west of San Juan, Puerto Rico
- Document the petroglyph, including its 3D geometry, external appearance, and GPS position,
- Compare TLS measurements of the petroglyph with the sketch prepared by Mr. Daniel O. Rendón (archeologist)
- Submit findings to the “Instituto de Cultura Puertorriqueña” (Puerto Rican Institute of Culture)

Documenting an Archaeological Petroglyph using TLS (cont.)

From Rendón, 2023

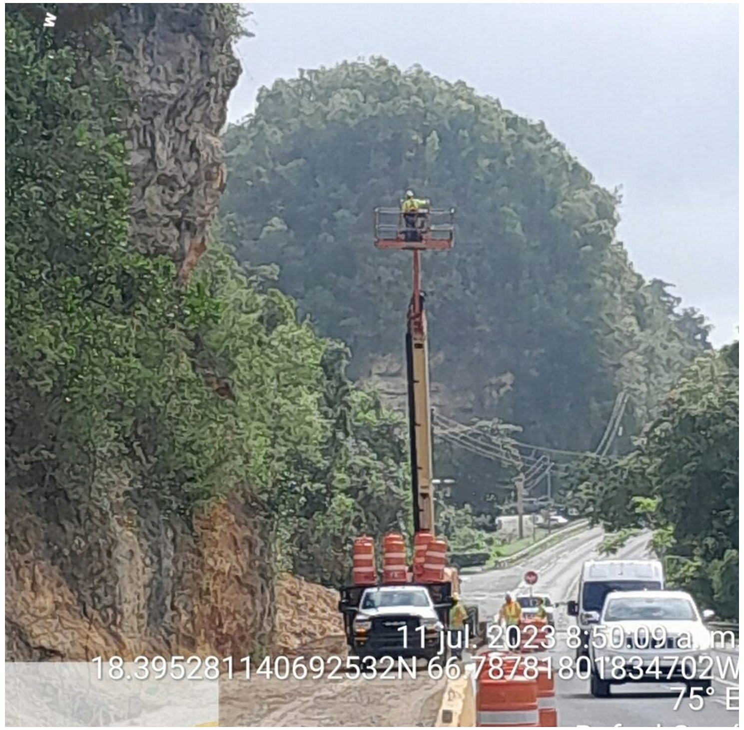


From Rendón, 2023

Documenting an Archaeological Petroglyph using TLS (cont.)

Articulated boom lift

(1200SJP JLG Ultra Boom)

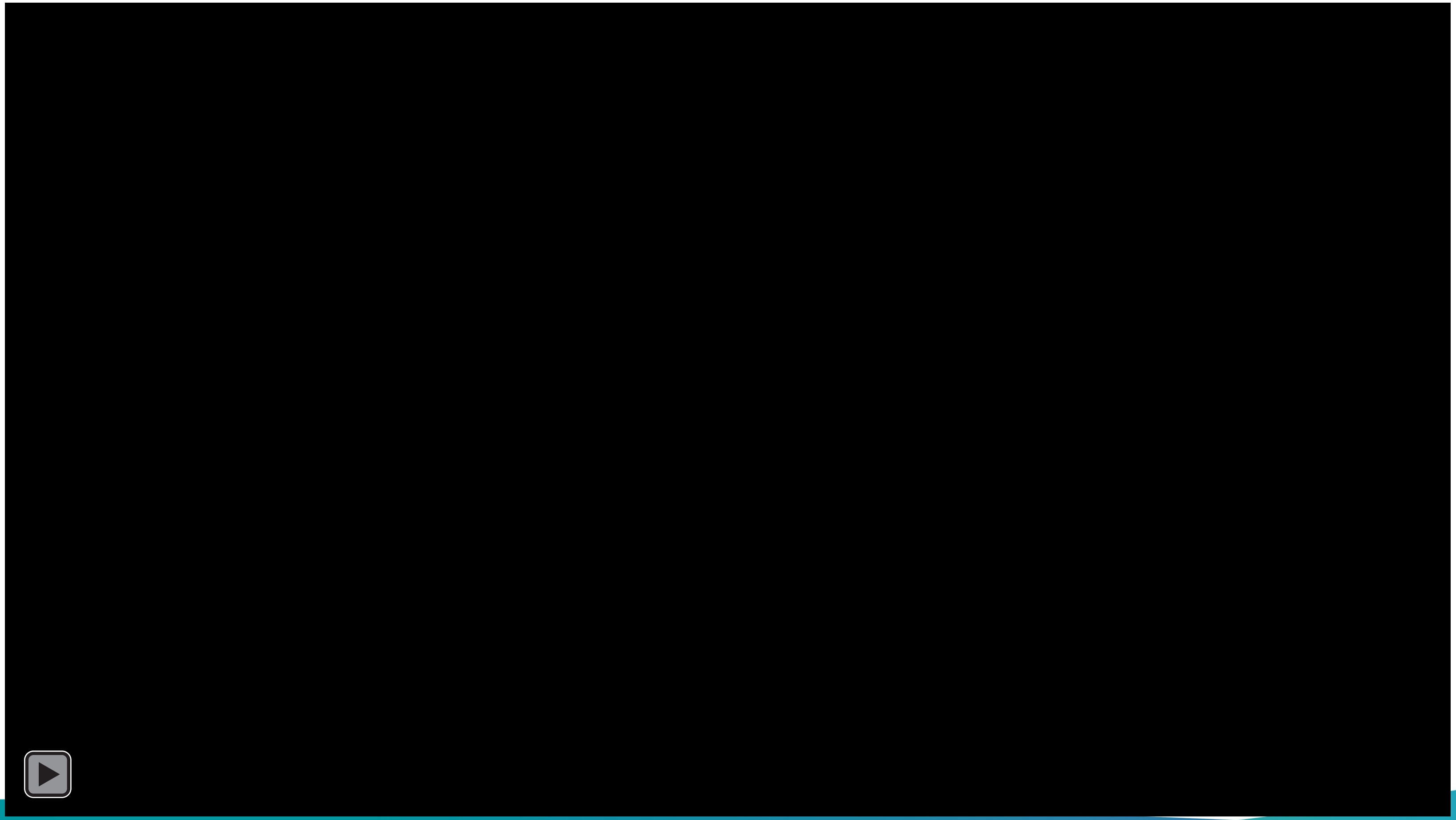


TLS strapped to the lift platform

Documenting an Archaeological Petroglyph using TLS (cont.)

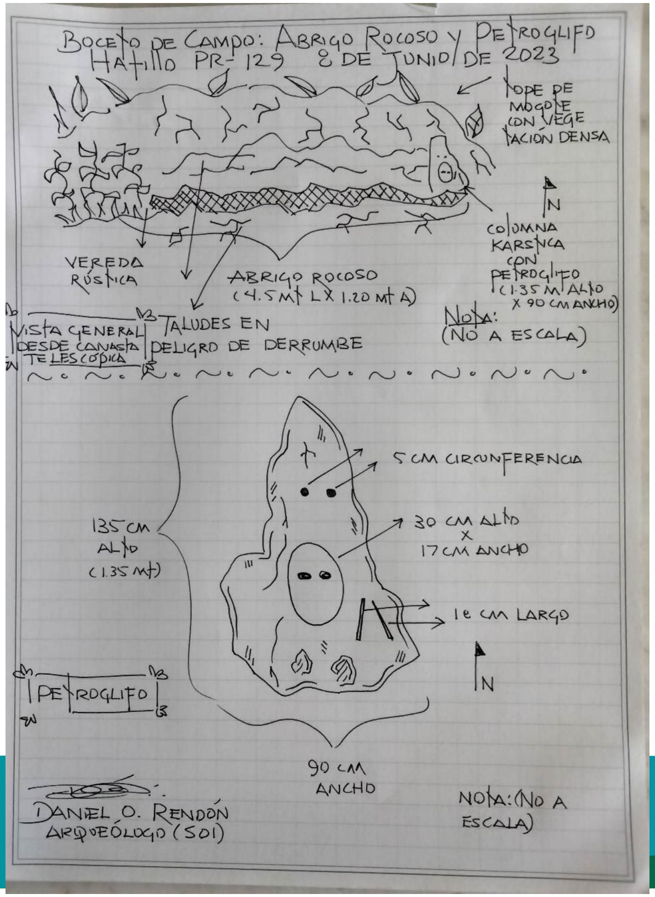
PUERTO RICO
HIGHWAYS &
TRANSPORTATION
AUTHORITY

Documenting an Archaeological Petroglyph using TLS (cont.)



Documenting an Archaeological Petroglyph using TLS (cont.)

Petroglyph sketch (from Rendón, 2023)



TLS Colored Point Cloud

Conclusions

- TLS data post-processed with the RiScan Pro software detected millimetric movements of aluminum plates under environmentally controlled conditions.
- TLS can be used to monitor rock slopes to detect movements during discontinuous measurement campaigns.
- TLS can be used to measure dip direction and dip of discontinuities.
- TLS can be used to document a petroglyph on a highway project.

Recommendations for Future Work

- Develop a Rock Monitoring System (RMS) in the PRHTA using TLS
- Monitor soil slopes using fixed markers inside and outside of the Area of Interest (AOI)
- Complement the Soils Engineering Office GAM efforts, specifically the Unstable Slope Management Program (USMP), by collecting TLS data for critical slopes.
- Develop an Early Warning System Protocol for critical slopes.

Acknowledgements

- Mr. José J. Rodríguez-Lozano, Chief Engineering Technician of the SEO, PRHTA, for his exceptional work as a public employee, exceeding his assigned duties.
- STGEC Committee
- STIC Committee
- Mr. Juan C. Rivera, PE, Highway Engineer, Puerto Rico and US Virgin Island Division Office, FHWA

References

- Joyce, James (2023). Geologic Report PR-203/932-San Lorenzo, PR.
- Kęsik, J.; Miłosz, M.; Montusiewicz, J.; Israilova, N. (2022). Documenting Archaeological Petroglyph Sites with the Use of 3D Terrestrial Laser Scanners—A Case Study of Petroglyphs in Kyrgyzstan. Appl. Sci. 2022, 12, 10521. https://doi.org/10.3390/app122010521
- Maerz, N. H., Boyko, K. J., Hill, B. J., Herries, B. J., Hopkins, M., & Lu, C. (2016). Displacement measurements of slow moving landslide using sub-mm LiDAR scanning. In Proceedings of the 67th Highway Geology Symposium, July, 2016, Colorado Springs, Colorado.

References (cont.)

- Rendón, Daniel O. (2023). Proyecto de Emergencia – Desprendimiento de Talud, PR-129, Km 10.9, Hatillo, Puerto Rico
- Romero, R. J. (2019). "Development of LiDAR assisted terrestrial radar interferometry for rock deformation monitoring". Doctoral Dissertation.
- Rosenblad, B. L., Gómez, F., Loehr, J. E., & Gilliam, J. (2016). Observations of Rockfall and Earth Slope Movements using Ground-Based Interferometric Radar. In Proceedings of the 67th Highway Geology Symposium, July 2016, Colorado Springs, Colorado.

PUERTO RICO
HIGHWAYS & TRANSPORTATION
AUTHORITY

Thank you!